October 2020 Vol.19 No.10 *ISSN 1582 - 9596*

Environmental Engineering and Management Journal

An International Journal

Founding Editor: **Matei Macoveanu**

Editor-in-Chief: **Maria Gavrilescu**

Guest Editor: **Fabio Fava**

Green and Circular Economy
ECOMONDO 2019

“Gheorghe Asachi” Technical University of Iasi

Environmental Engineering and Management Journal

Environmental Engineering and Management Journal encourages initiatives and actions concerning the improvement of education, research, marketing and management, in order to achieve sustainable development. This journal brings valuable opportunities for those offering products, technologies, services, educational programs or other related activities, creating thus a closer relation with the request of the market in the fields of environmental engineering, management and education.
This journal address researchers, designers, academic staff, specialists with responsibilities in the field of environmental protection and management from government organizations (central and local administrations, environmental protection agencies) or from the private or public companies. Also, graduates of specialization courses or of the Environmental Engineering and Management profile, as well as other specialists may find in this journal a direct linkage between the offer and request of the market concerned with the protection of the environment and the administration of natural resources in the national and international context.
The journal was conceived as a means to develop scientific and technical relationships between people who offer and request solutions for environmental protection and conservation of natural resources, creating thus the premises to enhance the transfer of technology and know-how, the confirmation and implementation of ecological products and services.
Taking into consideration these aspects, we gladly welcome any persons or companies which correspond to the above-mentioned purposes and objectives to use our journal to identify potential collaborators.

For subscriptions and orders please contact us at:
OAIMDD (*Academic Organization for Environmental Engineering and Sustainable Development*), 73 Prof. Dimitrie Mangeron Blvd., PO 10, Box 2111, 700050 Iasi, Romania, CIF: 10150285

Phone/Fax: 0040-232-271759
E-mail: brindusa.sluser.at.gmail.com, mgav_eemj.at.yahoo.com

In LEI:
ALPHA BANK ROMANIA (ABR)
SWIFT Code: BUCUROBU
IBAN: RO87BUCU1032235333663RON
Beneficiary: OAIMDD-EEMJ
Address: PO 10, Box 2111, 700050 Iasi, Romania

In EURO:
ALPHA BANK ROMANIA (ABR)
SWIFT Code: BUCUROBU
IBAN: RO79BUCU1031215940036EUR
Beneficiary: OAIMDD-EEMJ
Address: PO 10, Box 2111, 700050 Iasi, Romania

Department of Environmental Engineering and Management and
EcoZone Publishing House - O.A.I.M.D.D.
73 Prof. Dimitrie Mangeron Blvd., 700050, Iasi, Romania
Phone/Fax: 0040-232-271759

Environmental Engineering and Management Journal

Environmental Engineering and Management Journal

Environmental Engineering and Management Journal is included and indexed in:
CABI
Chemical Abstracts Service/SciFinder (ACS) (since 2002)
EBSCO Database (since 2002)
EVISA
ICAAP (International Consortium for Advancement of Academic Publications)
Index Copernicus Journal Master List (**ICV/2015=156.46**)
Journal Citation Reports® **2018** Edition (**IF=1.186**), (*Environmental Sciences*, Ranked **211 out of 250**; 5-Year Impact Factor: 0.936; Article Influence® Score: 0.080; Immediacy Index: 0.159; Normalized eigenfactor: 0.19; **Quartile: Q4**)
MedSci
ProQuest (since 2002)
The National University Research Council (RO)
Science Citation Index Expanded™
SJR (SCImago Journal&Country Rank) (*Environmental Sciences*, **SJR index/2019= 0.322**; Ranked **865 out of 1660**, Quartile **Q3**, **H=33,** *Environmental Engineering:* Ranked **86 out of 184, Quartile Q3**; *Management, Monitoring, Policy and Law:* Ranked **200 out of 349,** Quartile **Q3**; *Pollution*, Ranked **79 out of 151; Quartile: Q3**)
SCOPUS (since 2002), **CiteScore/2019=1.80, SNIP index/2019=0.796**
ISI Master Journal List, Web of Science® (**H=33**)

Home page: *hiip://www.eemj.icpm.tuiasi.ro;*
hiip://www.eemj.eu

Full text: *http://www.ecozone.ro, hiip://www.eemj.eu*

Founding Editor: Matei Macoveanu, Iasi (RO)
Editor-in-Chief: Maria Gavrilescu, Iasi (RO)

Environmental Engineering and Management Journal is edited by
***Gheorghe Asachi* Technical University of Iasi and *EcoZone* Publishing House of the *Academic Organization for Environmental Engineering and Sustainable Development* (O.A.I.M.D.D.)**

Editorial and Production Office:
Department of Environmental Engineering and Management – *Cristofor Simionescu* Faculty of Chemical Engineering and Environmental Protection and EcoZone - O.A.I.M.D.D., 73 *Prof. Dimitrie Mangeron* Bd., 700050 Iasi, Romania
Phone: +40-232-278680, ext. 2259, 2137
Fax: +40-232-271759
e-mail: eemjournal.at.yahoo.com, eem_journal.at.yahoo.com, eemjeditor.at.yahoo.com, eemj_editor.at.yahoo.com, eemjournal.at.gmail.com, eemj.editor.at.gmail.com, eemj.office.at.gmail.com

Published 12 issues per year, **under the aegis of the *Gheorghe Asachi* Technical University of Iasi, Romania**
by *EcoZone* Publishing House of the *Academic Organization for Environmental Engineering and Sustainable Development* (O.A.I.M.D.D.), **http://www.ecozone.ro**

Annual subscription rate 2019 (12 issues)

	Print:	Electronic full access:	Print+Electronic:
EURO	575 per volume	575 per year	1000 per volume/year
Individual costs			
EURO	55 per issue	45 per issue	

Order directly to the Editorial Office, 73 *Prof. Dimitrie Mangeron* Bd., 700050 Iasi, Romania
Phone/Fax: Fax: +40-232-271759, e-mail: brindusa.sluser.at.gmail.com, eemj.office.at.gmail.com

Electronic, full text: Order or purchase on-line at: **www.eemj.eu, www.ecozone.ro**

Bank account (EURO):
ALPHA BANK ROMANIA (ABR)
SWIFT Code: BUCUROBU,
IBAN: RO79BUCU1031215940036EUR
Beneficiary: OAIMDD-EEMJ, Address: PO 10, Box 2111, 700050 Iasi, Romania

Bank account (LEI):
ALPHA BANK ROMANIA (ABR), IBAN: RO87BUCU1032235333663RON,
Beneficiary: OAIMDD-EEMJ

Environmental Engineering and Management Journal October, Vol.19, No. 10, 1645-1926
http://www.eemj.icpm.tuiasi.ro/; hiip://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

CONTENTS

Environmental Engineering and Management Journal

October 2020, Vol.19, No. 10, 1645-1646
http://www.eemj.icpm.tuiasi.ro/; hiip://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

EDITORIAL

Green and Circular Economy ECOMONDO 2019

23th International Trade Fair of Material & Energy Recovery and Sustainable Development

The papers collected in this Special Issue of *Environmental Engineering and Management Journal* were presented as lectures or posters at the scientific and technical conferences hosted by *Ecomondo 2019 held* in Rimini, Italy, during 5-8 November 2019 (http://en.ecomondo.com).

Ecomondo is the one of largest European exhibitions in the field of *Green and Circular Economy*, with over than 100,000 delegates from 60 different nations and 1300 companies exhibiting their products and processes in 123,000 square meters. It is hosting over than 100 conferences and workshops, ensuring a weighted and rewarding balance between sales dimension and technical-scientific dimension, with extensive room dedicated to research and innovation, education and training and international networking.

As with the previous editions, the aim of *Ecomondo 2019* was to explore recent industrial advances and opportunities in industrial technical waste production reduction, recycling and exploitation; sustainable agrifood and wood chains, biowaste collection and exploitation via integrated biorefinery schemes, with the production of biobased chemicals, materials and biofuels, including methane; industrial eco-design; industrial symbiosis, renewable and critical resources; water resources monitoring, protection and sustainable use in the civil and agrifood sectors; wastewater treatment and valorization with nutrients recovery and water reuse; marine resources protection and sustainable exploitation; sustainable remediation of contaminated sites, ports and marine ecosystems; indoor and outdoor air monitoring and clean up; and circular and smart Cities.

Some of the international workshops were focused on the emerging trends in the in the circular economy domains and on the role of digitalization and industry 4.0 enabling technologies in process efficiency, eco-design and waste collection in the major industrial value chains. Some other workshops were focused on the technical and regulatory constrains currently affecting the implementation of circular economy value chains in the sectors of electronic and electric products, automotive, construction and demolition, packaging materials and textile and fashion. A special room has been dedicated to the recycling of plastic waste, biodegradable plastics and the monitoring, prevention and mitigation of marine litter. Finally, *Ecomondo 2019* dedicated a particular attention to the main challenges and needs of the Mediterranean macro-region, addressing, via dedicated workshops, the priorities of the area associated with the water scarcity, the Mediterranean Sea contamination (also due to marine litter) and the blue and sustainable growth of the area.

Ecomondo 2019 hosted about 100 conferences, more than 900 oral communications and almost 100 papers. This special issue contains some of such papers and provides some of the key information presented and discussed in the frame of some of the most relevant technical and scientific conferences of 2019 edition of Ecomondo.

We believe that this collection of papers will be useful to people who could not visited and participate in *Ecomondo 2019*. It is primarily towards them but it also aspires to provide permanent records in the promotion, adoption and implementation of the major priorities and opportunities of the green and circular economy in Europe and in the Mediterranean basin, with the conversion of some of the key local environmental challenges into new opportunities for a green and sustainable growth of the areas mentioned.

For additional info, please refer to the following links:

https://en.ecomondo.com
http://en.keyenergy.it/
http://en.cittasostenibile.net/

Guest editor:
Fabio Fava, PhD, Professor, *Alma Mater Studiorum - Università di Bologna*, Bologna, Italy

Fabio Fava, born in 1963, is Full Professor of "Industrial & Environmental Biotechnology" at the School of Engineering of University of Bologna since 2005.

F. Fava published about 280 scientific papers, 180 of which on medium/high IF peer-review international journals of industrial and environmental biotechnology. He has 7733 overall citations, a H-index of 50 and an i10 index of 127 (Google Scholar) along with 180 papers quoted by Scopus. He is actively working in the fields of environmental, industrial and marine biotechnology and of the Circular Bioeconomy in the frame of a number of national projects and collaborative projects funded by the European Commission. Among the latter, he coordinated the FP7 collaborative projects NAMASTE, on the integrated exploitation of citrus and cereal processing byproducts with the production of food ingredients and new food products, and BIOCLEAN, aiming at the development of biotechnological processes and strategies for the biodegradation and the tailored depolymerization of wastes from the major oil-deriving plastics, both in terrestrial and marine habitats. He also coordinated the Unit of the University of Bologna who participated in the FP7 collaborative projects ECOBIOCAP and ROUTES (on the production of microbial and biodegradable polymers from different organic waste and food processing effluents), MINOTAURUS and WATER4CROPS (on the intensified bioremediation of contaminated waste- and ground- water and the integrated valorization and decontamination of wastewater coming from the food processing industry and biorefineries), and ULIXES and KILL SPILL (on the development of strategies for intensifying the *ex situ* and *in situ* bioremediation of marine sediments contaminated by (chlorinated)hydrocarbons and microplastics and the isolation and industrial exploitation of microbes from such contaminated matrices). F. Fava served and is serving several national, European and international panels, by covering the following positions:

- Italian Representative in the Horizon2020 Programme Committee of Societal Challenge 2: European Bioeconomy Challenges: Food Security, Sustainable Agriculture and Forestry, Marine, Maritime and inland water research" (European Commission, DG RTD) (2013-);
- Italian Representative in the "States Representatives Group" (SRG) of the Public Private Partnership "Biobased Industry" (PPP BBI JU) (Brussels) (2014-); he is chairing the SRG since October 2018;
- Italian Representative in the BLUEMED WG of the EURO-MED Group of Senior Officials (EU Commission DG RTD and Union for Mediterranean) (2017-);
- Italian Representative in the initiative on sustainable development of the blue economy in the western Mediterranean the "Western Mediterranean Initiative" WEST MED, promoted by the EU Commission (DG MARE) in close cooperation with 10 countries of the area (2016-);
- Member of the "Working Party on Biotechnology, Nanotechnology and Converging Technologies" of the Organization for Economic Co-operation and Development (OECD, Paris) (2008-);
- Chair (2011-2013) and currently Deputy Chair of the "Environmental Biotechnology section" of European Federation of Biotechnology (EFB) (2013-).

Finally, he is the scientific coordinator of the International Exhibition on Green and Circular economy ECOMONDO held yearly in Rimini (Italy)

Environmental Engineering and Management Journal October 2020, Vol. 19, No. 10, 1647-1656
http://www.eemj.icpm.tuiasi.ro/; hiip://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

RESEARCH HUB FOR AN INTEGRATED GREEN ENERGY SYSTEM REUSING SEALINES FOR H_2 STORAGE AND TRANSPORT

Ilaria Antoncecchi[1,2*], Giada Rossi[1], Marzia Bevilacqua[1], Roberto Cianella[1], Giuseppe Vico[1,3], Sergio Ferrero[3], Felice Catania[3], Marco Pacini[4], Nicola Mondelli[4], Marzia Rovere[5], Marco Bibuli[5], Diego Vittorini[6], Davide Di Battista[6]

[1]Italian Ministry of Economic Development, Via Molise, 2, 00187, Rome - Italy
[2]Research on Energy System, S.p.A., Via R. Rubattino, 20134 Milan - Italy
[3]Polytechnic of Turin, Corso Duca degli Abruzzi, 24, 10129 Turin - Italy
[4]Rosetti Marino Group of Companies Via Trieste, 230, 48122 Ravenna - Italy
[5]National Research Council of Italy, ISMAR and INM, Via Piero Gobetti, 101, 40129 Bologna & Via De Marini, 6, 16149 Genoa - Italy
[6]Department of Industrial and Information Engineering and Economics, University of L'Aquila, Via G. Gronchi, 18, 67100 L'Aquila – Italy

Abstract

In this paper, we propose innovative solutions for reusing an inactive offshore gas platform and its associated infrastructures as a scientific research hub, where an integrated energy system and innovative environmental monitoring methods are envisaged. To this end, the Azalea A platform, located in the northern Adriatic Sea, is considered a good pilot site. This study analyzes the engineering solutions on Azalea A for the combined production of solar and wind energy coupled with hydrogen production from seawater electrolysis. It analyzes the potential for storage and transport on land of the produced hydrogen using the sealines connected to the platform. However, this study does not deal with the current structural conditions of the platform (corrosion, stability etc.), which should be evaluated before these solutions are put into practice.

The main outcomes of this work consist in a feasibility study for the reuse of existing infrastructures as a self-sufficient research hub using green energy systems, which include considerations about the measures needed to ensure the protection of the marine environment. Data show a positive feedback about the technical feasibility of the proposal in safety conditions. Furthermore, encouraging outcomes derive also by the economic evaluation that estimates sustainable costs comparing to those implicated with the decommissioning of the infrastructures in the order of tens millions euro. In addition, the proposed reuse seems to be a good opportunity to promote both energy transition toward renewable energy systems and environmental protection, avoiding decommissioning impacts and promoting an innovative monitoring program for the Adriatic Sea.

Key words: blue growth, offshore monitoring, renewable energy, reuse, technology

Received: February, 2020; Revised final: July, 2019; Accepted: July, 2019; Published in final edited form: October, 2020

1. Introduction

In the framework of the BlueMed Initiative, the SEALINES Start-up Action created a network of Mediterranean partners with the aim of contributing to identify best solutions such as standards, technologies, practices to reduce anthropogenic impacts on the marine environment supporting a healthy, productivity and resilient Mediterranean Sea. The main outcome of the Start-up Action is a proposal for a feasibility study on the conversion of a disused gas platform and its infrastructures into a research hub where a renewable integrated energy system would be tested.

* Author to whom all correspondence should be addressed: e-mail: ilaria.antoncecchi.ext@MiSE.gov.it; Phone: +39 3453232152

In detail the proposal consists in installing and testing offshore plants for the production of renewable energy (solar and wind) in an integrated system that foresees also storage and inland transportation of energy and hydrogen, reusing a hydrocarbon platform that would be decommissioned if not converted.

To this end, the Azalea A platform, located in the northern Adriatic Sea, has been selected because it may be subject to reuse or decommissioned (art. 5 of 15 February 2019 Ministerial Decree, D.M., 2019), as identified in the National Bulletin for hydrocarbon and geothermal resource published by the Italian Ministry of Economic Development (hereinafter MiSE) (Coppi et al., 2019).

This study analyzes the engineering solutions for the combined production of solar and wind energy coupled with a hydrogen production system by seawater electrolysis; it also analyzes the storage and transport on land of the produced hydrogen in the sealines connected to the platform. Since sealines were used for the transport of natural gas they can be reused for the transport of hydrogen (liquid or gaseous) under similar conditions of pressure and temperature. However, before they can be reused in practice, it would be necessary to check the current technical and structural conditions of the infrastructure.

At present, wind and photovoltaic (PV) power are among the most cost-effective renewable technologies, particularly in developed Countries. The interest towards offshore applications has experienced a spike during the last decade, mostly due to the extensive Research and Development activity, resulting in higher efficiency of components (e.g. turbines, gearbox components for wind; solar cells material, behavior at high operating temperatures for photovoltaic) and eventually in a higher attainable power output for the plant. This feature, along with increasing components durability, fail-safe, is key for a growing confidence of investors and stakeholders, on both the private and public scale. Nonetheless, a major hurdle to the full development of offshore wind and PV technology is represented by the lack of a concerted regulatory framework on an international basis. Despite the general trend towards more rational and expedite decommissioning and licensing process, the need to comply with maritime spatial planning and guidelines for the marine environment and landscape protection still prevent the offshore wind and PV technology from succeeding on a large-scale. In this regard, the re-use of existing offshore infrastructures would simplify the installation process and facilitate the implementation procedures and management operations.

The combined production of solar and wind power, as well as energy storage and transportation, is here suggested to be coupled with hydrogen generation systems from seawater. This addition can enhance the proposal for reuse, since it can mitigate the limits related to volatility and randomness of renewable energies. Hydrogen can be easily produced with high response time exploiting the electrical energy produced on board the platform (Hernández-Gómez et al., 2020) and it can be stored in bottles or in the sealines that will act as energy buffers. Hydrogen transportation to inland would be provided by the same sealines and sold as technical gas for special applications such as food technology, electronics industry or utilized for CO_2 abatement through methanation processes. A layout of the possible integrated energy system is provided in Fig. 1.

A further advantage of the offshore installation is represented by the larger storage capacity augmented by the sealines with respect to onshore plants, whose size, operating conditions and location are expected to meet stringent requirements in terms of safety. The larger storage capacity allows to reach the optimum trade-off, between the direct sale of Hydrogen to customers and its use as a storage medium to re-generate electricity at a time when it is more valuable.

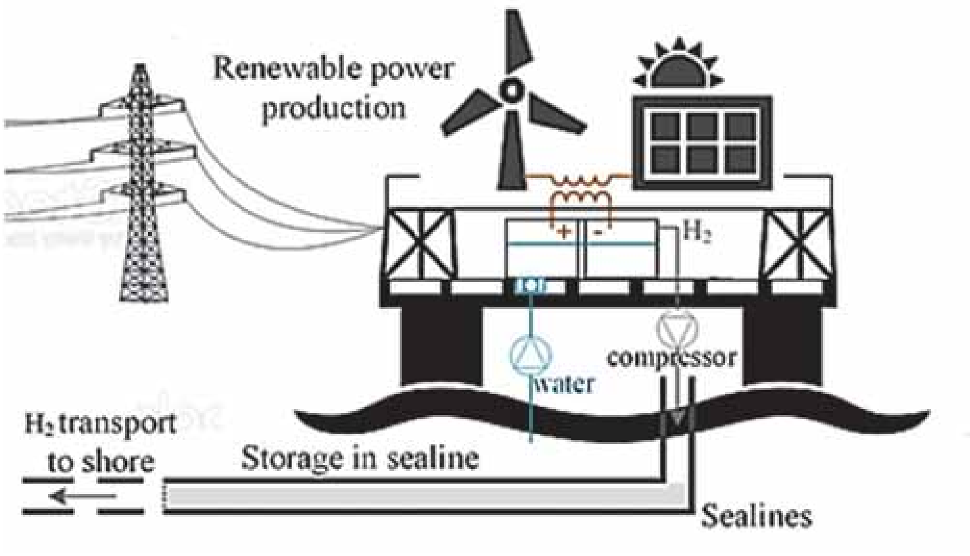


Fig. 1. Layout of the hypothesized integrated energy system.

The idea of converting a no longer productive platform, rather than decommissioning it, is certainly virtuous in terms of benefits from the economic, environmental and social point of view, as a preliminary study revealed (Grandi et al., 2017).

The decommissioning of offshore infrastructures is very sensible and several opportunities have been proposed to reuse them as artificial reef, which is the most explored one (Djokic, 2017), or for loading and unloading Liquefied Natural Gas (LNG) (Camporeale et al., 2017). However, other integrated ways of reusing the offshore infrastructures can be more effective (Rabindran et al., 2011). The possibility to reuse not only the main installation, but also the ancillary facilities (i.e. sealines) is not widely considered in this panorama. In particular, reuse of pipelines is widely studied for CO_2 transportation to Carbon Capture and Sequestration sites and Enhanced Oil and Gas Recovery options (Onyebuchi et al., 2018) and it can have good reliability, if regular maintenance and pigging operations are performed (Kaiser, 2020). Thus, the novelty introduced by this paper is the integrated reuse of a platform structure and sealines for energy production, transformation, electricity grid connection and hydrogen transportation or storage, avoiding the high cost of hydrogen pipelines (Gondal, 2019). In this regard, a further degree of innovation is represented by the use of the abandoned sealines not only for gas transportation, but also storage; this solution would enhance the yearly production, by decoupling the energy demand from the renewable energy availability, which is affected by seasonal and daily constraints.

Furthermore, this feasibility study proposes to use the platform as a research hub from which deploying marine environmental monitoring programs in the surroundings of the platform to verify the environmental impact of the activities using innovative technological systems.

2. Description of the pilot case in the northern Adriatic Sea

The general characteristics of the Azalea A platform are briefly described hereafter. Azalea A is a bitubular platform for gas extraction located 16 km off the coastline of the town of Rimini within the 12 nautical mile limit of the territorial waters in 19 meters water depth. Azalea A is 17 meters high above sea level (a.s.l.) and has a rectangular shape 19 x 4 meters; it was installed in 1984 as part of the mining concession A.C8.ME in the Adriatic Sea linked to the Rubicone central on land. Azalea A is connected to the nearby Anemone Cluster platform by two sealines that are no longer in operation. The end points of the sealines are available from the WebGis of MiSE (IMED, 2019) with some preliminary information about the name of the sealines, their geometry and their past use (**Error! Reference source not found.**-2).

More in detail, the project idea plans to reuse the platform for:

a) renewable power generation from wind and photovoltaic;

b) hydrogen generation from water electrolysis;

c) sealine reuse for hydrogen transport and storage.

2.1. Renewable power energy generation from wind and photovoltaic

To assess the potential renewable resources in the area of the Azalea A platform, mainly literature and public data (RSE, 2017) were used (Table 3).

Table 1. Location of sealines from Azalea A to Anemone Cluster

Center	*Line name*	*Start point coord-1*	*Start point coord-2*	*End point coord-1*	*End point coord-2*
Rubicone	Azalea 1-2 - Anemone Cluster	44°10’16.229”	12°42’52.329”	44°12’43.694”	12°42’19.862”
Rubicone	Azalea 1-2 - Anemone Cluster	44°10’16.229”	12°42’52.329”	44°12’43.694”	12°42’19.862”

Table 2. Main technical features of sealines from Azalea A to Anemone Cluster. From the left: Type, Carried fluid, Operative state, Year of installation, Length, Diameter

Line name	*Type*	*Fluid*	*Laying date*	*Offshore length (m)*	*Nominal diameter (“)*	*Thickness (mm)*
Azalea 1-2 - Anemone Cluster	Rigid	Glycol	1978	4580	3	4.78
Azalea 1-2 - Anemone Cluster	Rigid	Gas	1978	4580	6	10.97

Table 3. Summary table about the potential renewable resources around Azalea A platform (RSE, 2017)

PLATFORM NAME	***AZALEA A***		
Emerged part dimensions [m]	**19*4**		
Height m a.s.l.	**17**		
Distance from the shoreline [km]	**16**		
Seabed depth [m]	**19**		
WIND RESOURCE			
Annual mean wind speed at 25 m a.s.l. [m/s]	**3.8**	Specific annual energy production at 25 m a.s.l. [MWh/MW]	**632**
Annual mean wind speed at 50 m a.s.l. [m/s]	**4.1**	Specific annual energy production at 50 m a.s.l. [MWh/MW]	**891**
Annual mean wind speed at 75 m a.s.l. [m/s]	**4.3**	Specific annual energy production at 75 m a.s.l. [MWh/MW]	**992**
Annual mean wind speed at 100 m a.s.l. [m/s]	**4.4**	Specific annual energy production at 100 m a.s.l. [MWh/MW]	**1083**
SOLAR RESOURCE			
Optimal tilt angle of PV plant [°]	**34**		
Incident solar radiation on the horizontal plane [kWh/m^2]	**1463**		
Incident solar radiation on the plane with optimal tilt angle [kWh/m^2]	**1681**		
MARINE RESOURCE			
Annual mean power available from waves[kW/m/year]	**2.8**		
Marine current power flow [W/m^2]	**2.3**		

Summarizing the data of Table 3, marine renewable energy is not considered in this study, since it has very low potential in the northern Adriatic Sea. On the other hand, more interesting are solar and wind energy availability.

Considering the Wind Atlas (RSE, 2020), the average wind speed at altitudes of 75 meters above sea level is about 4.3 m/s with a specific production approximatively equal to 992 MWh/MW (Table 3). For the purpose of this study, an available loading capacity of the deck of the platform of 300 kg/m^2 (about 60% of the design condition) and 10-ton maximum load are assumed. According to this design and considering the technical data of the infrastructure, one wind turbine of 100 kW nominal power could be installed, with a turbine nacelle height of 75 meters above the sea level. Estimated electric energy production from this system is about 99,200 kWh/year. No turbulence and wake effects, resulting from possible interactions between contiguous turbines in case of a wind turbine field, need to be considered.

On the other hand, as previously observed, the PV technology is a mature renewable energy source, whose economic feasibility strongly depends on scale benefits and, ultimately, on space constraints. Moving solar cells to the space-abundant marine environment allows large-scale projects, in which the absence of the shading effects - that usually characterize on shore projects - and the large solar source availability compensate for the low energy density of the PV technology.

Assuming an available space on the Azalea A platform to allocate solar panels of about 100 m^2 and an incident solar radiation on the plane with optimal tilt angle of about 1680 kWh/year/m^2 (at the northern Adriatic latitudes), it would be possible to install 60 modules of 330 Wp and 1.6 m^2 each.

Considering these data, the total electrical energy production estimated for PV modules on the Azalea A platform is about 33,600 kWh/year, having considered a conversion efficiency equal to 0.2 for monocrystalline silicon modules (RSE, 2017). Hence, the final energy producible is equal to 132,800 kWh/y.

One issue related to the reuse of the platform for power production is the energy transport. The submarine power transmission technology already represents an effective and mature solution for bulk electric power transmission across large distances encompassing wide and deep-water bodies and exhibits characteristic values of operating reliability in the range of decades. The sector extensively relies on the experience for laying cables on the seafloor for telecommunication purposes. Reusing existing facilities permits to locate the power lines along the sealines, avoiding the operations of shoring approach. The electrical connection can be made to medium-high voltage grids, reducing the electric cable section and making easier its transportation.

2.2. Hydrogen generation

The solution for future energy production is often cited to be a hydrogen economy (Romm, 2004), and according to Sangster (2014) in the post fossil fuel age a clean hydrogen would have to be separated from water by electrolysis. For this reason, the hydrogen generation is considered in this feasibility study as the prime solution to transport energy by reusing sealines. Hydrogen could be generated in a volume compatible with the energy that is supposed to be produced using the above-mentioned values for wind and photovoltaic sources. An innovative energy conversion and storage solution using electrolysis that integrates renewable sources of generation, converts electricity to produce hydrogen and leverages the attributes of the existing natural gas infrastructure. Proton Exchange Membranes (PEM) may couple wide range of load, fast response to transient conditions and H_2 production at higher pressure. The whole amount of electric power produced by photovoltaic and/or wind turbine systems is planned to be used to feed the PEM electrolyzer in order to produce H_2. The electrolyzer energy consumption can be estimated in 4.8 kWh/Nm^3H_2 (considering 200 bar as operating pressure, (Scheepers et al., 2020) and about 1 liter of demineralized water is required. Assuming the available electric power as produced by the above systems approximately equal to 132,800 kWh/year, it is possible to generate about 27,700 Nm^3/year of H_2.

2.3. Sealines as lines for hydrogen transport and storage

The Azalea A platform is connected to the adjoining one (Anemone) through two sealines. The first one (Sealine 1) was used to transport natural gas extracted in the platform and has an inner diameter of 150 mm. The second one is smaller (75 mm diameter) and was used to carry glycol for technical utilities (Sealine 2). Both sealines are 4580 m long and are made of steel. The geometry of the existing sealines (diameter and length) allow to evaluate the flow rate of the gas that can flow in the duct, which depends on the thermodynamic condition of the gas (i.e. density, pressure and temperature). Since the current sealine was used to transport natural gas (methane), it can be used to transport hydrogen in the same ranges of pressure and temperature.

The preliminary assessment of the maximum gas pressure inside the pipe is key to evaluate the potential of the existing sealine for transport and storage. In line with the common practice in pipeline design, the maximum shear stress criterion is selected for calculating the mechanical stress to which the pipe undergoes. Indeed, the boundary conditions for the system are: (i) the storage pressure of the gas inside the pipe, (ii) the seawater hydrostatic pressure and (iii) the seawater temperature. The seawater pressure and temperature range around 3 bar and 15°C approximately (this value of temperature can be surely lower in winter conditions, but in that case the density of the inner fluid would be higher and so we are in safety condition underestimating the mass storable). The hydrogen temperature is kept constant and equal to such value, under the assumption that no thermal insulation is achieved in the pipeline.

The current thicknesses of the sealines assure a maximum allowable pressure of about 33 MPa for Sealine 1 and 29 MPa for Sealine 2, according to ASME Boiler & Pressure Vessel Code, section B31.1 (Meyer et al., 2020). These pressure limits consent to state that the ducts can be used for gas transportation. In any case, a checking procedure could be planned to verify the thickness, making use of non-intrusive sensors, in order to verify the ageing, fatigue and corrosion conditions.

In the following figures, the calculation of possible flow rates of hydrogen has been performed, and associated pressure drop. Pressure drops (*Δp, Pa*) have been evaluated varying the inner gas velocity (*v_{gas}, m/s*) up to 4 m/s and the gas transport pressure up to the maximum allowable one. In this way, it is possible to calculate the density of the gas and, thus the pressure drop according to Eq. (1), knowing the tube diameter (*D, m*) and length (***l**, m*), and fluid density (*ρ, kg/m^3*):

$$\Delta p = f \cdot \frac{l}{D} \cdot \frac{\rho \cdot v_{gas}^2}{2} \tag{1}$$

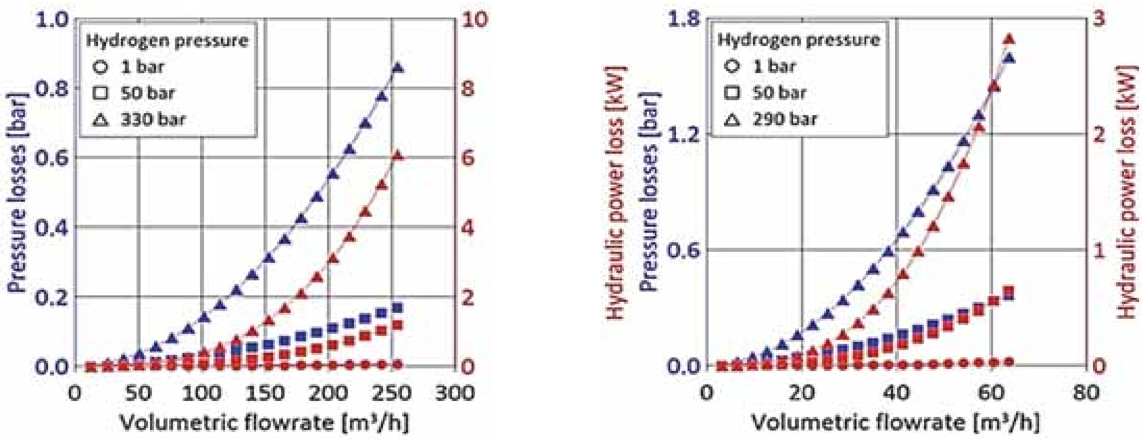
The friction factor (*f*, -) is calculated considering the laminar-turbulent flow transition. In particular, for laminar flow it depends only on non-dimensional Reynold Number (Re, Eq. 2):

$$f = \frac{64}{\mathrm{Re}} \tag{2}$$

While for turbulent flow, the relative roughness (*ε, m*) is introduced (*D* is the inner diameter) (Eq. 3):

$$f = \frac{1}{\left\{-1.8 \cdot \log\left[\frac{6.9}{\mathrm{Re}} + \left(\frac{\varepsilon / D}{3.7}\right)^{1.11}\right]\right\}^2} \tag{3}$$

Sealine 1 can easily allow a flow rate of about 250 m^3/h with a maximum pressure loss along the line of approximatively 0.9 bar. Negligible pressure drops are accounted for the case where the transport pressure is 50 bar, equal to the hydrogen production pressure. Higher pressure drops and lower flow rate are obviously experienced for the smaller inner diameter Sealine 2. Thanks to the evaluation of the pressure drops, the hydraulic power needed to move the fluid can be calculated and it is shown in Fig. 2. It is demonstrated that a compressor of about 6 kW and 3 kW (Sealine 1 and Sealine 2, respectively) can be used if the maximum allowable pressure is used for H_2 transportation. However, if a more suitable pressure of 50 bar is considered, the power needed by the compression is in the range of 500 W - 1 kW, which can be obtained with common commercial machines. In case the transport would be done in a liquid state, the sealine should be coated with proper insulation layers, in order to keep the temperature in a cryogenic condition.



(a) (b)

Fig. 2. (a) pressure drops and hydraulic power loss along the Sealine 1 crossed by hydrogen, (b) pressure drops and hydraulic power loss along the Sealine 2 crossed by hydrogen

The technology can be easily taken from the Liquefied Petroleum Gas (LPG) and LNG sectors and the thermal field across the layers calculated by a mathematical model of the duct (Cipollone et al., 2013), aimed to verify the inner temperature of the gas in worst external conditions of the sea (low temperature and high convective heat transfer conditions). When it comes to assess the actual margins for the reuse of sealines for hydrogen transport purposes, it is worth observing that whereas the higher heating value (HHV) of natural gas equals approximately 40 MJ/Nm^3, the HHV of hydrogen amounts to 13 MJ/Nm^3. Consequently, the same energy demand calls for a volume of hydrogen three times that of natural gas; the density of hydrogen is nine times smaller than that of natural gas. Hence, a flow rate of hydrogen three times larger than that of natural gas results in approximately the same pressure drop. Besides energetic considerations, also several material issues require some attention: e.g., the use of the existing compression and pressure-reduction devices, hydrogen embrittlement and leakages that may occur in existing pipelines, already suffering from a stress history and fatigue damage, induced by pressure fluctuations. This further confirms the importance of an intensive testing of pipelines and welds. In addition to this, the material of the pipeline also affects volumetric losses differently, as the working gas shifts from natural gas to hydrogen, calling for a proper preliminary analysis of actual volumetric losses under normal operation, at different flow rates. The incidence of leakage and diffusion through the material of the pipeline is a further element that drives assessment of actual feasibility of the re-conversion of existing pipelines: cast iron and fibrous cement pipelines are particularly incline to leakage phenomena, whilst polyethylene present large risk of diffusion of hydrogen.

As far as the compression devices are concerned, piston compressors seem to be the most easy-to-adapt technology, as they are not sensitive to the working gas. Centrifugal compressors working with hydrogen, on the other hand, have to face a volume three times the one of natural gas and in order to obtain the same pressure ratio, the rotational speed must be increased with respect to the natural gas case. A very interesting opportunity is represented by the use of the existing sealine as a storage volume of hydrogen. In fact, the sealine can be closed at one end, in order to create a bounded volume that can be used as storage, where a gas can be accumulated. The storage pressure is the main parameter for evaluating the amount of gas storable and it is surely higher than the one used to transport operation, so the thickness of the duct should be verified with more accuracy or eventually reinforced. For a pipe compliant with the API SPEC 5L standard, with a 150 mm inner diameter and length of 4580 m (Sealine 1), the volume of the sealine is about 80 m^3.

The common practice suggests lowering the yield strength through a proper coefficient of safety, resulting in a 240 MPa admissible tension of the used steel. In order to meet such a specification, the maximum storage pressure of the hydrogen turns out to be 330 bar. Table 4 reports some scenarios in terms of storage pressures, densities and mass of hydrogen. It suggests that:

- at 3 bar pressure, the hydrogen density is 0.25 kg/m^3 (superheated vapor), corresponding to a 20 kg stored mass. In such condition, the pressure inside the flowline and outside the pipe balance each other, which leads to a minimum stress on the pipeline material. Such a scenario, though, corresponds to a minimum storage inside the pipe, to be checked against both (i) the actual hydrogen producibility on the timescale of interest (e.g. daily, weekly, monthly, etc.) and (ii) the demand profile of hydrogen;
- at 13 bar pressure, the hydrogen is beyond its critical state. The density tops 1.1 kg/m^3 and 88 kg hydrogen can be stored, before the pipeline capacity is saturated;
- the upper limit pressure (330 bar) corresponds to a 23 kg/m^3 density and 1852 kg hydrogen stored.

The same analysis can be performed, accounting for the Sealine 2: in this case the volume is reduced and the storable hydrogen too. At maximum allowable pressure considered (290 bar) the mass storable is 416 kg.

3. Environmental challenge and monitoring solutions

The northern Adriatic is an area of intense maritime activities and overlapping uses of the sea (Barbanti et al., 2015), such as productive hydrocarbons platforms, borrowing areas for beach replenishment, military zones, aquaculture farms, fishing grounds. More recently, the installation of an offshore wind farm in the same area of Azalea A was under the scope of a feasibility study (Schweizer et al., 2016). The northern Adriatic represents a hot spot of Mediterranean biodiversity and is particularly important for the endemism of Mediterranean fish species of high commercial value, which have here their breeding and nursery areas (Giannoulaki et al., 2013).

Among marine mammals and endangered species, the loggerhead turtle (*Caretta caretta*) is an endemic species of the norther Adriatic Sea as well as the common bottlenose dolphin (*Tursiops truncates*). Maritime traffic in the Adriatic includes transport routes for tankers with crude oil, liquefied gas transport, dry cargo and container ships, chemical tankers and passenger ships, on top of fishing vessels, yachts, recreational boats and military vessels. Such large maritime shipping produces a number of negative effects on the marine environment (ballast waters, pollution and oil spill, collision, noise and habitat degradation) that require to be monitored.

Furthermore, the area is interested by historical seismicity; in 1916, a long seismic sequence (moment magnitude Mw = 6.0) caused intensity VIII damage in Rimini and neighboring towns with epicenter location offshore, which falls in the area of Azalea A (Rovida et al., 2011; Fig. 3). Some studies suggest that blind deep-buried Apenninic thrusts drive the growth of coastal anticlines, that may prove seismogenic (Vannoli et al., 2004; DISS Working Group, 2018). Notwithstanding, no significant tectonic deformation or dislocation is visible at the seabed around the study area (e.g. Fig. 4) and no significant tectonic implications have to be considered. In 1672, a tsunami hit the city of Rimini (Tinti et al., 2004), which is also frequently impacted by surges and floods, due to high waves with a lot of energy that are generated when strong winds blow over a long fetch, as in the case of the south-easterly Scirocco wind in the Adriatic Sea.

Considering the environmental characteristics and overlapping maritime uses of the study area, monitoring the marine environment and geo-hazard near the platform Azalea A plays an important role during both the decommissioning and reuse phases. Traditional monitoring systems are based on on-site sampling, transport of the samples onshore and laboratory analysis.

Table 4. Hydrogen storable in sealines.

H_2 pressure (bar)		3	7	13	20	100	200	290	330
H_2 density (kg/m^3)		0.3	0.6	1.1	1.7	7.9	14.9	20.6	22.9
H_2 mass storage (kg)	*Sealines1*	20	47	88	135	642	1209	1664	1852
	Sealines2	5	12	22	34	160	302	416	-

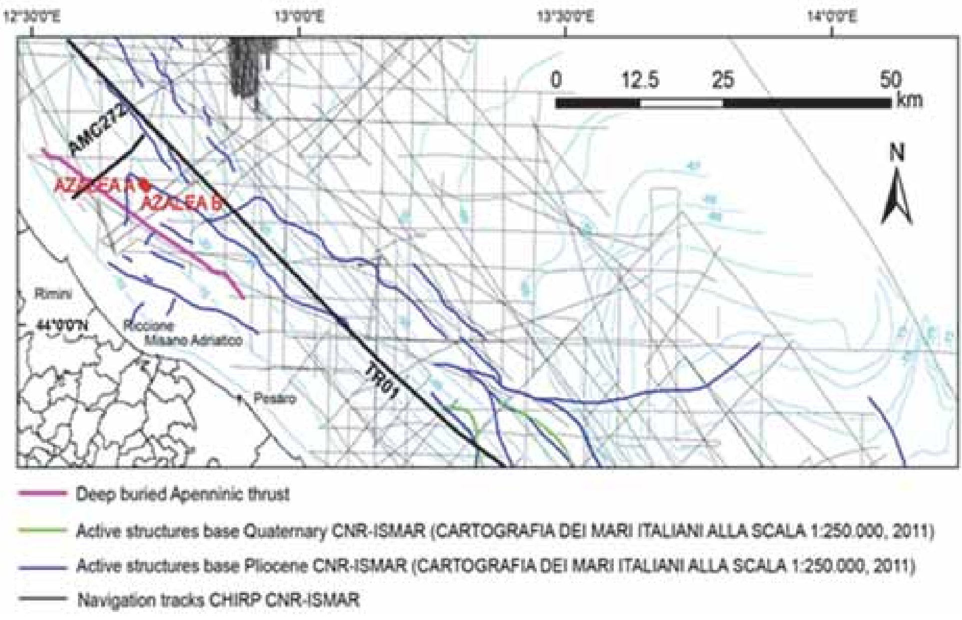


Fig. 3. Bathymetric contour map showing the location of the Azalea A platform in respect to the city of Rimini, the deep-buried Apenninic thrusts and 2 single channel seismic reflection profiles (CHIRP) and displayed as an example in Fig. 4

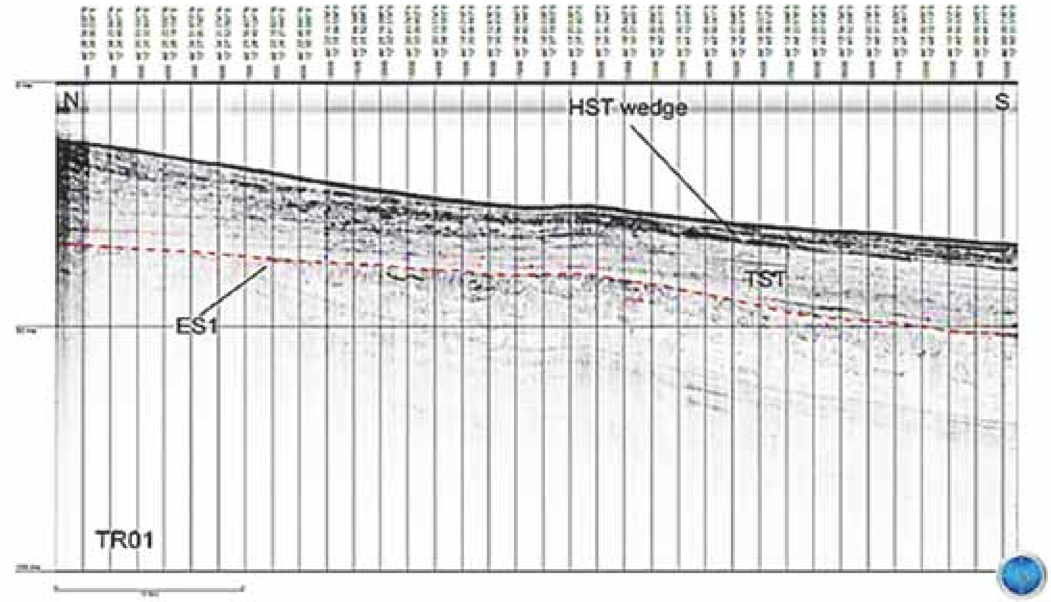


Fig. 4. CHIRP seismic profile running perpendicular to the High Stand (HST) sediment wedge in proximity of the Azalea A platform. ES1 is the subaerial erosional surface related to the last sea level low stand, occurred approximately 20,000 years ago and TST (Transgressive System Tract) is the sediment sequence deposited during the last sea level rise which culminated in the current high stand of the sea level around 6,000 years ago

This chain has numerous disadvantages, among which the low frequency of sampling campaigns, the implicated high costs related to mobilization and demobilization of the equipment, the slow response in case of polluting accidents or other environmental hazards, such as storms and earthquakes.

The reconversion of the platform Azalea A into a research hub, which will be reaching the self-sufficiency in terms of renewable energy production, would enable the rapid deployment of innovative technologies for efficient monitoring programs by applying methodologies shared between industry and academia. One technology, which is envisaged by this study, consists of the UPH2O chemical sensor installed on board an autonomous underwater vehicle (AUV), capable of performing in-situ chemical analysis on small samples of water for the detection of anomalies in the concentration of heavy metals and integrated by a real-time warning system. The UPH2O sensor provides the opportunity of water sampling with daily or sub-daily frequency, by activating a remotely controlled procedure based on the detected concentration of contaminants. The UPH2O integrated system offers also the opportunity to prepare samples that are ready for the quantitative analysis to be carried in the laboratories hosted by the research hub. This sensor uses Lab-On a-Chip microfluidic technologies for fluid and flow management in situ analysis of the water samples. Another monitoring technology, assess by this study, consists of the remotely operated vehicle (ROV) e-URoPe (e-Underwater Robotic Pet) equipped with geophysical and geochemical sensors, which would enable high resolution and space and time repeatability of the underwater measurements, including the fast detection of dissolved substances that are diagnostic of leakage from the decommissioned infrastructure or hydrocarbon reservoir depletion. The integration on board the vehicle of the calculation and visualization software and the use of adaptive procedures during the monitoring campaign will allow high speed of acquisition and real-time planning of the sampling stations. The monitoring program implemented by the ROV would allow the acoustic reconstruction of both the underwater environment and maintenance status of the decommissioned infrastructure, including the sealines, using multibeam sonar technology. The expected advantages for these technological applications consist in multifold benefits. They include the long-term monitoring; the scalable solution with multiple additional chemical and geophysical parameters that could be simultaneously detected; the higher sampling/analysis frequency; the possibility to operate in harsh weather conditions without human intervention; the wider spatial range of monitoring around the platform and the low operational costs and overall favorable benefit/cost ratio.

4. Result and discussions

The preliminary results of the study pointed out an alternative to decommissioning operations, supporting an energy transition phase and promoting the use of new fuels like hydrogen. The study provided a technical evaluation of the feasibility to reuse an offshore hydrocarbon platform and its sealines for renewable power generation and transport in safety conditions. The technical study highlighted that for an estimated energy generation of 132,800 kWh/year by solar and wind, it is possible to convert 27,700 Nm^3/year of H2 of hydrogen in safe conditions.

Furthermore, the economic analysis conducted on the real case study of the Azalea A platform in the northern Adriatic Sea shows positive feedback on the costs implicated to convert the platform into a research hub self-sufficient in terms of energy production with a green energy system. The investment costs of the equipment for solar and wind energy production are 0.4 million of euro; the cost of hydrogen conversion comprises the electrolyzed for about 0.3 million euro and auxiliaries' costs for about 0.1 million of euro. Therefore, the total investment cost amounts to about 0.8 million euro. On the other hand, if H_2 is stored in bottles for a total capacity/pressure of 19.2 m^3/200 bar, and considering storage and auxiliary's investment costs for about 0.9 million euro, the total investment cost rises to 1.3 million euro. In case of the H_2 is stored in the existing sealines, as in the case of Azalea A, the total cost is estimated about 0.9 million of euro. Therefore, the latter option seems to be a better choice both from the technical and economical point of view. Other relevant results regard the benefits that would derive from the implementation of innovative, effective and low-cost environmental and infrastructures monitoring programs. The costs benefit attached to this innovation are invaluable because they likely avoid the cost implicated with the development and employment of expensive early warning and real-time systems controlled from remote locations, such as leak detection based on monitoring stations and advanced processing. Overall, the overarching benefit derives from the enhanced monitoring and protection of the marine environment based on knowledge transfer and technology sharing between the academia and the oil and gas industry.

5. Conclusions

This study proposes an innovative approach to test a possible reuse of an oil and gas platform as a self-sufficient scientific research hub to integrate and test a renewable energies offshore system. The innovative idea is to reuse not only the main structure, but also the ancillary facilities (i.e. the sealines), an option that is not frequently considered in this panorama. In this regard, a further degree of novelty is represented by the use of the abandoned sealines not only for gas transportation, but also as storage volume for the gas produced on the platform: this enhances the yearly productivity, decoupling the energy demand from the renewable energy availability, which is affected by unpredictability during day and year.

For this study, the Azalea A gas platform, which is located at shallow water depths in the northern Adriatic Sea and has come to the end of its lifecycle, represents an optimal pilot site. The potential for marine renewable energy production in the Adriatic Sea is not sufficient for an industrial-scale economic investment, however the reuse of the existing offshore infrastructure for testing new technological solutions for power generation that support monitoring of the marine environment proved to be a good opportunity for knowledge and technological transfer. This study shows that the proposal to convert an offshore hydrocarbon platform into a marine research hub, with additional storage and transport of H_2, is technically feasible in safety conditions (considering the safety threshold defined by API standard) and supports both energy transition from fossil sources to renewable energies and marine protection. Furthermore, the results of the study indicate that proposal is workable also from the point of view of the cost analysis that estimates a total investment of about 0.9 Million euro, if the existing sealines are reused for energy transportation and storage. Therefore, despite a low investment with the engineering solutions provided by this study, the proposal supports both energy transition and environmental protection; first, avoiding the impacts of decommissioning operations and secondly, promoting an innovative approach in the monitoring of the marine environment around the offshore platforms.

The proposed study demonstrates the technical and economic feasibility of the integration of the existing offshore infrastructures with the new hybrid power generation systems, highlighting a positive and concrete example of "Blue Economy".

Acknowledgments

This project has been funded by European Union's Horizon 2020 Research Innovation program BlueMed under the Agreement number 727453. We thank all the partners of Sealines Start-Up action and CLYPEA network for their valuable support.

References

Barbanti A., Campostrini P., Musco F., Sarretta A., Gissi E., (2015), *Developing a Maritime Spatial Plan for the Adriatic-Ionian Region*, CNR-ISMAR Publisher, Venice, Italy.

Camporeale S., Antoncecchi I., Bonetti A., Ceruti F., (2017), Lng loading/downloading and circular economy: the opportunities related to the new legislation and the reuse of oil & gas platforms, *Geoingegneria Ambientale e Mineraria - GEAM*, **152**, 120-124.

Cipollone R., Di Battista D., Gualtieri A., Massimi M., (2013), *Development of Thermal Modeling in Support of Engine Cooling Design*, SAE Technical Papers, Internal Combustion Engine Conf., SAENA, Capri, Italy, https://doi.org/10.4271/2013-24-0090

Coppi O., Santocchi N., Orlandi A., Urtis R., (2019), Official Bulletin for Hydrocarbon and Georesources - *BUIG*, Ministry of Economic Development Directorate General for safety of mining and energy activities - UNMIG, 1-155, Rome, Italy, On line at: https://unmig.MiSE.gov.it/images/buig/63-8.pdf.

D.M., (2019), Ministerial Decree of Italian Ministry of Economic Development of 15th February 2019 and Annexes, art. 5, on Italian National guidelines for the mining decommissioning of offshore hydrocarbon platforms and related infrastructures, Official Gazette, 57, On line at: https://unmig.MiSE.gov.it/index.php/it/informazioni/normativa-di-settore/fonti-secondarie/2036038-decreto-ministeriale-15-febbraio-2019.

DISS Working Group, (2018), Database of Individual Seismogenic Sources (DISS), Version 3.2.1: A compilation of potential sources for earthquakes larger than M 5.5 in Italy and surrounding areas, National Institute of Geophysics and Volcanology, On line at: http://diss.rm.ingv.it/diss/.

Djokic D., (2017), *Offshore Decommissioning and Beyond - Reuse Case*, Business & Economics.

Giannoulaki M., Belluscio A., Colloca F., Fraschetti S., Scardi M., Smith C., Panayotidis P., Valavanis V., Spedicato M.T., (2013), Mediterranean Sensitive Habitats, DG MARE Specific Contract SI2.600741, Final Report, 557, On line at: https://www.coispa.it/docs/proj/MEDISEH%20final%20report.pdf.

Gondal I.A., (2019), Offshore renewable energy resources and their potential in a green hydrogen supply chain through power-to-gas, *Sustainable Energy Fuels*, **3**, 1468-1489.

Grandi S., Airoldi D., Antoncecchi I., Camporeale S., Danelli A., Da Riz W., De Nigris M., Girardi P., Martinotti V., Santocchi N., (2017), Planning for a safe and sustainable decommissioning of offshore hydrocarbon platforms: complexity and decision support systems. Preliminary considerations, *Geoingegneria Ambientale e Mineraria - GEAM*, **152**, 101-108.

Hernández-Gómez A., Ramirez V., Guilbert D., (2020), Investigation of PEM electrolyzer modeling: Electrical domain, efficiency, and specific energy consumption, *International Journal of Hydrogen Energy*, **45**, 14625-14639.

IMED, (2019), Italian Ministry of Economic Development, WebGIS DGS-UNMIG, On line at: https://www.arcgis.com/home/webmap/viewer.html?webmap=13fee4db46bd40a7a0113faf8cf1812e&extent=9.0555,42.3802,17.1689,45.8339.

Kaiser M.J., (2020), The Offshore Pipeline Construction Industry, Activity Modeling and Cost Estimation in the U.S. Gulf of Mexico, Elsevier, Cambridge, USA and Oxford, UK, https://doi.org/10.1016/B978-0-12-820288-3.00015-9.

Meyer J.E., Frey J., (2020), *ASME Piping Code: B31.1, Power Piping*, In: *Companion Guide to the ASME Boiler and Pressure Vessel Codes: Criteria and Commentary on Select Aspects of the Boiler & Pressure Vessel Codes*, ASME Press, vol 2, New York, USA.

Onyebuchi V.E., Kolios A., Hanak D.P., Biliyok C., Manovic V., (2018), A systematic review of key challenges of CO_2 transport via pipelines, *Renewable and Sustainable Energy Reviews*, **81**, 2563-2583.

Rabindran P., Cote P., Winning I.G., (2011), *Integrity Management Approach to Reuse of Oil and Gas Pipelines for CO_2 Transportation*, 6th Pipeline Tech. Conf. Proc., Hannover, Germany.

Romm J.J., (2004), *The Hype about Hydrogen: Fact and Fiction in the Race to Save the Climate*, Island Press, Washington, D.C., USA.

Rovida A., Camassi R., Gasperini P., Stucchi M., (2011), Italian Parametric Catalogue (CPTI11), National Institute of Geophysics and Volcanology (INGV), Milano, Bologna, Italy, https://doi.org/10.6092/INGV.IT-CPTI11.

RSE, (2017), *Energy Optimization of Offshore Oil&Gas Installations and Gis Database* (In Italian), 1-18, Technical Press, Rome, Italy, On line at: https://unmig.MiSE.gov.it/images/docs/ottimizzazione_energetica_piattaforme.pdf.

RSE, (2020), Interactive WIND ATLAS, On line at: http://atlanteeolico.rse-web.it/index-en.phtml.

Sangster A.J., (2014), Engineering the early demise of fossil fuels, *International Journal of Sustainable and Green Energy*, **3**, 115-122..

Scheepers F., Stähler M., Stähler A., Rauls E., Müller M., Carmo M., Lehnert W., (2020), Improving the efficiency of pem electrolyzers through membrane-specific pressure optimization, *Energies*, **13**, 612, https://doi.org/10.3390/en13030612

Schweizer J., Antonini A., Govoni L., Gottardi G., Archetti R., Supino E., Berretta C., Casadei C., Ozzi C., (2016), Investigating the potential and feasibility of an offshore wind farm in the Northern Adriatic Sea, *Applied Energy*, **177**, 449-463.

Tinti S., Maramai A., Graziani L., (2004), The new catalogue of Italian tsunamis, *Natural Hazards*, **33**, 439-465.

Vannoli P., Basili R., Valensise G., (2004), New geomorphic evidence for anticlinal growth driven by blind-thrust faulting along the northern Marche coastal belt (central Italy), *Journal of Seismology*, **8**, 297-312.

Environmental Engineering and Management Journal October 2020, Vol. 19, No. 10, 1657-1668
http://www.eemj.icpm.tuiasi.ro/; hiip://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

PAY AS YOU THROW - SYSTEMS FOR MUNICIPAL WASTE MANAGEMENT: ITALIAN EXPERIENCES AND A NEW PROPOSAL

Gaetano Drosi[1], Mattia Lorandi[1], Alberto Bossi[1], Federico Villani[2], Jennifer Avakian[1*]

[1]SOFTline Ltd., Via Antonio Grossich 8, 20131, Milano, Italy
[2]Consea Ltd., Km. 2.200, Via Mottola, Trav. Via Vito Consoli, 74015, Martina Franca TA, Italy

Abstract

Pay as You Throw (PAYT) is a usage-pricing model for the disposal of Municipal Solid Waste. The implementation of the PAYT approach requires three main elements: a) measurement of the generated amount of waste; b) a means to identify the waste generator; c) the unit pricing for individual charging based on the amount of waste collected and services provided.
The PAYT system splits the overall municipal solid waste tax into one fixed part, no-service dependent and a variable part related to the amount of waste generated and collected.
The PAYT approach is becoming widely applied in waste management because: a) it supports a more sustainable management of waste flows from economic, environmental and social points of view; b) it is a powerful instrument to help local authorities in supporting and optimizing waste management policies and to improve urban waste separation and recycling reaching a high percentage regarding selective collection of excellent quality materials; c) it makes citizens more conscious regarding waste production problems, orientating them to produce less waste and opt for reusable and easy to separate packaging because the PAYT approach charges citizens according to the quantity of waste produced. The aims of this paper are two: to give evidence that the Italian municipal solid waste tariff system already in use is a normalized method of pricing which is unfair to citizens and to introduce a new model that is an innovative implementation of the standard PAYT scheme. All data refers to real cases managed by Softline.

Key words: circular economy, economic instruments, environmental policies, Pay As You Throw, sustainable waste management

Received: February, 2020; Revised final: June, 2020; Accepted: July, 2020; Published in final edited form: October, 2020

1. Introduction

The "polluter pays" is a principle of the environmental law enacted in order to make the party responsible for producing pollution bear the costs of managing it to prevent damage to human health and the environment. The "polluter pays" principle is part of a set of broader principles to guide sustainable development worldwide. At the E.U. level, the principle has been included in the European Recommendation n. 436 of March 3, 1975 (CR, 1975) which is today's article n. 191 of the Treaty on the Functioning of the European Union 2016 (TFEU, 2016). An example of the implementation of this principle is the European Packaging Directive, of which an updated proposal has been defined by the European Commission (EC, 2014), according to which the responsibility for the waste produced lies upon the producer.

The Pay as You Throw (PAYT) method incorporates the "polluter pays" principle into the waste charge system. The user of the waste collection service pays a charge based on the real waste generated and the waste management service used. This principle has been introduced in the current European Waste Directive (EC Directive, 2018).

This principle is also aimed to reduce environmental impacts of Municipal Solid Waste Management (MSWM) with the primary objective of producing less waste flows by reducing waste at the

[*] Author to whom all correspondence should be addressed: e-mail: jennifer.avakian@wintarif.it; Phone: +39 02 70638326; Fax: +39 02 92879560

source and by re-using products, hence increasing recycling rates and avoiding landfills. Moreover, the review analysis points put forward by Elia et al, 2015, demonstrate that PAYT systems offer additional benefits other than environmental ones, especially from a social and economic point of view, such the reduction of service costs and the intensification of citizen participation. The technical implementation of the PAYT approach (also called trash metering, unit pricing, variable rate pricing, or user-pay) is based on the following three pillars: identification of the waste generator with the aim of quantifying the waste which has been generated, attaining accountability and unit pricing. The latter is the basis on which individual charging stands proportional to the services obtained. Needless to say that the PAYT system gives best results in the presence of a highly developed waste collection infrastructure, appropriate charging policies and effective media coverage.

Fig. 1 shows that the charging system can be either single or multi-component. The one-component charge system is a non-PAYT, flat rate scheme or is a fully variable one where there is not the fixed amount. The two or multi-component waste charge system is a better PAYT system. In fact, waste charging schemes relying on PAYT have to split the overall waste tax into one fixed part, no-service dependent, and a variable part related to the service or, more specifically, to the amount of waste generated and to differentiated fees for various additional services. In any case, a waste charging scheme should ensure the full coverage of the waste management related costs and the fair allocation of these costs to the beneficiaries of the services (Bilitewski et al., 1997; Bilitewski, 2008).

The variable fee can be implemented in different ways (Reichenbach, 2008) depending on the waste accounting method (Fig. 2).

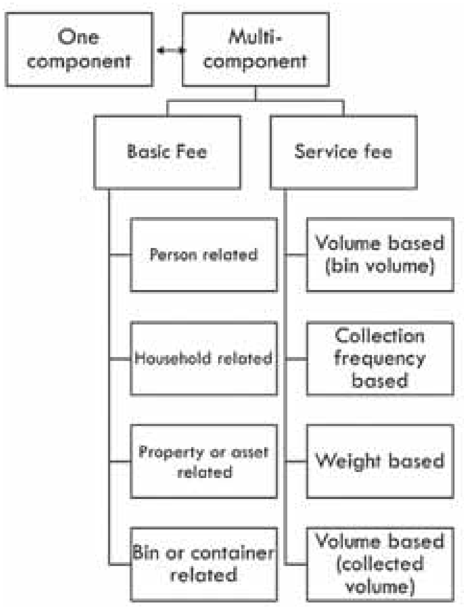


Fig. 1. Possible municipal solid waste fee components (adapted from Bilitewski, 2008)

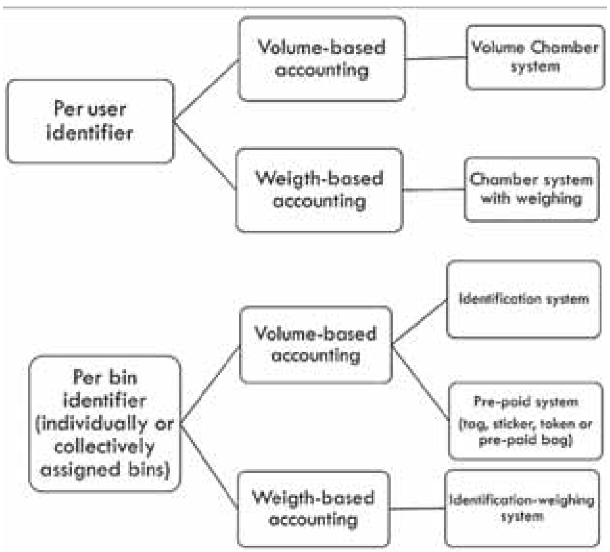


Fig. 1. Principle alternatives for implementation of PAYT (adapted from Morlok et al., 2017)

Therefore, the variable part of the fee, the one which reflects the principle that the "polluter pays", can be calculated using one of these main methods (EC DG ENV, 2012):

1) Volume-based schemes in which citizens pay for a specific size of bin/bag. This scheme may not correspond to the real waste weight delivered because bins/bags are often partially filled upon collection. Furthermore, the pre-paid bin/bag system is usually considered a volume-based one, although bins/bags are usually filled so that the volume and weight of a bin/bag is relatively constant in relation to the fee paid per bin/bag;
2) Bins/bags-based schemes which are dependent on the number of bins/bags collected;
3) Weight-based schemes based on the weight of the waste collected in a given bin/bag;
4) Frequency-based schemes based on how many times the bin/bag is collected. This method can be combined with volume and weight-based schemes.

Thus, the charging model formula (*Waste Fee*) for the *i-th* user is (Eq. 1) (Elia et al., 2015):

$$WF_i = FIXP_i + VARP_i \quad \forall i \tag{1}$$

FIXP stands for the Fixed Part of the waste fee, that is to say the basic fee aforementioned and *VARP* represents the Variable Part of the waste fee, in other words, the waste quantity collected from the user (Eq. 2):

$$VARP_i = QRW_i \times CRW + \sum_{j=1}^{k} Q_{ji} \times C_j \quad \forall i \tag{2}$$

respectively, QRW_i and Q_{ji} are the quantities of the collected residual waste and the quantities of the *j-th* recyclable waste for the *i-th* user in both cases; *CRW* and C_j are all those costs necessary to manage the waste quantities, such as collection, transport, final treatment and disposal or reuse/ recycling. It should be noted, however, that in most of the cases studied, the quantities refer to the undifferentiated fraction only.

PAYT strategies are applied all over the world for many years now. Almost 7100 jurisdictions across the US apply PAYT schemes for waste management, proving that this system is effective in cost and waste reduction (EPA, 1994; Skumatz, 2008), in increasing recycling rates (Dijkgraaf and Gradus, 2004; EC DG ENV, 2012) and in reaching economic benefits (Karagiannidis et al., 2008). In the European Union, 17 Member States have applied PAYT models for waste management, although only some of them apply PAYT systematically in all municipalities (EC DG ENV, 2012).

The 2017 ISPRA data analyses 760 Municipalities in Italy with almost 5.6 million inhabitants using the unit price system, the average percentage of separate waste collection standing at nearly 80%. Furthermore, almost 1.7 million inhabitants in other 221 Municipalities exceeded 85% of separate waste collection, whereas 430,000 inhabitants in 71 Municipalities averaged 90% (Data elaborated by IFEL, 2019).

The recent study of the Italian Institute for Finance and Local Economy (IFEL) reports that the PAYT implementation in Italy has achieved high recycling rates and low residual waste quantities (IFEL, 2009). The study reports that "the major citizen involvement achieved by PAYT systems is one of the main factors which determines the increment in separate waste collection".

The aim of this work is (a) to better understand the Italian framework of waste taxation and its use of the PAYT system across the national territory, (b) to demonstrate through real cases that PAYT is a fair method and (c) to present a proposal.

2. Case studies

2.1. The Italian framework

In Italy, the PAYT approach was introduced by the decree Edoardo Ronchi, at the time Minister of the Environment (LD, 1997). The tariff is divided into two parts: the fixed fee used to cover operating costs, such as street sweeping and investments; the variable fee, which depends on the waste produced by the user. The anticipated costs of the first type are shared by all users on the basis of fixed parameters. These parameters are the property surface area occupied and the number of family members of each domestic user. Domestic utility refers to any utility used or meant to be used as a civilian residence. The fixed fee is applied also to non-domestic users and this depends on the type of activity. Non-domestic utility refers to an activity with purposes other than those defined as civilian residence.

The determination of the variable quota is more complex. The first step is to determine the total cost of disposal (per unit of weight - €/Kg) of the various types of waste. Then, the costs have to be divided based on the waste produced by each service user. Different methods have been described in the introduction.

The PAYT system is the ideal method. It achieves maximum efficiency when weighing exactly the residual waste produced by the single domestic user. Obviously, it is also the most complicated method to implement, and it is quite expensive. A simplification of the punctuality is the volumetric tariff. Instead of weighing the waste produced, only the volume is considered and assessed according to the number of bags collected or the number of bins/containers emptied.

Despite the PAYT system having been introduced over 20 years ago, only 11.5% of Municipalities in Italy (ISPRA, 2019) detect and quantify the production of waste produced by each individual user and apply the waste measurement on the variable part of the tariff. 2.8% of municipalities investigated in the census use a PAYT method on a tax-based system and not a service-based one. The remaining 85.2% of municipalities use the so-called "Normalized Presumptive" method, which is the simplest to apply because it does not require any substantial modification of the management system. It is also the least effective, one that represents a minor improvement compared to the tax-based system. The "Normalized Presumptive" method consists in establishing the different variable costs between users by applying the indices of the Presidential Decree (DPR, 1999). These indices are varying coefficients (calculated with statistical surveys on the production of waste) for each category of users (there are 21 categories of non-domestic users and 6 of domestic ones for municipalities under 5.000 inhabitants; 30 categories of non-domestic users and 6 of domestic users for municipalities with over 5,000 inhabitants). The relative coefficient has to be multiplied by the corresponding surface area occupied by the service user.

The coefficients provided by law, however, can be improved at the local municipal level to render them more precise, but this requires a further statistical investigation of the waste produced.

2.2. Three PAYT systems implemented in Italy

In Italy, there are 7,904 municipalities with varying morphological characteristics and population depending on the territory. Table 1 lists the number of Italian municipalities and resident population divided into demographic classes. The Italian National Institute of Statistics, known as ISTAT, processes these data. In identifying the sample (Table 2), three realities were considered, covering four population groups representing 59.58% of the Italian population.

Table 3 summarizes the main aspects of the samples: extensions, type of waste monitored, measurement systems, reference periods, domestic and non-domestic user samples, and the waste disposal processed.

The analysis was carried out on the average weight of the not-recyclable waste produced by households and commercial activities. The not-recyclable waste is also known as residual waste. This consists of mixed waste, with the exception of separately collected fractions. The average residual waste taken into consideration covers a period of over three years of sampling.

Table 1. Number of Italian municipalities and resident population divided into demographic classes. (ISTAT, 01/01/2019)

Demographic range	***Municipalities***		***Population***	
	number	***%***	***residents***	***%***
From **500000** inhabitants and over	6	0.08%	7311109	12.11%
From **250000** to **499999** inhabitants	6	0.08%	1920434	3.18%
From **100000** to **249999** inhabitants.	33	0.42%	4912857	8.14%
From **60000** to **99999** inhabitants.	61	0.77%	4668937	7.74%
From **20000** to **59999** inhabitants.	418	5.29%	13637496	22.59%
From **10000** to **19999** inhabitants.	706	8.93%	9719812	16.10%
From **5000** to **9999** inhabitants.	1186	15.01%	8373668	13.87%
From **3000** to **4999** inhabitants.	1088	13.77%	4235557	7.02%
From **2000** to **2999** inhabitants.	942	11.92%	2316015	3.84%
From **1000** to **1999** inhabitants.	1518	19.21%	2210349	3.66%
From **500** to **999** inhabitants.	1093	13.83%	805606	1.33%
Less than **500** inhabitants.	847	10.72%	247706	0.41%
Total	**7904**	100.00%	**60359546**	100.00%

Table 2. Municipalities considered for the study model

Municipality	***Population (ISTAT, 30 September 2019)***
Abbiategrasso (MI)	32726
Rezzato (BS)	13470
Mesero (MI)	4193

Table 3. Main elements of the sample

Municipality	***Abbiategrasso (MI)***	***Rezzato (BS)***	***Mesero (MI)***
Extension	47.78 Km^2	18.21 Km^2	5.64 Km^2
Type of waste monitored	Mixed Municipal Waste (WEC 20 03 01)	Mixed Municipal Waste (WEC 20 03 01)	Mixed Municipal Waste (WEC 20 03 01)
Measurement systems	Volume-based with bin identification	Volume-based with bin identification	Volume-based with bin identification
Reference period	2014-2019	2014-2019	2009-2019
Domestic user sample	14641	5916	1884
Non-domestic user sample	1414	693	129
Waste disposal samples processed	1 Million	157 Thousand	284 Thousand

The change from volume to weight (kilograms) was made on the basis of the average specific weight of the period. To express the weight in kilograms, the value *Wi* was determined by Eq. (3):

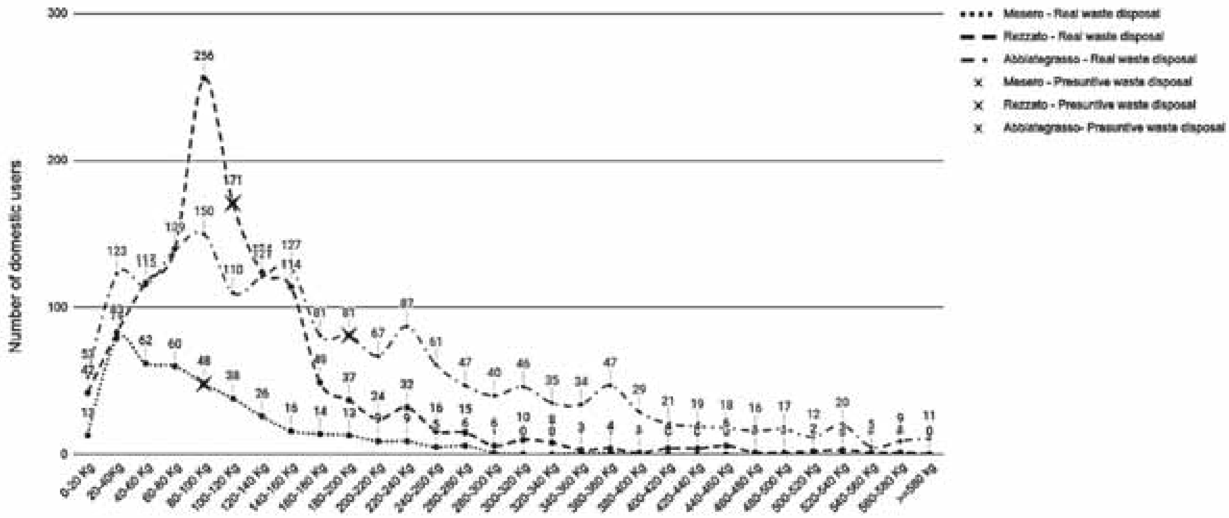
$$W_i = \overline{S} \times \sum_{b \in B_i} V_b \quad \forall i \tag{3}$$

where: B_i is the set of containers of the i-th user collected during the period; V_b is the volume of the *b-th* collected bin/bag, while $\overline{S}$ is the calculated average specific weight covering the period considered.

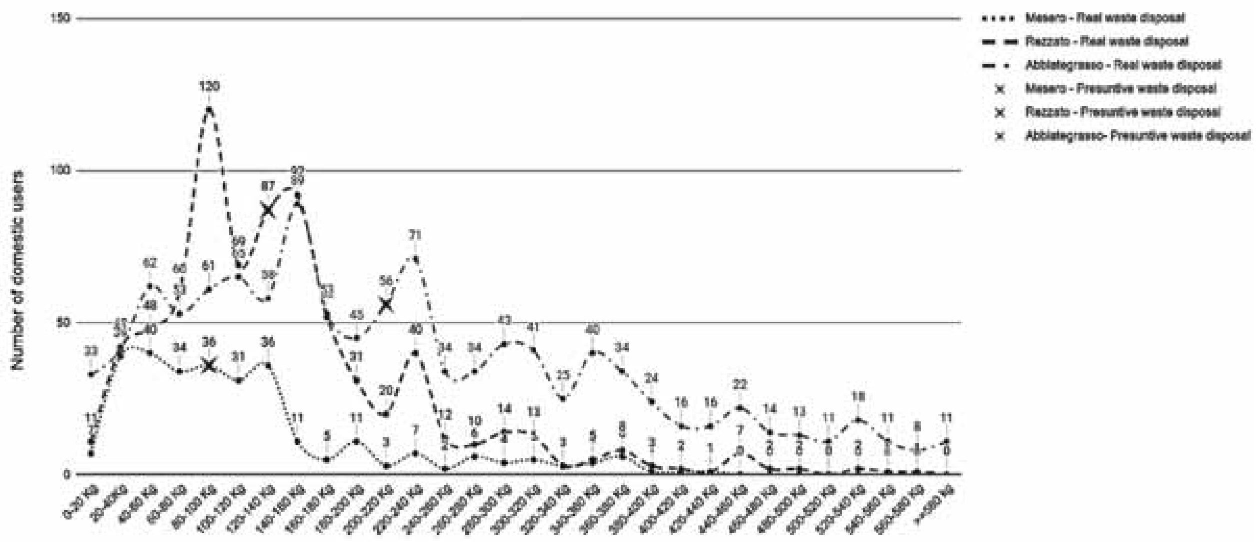
The sample users are those constantly present during all three years and who have not undertaken any changes during this period. The following Figures serve to demonstrate the difference in volume of the residual waste produced by users belonging to the same category defined by the “Presumptive Method”.

Among non-domestic users, the activities considered are the crafts pertaining to category n. 21 and the offices, agencies and professional studios listed in category n.11. These categories are chosen among others because of the extensive data available.

The upper part of Fig. 3 shows curves of the real residual waste production of the domestic users belonging to category 2 (two family members) in Mesero, Rezzato and Abbiategrasso Municipalities. The analyses are based on production bands of 20kg each. The symbol ● indicates the number of users whose production lies within the weight range. The symbol × indicates the production calculated with the “Normalized Presumptive” method for the domestic category n. 2 adopted in that specific municipality. The lower part of the Fig. 3 makes similar analyses of category 3.



(a)



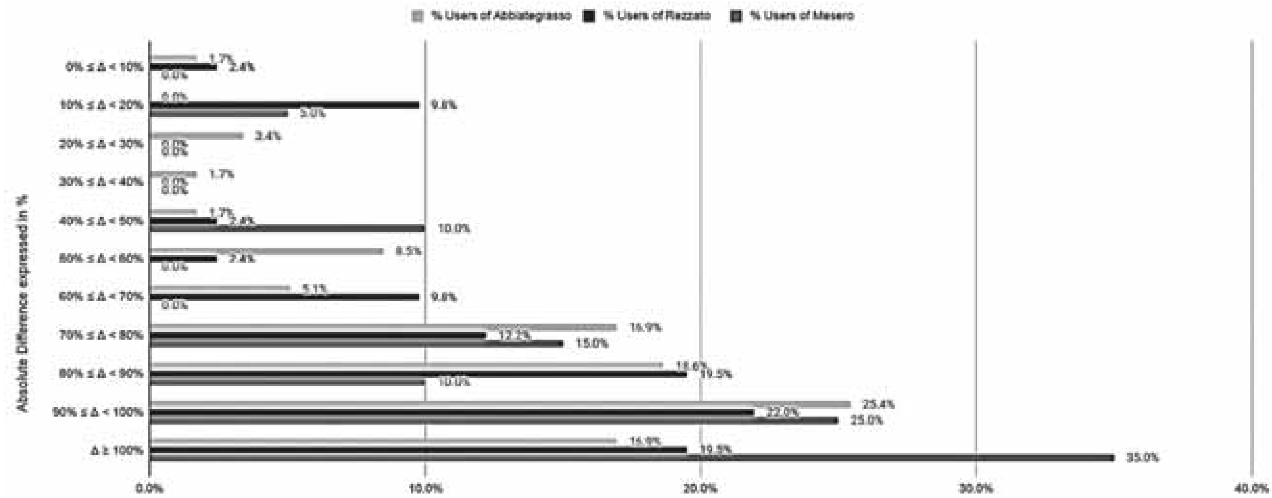
(b)

Fig. 3. Curves of the real residual waste production of the domestic users belonging to category 2 (upper part) and category 3 (lower part) in Mesero, Rezzato and Abbiategrasso Municipalities. ● indicates the number of users whose production lies within the weight range. × indicates the presumptive production for that category applied in that specific municipality: (a)(b) Annual quality delivered by production ranges [Kg]-Average in the period 2016-2019

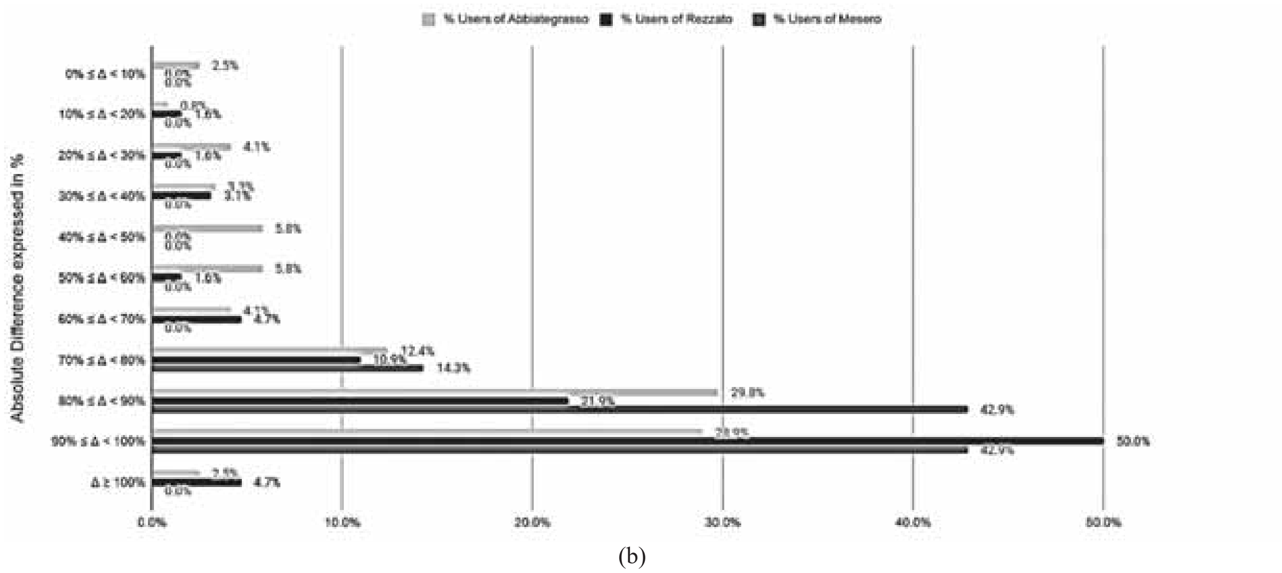
Fig. 4 shows the difference between real and presumptive residual waste production from craft activities (category n. 21) and from offices, agencies and professional studios (category n.11). In the case of the non-domestic users, it was chosen to indicate the percentage of the samples instead of the absolute values of the users in order to render comparable the samples pertaining to municipalities of different sizes.

The production coefficient, for non-domestic users, is linked to the surface area attributed to the users. This allows to present the deviation, where Δ is expressed in terms of absolute percentage values. The scope of the analyses is not to establish whether there has been an underestimation or overestimation of real waste production with respect to that calculated using the presumptive method. On the other hand, it is important to emphasize the differences. Fig. 4 shows the percentage of samples belonging to categories n. 21 and n. 11 whose real residual waste production differs from the presumptive waste production within the Δ value. The upper part of Fig. 4 shows that 35% of users listed in category n. 21 in the Municipality of Mesero have a real residual waste production which differs more than 100% from the presumed production. Instead, the lower part of the same Figure shows that 50% of users listed in category n. 11 in the Municipality of Rezzato have a real residual waste production which differs with 90% to 100% from the presumed production. Fig. 5 demonstrates the direct advantages in environmental terms when applying the PAYT method. As regards costs, the decrease of residual waste reduces waste management costs.

This Fig. also shows, for the Municipalities of Abbiategrasso (upper parte) and Mesero (lower part) a a) the quantities of separate and residual waste collected over the years; b) the trend in terms of percentage of separate waste collection and c) the residual waste production per-capita. Therefore, the residual waste destined for direct disposal is what affects most the waste tariff.

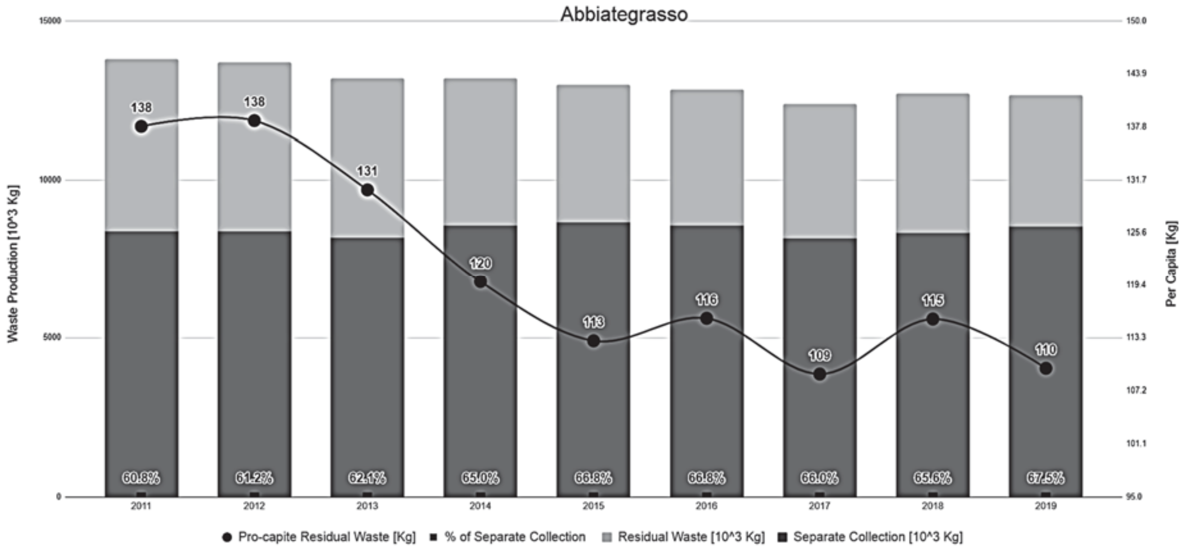


(a)

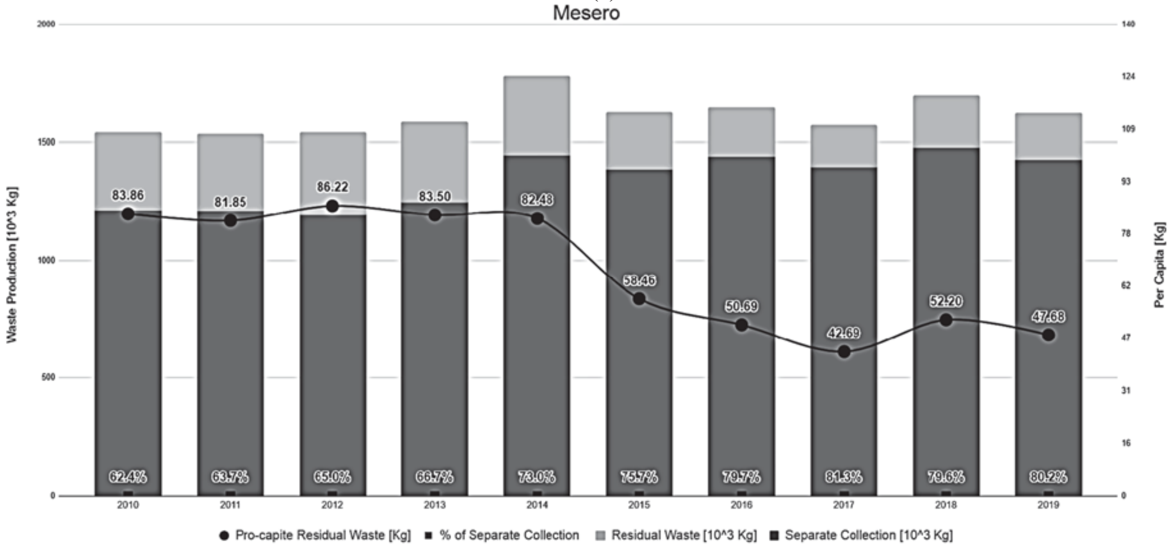


(b)

Fig. 4. Percentage of samples of category: (a) n. 21 and (b) n.11 whose real residual waste production differs from the presumptive waste production within the Δ value. Δ is the deviation expressed in terms of absolute percentage values



(a)



(b)

Fig. 5. Municipalities of (a) Abbiategrasso and (b) Mesero: the histograms show quantities of separate (dark gray) and residual waste (light gray) collected over the years; ● shows the trend of the residual waste production per-capita; ■ indicates the percentage of separate waste collection for each year

These data analyses highlight how the application of a PAYT method leads to a progressive decrease in pro-capita waste production and favours an increase in separate waste collection.

2.3. A new formulation

To articulate a fair fee, it would be appropriate to identify as many components as possible (partly fixed and partly variable) which, when operational, can represent a true correlation between the services used and the cost incurred by each user.

The proposal is formulated as follows:

1. In Italy, the variable part of the fee is determined by taking into account only the residual waste (IFEL, 2019). The tariff method to be applied will be based on the detection not only of the residual waste, but also of other waste fractions.

2. The tariff will be articulated without taking into account the surface, number of family members and reference categories. The proposal is that the fixed part should depend on the number of containers and their volume. This solution responds better to the principle of correlation, also in consideration of the fact that, as also shown in this study, the use of the parameters dictated by the standardized method referred to in the Presidential Decree 158/1999 (DPR, 1999) is not fair. In fact, with this latter method, the fixed part is applied regardless of the actual ability to produce waste, using only the metric data of the surfaces occupied by the user. Instead, the definition of a fixed part of the tariff based on costs related to the type and number of containers that the user has deemed necessary to acquire and has been supplied with allows overcoming this problem. Differentiated costs are considered in relation to the capacity of the containers and the user is allowed to choose which ones to utilise.

Eq. (1) can be articulated and enriched with further elements in the variable part. Therefore, *FIXP* is now articulated as Eq. (4):

$$FIXP_i = FIXC_i + SMC_i \quad \forall i \tag{4}$$

$FIXC_i$ are the fixed costs related to the waste management and the indivisible costs, such as street sweeping, while SMC_i is the Service Management Component of the *i-th* user determined on the basis of the number and volume of reusable waste collection bins supplied to users. The minimum number of bins given to users is standard, but a user can ask for more bins or bins with increased volume capacities. Each of the sub-components, number of containers and volume, will have a relative weight and the total component will be determined as follows (Eq. 5):

$$SMC_i = P(Nb_i) + P(Vb_i) \quad \forall i \tag{5}$$

where $P(Nb_i)$ is the part of the fee related to the number of bins Nb_i and $P(Vb_i)$ is the part of the fee related to the volume of the bins Vb_i of the *i-th* user. Hence, (Eq. 6):

$$SMC_i = w_1 \times Nb_i \times UQ_1 + w_2 \times Vb_i \times UQ_2 \quad \forall i \tag{6}$$

where w_1 and w_2 are the weights respectively associated to the number of bins and volume of bins delivered to the *i-th* user. Nb_i represents the number of bins delivered to the *i-th* user; Vb_i represents the volume of the bins delivered to the *i-th* user; UQ_1 and UQ_2 are the unitary costs associated to the type of bin and volume. The purpose of the two weights is to balance the effects of the variability of the fixed component of the tariff system. The higher the value of the weight is, relative to the number of containers, the lesser will be the variability of this component of the tariff. This allows the component SMC_i of the fixed part of the tariff to be divided in a less variable manner among users. This is to say that the greater the weight of the bin volume, the better the user's production potential is calibrated, assuring greater precision. This is why the two weights vary between 0 and 1, and the sum of w_1 and w_2 must be 1.

The $VARP_i$ is now composed as follow (Eq. 7):

$$VARP_i = CSSC_i + ISSC_i + DBSC_i - CRC_i + DMWCC_i + EIC_i \quad \forall i \tag{7}$$

The *CSSC* is the Collective Service Supply Component (Eq. 8):

$$CSSC_i = \sum_{l=1}^{m} Q_{li} \times UC_l \quad \forall i \tag{8}$$

where Q_{li} are the quantities of the *l–th* collected waste (residual and recyclable) of the *i-th* user, while UC_l is the unitary cost of the *l-th* fraction of the delivered and detected waste.

The quantity of waste detected is determined, in the first instance, by (Eq. 9):

$$Q_{li} = Nb_{li} \times Vb_{li} \quad \forall i \tag{9}$$

where Nb_i is the number of disposal bins and Vb_i is the volume of the bins used for the waste disposal and detected during the collection phase of the *l-th* waste fraction of the *i-th* user. The starting point of the hypothesis is that for every bin detected and emptied, the actual volume should be considered and not the level of waste filled in the bin.

The possibility for the individual user to request the delivery of bins of different sizes, adequate for the needs of the user, also allows to overcome or significantly reduce disputes rising from a presumptive emptying model.

In the case of aggregate users, where it is impossible to detect the single waste producer, a container of adequate volume can be used, allowing a certain number of users to create an association between their customer code and container code. The quantity of iated to users by means of appropriately identified coefficients. Therefore, the individual quota attributed can be calculated as follows (Eq. 10):

$$Q_{li} = TQc_l \times \frac{K_i}{\sum_{c \in C} K_c} \quad \forall i \tag{10}$$

TQc_l is the total waste quantity lying inside the container for the *l-th* waste fraction, while K_i is the coefficient applied to the *i-th* user and *C* is the set of users of the same condominium. *ISSC* is the Individual Service Supply Component (Eq. 11) related to services that are not utilized by all users. The costs of these services (parks/garden waste, bulky waste etc.) cannot be paid by the entire group of users:

$$ISSC_i = \sum_{s \in S} IS_{si} \times UC_s \quad \forall i \tag{11}$$

where IS_{si} is the *s-th* individual service at the unitary cost, UC_s, required by the *i-th* user.

DBSC are the Deferred Billing Service Costs (Eq. 12) related to those additional services that require the use of particular volumes which are not deliverable with the basic measurement system whose additional costs will be charged. Therefore, the municipality should allocate to each specific bin/bag a unit cost:

$$DBSC_i = B_i \times UCb \quad \forall i \tag{12}$$

where B_i is the bin/bag required by the *i-th* user and *UCb* is the unitary cost.

CRC is the CONAI Revenue Component (LD, 2006), which is the credit component in favour of the individual user in proportion to the differentiated waste conferred and for which a revenue is obtained from CONAI. The cost component relating to the variable part (*VARPi*) will be reduced through the clear display on the invoice of the amount of the revenue calculated by multiplying the quantity detected by the established €/kg price (Eq. 13):

$$CRC_i = \sum_{j=1}^{k} Q_{ji} \times RP_j \quad \forall i \tag{13}$$

Q_{ji} are the quantities of the Collected *j-th* Recyclable Waste of the *i-th* user, while RP_j are the recognized prices for the *j-th* type of recyclable waste.

Disposal at Municipal Waste Collection Centre (*DMWCC*) are the costs for the waste disposed of by the user. This is a net fee, where the unitary costs are an algebraic summation of costs and revenues of the *l-th* type of waste (Eq. 14):

$$DMWCC_i = \sum_{l=1}^{m} QMWC_{li} \times UCMWC_l \quad \forall i \tag{14}$$

$QMWC_{li}$ is the Quantity of the *l-th* fraction delivered at the Municipal Waste Collection Centre by the *i-th* user, while $UCMWC_l$ is the unitary cost of the *l-th* fraction of the waste disposed of at the municipal centre

EIC are the Extra Individual Charges for each extra service provided and which are directly attributable to the user during the year, such as the delivery of the duplicate of a card, the substitution of bins, etc.

3. Results and discussion

3.1. Standard PAYT results vs Normalized Presumptive Method

The production curves for the domestic category with two family members show that the trend, for the municipality of Rezzato, is more bell-shaped and the value of the waste production calculated with the presumptive method is closer to the real production. The Abbiategrasso curve is the most dispersed, while the Mesero curve shows that the real production is overestimated.

The curves obtained for the domestic category with three family members show a more dispersed trend in real production both for the municipality of Rezzato and Abbiategrasso, while the trend representing Mesero does not alter. This analysis shows that real production curves are more dispersed compared to the presumed production value. The same results are shown for non-domestic users. In fact, the real residual waste production significantly differs from the presumptive one.

The analysis presented in section 2.2, carried out over 3 years of punctual measurement and over 1 million monitored waste deliveries, shows that the real relationship between the quantities of waste produced is not representative of the reference categories provided for by the Presidential Decree n. 158/1999 (DPR, 1999). A recent study of PAYT Italia shows the same results (Drosi and Santi, 2014). For a fair and correct tariff to be applied on waste, it is necessary to overcome the concept of "production categories" and to introduce the concept of "producer entity". There are no production averages that can be used to apply a waste fee that is immune to macroscopic injustices. Depending on the municipality of residence and the quantity of waste delivered, it is possible to demonstrate that the presumptive method can be exaggeratedly expensive for some users in the same way that it is decidedly economical for others.

As mentioned previously, the PAYT system offers better results in the presence of a highly developed waste collection infrastructure, adequate payment policies and an efficient media coverage. Thanks to these three pillars, Municipalities have obtained several advantages, namely:

- Greater equity in tariffs;
- Increased quantitative performance of the system, translated into higher percentage of differentiated waste, lower production of residual waste, lower disposal costs and higher revenues for the sale of recycled fractions;
- Recovery of payment evasion thanks to the necessary mapping of users implemented by the PAYT system;
- Greater knowledge and control of the waste collection service due to the continuous monitoring offered by the PAYT system;
- Greater attention and transparency of costs communicated to and perceived by users, as well as growing consensus among citizens following widespread, clear and effective communications.

The analyses are also supported by the EU Directive Annex IV of The EU Waste Framework Directive (EC Directive, 2018) which considers PAYT as an incentive to a circular economy.

On the grounds of these observations, the paper introduced in section 2.3 a new version of the PAYT model. This formulation considers additional factors to establish a closer correlation between waste production and disposal costs incurred by each service user.

3.2. New PAYT results

The proposal in this paper allows for a) identification of technological components for the measurement of the quantities delivered; b) definition of the characteristics of the containers in order to enable the detection of the quantities to be delivered; c) consideration of all types of services for waste collection (door-to-door, ecological island, service-on-call, booking, etc.); d) inclusion of eventual aggregation of users; e) formulation of a measurement model to delineate which and in what way a certain type of waste is monitored (directly by weighing, or indirectly by considering the volume of the bin/bag/container); f) decision whether to collect a specific type of waste separately, like nappies, for instance.

To better understand the advantages of the proposal, three tariff methods have been simulated. The criteria for the simulations were: a) considering users in generic terms, without distinguishing between domestic or non-domestic categories; b) applying parameters (surface area, number of bins) constant for all users; c) taking into account the variability due to the fractions of waste production (differing number and volume of bins); d) dividing equally the fixed and variable components of the waste management costs amounting to € 500,00; e) distributing, in the proposed system, the fixed component: 50% as fixed costs (*FIXC*), 25% related to the Number of bins (*P(Nb)*) and 25% related to the Volumes of the bins (*P(Vb)*), while the variable component depends on the costs of disposal of each type of waste.

The fractions of waste taken into consideration are residual, organic, plastic, glass and paper. Disposal costs regarding residual and organic waste are higher compared to other waste types.

Fig. 6 shows the simulation results as being: a) the presumptive method gives always the same waste tariff cost; b) the Standard PAYT method evaluates only the residual waste production and c) the proposed PAYT model evaluates all fractions of waste in proportion to disposal costs. The increment in waste production in samples 1 and 2 causes an increase in costs with the proposed PAYT method, unlike the Standard PAYT system. This is due to the absence of residual waste variation. In samples 2 and 3 the increment in residual waste causes a significant increase in costs given by the Standard PAYT method. The proposed PAYT method mitigates the increase in costs because the other waste fractions are reduced. Sample 3 produces less waste compared to other samples, but pays more.

This is due to the major production of residual and organic waste, the disposal costs of which are higher. With an equal total waste production of samples 2 and 4, the division of the different components results in a diversity of costs when applying the proposed PAYT, while the PAYT Standard shows an increment dependent on the fraction of residual waste.

The presumptive method establish a fixed sum which does not depend on the amount of waste produced. The PAYT standard method establishes a cost which is only proportional to the residual waste produced and not depend on other types of waste. This method is based on a single waste type as though the management of all other fractions of waste are comparably homogenous and don't require ulterior cost valuation. The proposed PAYT method in this paper acts proportionally with regards to any waste type and relative weight because it takes into account single types of waste and services applied. The advantage of the proposed method is to define costs as close as possible to reality.

Briefly, users in Italy are presently charged for the total waste management cost in one of the two following ways:

- on a flat rate basis, if the municipality applies the presumptive method;
- on a residual waste production basis, if a PAYT system is used, especially if a municipality chooses to give more importance to the variable part of the fee.

This paper offers a third option:

- a new and fairer PAYT system which is more consistent with the user's behaviour.

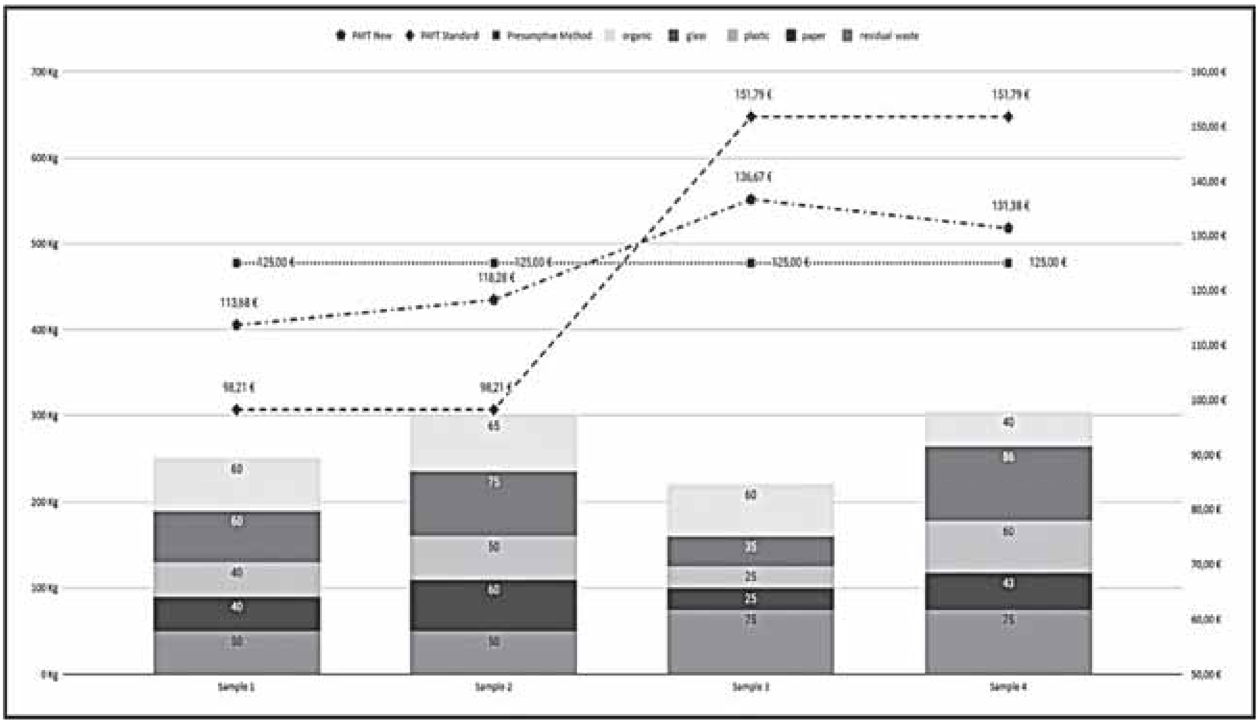


Fig. 6. Simulations of three waste tariff methods (dark dots) compared to different waste production hypothesis. The histograms represent simulations results of samples of waste produced

4. Conclusions

The Italian Legislative Decree No. 22/1997 (LD, 1997), Article 49, Establishment of the Tariff, has enabled municipalities in Italy to set up Pay-as-you-throw (PAYT) schemes, but only 11% of Italian Municipalities apply this system, while most use the Normalized Presumptive method.

Among the 11% of municipalities cited above, the authors investigated Abbiategrasso, Rezzato and Mesero Municipalities. These Cities provide door-to-door collection services using PAYT models. PAYT splits the fee for waste generation into a fixed part and a variable part. The fixed part is based on the number of household members among domestic users or on the surface area occupied for an activity by non-domestic users. The variable part is related only to residual waste production.

By comparing the data obtained from more than 1 million contributions, it was possible to establish that, whatever choice is made for the variable part of the tariff, as well as for the measurement methods chosen, the actual production of waste is different from the one assumed with the presumptive method which depends on factors like the occupied area and the number of family members.

Having shown the fairness of the PAYT system in section 2.2, the study goes further by proposing a new version of the system in section 2.3 which best reflects the user's behavior and from which better results can be derived.

Taking into consideration various waste fractions, including some recyclable ones like plastic or wet waste, can lead to a reduction in the per capita production of waste. The need for users to produce a smaller quantity of packaging as well as dry residual waste will encourage the adoption of better consumer choices by abandoning, for example, the use of disposable tableware or the purchase of plastic bottles.

As a matter of fact, municipalities have already defined the management cost of their services. Dividing this cost among users means defining a waste tariff. This paper analyses methods of tariff determination.

The aim of this study is to demonstrate that the PAYT system is a method of applying fairer tariffs. The proposed PAYT goes further by investigating additional components. This study is centered on the phase when tariff policies are to be applied after the overall service costs have been determined. It is about what a municipality may opt to do in collecting fairer tariffs from service users. Undoubtedly, cultural, educational, micro/macro economical, infrastructural, social , technological, political and integrated solid-waste management systems are among the principle factors which influence solid waste systems and user response.

The application of a fairer tariff system (pay on the basis of the waste produced) generates virtuous behaviour with a positive impact on management costs. Said mechanism stimulates a user to be beneficially selective, increases the quality of disposed material, increments revenues derived from the sale of quality materials and decreases the quantity of waste destined for disposal and difficult to recover.

Acknowledgements
The authors of this report would like to thank for their collaboration and data supplied the Municipalities of Abbiategrasso, Rezzato and Mesero and the Management Companies Amaga, Secoval and Consorzio dei Comuni dei Navigli.

References

Bilitewski B., Haerdtle G., Marek K., (1997), *Waste Treatment*, In: *Waste Management*, 1st Edition, Springer, Berlin-Heidelberg.

Bilitewski B., (2008), From traditional to modern fee systems, *Waste Management*, **28**, 2760-2766.

CR, (1975), Council Recommendation of 3 March 1975 regarding cost allocation and action by public authorities on environmental matters, Official Journal of the European Communities, L194/4, 25.7.75, On line at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31975H0436&from=IT.

Dijkgraaf E., Gradus R.H.J.M., (2004), Cost savings in unit-based pricing of household waste: the case of The Netherlands, *Resource and Energy Economics*, **26**, 353-371.

DPR, (1999), Regulation containing rules for the development of the standardized method for defining the tariff of the municipal waste cycle management service, Decree of the President of the Republic of 27 April 1999 n. 158, published in Official Gazette of the Italian Republic, General Series, 129 of 04-06-1999, Ordinary Supplement no. 107, On line at: https://www.gazzettaufficiale.it/eli/id/1999/06/04/099G0235/sg.

Drosi G., Santi M., (2014), Presentation of the results of the data analysis regarding municipalities which have applied Unit Pricing for years, PAYT Italy's 1st National Seminar Proceedings - Unit Rate: from Theory to Practice, Thursday 25 September 2014, Rome, On line at: www.payt.it/wp-content/uploads/2014/06/ATTI_SEMINARIO_ROMA_250920141.zip.

EC DG ENV, (2012), Use of economic instruments and waste management performances, Final Report, 10 April 2012, Contract ENV.G4/FRA/2008/0112, On line at: https://ec.europa.eu/environment/archives/natres/pdf/BIO_TSR_FinalReport.pdf.

EC Directive, (2018), Directive (EU) 2018/851 of The European Parliament and of The Council 30 May 2018, amending Directive 2008/98/EC on waste, Official Journal of the European Union, L150/109, 14.06.2018, Brussels, On line at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L0851&from=IT.

EC, (2014), Proposal for a Directive of the European Parliament and of the Council amending Directives 2008/98/EC on waste, 94/62/EC on packaging and packaging waste, 1999/31/EC on the landfill of waste, 2000/53/EC on end-of-life vehicles, 2006/66/EC on batteries and accumulators and waste batteries and accumulators, and 2012/19/EU on waste electrical and electronic equipment, Procedure 2014/0201/COD, 2.7.2014, Brussels, On line at: https://eur-lex.europa.eu/resource.html?uri=cellar:e669092f-01e1-11e4-831f-01aa75ed71a1.0001.01/DOC_1&format=PDF.

Elia V., Gnoni M.G., Tornese F., (2015), Designing Pay-As-You-Throw schemes in municipal waste management services: A holistic approach, *Waste Management*, **44**, 188-195.

EPA, (1994), Pay-As-You-Throw: Lessons Learned about Unit Pricing of Municipal Solid Waste, U.S. EPA Office of Solid Waste, EPA530-R-94-004, U.S. Environmental Protection Agency, Washington, D.C., Report, Canterbury J., On line at: https://archive.epa.gov/wastes/conserve/tools/payt/web/pdf/payasyou.pdf.

IFEL, (2019), Guide to the unit pricing of municipal waste – 2019 Edition, Dossiers and manuals, IFEL ANCI Foundation, On line at: https://www.fondazioneifel.it/documenti-e-pubblicazioni/item/download/3423_9fe2c7cce1a8c1b6bbffab9ed4dca50f.

ISPRA, (2019), Urban waste report – 2019 Edition, ISPRA, Public Relations 313/2019, On line at: http://www.isprambiente.gov.it/files2019/pubblicazioni/rapporti/RapportoRifiutiUrbani_VersioneIntegralen313_2019_agg17_12_2019.pdf.

Karagiannidis A., Xirogiannopoulou A., Tchobanoglous G., (2008), Full cost accounting as a tool for the financial assessment of Pay-As-You-Throw schemes: a case study for the Panorama municipality, Greece, *Waste Management*, **28**, 2801-2808.

LD, (1997), Legislative Decree of 5 February 1997 n. 22, Implementation of directives 91/156 / EEC on waste, 91/689/EEC on hazardous waste and 94/62/EC on packaging and packaging waste, published in *Official Gazette of the Italian Republic*, General Series n.38 of 15-02-1997, Ordinary Supplement no. 33, On line at: https://www.gazzettaufficiale.it/eli/id/1997/02/15/097G0043/sg.

LD, (2006), Legislative Decree of 3 April 2006 n.152, Environmental Regulations, published in *Official Gazette of the Italian Republic*, General Series n. 88 of 14-04-2006, Ordinary Supplement no. 96, On line at: https://www.gazzettaufficiale.it/dettaglio/codici/materiaAmbientale.

Morlok J., Schoenberger H., Styles D., Galvez-Martos J.L. and Zeschmar-Lahl B., (2017), The impact of Pay-As-You-Throw schemes on municipal solid waste management: the exemplar case of the county of Aschaffenburg, Germany, *Resources*, **6**, 8, https://doi.org/10.3390/resources6010008

Reichenbach J., (2008), Status and prospects of pay-as-you-throw in Europe - A review of pilot research and implementation studies, *Waste Management*, **28**, 2809-2814.

Skumatz L., (2008), Pay as you throw in the US: implementation, impacts, and experience, *Waste Management*, **28**, 2778-2785.

TFEU, (2016), Treaty on the Functioning of the European Union: Consolidated Version, Official Journal of the European Union, C/2016/202/TOC, 7.6.2016, On-line at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:C:2016:202:FULL&from=EN.

Environmental Engineering and Management Journal

October 2020, Vol. 19, No. 10, 1669-1676
http://www.eemj.icpm.tuiasi.ro/; hiip://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

DESIGN AND CHARACTERIZATION OF CONTROLLED RELEASE PK FERTILIZERS FROM AGRO-RESIDUES

Silvia Barbi[1], Francesco Barbieri[2*], Fernanda Andreola[3], Isabella Lancellotti[3], Carmen Martínez García[4], Teresa Cotes Palomino[4], Monia Montorsi[1,2], Luisa Barbieri[3]

[1]Department of Science and Methods for Engineering, University of Modena and Reggio Emilia, Via Amendola 2, 42122, Reggio Emilia, Italy
[2]Interdepartmental center for applied research and services in advanced mechanics and motoring, INTERMECH-Mo.Re., Via P. Vivarelli 10/1, 41125, University of Modena and Reggio Emilia, Modena, Italy
[3]Department of Engineering "Enzo Ferrari", University of Modena and Reggio Emilia, Via P. Vivarelli 10/1, 41125, Modena, Italy
[4]Department of Chemical, Environmental and Material Engineering, High Polytechnic School of Linares, University of Jaen, Linares Scientific and Technological Campus, Cinturon Sur, s/n, 23700 Linares, Spain

Abstract

The aim of this study is to design and characterize a new controlled release fertilizers category by using valorization of residues from agri-food, industrial and post consumers activities normally allocated into landfill disposal. The underlying strategy in materials research fully agreed with the circular economy perspective and the more recent European legislation about critical raw materials recovering. This study covers the development of lightweight aggregates, based on a local red clay (km 0 concept) and pores former such as coffee grounds and brewery sludge. Functionalization has been performed with vegetable biomass and cattle bone flour ashes, as received and after vitrification in a tailored fertilizer glass, containing high quantity of potassium and phosphorous. Fully characterization by means of a multidisciplinary approach, including chemical, mineralogical, thermal, physical, and plants growth in soils tests has been performed on starting and derived materials. Finally, growth test on basil's plant have demonstrated the beneficial effect of the aggregates designed and produced in this study in comparison with standard fertilizer already on the market.

Key words: agro-waste, circular economy, core-shell fertilizer, LWAs, PK fertilizers

Received: February, 2020; Revised final: June, 2020; Accepted: July, 2020; Published in final edited form: October, 2020

1. Introduction

The exponential growth of the global population forces agriculture to use more efficient fertilizers to increase crop production. Over the next five years the global soil demand for nitrogen, phosphorous and potassium will annually grow on average by 1.5%, 2.2% and 2.4%, respectively, and so for the global demand of fertilizer products (FAO, 2017; Herrera-Estrella and López-Arredondo, 2016; Taddeo et al., 2016). At the same time, hydro-culture and roof garden, that are favorable culture techniques to avoid soil exploitation, arise the demand for high-engineered lightweight fertilizers (Kim et al., 2018). Lightweight aggregates (LWAs) may take advantage of their intrinsic characteristic to be highly porous materials promoting the ability to retain nutrients and water for certain times promoting a controlled release (Lubkowski and Grzmil, 2007; Tomaszewska and Jarosiewicz, 2006). Controlled release fertilizers (CRFs) peculiar slow release make them the best choice to reduce toxicity related to a sudden solubilization and loss of ions into the soil (Mikkelsen et al., 1994). On the other hand, they have high costs

* Author to whom all correspondence should be addressed: e-mail: fbarbieri@unimore.it; Phone: +39 059 2056221

for production and raw materials purchase while their storage is difficult because of premature release of nutrients due to moisture absorption (Davidson and Gu, 2012). Among them, nutrients incorporation based CRFs are easier and cheaper to produce, nevertheless the nutrient's content is reduced since it has to be mixed with other compounds (Al-Zahrani, 1999; Liang et al., 2007), such as montmorillonite (Rashidzadeh and Olad, 2014), bentonite (Xiaoyu et al., 2013) and zeolites (Hoeung et al., 2011). In this context strong effort should be done in order to reduce CRFs disadvantages and, therefore, research of new raw materials for the fertilizer's manufacturing became a critical issue. Moreover, it must be considered that the employment of renewable resources for the design and development of innovative fertilizers has been recently recognized as a key point since these nutrients are exhaustible (EEA, 2015). This it is particularly true for phosphorus that was recently included in the list of critical raw materials (CRMs) by European commission.

In the present study, LWAs have been designed and characterized to act as CRFs starting from agri-food industry and post-consumer activities residues, reducing starting material costs, and therefore fit into a context of cleaner products (Farias et al., 2017). In this sense this work can be also considered as innovative example of food residues valorization as CRFs (Du et al., 2018). Ceramic core of the fertilizer has been investigated employing a local red clay, thereafter, employing km 0 concept: saving time and costs for transport, leading to a reduced environmental impact of the overall recycling process. Red clay was obtained from industrial manufacturing processes, as base material. Organic residues such as brewery sludge and spent coffee grounds (SCGs), that are produced in high quantities close to 6 million of tons yr^{-1}, have been employed as expandable materials promoting an alternative way of reuse (ICO, 2017; Murthy and Madhava Naidu, 2012; Tokimoto et al., 2005). In addition, cattle bone flour ashes, vegetable ashes and a tailored fertilizer glass have been studied to include potassium (K) and phosphorus (P) to be further released in soil. Therefore, this study promotes reliable alternative to well-known phosphor-enriched leftovers (e.g. phosphogypsum) characterized by a too high toxic metal content (e.g. As, Cd, Ni, Cr, Se, Pb) that could be potentially transfer in soil (Cánovas et al., 2018).

2. Material and methods

2.1. Materials

All the residues employed to produce LWAs come from brewery fabrication, meat and vegetable transformation or post-consumer activities (coffee consuming, pruning) geographically near to each other (in the North of Italy), with the aim to promote the local re-employment and therefore reducing costs related to transports. The only natural raw material is represented by the red clay used as matrix, which is also of local origin of the same part of Italy, having grain size <1mm. Sludge from wastewater treatment during brewery fabrication and spent coffee grounds were employed as pores former agents for clay. Vegetable biomass and cattle bone flour ashes were introduced in LWAs formulation as received and through the creation of a well-tailored glass (fertilizer glass), based on vegetable biomass, differently from other studies (Andreola et al., 2019).

2.2. Fertilizer glass and LWAs preparation

Fertilizer glass was prepared using Glassy Sand (40 wt%) and ashes (60 wt%). All the compounds had a grain size lower than 100 μm (D90). All the starting materials were mixed in a low-velocity rotatory mill for 30 min to enhance the homogenization of the mixture. Subsequently, the mixture was put in a refractory crucible and melted (Lenton, EHF 1700) until 1450 °C employing a heating rate of 10 °C min^{-1} with four isothermal steps: 900 °C for 40 min, 1000 °C for 60 min, 1300 °C for 30 min and 1450° C for 120 min. At the end of the heating cycle the melted glass was poured in water to obtain a frit that was ground in an agate mill for 45 min and sieved through a vibration laboratory machine (Retsch, AS200, Haan, Germany), to obtain a powder with D99 <100 μm. LWAs formulations were reported in Table 1 in wt% showing the presence of two main categories, the first containing PK nutrients sources (ashes) as received, the second including fertilizer glass. To obtain LWAs, raw materials were mixed and then spherical shape were realized manually, dried at 105 ± 5°C and then fired at 1000°C for 60 min into a hot oven, as reported in detail elsewhere (Andreola et al., 2019). Fertilizer glass and LWAs production processes are reported in Fig 1.

Table 1. LWAs formulation in wt%

	Clay	*Brewery sludge*	*Coffee grounds*	*Vegetable biomass ash*	*Cattle bone flour ash*	*Fertilizer glass*
B-STD	85	15	-	-	-	-
B-Ash	64	12	-	12	12	-
B-Glass	57	10	-	-	-	33
C-STD	85	-	15	-	-	-
C-Ash	64	-	12	12	12	-
C-Glass	57	-	10	-	-	33

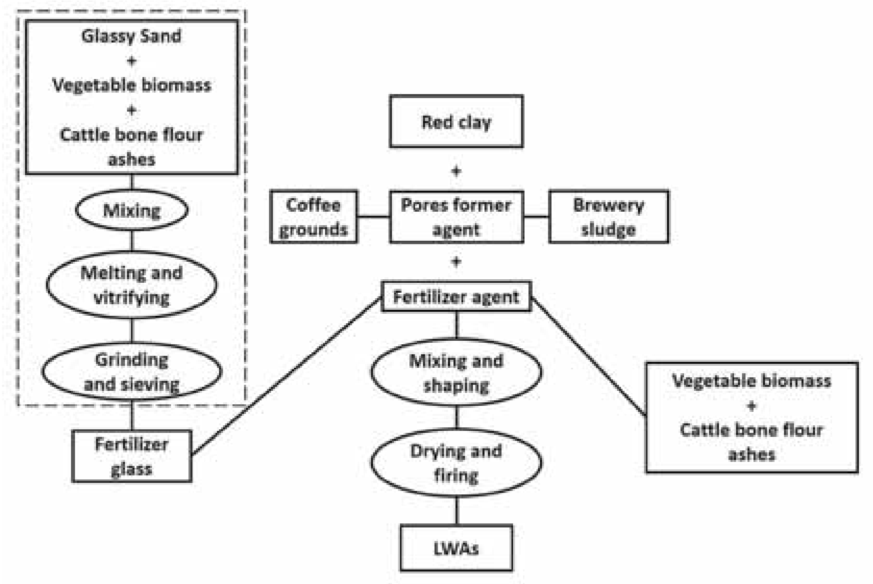


Fig. 1. Fertilizer glass and LWAs production process

2.3 Characterizations

Chemical and elemental compositions, respectively measured through X-Ray fluorescence (XRF, Thermo Fisher, ARL ADVANT'XP+) and elemental analyzer (Thermo Fisher, FLASH 2000), of the two ashes and fertilizer glass were reported in Table 2, while the complete characterization of the other raw materials can be founded elsewhere (Andreola et al., 2019). Also X-Ray Diffraction (XRD, Philips, PW3710) was performed on LWA's base materials. Thermal analysis such as differential scanning calorimetry (DSC) coupled with thermogravimetric analysis (TG) were employed to determine the raw material degradation profile and therefore suitable heating treatment for LWAs sintering (Netzsch, DSC 404). DSC was performed in air at the heating rate of 10 °C min^{-1} using 30 mg of the powdered sample, whereas TG was done using a ramp temperature of 10 °C min^{-1} from 0 °C to 1200 °C in inert atmosphere (nitrogen, 50 mL min^{-1}).

Physical tests were mainly focused on the estimation of LWAs porosity. Therefore, environmental scanning electron microscopy (ESEM, Quanta-200) was employed to evaluate LWAs morphology and shape porosity, whereas, static water absorption (for 24 hours) following EN 772-21:2011 and dynamic water absorption (boiling for 6 hours) according to EN 772-7:1999 were employed to evaluate the technological performance of the materials.

Water absorption tests were performed through analytical scale (Bel Engineering M124A), with a full scale of 120g and an accuracy of 0.0001g on the average of 10 measurements. Moreover, apparent density measurement (GeoPyc 1360, Micromeritics), absolute density analysis (AccuPyc II 1330, Micromeritics) and calculation of total porosity were carried out according to EN 1936-2006. For density measurements an accuracy on the average of 5 measurements and a standard deviation of 0.0001 g cm^{-3} must be considered in order to obtain reliable comparison among data. LWAs total porosity was calculated as densities difference - absolute density ratio. Chemical tests included pH determination (pH meter XS Instruments model pH 6, sensibility: 0.01) according to EN 13037:2012 and specific conductivity measurement (Oakton portable conductivity meter model CON 6 / TDS 6, sensibility: 0.01) following UNI EN 13038: 2012.

Finally, germination and growth tests were performed to investigate the possible phytotoxic effect of the materials and the influence on the growth of a plant species in vivo, respectively. Growth tests were performed only on LWAs containing SCGs, which resulted in higher porosity, leading SCGs as a more effective pores former agent than brewery sludge (as will be discussed ahead in Result and Discussion section). Basil seeds were employed (5 seeds for each test) under LED light (45W) and over a period of 40 days. Basil was selected because its direct seeding is often difficult and seed germination may be limited, especially in cold soils. In particular, four different types of soil for burial were evaluated: 1) commercial control soil (base cultivation substrate containing NPK fertilizer with a composition of N 1.65%, C 39.97%, H 4.65%, P 5.04 %, K 6.10%, *CNTR*; 2) soil with LWAs containing only SCGs as poring agent, *C-STD*; 3) soil with LWAs nutrients enriched as ashes, *C-Ash*; 4) soil with LWAs containing fertilizer glass, *C-Glass*.

The germination was evaluated by monitoring the number of shoots, while the growth was measured in terms of plant's weight, highness and number of leaves after 40 days. Plants weight was measured through analytical scale (Bel Engineering M124A), with a full scale of 120g and an accuracy of 0.0001g on the average of 10 measurements. Plants highness was measured with a digital micrometer (Mitutoyo, YY-T1BD-2GYE, sensibility: 0.02 mm).

3. Results and discussion

3.1. Raw materials characterization

Chemical analysis (Table 2) confirms the high organic and carbonates content of brewery sludge, which show a loss on ignition (L.O.I.) above 50 wt%. These values are similar to those of SCGs reported in Andreola et al., 2019 and prove that brewery sludge can be tested as contribute to gas formation during sinterization of the LWAs. At the same time, Table 2 confirms the not-negligible content of nutrients in the fertilizer glass and in the two ashes: above 40 wt% for phosphor pentoxides into cattle bone flour ash and above 60 wt% for potassium oxide into vegetable biomass ash. At the same time chemical analysis confirms the absence of pollutant due refractory crucible employed for fertilizer glass melting. Not-significant amount of potential toxic compounds, such as heavy metals or sulfur dioxide and chlorides has been detected, therefore the risk of soil contamination is restrained. Clay's detailed chemical analysis is reported in (Andreola et al., 2019) and shows values expected from a red clay composition (Fiori et al., 1989).

Elemental analysis (Table 2), indicates that the main organic content is due to compounds related to carbon, in brewery sludge. On the other hand, cattle bone flour ash is enriched in nitrogen, whereas vegetable biomass ash presents a negligible amount of carbon, while nitrogen and sulfur are totally absent. A not-negligible content of sulfur is present only in cattle bone flour ash (~2%) but, considering the amount of this compound in the final aggregates following (12 wt%), the formation of possible toxic species such as SO_2 is strongly limited.

The mineralogical analysis performed on the red clay was previously reported elsewhere and confirms that it is composed mainly by crystalline materials (Andreola et al., 2019). Selected clay fits the most important requirement necessary to act as LWAs matrix: plastic clay materials favors the processing of the LWAs mixture and promotes mechanical resistance. All the crystalline phases detected suggest that the employed raw materials lead to formation of non-toxic crystalline compounds. Finally, the XRD pattern of glass fertilizer (data not reported) confirms the amorphous nature of this material, with the presence of crystalline silicate-sodium calcium phosphate ($Na_2Ca_4(PO_4)$ $2SiO_4$, ICDD:00-033-1229). The presence of nutrients in different crystalline phases could explain differences in release behavior depending on the raw materials employed.

Fig. 2a shows DSC and TG curves related to the clay employed as LWAs matrix: around 100 °C there is the loss of free water with an endothermic phenomenon, subsequently, around 250 °C combustion of the organic compounds is shown, around 600 °C dehydroxylation of interlayer water occurs, at about 800 °C decomposition of the carbonates appears, finally, around 1200 °C fusion occurs characterized with an endothermic process. For each of these peaks the related weight losses (%) are presented in the same figure through a red curve; the main are humidity loss (1.89 wt%), dehydroxylation (4.40 wt%) and carbonates decomposition (4.74 wt%). In Fig. 2b the thermal behavior of coffee grounds has been represented, with the aim to show an example of the overall thermal attitude shared with brewery sludge and vegetable biomass: up to 200 °C a fairly stable situation is evident, with a limited decrease in weight of the sample in proximity to small endothermic peak which implies the sole loss of moisture inherent the material. In the range from 250 to 600 °C several exothermic peaks are detectable on the DSC curve, with particular relevance around 300 °C, due to the combustion of the organic fraction. These peaks are in fact accompanied by an overall considerable weight loss near to 50 wt%. Around 650-700 °C a further endothermic peak occurs due to the decarbonation of the material, in strong similarity of what has been shown previously about clay. Above 700 °C no further peaks are detected, therefore, there are no more significant thermal decomposition. As confirmed by thermal characterization the employment of 1000 °C for LWAs sintering should reach both the objectives: clays sinterization and organic fraction degradation and consequently pore formation.

3.2. LWAs physical characterization

Weight loss % has been calculated through LWAs weight measurements before and after aggregates firing in order to evaluate the content of humidity and volatile compounds into the different LWAs. As shown in Table 3 LWAs containing brewery sludge have a lower weight loss than those containing spent coffee grounds (~ -5%), that is coherent to the higher amount of organic fraction in spent coffee ground with respect to brewery sludge. On the other hand, even if no particular difference can be detected comparing the STD samples with the ones containing ashes a further decreasing of weight loss is observed employing fertilizer glass, in agreement to a content of volatile compounds equal to zero for the fertilizer glass (Table 2). This result is verified for both LWAs series: containing brewery sludge or spent coffee grounds. Therefore, higher porosity and lower density is expected in samples containing ashes and spent coffee grounds.

ESEM analysis (Fig. 3) have been performed on the inner part of the LWA showing, as expected by weight loss measurement, that LWAs containing spent coffee grounds (Fig. 3b) show higher porosity with respect to brewery sludge (Fig. 3a). In addition, LWAs containing brewery sludge show a more heterogeneous microstructure which could favor the nutrients release in soils (Fig. 3a). Pore's amount decreases when the fertilizer glass is included (Fig. 3c and Fig. 3d), at the same time an agglomeration and general increasing of grain phases is observed, that is coherent with the marked decreasing of measured porosity moving from B-Ash to B-Glass (or C-Ash to

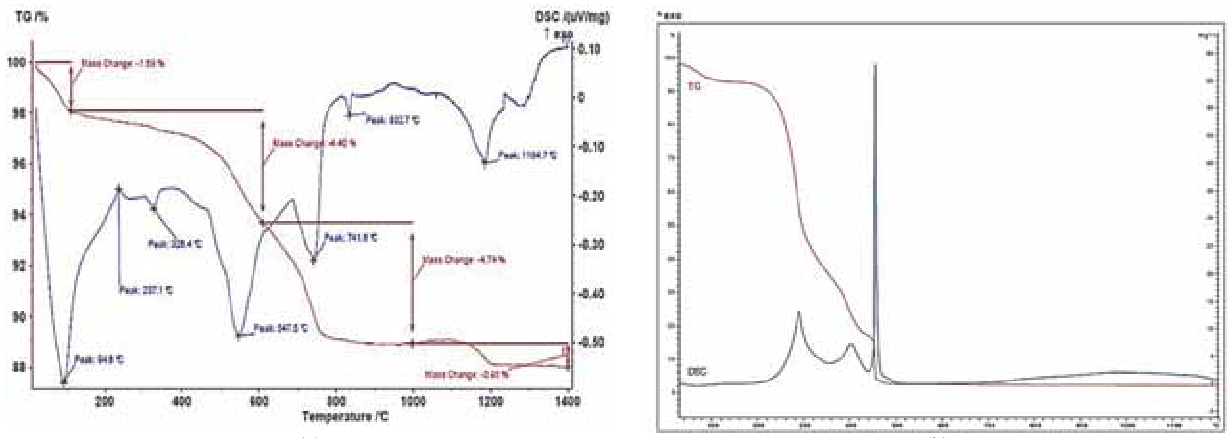
C-Glass) as reported in Table 3.

Table 3 shows that water absorptions strongly increase if ashes are included directly as LWAs component with respect to STD samples, because ashes are highly organic and hygroscopic materials. On the contrary water absorptions decrease with the addition of fertilizer glass in LWAs composition for the same reason. Furthermore, fertilizer glass acts as pore closure, with respect of STD and ashes containing samples. This result is also confirmed by the apparent density measurements (Table 3) which show an increase of the apparent density with fertilizer glass addition, therefore indicating a decreasing of the open porosity available to water permeation. On the contrary not significant variation of apparent density has been found moving from B-STD to B-Ashes or from C-STD to C-Ashes.

The increasing of absolute density moving from STD to ash containing samples and to glass containing samples agrees with the higher crystalline degree of the LWAs microstructure investigated through ESEM (Fig. 3) suggesting a more packed microstructure due to the presence of crystalline phases and vitrified areas.

Table 2. Chemical and elemental analysis of the raw materials and fertilizer glass (XRF sensibility ± 0.05; ICP sensibility ± 0.01%)

wt(%)	***Brewery sludge***	***Cattle bone flour ash***	***Vegetable biomass ash***	***Fertilizer glass***
Chemical Analysis				
SiO_2	11.86	0.43	2.38	31.97
Al_2O_3	1.10	<0.05	0.24	3.85
Fe_2O_3	7.40	<0.05	0.21	0.46
CaO	18.52	53.89	6.07	24.83
MgO	1.17	1.11	0.73	1.49
Na_2O	1.82	1.4	0.31	6.04
K_2O	0.26	<0.05	61.20	15.96
TiO_2	0.18	<0.05	--	0.02
MnO	0.06	--	--	--
P_2O_5	2.18	41.24	1.07	14.97
PbO	--	--	--	0.01
L.O.I.	55.44	1.74	18.60	0.00
Total	99.14	99.9	90.81	99.60
Elemental analysis				
N	3.02	8.34	0.00	/
C	23.45	31.72	6.28	/
H	3.32	4.32	0.62	/
S	0.09	2.16	0.00	/



(a) (b)

Fig. 2. DSC and TG analysis (a) clay; (b) coffee grounds

Table 3. Physical properties and growth test results after burial in soil and seeding of selected samples

	CNTR	***B-STD***	***B-Ash***	***B-Glass***	***C-STD***	***C-Ash***	***C-Glass***
pH	***/***	***6.72***	***6.40***	***8.24***	***7.06***	***6.52***	***8.42***
Conductivity (dS m^{-1})	/	0.25	1.39	0.17	0.40	0.97	0.19
Water absorption 24h (%)	/	11.65	17.69	9.09	15.34	18.87	11.00
Water absorption 6h (%)	/	11.93	21.37	9.92	22.16	24.96	16.45
Absolute density (g cm^{-3})	/	2.62	2.72	2.82	2.49	2.68	2.80
Apparent density (g cm^{-3})	/	1.44	1.45	1.73	1.30	1.27	1.49

Total porosity (%)	/	45.28	47.72	38.60	46.82	52.50	46.81
Weight Loss (%)	/	15.7	15.4	9.3	21.1	20.2	14.1
Growth test results							
Number of plants	5±0.1	/	/	/	4.7±0.6	5.7±0.6	4±1.4
Highness (cm)	10.2±0.2	/	/	/	9.4±0.1	10.6±1.5	10.7±1.3
Weight (g)	7.234±2.309	/	/	/	6.035±1.180	6.349±0.722	5.510±1.329
Number of leaves	25.6±1.4	/	/	/	21.6±0.4	23.6±0.2	22.4±0.1

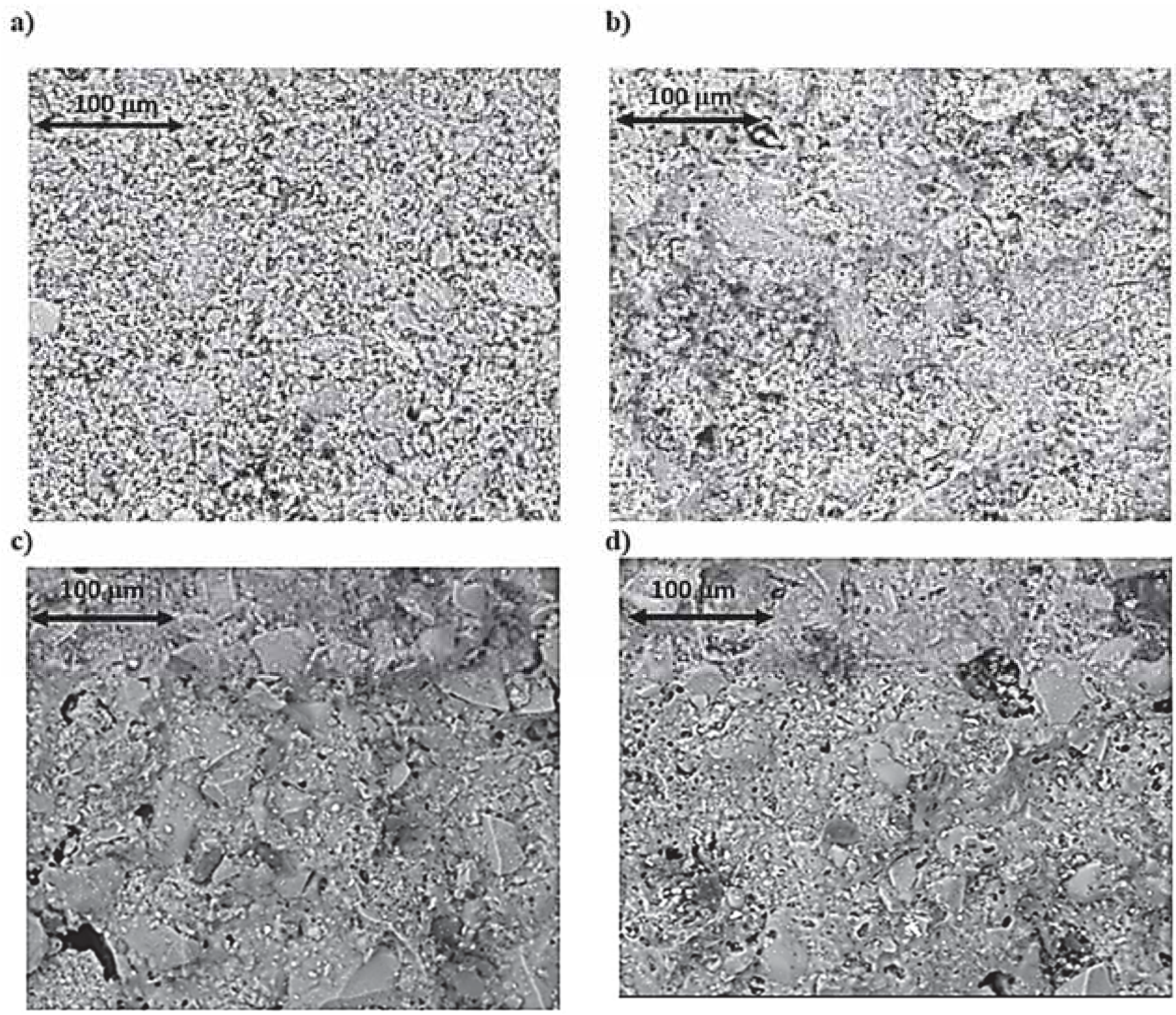


Fig. 3. ESEM analysis of LWAs (300x): a) B-Ash, b) C-Ash, c) B-Glass, d) C-Glass

According to results obtained through ESEM and weight loss measurement, spent coffee grounds-containing LWAs show in general higher porosity and water absorption with respect to brewery sludge-containing ones. According to these results the highest porosity is obtained through the sample C-Ash with a value above 50%. As expected, the dynamic water absorption enhances the water uptake, leading to generally higher values of water absorption for all the investigated samples. The water absorption is a key issue for CRFs functionality because it is strictly connected with nutrients release. In fact, a promising mechanism to better understand the working principle of CRFs is the one called multiphase diffusion model (Liu et al., 2008). According to this mechanism, after the fertilizer has been released into the soil, the irrigation water penetrates the coating, condenses at the core and causes the partial, but progressive, dissolution of the nutrients. Finally, as already reported considering the raw materials employed, no toxic elements have been founded through XRD analysis after the sinterization of the lightweight aggregates.

The results obtained about pH and conductibility are shown in Table 3 and demonstrate that all LWAs designed in this study fall into the category of aggregates that can be used for all type of culture, since they have a pH value between 6 and 7 or very close to this range. Even if slight deviations from this range to a basic pH have been observed (B-Glass and C-Glass), they are not significant considering the requirements needed for the greatest number of cultivations. The same happens for conductivity values which are mainly less than 2 dS m^{-1}, that is the threshold to consider a fertilizer suitable for most type of soils. It must be noted that ashes containing LWA shows in general higher conductivity and lower pH due to CaO and MgO in their composition (Table 3).

3.3. Growth test

Germination and growth test results are reported in Table 3, where a notable increment of the germination parameter has been found employing C-Ash with respect to others compounds. This result reflects the fact that the overall PK content of the commercial CRFs (~11 wt%) is lower than the PK content of C-Ash (~14 wt%). In fact, the number of plants germinated is higher employing C-Ash with respect to CNTR. On the other hand, similar results have been found employing C-Ash with respect to CNTR about growth parameters. As expected, sample C-STD is the one that shows lower beneficial effect, due to the absence of PK nutrients, whereas the glass employment (C-Glass) lead to a restrained nutrient release, confirmed by its overall PK content (~8 wt%).

These results suggest that the PK release of the fertilizer employed in this study has a beneficial effect on plant's germination with respect to a commercial fertilizer soil. With respect to other studies on basil cultivation with standard fertilizers (NH_4^+ and commercial NPK) , the present study demonstrates the possibility to obtain similar or enhanced plant's highness and number of leaves during growth (Frerichs et al., 2019; Setti et al., 2019).

Thereafter, the balanced employment of residues in this field of application overcomes theirs possible limitation due to source variability and chemical composition variation, avoiding possible costs due to residues purification, but strongly promoting a circular economy processing.

4. Conclusions

In this work, lightweight aggregates (LWAs) were successfully designed to host very tailored compounds, allowing the controlled release of nutrients and water when buried in soil. Their obtainment was reached by powders sinterization of mixtures containing local raw materials, agro-residues and red clay, in a circular economy perspective. At the same time a new type of fertilizer glass, from different type of recycled materials was engineered to be enriched in potassium and phosphorous, 16 wt% and 15 wt% respectively, also according to the actual EU regulation about critical raw materials recovery and re-employment.

Porosity evaluation has shown that spent coffee grounds have increased the overall porosity up to 52% which lead to an increasingly higher water absorption value. Therefore, they could be particularly suitable for green roofs and hanging gardens due to their particularly lightweight. Chemical tests have shown that aggregate's pH and conductivity values fall within the range suitable for agronomic use. The basil germination tests have confirmed the beneficial effect of the aggregates containing ashes (PK content ~14 wt%) with respect to a standard fertilizer (PK content ~11 wt%), whereas growth test showed similar results. Consequently, quantitative life cycle analysis and life cost analysis should be done in comparison with products already on the market to estimate the beneficial effects.

Acknowledgements

Authors would like to thank Project FAR UNIMORE 2017 entitled "The enhancement of agro-industrial waste between law and science: innovative processes from experimentation to industrialization in the legal context" for financial support. Italian company suppliers for the raw materials supply and Eng. Alessandro Borghi, Eng. Galia Agnoletto, Dr. Romina Farias and Dr. Giulia Santunione for the experimental support.

References

Al-Zaharani S.M., (1999). Controlled-release of fertilizers: modelling and simulation, *International Journal of Engineering Science*, **37**, 1299-1307.

Andreola F., Borghi A., Pedrazzi S., Allesina G., Tartarini P., Lancellotti I., Barbieri L., (2019), Spent coffee grounds in the production of lightweight clay ceramic aggregates in view of urban and agricultural sustainable development, *Materials*, **12**, 3581-3591.

Cánovas C.R., Macías F., Pérez-López R., Basallote M.D., Millán-Becerro R., (2018), Valorization of wastes from the fertilizer industry: Current status and future trends, *Journal of Cleaner Production*, **174**, 678-690.

Davidson D., Gu F.X., (2012), Materials for Sustained and Controlled Release of Nutrients and Molecules To Support Plant Growth, *Journal of Agricultural and Food Chemistry*, **60**, 870-876.

Du C., Abdullah J.J., Greetham D., Fu D., Yu M., Ren L., Li S., Lu D., (2018), Valorization of food waste into biofertiliser and its field application, *Journal of Cleaner Production*, **187**, 273-284.

EEA, (2015), Growing pressures on ecosystems (GMT 8), SOER 2015, European Environment Agency, On line at: https://www.eea.europa.eu/soer-2015/global/ecosystems

FAO, (2017), World fertilizer trends and outlook to 2020, Summary Report, On line at: http://www.fao.org/3/a-i6895e.pdf

Farias R.D., García C.M., Palomino T.C., Andreola F., Lancellotti I., Barbieri L., (2017), Valorization of agro-industrial wastes in lightweight aggregates for agronomic use: Preliminary study, *Environmental Engineering and Management Journal*, **16**, 1691-1700.

Fiori C., Fabbri B., Donati G., Venturi I., (1989), Mineralogical composition of the clay bodies used in the Italian tile industry, *Applied Clay Science*, **4**, 461-473.

Frerichs C., Daum D., Koch R., (2019), Influence of nitrogen form and concentration on yield and quality of pot grown basil, *Acta Horticulturae*, **1242**, 209-216.

Herrera-Estrella L., López-Arredondo D., (2016), Phosphorus: The Underrated Element for Feeding the World, *Trends in Plant Science*, **21**, 461-463.

Hoeung P., Bindar Y., Senda S.P., (2011), Development of Granular Urea-Zeolite Slow Release Fertilizer using inclined pan granulator, *Jurnal Teknik Kimia Indonesia,* **10**, 102-111.

ICO, (2017), Trade Statistics Tables, International Coffee Organization, On line at: http://www.ico.org/trade_statistics.asp

Kim J.A., Vijayaraghavan K., Reddy D.H.K., Yun Y.-S.Y.S., (2018), A phosphorus-enriched biochar fertilizer from bio-fermentation waste: A potential alternative source for phosphorus fertilizers, *Journal of Cleaner Production*, **196**, 163-171.

Liang R., Liu M., Wu L., (2007), Controlled release NPK compound fertilizer with the function of water retention, *Reactive and Functional Polymers*, **67**, 769-779.

Liu L., Kost J., Fishman M.L., Hicks K.B., (2008), *A Review: Controlled Release Systems for Agricultural and Food Applications*, In: *New Delivery Systems for Controlled Drug Release from Naturally Occurring Materials*, Parris N., Liu L., Song C., Shastri V. P.(Eds.), ACS Symposium Series, Vol. 992, American Chemical Society, 265-281.

Lubkowski K., Grzmil B., (2007), Controlled release fertilizers, *Polish Journal of Chemical Technology*, **9**, 83-84.

Mikkelsen R.L., Williams H.M., Behel A.D., (1994), Nitrogen leaching and plant uptake from controlled-release fertilizers, *Fertilizer Research*, **37**, 43-50.

Murthy P.S., Madhava Naidu M., (2012), Sustainable management of coffee industry by-products and value addition-A review, *Resources Conservation and Recycling*, **66**, 45-58.

Rashidzadeh A., Olad A., (2014), Slow-released NPK fertilizer encapsulated by NaAlg-g-poly(AA-co-AAm)/MMT superabsorbent nanocomposite, *Carbohydrate Polymers*, **114**, 269-278.

Setti L., Francia E., Pulvirenti A., Gigliano S., Zaccardelli M., Pane C., Caradonia F., Bortolini S., Maistrello L., Ronga D., (2019), Use of black soldier fly (Hermetia illucens (L.), Diptera: Stratiomyidae) larvae processing residue in peat-based growing media, *Waste Management*, **95**, 278-288.

Taddeo R., Kolppo K., Lepistö R., (2016), Sustainable nutrients recovery and recycling by optimizing the chemical addition sequence for struvite precipitation from raw swine slurries, *Journal of Environmental Management*, **180**, 52-58.

Tokimoto T., Kawasaki N., Nakamura T., Akutagawa J., Tanada S., (2005), Removal of lead ions in drinking water by coffee grounds as vegetable biomass, *Journal of Colloid and Interface Scienc*e, **281**, 56-61.

Tomaszewska M., Jarosiewicz A., (2006), Encapsulation of mineral fertilizer by polysulfone using a spraying method, *Desalination*, **198**, 346-352.

Xiaoyu N., Yuejin W., Zhengyan W., Lin W., Guannan Q., Lixiang Y., (2013), A novel slow-release urea fertiliser: Physical and chemical analysis of its structure and study of its release mechanism, *Biosystems Engineering*, **115**, 274-282.

Environmental Engineering and Management Journal October 2020, Vol.19, No. 10, 1677-1681
http://www.eemj.icpm.tuiasi.ro/; hiip://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

ALLIANCE FOR WATER STEWARDSHIP: A NETWORK OF SUSTAINABLE WATER STEWARDS

Short communication

Matteo Magagni[1], Chiara Rizzi[1], Maria Giuseppina Iannacci[1], Eugenio Brancone-Capponi[2], Beatrice Bizzaro[2*]

[1]Philip Morris Manufacturing & Technology Bologna S.p.A., Via Giacomo Venturi 1/2, 40053, Crespellano, Bologna (Italy)
[2]HPC Italia S.r.l., Via Francesco Ferrucci 17/A, 20145, Milan (Italy)

Abstract

Overexploitation and competitiveness over shared fresh water resources are some of the growing problems that affect numerous countries world-wide, in particular those characterized by high water-related risks linked to water scarcity, droughts and baseline water stress. Private and public sectors are driven to find alternative or best-practice strategies to conserve and optimize the water resource and guarantee a future use to all. The affiliate of Philip Morris Manufacturing and Technology Bologna of Crespellano has, with support of the INOGEN International Alliance and environmental consultants Denkstatt and HPC, implemented the Alliance for Water Stewardship (AWS) in order to promote a sustainable and feasible water use in the Emilia-Romagna Region as the second certified AWS Site in Italy after the Sicilian affiliate of Nestlé.

Key words: innovation, sustainability, water use

Received: February, 2020; Revised final: June, 2020; Accepted: July, 2020; Published in final edited form: October, 2020

1. Introduction: A world-wide water crisis

Water is a key resource and most essential element of life, yet less than 1% of Earth's fresh water is usable (WWF, 2020a). In 2019 the World Economic Forum listed water scarcity, the lack of sufficient available water for usage demands, as one of the largest global risks of the 21st century. Overuse, increasing demands, pollution, unsustainable management and changes in weather patterns due to global warming are key stressors that are affecting water availability and triggering an ever-growing water scarcity (Hirschnitz-Garbers et al., 2016; Pellicer-Martínez and Martínez-Paz, 2016).

The United Nations foresee two-thirds of the world's population living in water-stressed environments by 2030 (UNESCO, 2006). The potential impact on the environment and humanity could lead to a water crisis that would face over 6 billion people, in conflict over water for basic needs.

The sustainable management and conservation of this fundamental resource is a shared responsibility and a rapidly growing worldwide demand that faces every single country (Liu et al., 2020; Steinfeld et al., 2020).

Italy, as most Mediterranean countries, is dominated by a temperate climate but with an uneven distribution of rainfall between north and southern regions, which does not allow a uniform water use or reserve. According to the Water Risk Filter (Fig.1), the Italian regions of Sicily, Puglia, Molise, Campagna, Toscana, and Emilia-Romagna are amongst those most subjected to high water depletion risk (WWF, 2020b).

* Author to whom all correspondence should be addressed: e-mail: beatrice.bizzaro@hpc.ag

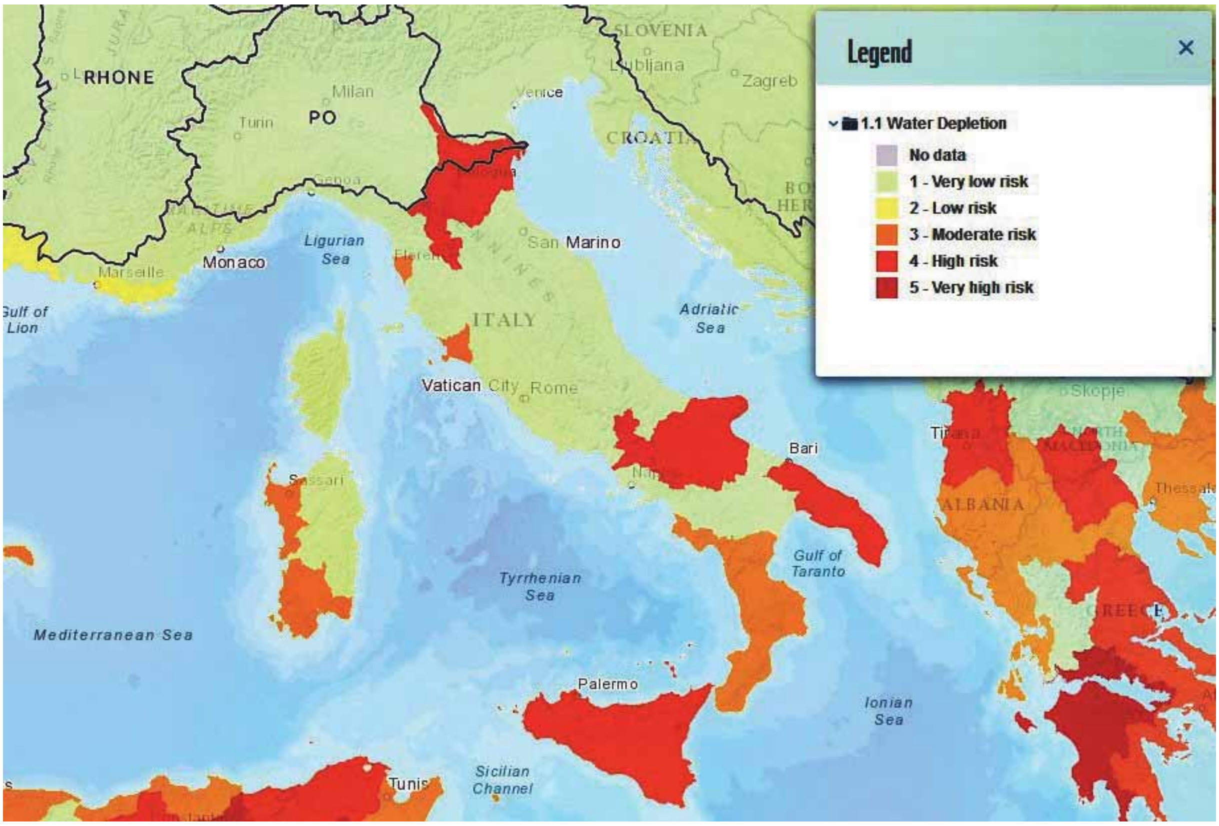


Fig. 1. Water depletion in Italy according to the Water Risk Filter: the black perimeter delimitates the watershed of main superficial water bodies

The scope of the current study is to investigate on an innovative water-saving management standard which can be applied to different Italian realities and production activities with the aim to work collaboratively towards a more sustainable use of the water resource.

2. Material and methods: The alliance for water stewardship

The Alliance for Water Stewardship (AWS) is the first globally acclaimed standard that assesses water-use across a 5-step certification procedure (Fig. 3) (AWS, 2020). With the aim to sustainably manage the water resource, AWS is proving to be an innovative certification adopted by a wide range of multinational companies such Nestlè in order to reduce their water footprint (Fig. 2). The AWS standard promotes water management by considering a variety of social, economic and environmental criteria, with the scope to reduce water consumption on-site and spread good water use practices throughout the entire catchment area.

Philip Morris International (PMI) has always adopted ambitious sustainability initiatives as core of their business strategy and is ranked by the Carbon Disclose Project (CDP) amongst the top companies for sustainability programs. PMI firmly believes that working efficiently goes hand in hand with helping and managing the environment. In 2017 PMI's environmental milestones included an active commitment to responsible and sustainable water management by piloting the AWS standard. After the success of the Brazilian facility of Santa Cruz do Sul, the AWS certification was launched to all PMI affiliates world-wide, with a target of certifying ten facilities by 2020 and all operations by 2025. PMI is assisted and aided in the certification procedure by the environmental consultants Denkstatt and HPC of the INOGEN International Alliance.

Philip Morris Manufacturing & Tecnology Bologna (MTB), located in the Italian region of Emilia-Romagna, is a global lead site for the large-scale production of *HeatSticks*, reduced risk products (RRP) used in the *IQOS* tobacco heating system. MTB is certified AWS since July 2019, is the second to be certified in Italy after the Sicilian affiliate of Nestlé and the first ever RRP site in the world to be certified AWS.

MTB is changing their business and their commitment towards a *best-practice* water management. The AWS standard abled MTB to not only follow the AWS 5-step wheel towards a Core-Level certification but also become a *water steward*, a sustainable water-user with the scope of reducing potable water consumption and impact on the territory (Tortajada et al., 2006). The AWS Standard allowed MTB to understand, identify and implement several AWS principles:

• Identification of the catchment area, the area of land that the site affects and is reliant upon MTB's catchment area was defined based on its potable water supplier, HERA, which draws water from rivers and deep aquifer water bodies.

• Understanding and prioritizing water-related risks: MTB is located in the Italian region of Emilia-Romagna and consequently subjected to a high baseline water stress and high-water depletion risk, due to the presence of many water-demanding industries, high competition between users and an estimated increase in drought occurrence.

• Identification of important water related areas (IWRA), sensitive areas of high conservational value, in the catchment area territory: MTB identified 9 IWRA of relevance and defined their status in order to evaluate the dynamics of the water resource.

• Active outreach to stakeholders and active participation in catchment governance: MTB created mutual collaborations with stakeholders such as the local community, environmental authorities ARPAE, Municipality of Valsamoggia and Consorzio della Bonifica Renana, local companies such as Granarolo, service provider HERA, and environmental federations Confindustria. MTB also implemented multiple awareness activities in order to increased public awareness on catchment water-related risks and promote water-saving efforts.

• Maintain and improve direct and indirect water use within the catchment: MTB implemented initiatives and strategies in order to reduce potable water consumption on-site and consequently remove less water from the catchment area and sensitive environments. By recycling waste water and steam in various processes, implementing water-saving plant settings and introducing new and innovative technologies such as Electrodialysis Reversal (EDR) and Cold Plasma, MTB has obtained outstanding results in 2019: a 20% water saving and a water efficiency index (WEI) of 12 m^3 per million of HeatSticks produced.

• Increase awareness of water issues and disclose best-practice performance within the site and catchment area: MTB strongly believes in effective communication and the AWS philosophy has been disclosed to every employee through water sensibilization presentations, internal communications and newsletters. MTB is active in raising public awareness on water sustainability practices and committed towards catchment wellbeing by engaging in events and campaigns with stakeholders and the local community.

3. Results and discussion: Transforming our business

The AWS standard certifies PMI's commitment to responsible water management and sustainable innovation for the wellbeing of the environment and future generations. The AWS journey enabled MTB to minimize its water footprint by understanding onsite water use and impacts and working collaboratively together with local stakeholder to establish a responsible water use within the territory. MTB implemented the AWS principles and steps and consequently established a good water stewardship not only inside the site premises but throughout the catchment area.

The process is still in progress, but MTB and PMI are proudly transforming their business towards a sustainable future with the hope that their commitment towards the environment with be followed by other water stewards world-wide.

Fig. 2. Members of Alliance for Water Stewardship

Fig. 3. The AWS 5-step wheel

Thanks to the implementation of the AWS certification, MTB has recorded a decrease of water of 20% for the production of one million HeatSticks. This represents an important goal achieved by the business that will certainly improve in the future. This aim, like AWS certification, is constantly evolving in order to amplify year after year these important benefits for the environment.

Moreover, MTP has implemented a press campaign in order to communicate and disclose progress with stakeholders such as local community, authorities, water service providers, local manufacturing facilities and industrial federations. Increased awareness of water issues and shared goals is fundamental to improve the collaboration of the stakeholders but also to demonstrate the AWS philosophy and values. MTB, in fact, could be a great example for other companies on how to be a conscious business. Another significant aspect of the standard is that it meets one of the 17 aims of Sustainable Development Goals set by NU in 2015 (Fig. 4). In particular, the certification is able to satisfy the goal number 6 Clean Water and Sanitation (United Nations, 2015). Philip Morris International wants to continue to take care of the responsible use of water. For this reason, PMI is committed to certifying all its production sites to the AWS standard by 2025. First sites certified are in Brazil, Portugal and Italy.

The business has obtained several benefits:

- Water resource efficiencies Increase (by reuse and optimization)
- Common understanding of shared water-related challenges/risk mitigation
- Water Knowledge sharing amongst MTB employees and local stakeholders
- Enhanced local collaboration and strengthened stakeholder relationships
- Growth in MTB capabilities towards AWS principles and water-related risks

Higher ranking in CDP water at Global Level. CDP is a not-for-profit charity that manages a global disclosure network for various members which includes countries, companies and investors for their environmental impacts. (CDP, 2020).

Reinforcement of PMI's sustainability credentials i.e. contribution to Goal 6 of Sustainable Development Goals (SDG).

4. Conclusions

The implementation of the AWS Standard offered a globally acclaimed solution to understand water use and impacts, as well as being a valid tool for working together with local stakeholders for the sustainable management of the water resource in the catchment context.

The implementation of AWS Standard not only contributed to achieving a water stewardship policy and outcomes but also work towards wider sustainability goals. A better understanding and management of the water resource in the local territory has been achieved as well as a significant decrease in potable water use at site-level.

Water is a precious resource for everyone for this reason is important to take care of it and find innovative solutions to preserve it.

Fig. 4. Sustainable Development Goals of ONU

References

AWS, (2020), Alliance for Water Stewardship On line at: https://a4ws.org/

Carbon Disclose Project, 2020, On line at: https://www.cdp.net/en

Hirschnitz-Garbers M., Tan A.R., Gradmann A., Srebotnjak T., (2016), Key drivers for unsustainable resource use – categories, effects and policy pointers, *Journal of Cleaner Production,* **132**, 13-31.

Liu Y., Chen B., Chen G., Li Z., Meng J., Tasawar H., (2020), Globalized energy-water nexus through international trade: The dominant role of non-energy commodities for worldwide energy-related water use, *Science of The Total Environment,* **736**, 139582, https://doi.org/10.1016/j.scitotenv.2020.139582

Pellicer-Martínez F., Martínez-Paz M.J., (2016), The Water Footprint as an indicator of environmental sustainability in water use at the river basin level, *Science of The Total Environment,* **571**, 561-574.

Steinfeld C.M., Sharma A., Mehrotra R., Kingsford R.T., (2020), The human dimension of water availability: Influence of management rules on water supply for irrigated agriculture and the environment, *Journal of Hydrology*, **588**, 125009, https://doi.org/10.1016/j.jhydrol.2020.125009

Tortajada C., Taylor R., Group F., (2006), *Integrated Water Resources Management: From Research to Implementation*, Helmholtz Centre for Environment Reasearch – UFZ, On line at: http://www.glowa-jordan-river.de/uploads/Links/IWRM.pdf.

UNESCO, (2006), World Water Assessment Programme, Water: A Shared Responsibility, On line at: http://www.unesco.org/new/en/natural-sciences/environment/water/wwap/wwdr/wwdr2-2006.

United Nations, (2015), 17 Sustainable Development Goals (SDGs), On line at: https://sustainabledevelopment.un.org/?menu=1300

WWF, (2020a), World Wildlife Fund, Water-scarcity, On line at: https://www.worldwildlife.org/threats/water-scarcity).

WWF, (2020b), World Wildlife Fund Water depletion in Italy, On line at: https://waterriskfilter.panda.org/en/Explore/CountryProfiles#overview/150

Environmental Engineering and Management Journal

October 2020, Vol. 19, No. 10, 1683-1692
http://www.eemj.icpm.tuiasi.ro/; hiip://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

APPROPRIATE SOLUTIONS FOR WASTEWATER REUSE IN AGRICULTURE: A PILOT PLANT IN RAFAH, GAZA STRIP

Alessandra Bonoli[1]*, Sara Pennellini[1], Tamer Eshtawi[2], Luay Qrenawi[2], Massimo Solaroli[3], Nidal Al-Zaanin[4], Ghassan Abu Saada[4], Enrico Barilli[5]

[1]Department of Civil, Chemical, Environmental and Materials Engineering (DICAM), University of Bologna, Via Terracini 28, 40131 Bologna, Italy
[2]Engineering and Information System Department, University College of Applied Sciences (UCAS), 1415 Gaza, Palestine;
[3]Engineer, Environmental Consultant
[4]Union of Agricultural Work Committees (UAWC), Gaza, Palestine
[5]Project coordinators Overseas – Onlus, Via per Castelnuovo R., 1190, 41057 Spilamberto, Italy

Abstract

Water supply represents a constant worldwide challenge for people and authorities. This issue is significantly severe in semiarid regions such as Gaza Strip, where groundwater constitutes the only fresh water source. Furthermore, Gaza Strip area suffers from water scarcity due to the decrease in water recharge and a constantly groundwater over-pumping, along with seawater intrusion, which cause serious problems in fresh water supply. Treated wastewater reuse represents a sustainable approach to increase water resource availability, to alleviate stressed polluted Gaza's coastal aquifer and to contribute to local agriculture development. On this issue, a pilot-scale plant has been designed to evaluate the feasibility of a municipal wastewater recovery for agricultural purposes in Rafah (Gaza Strip), reproducing the working conditions and performances of a real plant, which will be built by summer 2020. The paper aims to describe the case study in the context of Appropriate Technology (AT) for Developing Countries approach.

Key words: appropriate technologies, Gaza Strip, natural treatment system, wastewater reuse

Received: February, 2020; Revised final: June, 2020; Accepted: July, 2020; Published in final edited form: October, 2020

1. Introduction

The serious situation in Gaza about water supply is worldwide considered as a humanitarian crisis (UNRWA, 2019): the primary freshwater source is, after all, represented by groundwater, which is severely contaminated, and, at present yields, there is almost no water of acceptable quality for domestic use. Considering the presence of about 2 million inhabitants in Gaza, the availability of water is inadequate, both in terms of quantity and quality, with severe risks for public health. According to the latest Palestinian Water Authority (PWA) database, municipal water consumption is about 103.34 million m^3 (52%), of which 13 million m^3 suitable for drinking purposes and agricultural water consumption about 95.3 million m^3 (48%) (PWA, 2014).

The annual net deficit in the groundwater aquifer has been about 90 million m^3 in 2016, and it is expected to reach 180 million m^3 by 2035, because of the massively over pumping for freshwater supply purposes. The aquifer is showing clear signs of imminent failure or collapse, with resulting degradation and robust depletion of the water resources (Al-Dadah, 2013; Aiash and Mogheir, 2017). At the same time, there is an increasing water demand in Gaza Strip depending on the unexpected rise of the population.

* Author to whom all correspondence should be addressed: e-mail: alessandra.bonoli@unibo.it; Phone: +390512090234; Fax: +390512090234

In the recent decades, wastewater recovery and reuse techniques gained attention worldwide as a reliable alternative source of water based on a new approach of integrated water resource management. From one side, recycled water can be used for many different purposes, from irrigation to drinkable water supply, from the other side, the urgent need of wastewater reuse and recycling represents an indicator of scarcity of water, highly demanded for all anthropic uses (Aiash and Mogheir, 2017; PWA, 2014).

Treated wastewater can be an additional water source intended to increase agricultural production in Gaza Strip, where irrigation supplies are actually not sufficient to meet crop water needs (Al-Dadah, 2013). It can play an important role in agriculture, responsible of the major part of fresh water consumption in Gaza Strip (Gharbia et al., 2016), contributing also to increase agricultural production thanks to the presence of important nutrients (WWAP, 2017).

However, if not properly treated and controlled, recycled wastewater may create environmental problems. Most of the wastewater treatment plants in Gaza Strip are not properly managed and fail to provide water at adequate quality for its reuse and the possibility to reuse wastewater depends on the capability to implement wastewater treatment facilities (Al-Dadah, 2013; Abu Sultan, 2015). Reclaimed water can be used mainly for irrigation, industry, surface water and groundwater recharge and municipal purposes as well (Metcalf and Eddy, 2003).

The aim of the project was to contribute to agriculture economic development in Gaza Strip through new synergies, involving several civil society organizations. Specifically, the research has been focused on the examination and development of wastewater treatment methods in Rafah area to study appropriate technologies available for the finishing plant design, by implementing the existing primary treatment plant and the water availability in the north-east of the city.

The concept of "Appropriate Technology" (AT) has been introduced many years ago, by the British economist E. F. Schumacher in his famous book *Small is Beautiful* (Schumacher, 1973) and it is spread considered and accepted. AT is a strategy that enables people to rise out of poverty and improve their economic condition by meeting their basic needs, through developing their own skills and capabilities while making use of their available resources in an environmentally sustainable manner (Murphy et al., 2009). These solutions must have a low environmental impact and a low cost and they have to be easily managed by the communities in order to allow people to improve their socio-economic conditions (Feige and Vonotars, 2017).

The research intends to demonstrate that the identified technologies for wastewater treatment, should ensure the standard effluent's quality required for water reuse purposes, as an integral part of water management in Gaza Strip.

2. Materials and methods

2.1. Description of the project area

The Rafah WasteWater Treatment Plant (WWTP), managed by the Coastal Municipality Water Utilities (CMWU), deals with, about 10,000 -12,000 m^3/day, with a pick of 18,000 m^3/day (ICRC, 2013), of domestic wastewater related to around 145,000 inhabitants (the 70% of the Rafah Governorate citizens). It has been expanded over the years to meet the increasing demand of the growing population. It has established in 1989 for a designed capacity of 1,800 m^3 per day (equivalent to a population of 21,000 inhabitants), augmented up to 20,000 m^3/day in 2011. A first phase had involved the construction of two anaerobic ponds, a new grit removal chamber, sludge drying beds and other improvements of the station. A second phase aimed at the construction of two bio-towers and related pipe-works as well as improving the pipeline for the treated waters collection to the sea (Fig. 1). The general layout of Rafah WWTP is shown in Fig. 2. Despite its poor quality, the effluent is still disposed into the sea by a pumping station and 3 km long pressure line. However, the renovation of the WWTP has allowed to slightly improve the quality of the effluent, which is although under the recommended values. The main monitoring data of the effluent of Rafah WWTP are shown in Fig. 3 (CMWU, 2018; ICRC, 2013; PCBS, 2018).

2.2. Characterization of wastewater effluent

Since reclaimed water reuse became an integral component in water supply and management in many countries, several organizations and authorities implemented water reuse guidelines and regulations (Metcalf and Eddy, 2003; Crook and Surampalli, 1996; EPA, 2012). The Palestinian standards of Waste Water (WW) reuse in irrigation are shown in Table 1.

A weekly sampling activity has been conducted during two months, in order to test the effluent, coming from the Rafah WWTP, in terms of Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), Ammonia, Nitrite, Nitrate and Total Phosphorus (TP). Their average concentrations are shown in Fig. 4.

These preliminary results confirm the poor quality of the treated wastewater and the insufficient performances of the existing plant. In this condition, the output water cannot be reused nor for irrigation purposes or safely collected and discharged and it can be dangerous for the health of workers and utilizers.

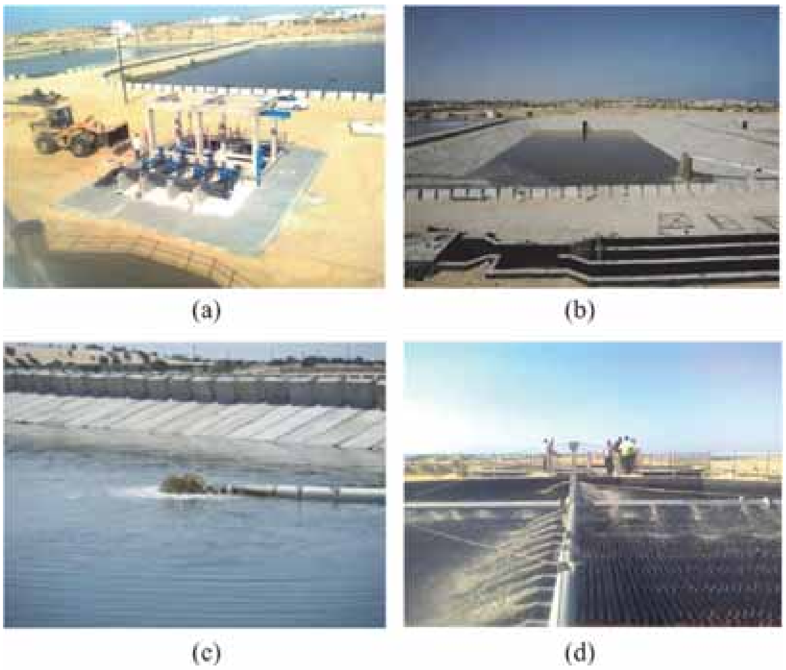


Fig. 1. Representation of Rafah WWTP: (a) Pump station, (b) Grit removal and lagoon, (c) Aeration Lagoon, (d) Bio-Towers (ICRC, 2013)

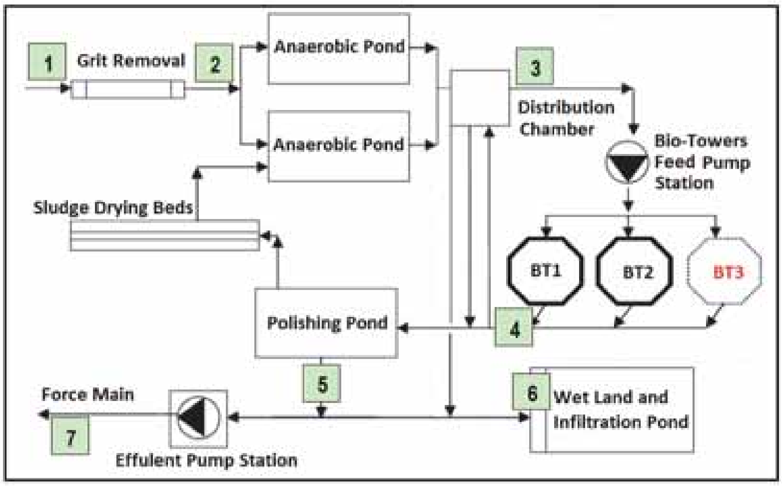


Fig. 2. General Layout of Rafah WWTP (ICRC, 2013)

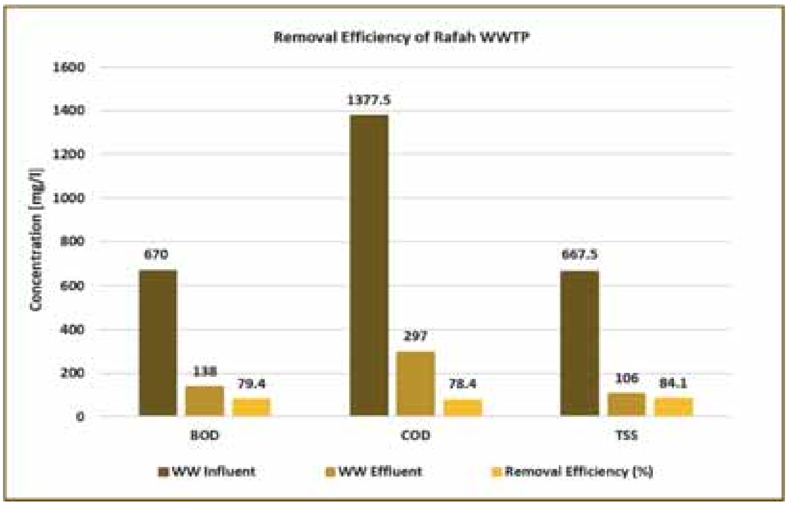


Fig. 3. Removal Efficiency of Rafah WWTP

Table 1. Palestinian Standards of WW Reuse in Irrigation (Aiash and Mogheir, 2017; PWA and MOA, 2012)

Treatment level	*Quality characteristics*		*Possible uses in irrigation*
Primary	-	-	Not allowed
Secondary low	Total BOD_5 Total SS DO	60 mg/L 50 mg/L 0.5 mg/L	Cotton, sugar beets, dry fodder, forests, seeds, cereals.
Secondary high	Total BOD_5 Total SS DO	45 mg/L 40 mg/L 0.5 mg/L	Green fodder, olives, peanuts, citrus, banana, almonds, nuts.
Secondary high + disinfected	Total BOD_5 Dissolved BOD_5 Total SS DO Coliform (unit /100 mL) Residual Chlorine	35 mg/L 20 mg/L 30 mg/L 0.5 mg/L 250 0.15 mg/L	Green vegetables for cooking, fruits for canning, deciduous fruits trees, groundnuts, sports grounds.
Tertiary	Total BOD_5 Dissolved BOD_5 Total SS DO Coliform (unit /100 mL) Residual Chlorine	15 mg/L 10 mg/L 15 mg/L 0.5 mg/L 12 0.5 mg/L	Unrestricted use in irrigation, vegetables for fresh consumption, public parks, lawns.

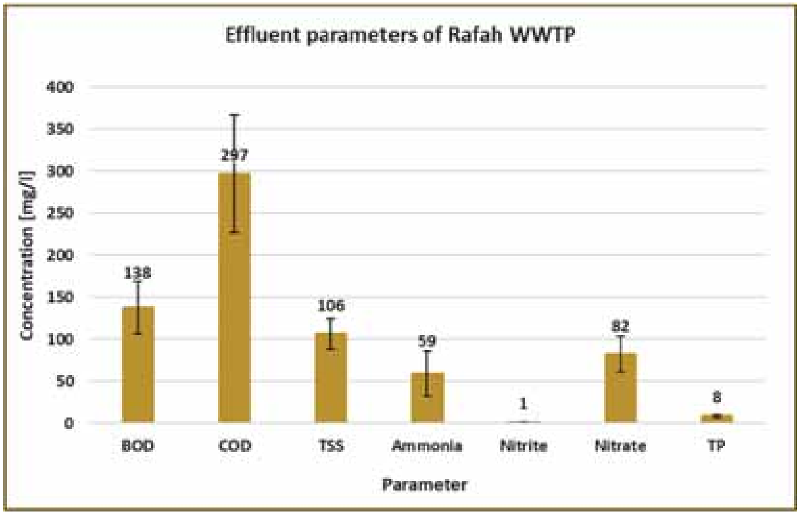


Fig. 4. Effluent Parameters of Rafah WWTP

2.3. Choice of appropriate technologies

In order to reuse the effluents coming from the Rafah's primary treatment plant, it has been considered the opportunity to implement a finishing phase by an AT approach, which is context-specific and depending on the local conditions where they are applied. In this case, preliminary useful information was collected thanks the collaboration of a local agricultural organization, an Italian NGO and the Palestinian Water Authorities (PWA), considering the critical environmental, economic and social issues of the area and the existing water management system.

The starting points for choosing the appropriate technology are:

- the analysed local criticalities suggesting to carry out a treatment system with low energy consumption avoiding chemical reagents in order to obtain a cheaper treated wastewater, to be destined mainly to agriculture purposes;
- previous excellent experiences in other areas, i.e. a case study carried out in Mozambique, that has been considered comparable in terms of weather condition, soil properties and water issues;
- a sustainability assessment approach, enabling to compare the various finishing wastewater treatment technologies feasible in this specific case study (Kakavand, 2019);
- a preliminary analysis of wastewater coming from the existing primary plant in the city of Rafah, provided by Coastal Municipalities Water Utility (CMWU) Central Lab – State of Palestine.

2.4. Technologies selected

This case study focused on implementing a finishing natural treatment composed by phytoremediation and natural disinfections, aiming to optimize the overall wastewater treatment process and manage them for irrigation purposes. The choice of these two technologies, in fact, should ensure the standard effluent's quality required for water reuse purposes.

There are many applications of natural purification techniques, carried out throughout the world (i.e. in Great Britain, France, Denmark, Germany, Sweden, Slovenia, USA, Australia, etc.) (EPA, 2012), which have provided positive answers both in terms of landscape insertion and environmental efficiency, and in terms of depurative efficiency and of cost-effectiveness of implementation and management. In addition, agriculture is one of the worldwide significant destination sectors of reclaimed water (EPA, 2012) and Constructed Wetlands (CWs) are widely applied as a low-cost alternative or supplementary system for wastewater treatment. In addition, proper management of recycling wastewater for the agricultural purpose will help decrease soil and plant contamination in addition to moderating water shortage (FAO, 2003).

The phytoremediation system has been selected because of the quite absence of energy and chemical reagents and its high efficiency in the removal of the main physico-chemical pollutants and nutrients by using plants for environmental depuration, more effective than traditional methods based on chemical extraction of xenobiotics. Biological methods, in fact, do not cause secondary pollution and phytoremediation techniques are cheaper when compared with to conventional techniques (such as activated sludge process, biofilters, trickling filters, etc) (Materac et al., 2015). However, phytoremediation can present some limitations: it requires a large surface for the construction of the system and provides a slow rate of the process.

The aerated lagoon unit, if combined with phytoremediation system, represents the final treatment stage. The aerated lagoon can be considered as a pervading finishing system. It also needs a large surface and a good brightness that allow the penetration of light and consequently the photosynthetic production of oxygen in all over the lagoons. The system works by supporting aerobic bacterial degradation with artificial oxygen supply provided by surface turbo-aerators or submerged aerators or diffusers with blowers, to augment the oxygen supplied from natural means, such as re-aeration surface or photosynthesis (FCM, 2004).

Aerated lagoons, typically from 2 to 6 meters deep, provide the mixing of the reactor and a high removal of the main microbial groups.

2.5. Sampling points

The performance of the whole system has been assessed by evaluation of influent and effluent parameters at each treatment unit. Influent and treated wastewater samples have been collected every week during two months, from 2nd December 2019 to 3rd February 2020, respectively at the storage tank (Point A), where the influent of the designed system corresponds to WWTP effluent, after the phytoremediation pond (Point B) and after the lagooning system (Point C) (Fig.5). All samples have been collected using sterile bottles and transported to the "Coastal Municipalities Water Utility (CMWU) Central Lab – State of Palestine" for further analysis, that have been performed according with standard methods for water and wastewater tests (APHA, AWWA, WEF, 2005). The quality of the effluent has been compared to the Palestinian legal limits for wastewater reuse in irrigation (as shown in Table 1). Influent and treated wastewater samples were analysed in order to test the following parameters: Biochemical Oxygen Demand (BOD_5), Chemical Oxygen Demand (COD), Total Suspended Solid (TSS), Total Phosphorus (TP), Chloride, Free Active Clorine, Ammonia (NH_4); Nitrite (NO_2); Nitrate (NO_3).

3. Results and discussion

3.1. Construction phases of pilot plant

In order to study and monitor effluent contamination parameters and understand the real efficiency of the system, a wastewater finishing pilot plant has been designed and constructed with a capability of about 6 m^3/day. The pilot plant dimensions have been assumed on the base of the USA Environmental Protection Agency indications (Davis, 1994). Fig. 6 shows the scale model drawing.

In Table 2 the main dimensions are reported.

The phytoremediation pilot-scale system presents 3 layers, composed by the following materials: from bottom to top, respectively a big gravel, a washed sand and a vegetative soil and plants (Fig. 7 (A)).

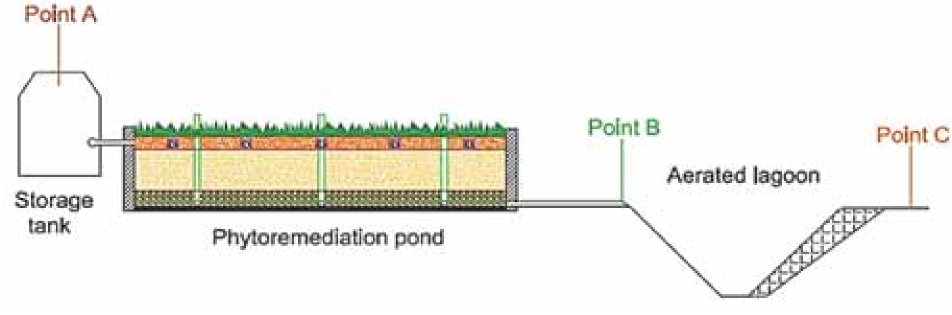


Fig. 5. Sampling points in the scale-pilot plant

The plants selected are “persistent emergent plants”, a mixture of gramineous and legumes, that have two different functions. During their growing, plants provides adhesion places for microbial development and contribute to create a vegetative mass that regulates the water flow direction, while their death creates a release of organic carbon functional for the microbial metabolism (Willey, 2007). Plants also influence the wastewater quality by optimizing various removal processes and consumption of organic matter and other physico-chemical elements (Ko et al., 2011; Ong et al., 2010).

The pilot-scale plant has been fed by the real sewage coming from the municipal WWTP after the primary treatment. The construction phase of this plant has been completed in October 2019.

3.2. Monitoring phase

The monitoring campaign started in December 2019. In the monitoring phase the Biological and Chemical Oxygen Demand (BOD_5 and COD) values and nitrification and denitrification processes taking place in the plant have been measured.

These parameters should respect pollutants concentrations limits and be below the Palestinian legal limitations (Table1), maintaining a good efficiency of the process.

3.4. Preliminary results

The values of physico-chemical parameters, recorded at the different sampling points for the entire monitoring period, are reported in Fig. 8. Rafah WWTP is treating municipal wastewater having higher organic pollutant levels, especially for BOD and COD, than the common expected ones.

However, they seem to be in line with the typical wastewater values for the specific area, due to the problem of water scarcity that leads to an high ratio organic load/water and without a proper dilution. In addition, the high organic load may be due both to several different local sources of organic pollutants, such as domestic or restaurants’ exhausted cooking oils, agricultural and soil leachate, laundries wastewater etc. and to a very bad and irregular maintenance practices and to the lacking or discontinuous electricity supply. So high values, mainly in terms of BOD and COD, don’t respect the limits needed for agricultural use or for a safe collection and release in the environment. Inside the aerated lagoon, residual nutrients are transformed in biomass. In that way, during the first phases of treatment, some parameters, such as BOD, phosphorus and ammonia, are destined to grow, related with the presence of a convenient and effective biomass, while pathogens decrease.

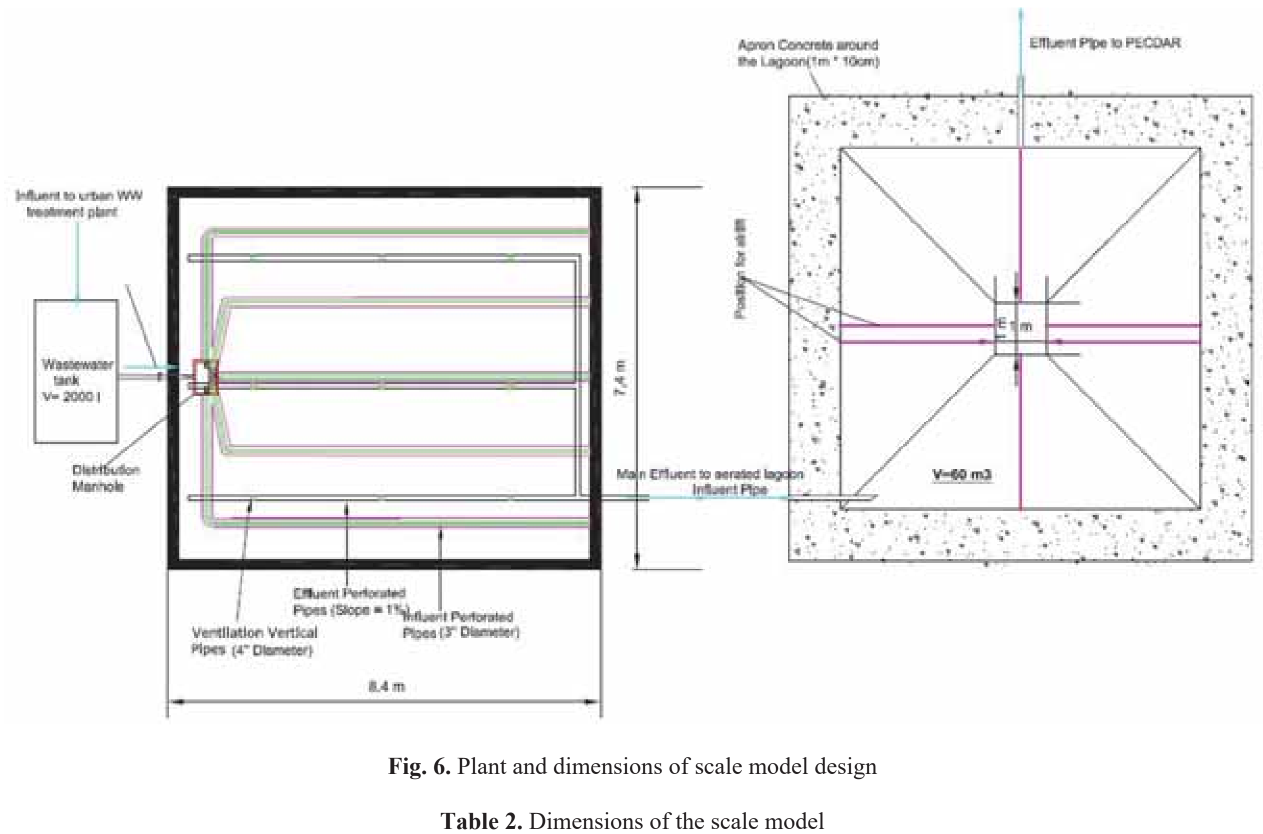


Fig. 6. Plant and dimensions of scale model design

Table 2. Dimensions of the scale model

Area of the phytoremediation system	$A_{Phytoremediation} = 62\ m^2$
Volume of Aerated lagoons (considering Depth: H = 3 m and Area: A = 20 m²)	$V_{Useful} = 60\ m^3$
Capacity of a storage tank	$C_{tank} = 2000\ l$

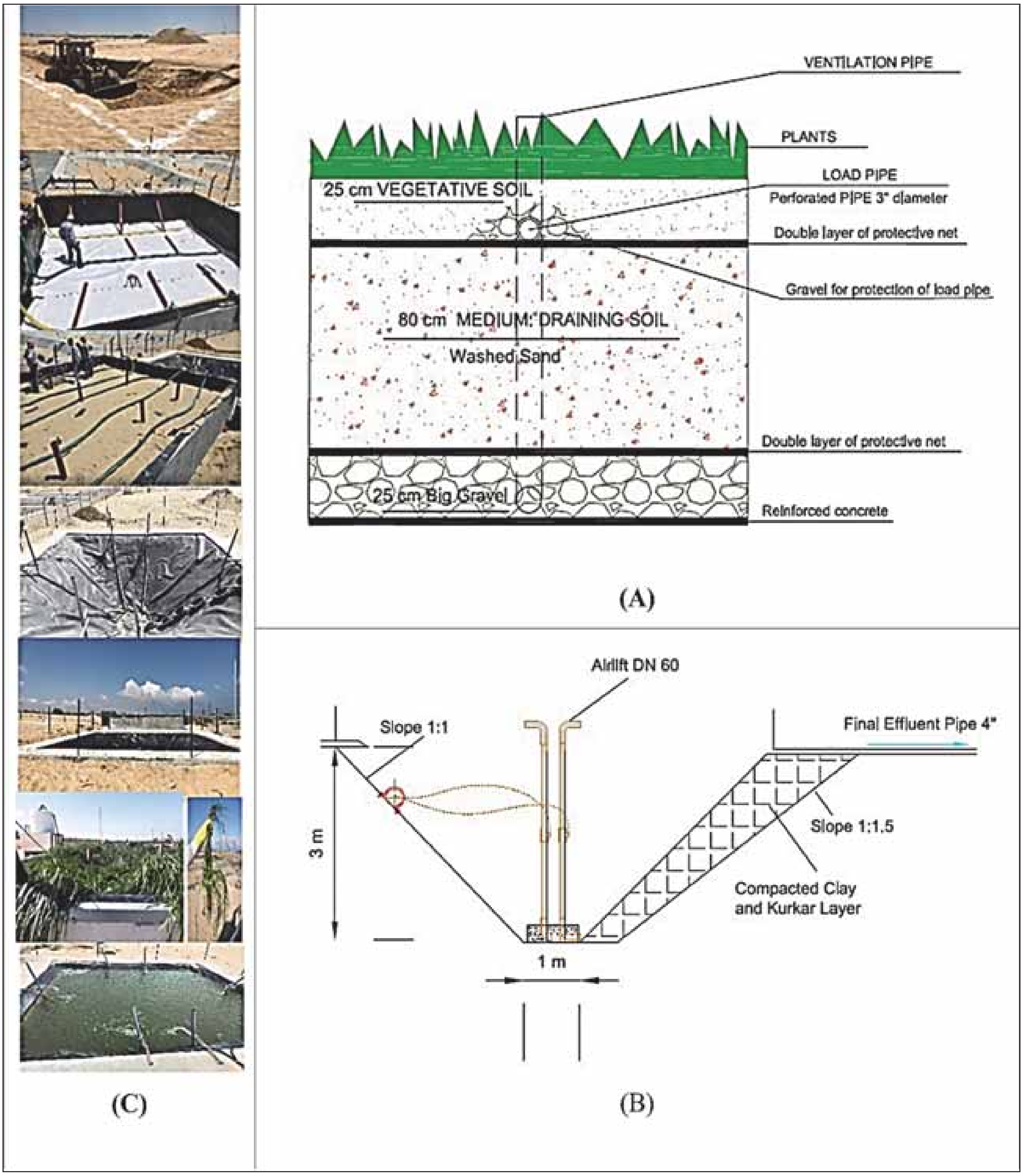


Fig. 7. (A) The 3 layers in the phytoremediation system, (B) Section of the aerated lagoon, (C) General pictures of the main construction phases of the pilot plant

Algae maintain a high level of oxigen, avoiding anoxia risks. Downstream the pilot plant treatment, as shown in Fig. 8, the concentration values are lower than the Palestinian limits for agriculture (Table 1). In this way, it is possible to use the treated wastewater for irrigation also for food production purposes, such as for green vegetables, fruits, deciduous fruits trees, groundnuts and sports grounds. In addition, Fig. 9 shows the average value of inflow and outflow wastewaters and the removal efficiency. The average TSS and BOD_5 values, respectively 20 and 23 mg/L, have been resulted within Palestinian limits for agricultural reuse. Average TSS concentration (106 mg/L in phytoremediation influent) dropped to 20 mg/L, showing a mean removal efficiency of about 81%, that is mainly due to physical processes, such as sedimentation and filtration (Vymazal and Kröpfelová, 2009). The mean reduction of organic matter concentration during the detention period is about 83% for the BOD_5 and 79% for the COD.

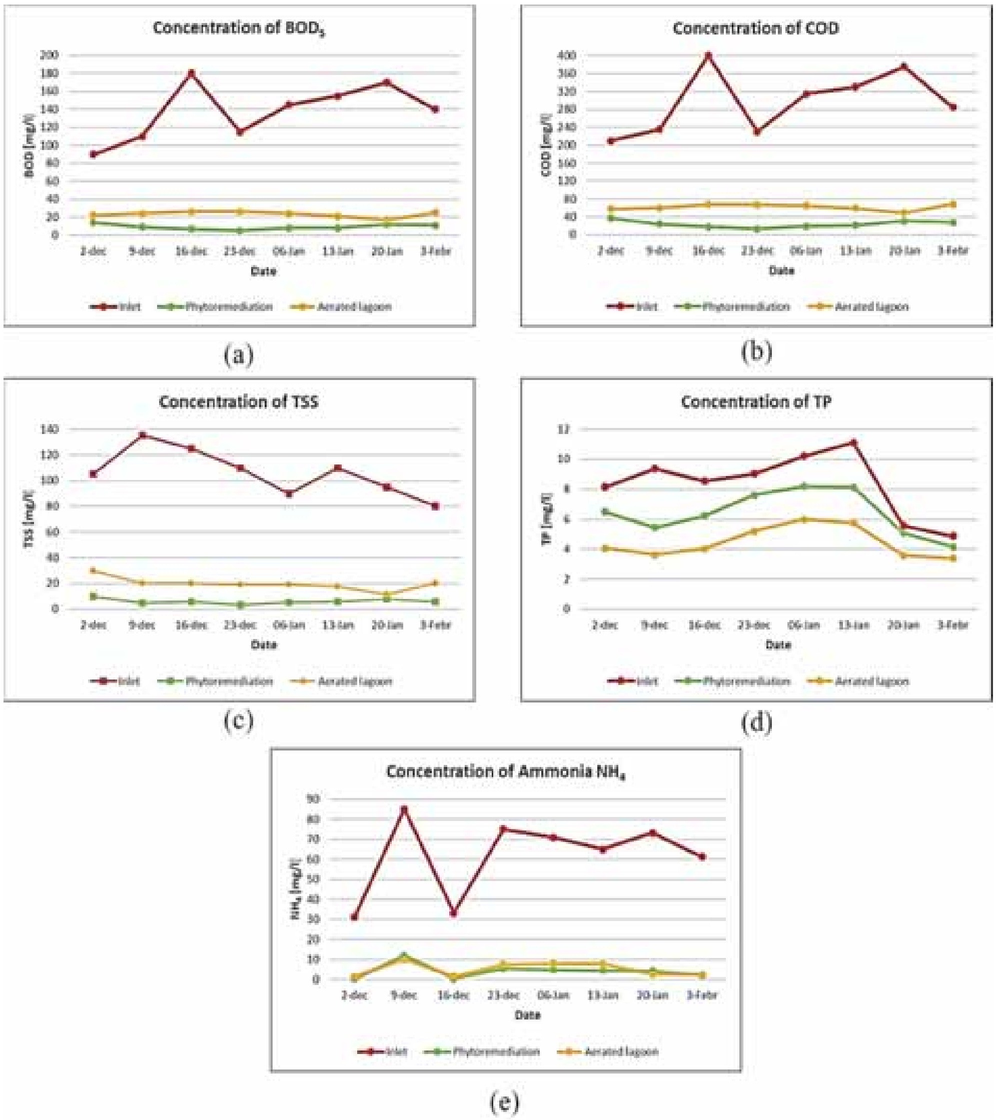


Fig. 8. Concentrations [mg/L] of the physico-chemical parameters at the different sampling points: (a) BOD_5, (b) COD, (c) TSS, (d) TP (e) NH_4

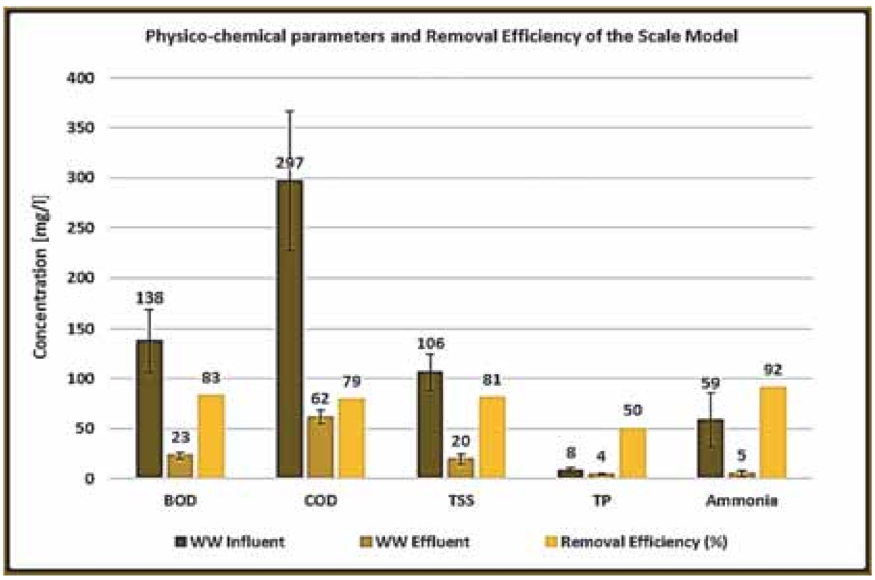


Fig. 9. Influent and effluent at the scale-plant: average values

and removal efficiencies of BOD_5, COD, TSS, TP and NH_4

The mean percentage of organic components removal is significantly the same for COD and BOD_5, since municipal wastewaters usually contain elevated concentrations of easily degradable organic compounds (Vymazal and Kröpfelová, 2009). The effluent provides BOD_5 values between 17 and 25 mg/L, with a mean value of 23 mg/L, and COD values between 49 and 69 mg/L, with a mean value of 62 mg/L. Both results are compatible with law limits for reuse. The nutrients removal efficiency is 92 % for NH_4 and 50% for TP. Their average values, after the treatment processes, are 5 mg/L and 4 mg/L. The strong reduction of the nutrient's concentration is due to the lagooning unit with the aerobic decomposition of algal substances.

4. Conclusions

The finishing pilot-scale plant, designed to evaluate the feasibility of municipal wastewater reuse in Rafah (Gaza Strip), has shown a very good efficiency, according with the Palestinian regulation for wastewater reuse in agriculture.

The preliminary results highlight that the phytoremediation system, followed by a natural disinfection, improve the overall wastewater treatment process. The analysis of the effluents demonstrates that, under controlled conditions, treated municipal wastewater can be used for agriculture purposes with of effective economic and environmental benefits.

The preliminary pilot-scale results are encouraging to construct a real scale finishing treatment plant, in the same area, able to treat a municipal wastewater flow of about 2,000 m^3/day that will be used for local crops (such as olives, citrus, potatoes, grapes and guava) by many farmers, final beneficiaries of the project.

The whole project has been designed according with a sustainability approach, demonstrating an actual environmental, social and economical effectiveness.

Acknoledgements

This work was carried out within the project "Reuse of waste water treated for agricultural use in Al-Mawasi district – Rafah Governorate - Gaza Strip" (project code: 11473/OVERSEAS/TOC), funded by the "Italian Agency for Development Cooperation".

References

Abu Sultan I., (2015), *Wastewater reuse tariff for agriculture in the Gaza Strip*, MSc Thesis, Islamic University of Gaza, Palestine.

Aiash M., Mogheir Y., (2017), Comprehensive solutions for the water crisis in Gaza Strip, *IUG Journal of Natural Studies*, **25**, 3, 63-75.

Al-Dadah J., (2013), Using treated wastewater as a potential solution of water scarcity and mitigation measure of climate change in Gaza Strip, *Journal of Water Resources and Ocean Science*, **2**, 5, 79-83.

APHA, AWWA, WEF, (2005), *Standard Methods for the Examination of Water and Wastewater*, 21st edition, American Public Health Association, Eaton A.D. (Eds.), American Water Works Association, Water Environment Federation, Washington D.C.

CMWU, (2018), Annual Report 2017, Coastal Municipalities Water Utility. On line at: https://docplayer.net/133196125-Coastal-municipalities-water-utility-annual-report-2017.htmL

Crook J., Surampalli R.Y., (1996), Water reclamation and reuse criteria in the U.S., *Water Science and Technology*, **33**, 10-11.

Davis L., (1994), *A Handbook of Constructed Wetlands*, **1**, USDA – Natural Resources Conservation Service and US Environmental Protection Agency, Washington D.C., 1-53.

EPA, (2012), *Guidelines for Water Reuse*, EPA/600/R-12/618, U.S. Environmental Protection Agency, Washington D.C., On line at: https://www.epa.gov/sites/production/files/2019-08/documents/2012-guidelines-water-reuse.pdf.

FAO, (2003), User's manual for irrigation with treated wastewater, FAO Regional Office of the Near East, Cairo, Food and Agriculture Organization of the United Nations, On line at: http://www.fao.org/tempref/GI/Reserved/FTP_FaoRne/morelinks/Publications/English/Usersmanual-en.pdf.

FCM, (2004), Optimization of lagoon operation, a best practice by the national guide to sustainable municipal infrastructure, Issue No. 1.0, Federation of Canadian Municipalities and National Research Council Publisher, Canada, On line at: https://www.grandriver.ca/en/our-watershed/resources/Documents/Water_Wastewater_Optimization_InfraguideLagoons.pdf

Feige D., Vonortas N.S., (2017), Context appropriate technologies for development: Choosing for the future, *Technological Forecasting and Social Change*, **119**, 219-226.

Gharbia S.S., Aish A., Abushbak T., Qishawi G., Al-Shawab I., Gharbiac A., Zelenakova M., Gill L., Pilla F., (2016), Evaluation of wastewater post-treatment options for reuse purposes in the agricultural sector under rural development conditions, *Journal of Water Process Engineering*, **9**, 111-122.

ICRC, (2013), International Committee of the Red Cross, Consultancy Services for Systems and Process Assessment for Rafah Wastewater Treatment Plant in Gaza Strip, assessment Report, Phase 1, Châtelaine-Genève, 30 September 2013.

Kakavand N., (2019), *Sustainability assessment of applicable treatment technologies using multi-criteria decision making analysis on wastewater treatment plant of City of Rafah*, MSc Thesis, Alma Mater Studiorum University of Bologna, Italy.

Ko C-H, Lee T-M, Chang F-C, Liao SP, (2011), The correlations between system treatment efficiencies and aboveground emergent macrophytes nutrient removal for the Hsin-Hai Bridge phase II constructed wetland, *Bioresource Technology*, **102**, 5431-5437.

Materac M., Wyrwicka E., Sobiecka E., (2015), Phytoremediation techniques in wastewater treatment, *Environmental Biotechnology*, **11**, 10-13.

Metcalf and Eddy, (2003), *Wastewater Engineering, Treatment and Reuse*, 4th Edition, McGraw Hill Higher Education Publisher, New York (NY), North America.

Murphy H.M., Mc Bean E.A., Farahbakhsh K., (2009), Appropriate technology – a comprehensive approach for water and sanitation in the developing world, *Technology in Society*, **31**, 158-167.

Ong S.A, Uchiyama K., Inadama D., Ishida Y., Yamagiwa K., (2010), Performance evaluation of laboratory scale up-flow constructed wetlands with different designs and emergent plants, *Bioresource Technology*, **101**, 7239-7244.

PCBS, (2018), Palestinian Central Bureau of Statistics, Preliminary results of the general census of population, housing and establishments for the year 2017, On line at: http://pcbs.gov.ps/Downloads/book2364-1.pdf.

PWA and MOA, (2012), Palestinian Water Authority (PWA) and Ministry of Agriculture (MOA), Mandatory Palestinian Technical Instructions for Treated Wastewater Reuse in Agriculture, (in Arabic), On line at: http://www.psi.pna.ps/en/TechnicalInstructions/MandatoryPalestinianTechnicalInstructions/Treated%20water%20for%20ittigation%20uses.pdf.

PWA, (2014), Palestinian Water Authorities, Gaza Water Resources Report, PWA, Ramallah 2013/2014, On line at:
http://www.pwa.ps/userfiles/server/المركز%20الاعلامي/تق
ارير/وضع%20مصادر%20المياه%20في%20غزه.pdf?fbclid=IwAR1cGp_N9TM_vhTCK4tzLfR4O8sxOXFZfj9WuTJCDKsiR46nGcwkLry5M6A.

Schumacher E.F., (1973), *Small is Beautiful: Econonimics as if People Mattered*, Harper and Row Publisher, New York.

UNRWA, (2019), Occupied Palestinian Territory Emergency appeal 2019, The United Nations Relief and Works Agency for Palestine Refugees in the Near East, On line at: https://www.unrwa.org/sites/default/files/content/resources/2019_opt_ea_final.pdf

Vymazal J., Kröpfelová L., (2009), Removal of organics in constructed wetlands with hori- zontal sub-surface flow: a review of the field experience, *Science of the Total Environment*, **407**, 3911-3922.

Willey N., (2007), *Phytoremediation: Methods and Reviews*, In: *Methods in Biotechnology*, Willey N.J. (Ed.), Vol. 23, Humana Press, Totowa New Jersey.

WWAP, (2017), World Water Assessment Programme, The United Nations World Water Development Report 2017, Wastewater: the untapped resource, UNESCO, Paris, On line at: http://www.unesco.org/new/typo3temp/pics/0d623deb50.jpg.

Environmental Engineering and Management Journal

October 2020, Vol. 19, No. 10, 1693-1699
http://www.eemj.icpm.tuiasi.ro/; hiip://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

HOW TO TURN CAR FLUFF PROBLEM INTO AN OPPORTUNITY

Ivana Moscato[1], David Callejo Munoz[1]*, Sergio David González[2]

[1]*B1Shop Srl, c/o Kilometro Rosso Innovation District, Bergamo Italy*
[2]*University of Alcala, Centre for Applied Chemistry and Biotechnology*

Abstract

Car fluff is an important problem for the industrial compartment, especially for Italy, considering the huge amount of waste produced by the automotive sector, approx. 180.000 ton/year. Although car fluff (CER 191004) is suitable for CSS-Combustible production, with destination to cement factories, a very low amount of it reaches this destination.
An alternative way to transform this problem into an opportunity consists into the transformation of bioliquid after its thermo-chemical transformation (Reach qualified), applicable to the advanced fuel market as well as for the green bio-chemistry plants, transforming a typical destruction cost in the range of 150-200 €/TON (Lombardy region, Italy, internal market data) into an income of 700€/TON (internal market data), as well as the closing of the circular economy cycle.
A typical car fluff quality range will be defined in order to select only suitable car fluff for the process transformation; a mass balance and a treatment scheme will demonstrate the proposed solution. A case study with economical information and basic BP completes the presentation.

Key words: car-fluff, pyrolysis, circular economy, chemical material recovery, biorefinery, pyrolysis oil

Received: February, 2020; Revised final: June, 2020; Accepted: July, 2020; Published in final edited form: October, 2020

1. Introduction

A possible way to transform a problem into an opportunity consists in its valorization through its thermo-chemical transformation into a liquid product (Reach qualified), classified as second-generation fuel, with high market request. The NEOLIQUID technology demonstrates to be the only industrial technology able to recovery most of the car-fluff multi-material waste with the required process flexibility, while all other approaches are driving to accumulation as well as incineration, cutting the circle of the material recovery cycle, as well as increasing the CO_2 footprint of the fabrication processes (Mancini et al., 2010; Morselli et al., 2010).

A typical car fluff quality range will be defined in order to select only the suitable car fluff portion for the process transformation; a mass balance and a treatment scheme will show the proposed solution. A case study with economical information and basic BP completes the presentation.

The materials that make up cars are changing today. The cars were made of steel and now they are also made of aluminium and its derivatives. This has meant a significant weight loss. Currently, cars carry many plastics and in the near future they will be increasingly made of plastic materials. These plastic materials offer lightness, strength and versatility. The incorporation of the electric car is assuming greater plasticization of cars. Another factor that will influence the coming years is the manufacture of cars and their components using 3D printers. 3D printers use a varied composition of plastics that can be mixed with other components to give more performance. In relation to plastic materials, it can be emphasized that cars and vehicles in general are made up of very diverse plastics, composite plastics or composites, textiles and derivatives of electrical and electronic components.

* Author to whom all correspondence should be addressed: e-mail: d.callejo@b1shop.it

In the EU, the demand for plastics to produce automobile components amounts to a total of 4,3 million tons per year, as shown in Figs.1-2, according to the data analyzed in European Strategy for plastic in a Circular Economy. Over the past 50 years, there has been a continuous increment of the importance of plastics in our economy. Worldwide production of plastics has increased twentyfold since the 1960s, reaching 322 million tonnes in 2015. It is expected to double again over the next 20 years.

In the EU, there is a minimum capacity of plastic recycling. Reuse and recycling of waste plastics remains too low, especially if we compare this level to the level of other materials such as paper, glass or metals (Plastics – the Facts 2019, An analysis of European plastics production, demand and waste data, online at: https://www.plasticseurope.org/application/files/9715/7129/9584/FINAL_web_version_Plastics_the_facts 2019_14102019.pdf). At the same time, the amount of plastic waste deposited in landfills or incinerated remains high (31% and 39%, respectively) and although the landfill disposal has decreased in the last decade, the incineration has increased. It is estimated that 95% of plastic containers, namely between 70.000 and 105.000 million Euro per year, is lost to the economy after a very short cycle of first use.

The waste derived from the mixture of plastics that makes up cars is called Car fluff. Car fluff is a big issue for the industrial compartment, especially for Italy, considering the huge amount of waste produced by the automotive sector, approx. 180.000 ton / year. Although car fluff (CER 191004) is suitable for CSS-Combustible production, with destination cement factory, a very low amount of it reaches this destination.

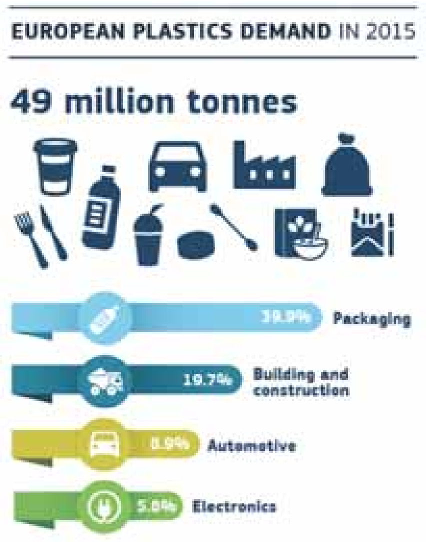


Fig. 1. European Plastic Demand and EU Plastic Waste Generation in 2015 (Adapted upon Plastics Europe, 2016)

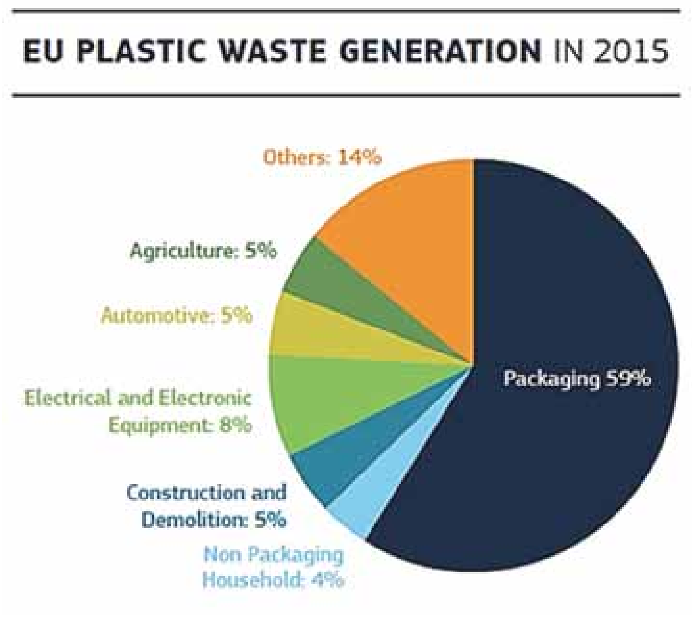


Fig. 2. EU Plastic Waste Generation in 2015. Source: Plastics Europe (2016)

The legislation emphasizes that as established by the provisions derived from the European Circular Economy package and those of vehicles at the end of life. Circular economy legislation considers waste as raw materials. This new approach is promoting major changes at the level of legislation. Sectorial legislation for out-of-use vehicles imposes a high rate of reuse and recovery of car materials. EU Directive, (2000) on out-of-use vehicles, establishes that by 2020 a reuse and recovery rate of at least 95% of the vehicle's weight must be achieved.

Currently, 20% of the weight of a vehicle corresponds to plastic materials. With this data the recovery and valorization of the plastic materials present in the vehicles is of great importance. Up to now, the sector has been primarily concerned with the recycling of metallic materials. Regarding plastic waste, the EU is committed to the recycling and recovery of it. This position is established in the Communication called: A European strategy for plastic in a circular economy, dated January 16, 2018. (EU Communication, 2018).

In this strategy the EU makes a global commitment to be the best placed to lead the transition to the plastics of the future. This commitment arises as a result of evaluating the technological and industrial chemical potential, as well as the need for the adoption of the Circular Economy. A new economy of plastic is based on the design and production of plastics and plastic products fully respecting the needs of reuse, repair and recycling, as well as the development and promotion of more sustainable materials (Fraunhofer Umsicht, Sustainability Assessment and Management, online at http://www.umsicht.fraunhofer.de).

The added value must be based on technological development and innovation in the field of plastics. Europe will drive innovation through cross-cutting programs to reduce plastic pollution and its adverse impact on our lives and the environment (World Economic Forum, Ellen MacArthur Foundation and McKinsey & Company, The New Plastics Economy - Rethinking the future of plastics (2016), online at http://www.ellenmacarthurfoundation.org/publications).

The strategy presents key commitments for the adoption of measures at EU level involving the whole society. Therefore, all the involved sectors, including authorities and citizens, will have to address their efforts towards innovation, and towards a more efficient and intelligent use of resources and circular raw materials (EU Communication, 2020).

The EU approach to consider waste as raw material establishes an innovative field of waste treatment and its transformation into raw materials or secondary raw materials. (EU Directive 53, 2000 and EU Directive 76, 2000). A simple analysis of European waste data shows that the amount of plastic waste disposed in landfills (31%) or incinerated (39%) remains high. These data show the low efficiency of the current economic model. Each material generated and not valorized is an unused resource. Regarding car fluff waste, it can be generalized that at European level the majority are destined to landfills. Only a small fraction is energetically valued in incinerators or cement plants. The European position establishes a new economy of plastic for Europe. The plastics sector must be an intelligent, innovative and sustainable sector. Design and production must respect the needs of reuse, repair, recycling and material recovery. This sector must generate growth, employment, reduce greenhouse gas emissions and dependence on fossil fuels. It is estimated that this approach will create more than 200.000 new jobs across Europe as for the communication of the European Parliament (EU Communication, 2018). Products containing plastic should consent greater durability, reuse and high-quality recycling. Changes in production should offer higher recycling rates for all key applications. In 2030, more than half of the plastic waste generated in Europe must be recycled.

Another big commitment of the European Union in the one of the renewable energies is second-generation biofuels, against biofuels derived from food raw materials. The position is in (EC Directive, 53, 2000 and EC Directive, 76, 2000). Advanced second-generation biofuels are generated by the transformation of waste. With reference to car fluff, thermochemical processes make this transformation possible.

As these wastes have a mixture of plastics, it is possible to produce a liquid with a Reach classification with an important market. This mixture of liquid hydrocarbons is valuable for second-generation biofuel market or for chemical recycling of plastics market.

2. Problem analysis

The problem of the plastics present in the car fluff derives from the fact that these materials are manufactured for high durability and technical performance. They are very diverse materials, of different chemical composition and different physical properties. Currently, the materials that make up the car fluff is a mixture of paper, wood, rubber, glass, fabric, urethane foam, and resins., as shown in Table 1. They are mostly non-biodegradable fossil plastics. The polymers that form them are composed of various groups, among which oxygenated derivatives combined with sulphur and nitrogen derivatives. Each of these polymers give rise to different molecules depending on the bonds that are cracked by pyrolysis (Miranda et al. 2001).

The materials that make up the dashboards and other structural elements are usually plastic composites reinforced with glass or carbon fibers. Some of the more modern models are replacing the structural elements and the aluminum body with carbon fiber composites. These materials are composed of a matrix of carbon fibers with a resin that permeates the entire material.

Table 1. Automotive shredder residue composition. (Jason et al. 2012)

Material/component	***Composition (% by weight)***
Paper	2%
Wood	3%
Non-ferrous metal	4%
Wire harnesses	5%
Rubber	7%
Glass	7%
Iron	8%
Fabric	15%
Urethane foam	16%
Resins	33%
TOTAL	**100%**

The resin provides the hardness, and the moldability and the fibers the resistance. Carbon fibers are very durable, they can be recycled by pyrolysis. Under pyrolysis conditions the polymeric resin hue degrades, and the fibers of the composites are released. With the implementation of 3d printers and electric cars we will see the emergence of new car brands and models made of carbon fiber composites and printed components in small workshops. This evolution of cars will further complicate the recycling of its components.

In the seats and foams polyurethane predominates, as well as in some gears and technical belts. The polyurethanes can be processed by pyrolysis to produce hydrocarbon chains with carbonyl groups and others in the form of amines or diamines. As the pyrolysis technology is implemented at an industrial level, these molecules can be recovered selectively to produce new polyurethanes. This recycling route is what is called chemical polymer recycling.

Other important components of these wastes are those derived from textile materials and carpets. Car carpets are made of different materials. Among the materials of carpeting textiles are polypropylene, polyethylene, polyesters and cotton mainly. The carpets may also contain some proportions of polyamides and polyurethanes. You can also find products derived from cellulose such as rayon or viscose. The components proportions vary a lot and depend on the manufacturer, model and age of the vehicles.

It can be noted that there are some manufacturers that may have more than 33% cotton. Under pyrolysis conditions, cotton and viscose behave like biomass. These components provide high percentages of organic acids to thermochemical reactors. It is essential that thermochemical reactors are designed for co-pyrolysis conditions of different plastics with biomass derivatives.

At the energy level, this mixture of polymers with natural fibres complicates, to a certain extent, their use and recovery. Polyolefin have a composition with carbon and hydrogen with high energy, so they are hydrocarbons. The calorific value of polyolefin is 40-45 MJ / kg. The calorific value of biomass materials such as cotton or viscose is between 15-20 MJ/kg. The calorific value of the polyesters is 20-26 MJ/kg and the polyurethanes between 20-22 MJ/kg.

Depending on the compositions, a heterogeneous mixture with a calorific value between 25-35 MJ / kg can be considered. This data strongly depends on the humidity present in the car fluff.

3. Thermochemical transformation

Materials that are processed at high temperatures in the presence of oxygen undergo combustion or gasification processes and release an amount of thermal energy that can be used. These processes convert materials into solid products and gases derived from combustion. Combustion processes present technological and environmental problems and do not allow the recovery of materials. If we process organic materials at high temperatures and in the absence of oxygen, the material undergoes thermochemical transformations resulting in other molecules. Thermochemical processes in the absence of oxygen are called pyrolysis. Thermochemical transformation in pyrolysis conditions of the materials present in the organic fraction will give the typical products of these processes: a gas fraction, a solid fraction and a liquid fraction.

The gas fraction consists in a mixture of non-condensable hydrocarbon gases, under normal conditions, with H_2, CO, CO_2, water vapour. This gas is called synthesis gas or syngas. The most abundant hydrocarbon is usually methane, followed by ethane, propane, butane in different configurations. The composition of the syngas depends on the process conditions and on the processed raw material. This syngas can be used for chemical processes, as fuel for electricity generation, for a cogeneration system, or as fuel for the pyrolysis process itself. The use as fuel in the pyrolysis process itself provides high energy efficiency and has a low carbon footprint.

The solid fraction is formed by carbon materials. In this fraction the inorganic salts and the carbon fibers present in the raw material and carbonaceous materials are concentrated. This solid is called char or biochar depending on the raw material processed. Glass or carbon fibers treated by thermochemical process can be separated from carbon and used for various uses. In the coming years, markets of this type of products will emerge for less technical uses than composites. An example is the use of recycled fibers in the manufacture of asphalt pavements, rubber or concrete pavements.

The liquid fraction is formed by a mixture of aqueous and organic products. The aqueous fraction is composed of oxygenated compounds mainly derived from cellulose and hemicellulose cracking. The organic fraction is a mixture of hydrocarbons useful as fuel or as raw material for the production of plastics. In the car fluff there are components with a lot of interest at the chemical level. Depending on thermochemical technology, this liquid fraction can be generated as a single fraction or as two fractions. At industrial level, the technology that generates the liquid fraction separately represents an important advance in industrialization.

The thermochemical transformation of products derived from cellulose, cotton and other vegetable fibers is similar, in a way, to that generated by lignocellulose biomass. After analyzing the chemical composition of the major components present in car fluff, it is observed that all are processable by thermochemical technology. The more complex carbonaceous materials will give solid products in the form of char. This char will be mixed with the mineral fillers used in plastics, as well as with the fibers used in composites.

Due to the materials and their composition, it is necessary that the industrial technology is designed for the processing of car fluff residues as they are currently produced in vehicle fragment plants. Therefore, the industrialization of these technologies must be able to treat the mix of current materials of the car fluff and future mixtures. Every time cars are going to carry more plastics and these plastics are going to be increasingly complex.

The kinetics of pyrolysis is complicated since there are many reactions involved. This is even more complicated when we treat a mixture of plastic waste, since it not only depends on each type of plastic, it depends on its state of degradation, which in turn depends on many factors prior to pyrolysis (exposure to oxidation, UV, temperature of use etc.). This variability is typical of waste. A simple formula is based on mass balances, the matter that enters as waste corresponds to the sum of gases, condensable gases (liquids) and solids. This formula is revered since the first studies of pyrolysis.

Another way to approach the study of the kinetics of the mixture of plastics is by studying the equations of each type of material, as for Fig. 3. Another study that addresses the behaviour of different materials at different temperatures is the one carried out by. Encinar and González (2008), Pyrolysis of synthetic polymers and plastic wastes. Kinetic study, 2008.

At the experimental level, a first approximation of the behaviour of the different materials under pyrolysis conditions can be estimated based on thermogravimetries (TGA) in the absence of oxygen, usually carried out with nitrogen and with different temperature ramps (5, 10, 20 or 50 ºC / minute). They offer valuable information on loss of mass depending on the increase in temperature, depending on the slope of the curve, it provides information on decomposition and, depending on the final shape, it provides information on inorganic or carbonaceous materials that are not thermally degraded by cracking reactions. There are various behavioural and kinetic studies based on TGA in the kinetic literature. One of which we can highlight is the Kinetic study of municipal plastic waste prepared by Díaz and Phan (2016), which addresses the residual plastics present in municipal waste. The patented technology by NEOLIQUID allows quality recycling through the conversion of plastic waste and materials derived from other natural polymers into a synthetic crude oil.

Synthetic crude oil can be used as a raw material in chemical processes for the production of new plastics or as an advanced biofuel. In both cases it has a low carbon footprint. At chemical level, the new plastics produced with this liquid will be of high quality, it will allow its additivity and use in complex applications such as those required for vehicles.

The liquids produced by the thermochemical process under pyrolysis conditions of NEOLIQUID technology are light hydrocarbons similar to a pyrolysis naphtha stream of a conventional refinery. This is a gasoline with a high content of aromatic components, this characteristic makes it very interesting as a raw material for the petrochemical industry. Globally, petroleum-derived pyrolysis naphtha is a commodity, which is a commercial raw material used for the plastics industry.

Therefore, the thermochemical processes of the waste are a key application to close the cycle of the plastic materials that are inside the Car Fluff. It is necessary to implement thermochemical industrial plants that process this material and transform it into a liquid composed of hydrocarbons called synthetic crude oil. This liquid will be transported to the chemical plants to manufacture new polymers that in turn will give new plastic materials. After reviewing the technical aspects of the materials present in the Car Fulff residue and the thermochemical processes, an analysis of the industrialization of the technology for these wastes can be carried out.

Industrial plants must meet the following requirements:

A.- Specific design for multi-materials waste

The residual materials present in the Car Fluff are of very variable, changing composition and are characterized by different mixtures of materials. It is important that the technology is designed for multi-materials mixtures. Technology must be able to process polyurethanes, rubbers, thermoplastics, composites, textiles and biomass derivatives.

B.- Operation that allows obtaining valuable products

The most important thing is that the technology makes it possible to obtain liquid products that are used as raw material in the chemical industry. Thermochemical technology must produce liquids and solids with the possibility of using productive processes. The hydrocarbon mixture can also be used as advanced second-generation biofuel or recycled carbon fuel, as established by the Renewable Energy Directive.

C.- Compliance with legislation

The technology must comply with waste legislation and must be a key application that enables the recycling of high-quality plastic materials and the closing of the materials cycle. In relation to compliance with environmental impact legislation, emissions, treatment and recovery of waste, the technology must have a thermochemical and combustion process control, as well as an adequate post-combustion treatment.

The technology needs the thermochemical treatment to be correct and guarantee a good combustion of the syngas with temperature control. Good combustion control of the synthesis gas ensures that atmospheric emissions are adequate. The treatment of gases through different stages allows the quality control and controlled combustion.

D.- Technology with high rate of Circular Economy

Technology should enable the recycling of high-quality material. The path involves obtaining stable pyrolysis oil that can be used as a raw material for chemical processes. In this section it is important that the technology has a high efficiency rate and allows obtaining materials that can be used as raw materials in production processes. In the case of pyrolysis, the main characteristics related to the circular economy are sustainability verification, carbon footprint reduction and material recovery of waste. Neo-liquid's studied technology means a carbon footprint reduction of more than 95%. This technology has high energy efficiency and does not use electrical energy to generate thermal energy.

4. Study mass balance

Here enclosed the study presents the data for a typical feedstock use coming from car fluff waste material. The yields of the different pyrolysis products largely depend on the reaction conditions and the mixture of the different polymers present. The balances obtained by NEOLIQUID technology are within the ranges obtained by various authors under pyrolysis conditions.

We can estimate that the pyrolysis carried out in the proposed industrial plants can be classified into an intermediate pyrolysis between fast and flash, with reaction times of 20-30 minutes for the solid fraction but with reaction times of 2-3 seconds for the gaseous fraction. In Tables 2-4, typical values as well as a range of the mass balance are presented, including the technical characteristic and limitations for the feedstock material.

5. Basic BP

The business plan for this kind of project, strongly depends on the cost of dumping the waste material in traditional landfills or incinerators. In our particular case, we will use an average value of 170 €/Ton (8.000 Ton/year), as a typical value for Nord-Italy (from internal market studies and discussions with waste material management plants), including transportation cost. To have access to this value, the material has to be selected and certified, otherwise, the cost will rise over 200 €/Ton (from internal discussions with landfill and incinerator management teams in North Italy).

The bio-liquid (3.600 Ton/year for our case study) has been in the market for now more than 5 years, and the last average values oscillate from 550€/Ton to 750€/Ton (from internal sale contracts), depending on the quality and the final market application. If we take into account the material valorization, as pyrolysis oil, the price will be optimized in the highest portion of the interval.

Including all operational costs (labour is the main voice, electricity, raw materials, maintenance, quality control …) below 1M€/year, the investment, including financial costs, will be fully paid in less than 36 months, if we engage two plants together, the labour cost will be optimized, and the return of the investment will decrease down to 24 months.

6. Conclusions

The Neo-liquid technology is the only one present and operating at industrial level in the market. The treatment of car-fluff feedstock has been presented ad its economic and environmental advantages shown.

Table 2. Feedstock (Neoliquid internal calculations)

Feedstock	
PCI (kcal/kg)	7.500-8.000
Humidity	<15%
Particle size (cm)	3-5
Clorine	<0.2 %
Sulfur	<0.3%
Density (kg/m^3)	>70
Biomass (paper, wood …)	<25%
Plastic	>75%

Table 3. Outlet balance (Neo-liquid internal calculations)

Outlet balance			
	% CSR inlet	***ton/h***	***ton/year***
CRUDE OIL	45%	0.554	3600
CHAR	18%	0.222	1440
Water	10%	0.123	800
No condensable gas	27%	0.332	2160

Table 4. Working time (Neo-liquid internal calculations)

Plants	1
Bioliquid yearly production (t/y)	3.600
Char yearly production (t/y)	1.440
Working hours	
Yearly working hours (h)	6.500
Yearly working days (d)	270
Daily working hours (h)	24
CSR inlet	
Year CSR quantity (t/y)	8.000
Daily CSR quantity (t/d)	29,6
Hourly CSR quantity (t/h)	1.235

This technology presents a step forward to solve the industrial waste problem, by the recycle and valorization of the waste material, looking forward towards the complete circular economy.

References

Díaz S.L.S., Phan, A.N., (2016), Kinetic study of municipal plastic waste. *International Journal of Hydrogen Energy*, **41**, 16352-16364.

Encinar J.M., González J.F., (2008), Pyrolysis of synthetic polymers and plastic wastes. Kinetic study, *Fuel Processing Technology*, **89**, 678-686.

EU Communication, (2018), Communication from the Commission to the European Parliament, the Council, the European economic and Social Committee and the committee of the regions. (2018) A European strategy for plastic in a circular economy, COM(2018) 28 final, Brussels,16.1.2018.EU Communication, (2020), COM (2020) Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Sustainable Europe Investment Plan European Green Deal Investment Plan, Brussels, Factsheet 14.1.2020 COM (2020), 21 final.

EU Directive 53, (2000), Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of life vehicles - Commission Statements, *Official Journal of the European Communities*, L 269/21.10.2000, Brussels.

EU Directive 76, (2000), Directive 2000/76/EC of the European Parliament and of the Council of 4 December 2000, on the incineration of waste, Annex V, *Official Journal of the European Communities*, L 332/91, 28.12.2000, Brussels.

Lee J.J.S. Mo J.P.T, Wu D.Y., (2012), Polymer recovery from auto shredder residue by projectile separation method, *Sustainability*, **4**, 643-655.

Mancini G., Tamm R., Viotti P., (2010), Thermal process of fluff: Preliminary tests on a full-scale treatment plant, *Waste Management*, **30**, 1670-1682.

Miranda R., Yang J., Roy C., Vasile C., (2001), Vacuum pyrolysis of commingled plastics containing PVC I. Kinetic study. *Polymer Degradation and Stability*, **72**, 469-491.

Morselli L., Santini A., Passarini F., Vassura I., (2020), Automotive shredder residue (ASR) characterization for a valuable management, *Waste Management*, **30**, 2228-2234.

Web sites:

https://www.plasticseurope.org/application/files/9715/7129/9584/FINAL_web_version_Plastics_the_facts2019_14102019.pdf

Environmental Engineering and Management Journal October 2020, Vol. 19, No. 10, 1701-1710
http://www.eemj.icpm.tuiasi.ro/; hiip://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

CIRCULAR ECONOMY GOOD PRACTICES SUPPORTING WASTE PREVENTION: THE CASE OF EMILIA-ROMAGNA REGION

Francesca Cappellaro[1*], Valentina Fantin[2], Grazia Barberio[3], Laura Cutaia[4]

[1]*Circular Economy Section, Department for Sustainability, Italian National Agency for New Technologies, Energy and Sustainable Economic Development, ENEA C.R. Bologna, Via Martiri Monte Sole,4, 40129 Bologna, Italy*
[2]*Laboratory of Resource Valorisation, Department for Sustainability, Italian National Agency for New Technologies, Energy and Sustainable Economic Development, ENEA C.R. Bologna, Via Martiri Monte Sole,4, 40129 Bologna, Italy*
[3]*Circular Economy Section, Department for Sustainability, Italian National Agency for New Technologies, Energy and Sustainable Economic Development, ENEA C.R Casaccia, Via Anguillarese, 301, 00123 Roma, Italy*
[4]*Laboratory of Resource Valorisation, Department for Sustainability, Italian National Agency for New Technologies, Energy and Sustainable Economic Development, ENEA C.R. Casaccia, Via Anguillarese, 301, 00123 Roma, Italy*

Abstract

Waste prevention is one of the main strategic objectives of the European waste management policy and it is also at the basis of circular economy concept. This paper explores the connection between waste prevention and circular economy in the context of Emilia-Romagna Region (Italy). Since 2015, Emilia-Romagna regional government has approved a circular economy Regional Law, including a series of actions supporting both European waste hierarchy and circular economy. All these actions promote a transition towards circular economy at systemic level and an analysis of Emilia-Romagna circular economy good practices has been carried out in this paper. Good practices are defined as relevant initiatives and innovative processes which start an innovation according to circular economy. This paper classifies more than 30 economic realities in Emilia-Romagna Region according to circularity criteria defined in the framework of European and Italian good practice collections. This analysis highlights several practices, concerning not so much waste management but rather innovative production processes of reuse, repair, and refurbishment. As a result, a strong connection between circular economy and waste prevention is confirmed.

Key words: circular economy, good practice, recovery, reuse, waste prevention

Received: February, 2020; Revised final: June, 2020; Accepted: July, 2020; Published in final edited form: October, 2020

1. Introduction

It is worldwide recognized the high potential of circular economy (CE) (Geissdoerfer et al., 2017; Korhonen et al., 2018). A variety of international organizations have actively produced "grey literature" on circular economy: from the United Nations (UNEP, 2006) to the European Union (EC Communication, 2014; EC Communication, 2015a; EC Communication, 2020), as well as entities such as the World Economic Forum (WEF, 2014), and non-governmental organizations like the Ellen MacArthur Foundation (Ellen Mac Arthur Foundation, 2012; Ellen Mac Arthur Foundation, 2015).

According to the European Commission, circular economy systems "keep the added value in products for as long as possible and eliminates waste. They keep resources within the economy when a product has reached the end of its life, so that they can be productively used again and again and hence create further value" (EC Communication, 2014). The aim of circular economy is therefore to develop production and consumption models which decouple economic growth from the intensive use of rapidly expiring resources and the consequent environmental impacts,

* Author to whom all correspondence should be addressed: e-mail: francesca.cappellaro@enea.it; Phone: +39 0516098775; Fax: +39 0516098280

minimising waste disposal, carbon emissions and extending products lifetime, promoting reparability and reuse and finally maximizing recycling. Waste prevention, which is one of the main strategic objectives of the European waste management policy (EC Communication, 2005), is also at the basis of circular economy concept. In fact, the European Circular Economy Package adopts a systemic approach for waste reduction, and plans to develop actions promoting the reparability, upgradability, durability and recyclability of products (EC Communication, 2015a; EC Communication, 2020), prioritising the waste reduction by ecodesign and the recovery of the highest possible value, also increasing the recycling rate (EC Communication, 2015). Moreover, circular economy approaches promote resource efficiency by an increase of waste prevention, which is the top of the waste hierarchy as defined by the European Waste Framework Directive (WFD) (Cole et al., 2019; EC Directive, 2008; EC Directive, 2018). In addition, the 4R principles, centre of circular economy practical framework (reduce, reuse, recycle and recover) (Ghisellini and Ulgiati, 2020; Kirchherr et al., 2017), are in line with the waste hierarchy (prevention, reuse, recycle, recovery and disposal). In particular, waste prevention can be achieved thanks to the introduction of circular and collaborative business models based on sharing economy and product service systems (Larsson, 2018; Sposato et al., 2017). These models favour an efficient use of resources and goods by means of product system redesign aimed at lifetime extension (McDonough and Braungart, 2009). Moreover, CE allows the adoption of the reuse and recycling principles, avoiding the raw material extraction and resource consumption (Iacovidou et al., 2017) and re-introducing secondary materials in a new economic cycle (Panaitescu and Bucuroiu, 2014, Mihajlov et al., 2015). Finally, CE models can enhance the waste transformation into resources, comprising energy recovery and waste management optimization (Ghinea and Gavrilescu, 2010).

This paper aims to investigate the connection between waste prevention and circular economy in the Emilia-Romagna Italian Region case study. To achieve that goal, an analysis of real CE good practices (GP) in Emilia-Romagna Region has been carried out on the basis of the following research methodology:

- Identification of CE GP collections and criteria;
- Selection of criteria for CE GP classification;
- Emilia-Romagna Region CE GP classification according to the selected criteria.

2. Materials and methods for analysis of CE good practices in Emilia-Romagna Region

2.1. Connection between waste prevention and circular economy

According to the WFD (EC Directive, 2008), waste hierarchy is a priority order for waste management legislation of the EU Member States, which aims to guarantee that the options with the best environmental performance are chosen (Cristobal et al., 2016) (Fig. 1). According to this principle, waste prevention is the most environmentally-friendly option, which can be defined as “the measures taken before a substance, material or product has become waste, that reduce: (a) the quantity of waste including through the re-use of products or the extension of the life span of products; (b) the adverse impacts of the generated waste on the environment and human health; (c) the content of harmful substances […]” (EC Directive, 2008). Waste prevention refers therefore to all technological, management and policy actions to reduce the production of waste and its environmental and health impacts and is connected with the improvement of manufacturing methods, the promotion of reuse and the extension of the product life time as well as the communication to consumers who should request environmentally-friendly products (Zorpas et al., 2015). In compliance with the WFD, Member States have to develop both Waste Management Plans (WMP), in order to deal with the objectives established by the Directive and the implementation of waste hierarchy and Waste Prevention Programmes (WPPs), which should identify waste prevention measures and targets (Cristobal et al., 2016). The CE Action Plan (EC Communication, 2015b) strengthens the connection between a sustainable and resource efficient economy and waste prevention, because it states that waste management and in particular waste minimisation is essential for the transition to circular economy.

Fig. 1. Waste hierarchy according to Directive 2008/98/EC on waste

2.2. The case of Emilia-Romagna region

Emilia-Romagna was the first Italian Region to have approved a law on circular economy (Emilia-Romagna Region, 2015). This law aims to innovate waste management regional system, ensuring environmental and health protection and reducing the overall impacts due to resource use. In particular, waste management regional system introduces specific actions and tools in line with the waste hierarchy which places prevention as top priority (Table 1).

Table 1. Emilia-Romagna Region actions and tools connected to waste hierarchy

Waste hierarchy principles	***Emilia-Romagna Region actions and tools***
All	Creation of regional forum on circular economy
Prevention	Incentives for prevention
Prevention/Reuse	Information and education activities on prevention and reuse
Preparing for reuse	Promotion of reuse
Preparing for reuse/ Recycling	Establishment of a permanent coordination group for by-products
Disposal	Application of pay-as-you-throw system (system disincentives to waste disposal)

An important tool of the regional law is the Waste Management Plan (WMP). The WMP sets very large targets, even more ambitious than those of the EU CE package. For example, two WMP main targets aim to:

- Reduce waste production by 20-25% compared to the 2011 values and achieve an average waste production of 150 kg/year per capita by 2020;
- Increase separate waste collection, enhancing the target to 73%, of which at least 70% to be sent for actual recycling.

Therefore, thanks to the Regional Law n.16 (Emilia-Romagna Region, 2015), several steps towards circular economy were introduced. For a real accomplishment, a strong collaboration among regional stakeholders, such as citizens, businesses, research and public institutions is strongly required. In 2018, a multi-stakeholders Circular Economy working group (CE WG) was established. The CE WG objective is to investigate the state of circular economy in Emilia-Romagna Region after the Regional Law n. 16 (ART-ER, 2020).

2.3. Circular economy good practices definition and collections

This paper investigates CE GP in the Emilia-Romagna Region to better understand the connection between CE and waste prevention.The first step includes the definition of what a CE good practice is. Literature is quite lacking in this context, because few scientific papers have been published at national level about CE GP collection, despite good practices are strongly recommended in several contexts. As regards Italy, Ghisellini and Ulgiati (2020) collected italian CE GP from three mapping initiatives (Atlas of Circular Economy in Italy, ENEL and Symbola Foundation and Legambiente) on the basis of the type and size of organisations, the economic sectors and the strategies implemented. Anyway, the authors did not collect the GP on the basis of specific criteria related to circular economy, differently from the CE GP collection performed in this work.

A first circular economy good practice definition was provided by ECESP (2018), the European Circular Economy Stakeholder Platform. This platform was established in the framework of the European Circular Economy Package (EC Communication, 2015) and aims at bringing together stakeholders active in the broad field of circular economy in Europe. Since its foundation, ECESP has committed to support the exchange of good practices and therefore promoted a CE GP collection as a way to favour the widespread of circular economy knowledge.

A first CE GP definition is actually provided in ECESP website (ECESP, 2018):

"*Good practices are relevant initiatives, innovative processes and 'learning from experience' examples involving companies or other relevant stakeholders such as research, academia and civil society*".

According to ECESP, CE GP are examples of excellence which can further contribute and stimulate the application of circular economy.

During the last years, not only ECESP but also other organizations have been committed in the CE GP mapping and collection. Examples of Italian CE GP collections related to Italy are carried out by the following organizations:

- ICESP (Italian Circular Economy Stakeholder Platform): similarly to ECESP, ICESP is the Italian Circular Economy Stakeholder Platform. ICESP was set up by ENEA in 2018 with the aim to create an Italian national meeting point of the initiatives, experiences, threats and perspectives within the circular economy framework. All the information coming from ECESP are transferred to Italian stakeholders and the Italian good practices in the field of circular economy collected through ICESP are spread in Europe at the same time.
- Symbola Foundation-ENEL: Symbola foundation is a non-profit organization, aimed at promoting innovative economic models, quality, territoriality, research and technology. In 2018, the Symbola Foundation and Enel published the Report "100 Italian Circular Economies Stories" (ENEL and Symbola Foundation, 2018). The report gathers one hundred circular practices on Made-in-Italy supply chains, technologies and business cases.
- CDCA team: the Documentation Centre on Environmental Conflicts (CDCA) is an Italian association aimed at providing information about both the causes of the environmental conflicts produced by the exploitation of natural resources, and its consequences. In collaboration with the Scientific Committee, which includes experts from ECODOM, Ecosystem Foundation and in collaboration to Poliedra Consortium of Politecnico di Milano, CDCA edited the Italian Atlas of Circular Economy, an interactive web platform which records Italian companies' experiences of circular economy.

2.4. Selection of circularity criteria for the CE GP identification

In order to collect the CE good practices, the previous organizations have introduced specific circularity criteria which characterize the CE GP. In the following, an overview of the different circularity criteria is described.

ECESP criteria

As already described, good practices collection and mapping is one of the main activities of ECESP. A dedicated form is available on the ECESP website for the CE GP collection and dissemination. In particular, GP can be taken into consideration for publication in the ECESP CE GP database only if they are compliant with the CE GP guidelines (ECESP, 2018).

In particular, five criteria are considered as indispensable principles:

1. Relevance to the European circular economy
2. Completeness and clarity of information
3. Practical character of expected results
4. Behavioural change and educational contribution
5. Compliance with Europa publishing rules.

In terms of circularity and closing the loop, the criterion of relevance to the circular economy is the most significant and CE GP have to demonstrate to apply one of the following criteria:

- Improvement of materials recyclability or use of secondary raw materials;
- Waste prevention, waste collection and selection to facilitate a further use;
- Product life extension by the reuse, repair and maintenance or redesign;
- A more efficient use of resources including energy resources in industrial processes;
- Introduction of new consumption models and / or providing consumers with information on the efficient use of products;
- Improvement of resources and by-products flows and exchanges through industrial symbiosis.

Moreover, ECESP classifies good practices in key areas which describe the life cycle phase where GP are occurring. In particular the key areas are described in the following:

- Production area is connected to GP adopting a waste prevention approach since the design phase with the aim to achieve product eco-innovation. Examples are the application of ecodesign approaches and techniques for the realisation of products and services in according to circular economy.
- Consumption area is related to GP which lead consumers to a behavioral change. Examples are GP to encourage circular consumption through products sharing, reuse and repair. Other GP are also those which conduct to greater awareness of circular economy principles such as educational projects.
- Secondary materials criteria are related to CE GP which implemented reuse. Examples are the valorisation of residues and by-products to obtain new products for other companies, such as industrial symbiosis.
- Waste management criteria concern good practices aimed at improving separate waste collection, recycling and recovery. Examples are ICT applications for the increase of household waste collection and the provision to citizens of relevant information on resource saving.
- Innovation and investment criteria are related to specific drivers which do not deal directly with production processes or loops closing, but which contribute to the indirect realization of a circular economy. Examples are financial opportunities for the promotion of circular economy or the introduction of green criteria in public procurement.

Finally, ECESP considers CE GP which demonstrate their real feasibility through measurable results such as:

- Actual environmental or social changes;
- Reduction of costs for companies;
- Opening of new markets;
- Facilitation of innovative processes and financial opportunities.

ICESP criteria

ICESP is the Italian Circular Economy Stakeholder Platform. ICESP was established by an ECESP commitment, and, likewise ECESP, promotes and carries out a CE GP collection especially related to the initiatives carried out by Italian stakeholders. ICESP follows the same criteria of ECESP for the CE GP collection. Moreover, in the ICESP collection form, further information are required. In particular, additional circularity criteria are related to:

- GP funding/investment costs;
- Barriers to GP implementation;
- Replicability conditions.

Symbola Foundation and ENEL criteria

In 2018, Symbola foundation and ENEL realized a CE GP collection in Italy (ENEL and Symbola Foundation, 2018), identifying one hundred of GP divided into 11 industrial sectors categories (i.e. clothing/accessories, agri-food, furniture/construction, industrial automation, etc.). The criteria for this CE GP collection were defined according to economic studies (Lacy et al., 2016), that identified methods for the implementation of circular economy associated to five circularity pillars. These pillars are listed in the following:

1. Sustainable inputs: this criterion is related to GP favoring the use of renewable energy and renewable materials. Other sustainable inputs are recyclable or biodegradable materials and consecutive lifecycles are recommended. Examples of sustainable inputs GP are renewable energy production plants or bioplastics.
2. Life extension: this criterion is based on the extension of useful product life. It especially concerns the adoption of eco-design strategies in the design and production lifecycle phases, thus avoiding the

replacement of the entire product (i.e. repair, update, regenerate or remarketing). Examples are GP that extend operative lifespans, such as modular products and/or maintenance methods aimed at replacing damaged parts or adding new features.

3. Sharing platforms: this criterion is based on sharing economy principles which allow multiple users to access and share products. Sharing has several benefits for the users in terms of savings and profits, but a further advantage is the promotion of a more efficient use of resources. Examples are collaborative platforms and rental marketplace for goods sharing.

4. Product as a service: this criterion concerns the shift from product to service. The producer is the owner of the asset and the customer pays for the use of a particular product. This service often comprises further related benefits (i.e. assistance). An example of 'product as a service' GP is the mobility service as the car sharing system.

5. End-of-life: this criterion is related to waste valorisation and to minimize wasted materials at the product end-of-life. Examples are GP of reuse, regeneration and recycling, where waste are considered inputs for new processes.

Italian Atlas of Circular Economy criteria

Another Italian CE GP collection was promoted by the Scientific Committee together with the research team of the "Circular Economy Stories" project (Ecodom and CDCA, 2019). This collection, named Circular Economy Italian Atlas, was realized according to a grid of environmental and social circularity criteria. These criteria grid identify ten dimensions for the circularity, each divided into a variable number of indicators.

The ten circularity criteria are listed below:

1. Ecodesign - Design of products which can last a longer lifetime and easily disassembled, in order to favour the repair and / or reuse and / or recovery of the overall products or of their parts (circular design, design-out waste, etc.).
2. Materials and Resources Procurement - Environmental impact of energy supply and choice of renewable and sustainable sources.
3. Materials and Resources Consumption - Efficient use of resources at all production stages and replacement of virgin raw materials with secondary raw materials deriving from the recycling industry. Energy efficiency or optimization of energy consumption through targeted reduction policies.
4. Waste, Scraps and Emissions Management - Environmental impact of production scraps, waste and end-of-life products management.
5. Transport and Distribution - Environmental impact of transports connected to the various phases of the production process, distribution and logistics.
6. Promotion of Sustainable Life Styles - Promotion of virtuous behaviour of employees/ members / volunteers through the use and dissemination of tools to support the reduction of energy and water consumption, waste reduction and their correct management, sustainable mobility.
7. Circular Supply Chain - Building of the supply chain based on environmental and social compatibility criteria.
8. Reporting / Accountability / Environmental Certification and other forms of Environmental Management related to the existence of reporting activities that analyze, qualify, certify and/or make environmental information transmissible.
9. Shared Value and Territorial Communities - Impact on the other connected realities (supply chains or non-supply chains) in terms of maximizing environmental compatibility and creating shared social value and development of other economic forms, organized in plural forms.
10. Social Inclusivity - increase of the rate of economic inclusion or creation of social and economic value according to a shared value approach with particular attention to the involvement of disadvantaged subjects.

2.5. Analysis of CE GP in Emilia-Romagna Region

With the aim to investigate the connection between waste prevention and circular economy, an analysis of these CE GP was carried out in the Emilia-Romagna Region. All the previously described CE GP collections have allowed to identify the CE GP located in Emilia-Romagna and, according to the data available in 2018, 33 CE GP were identified. The analysis of CE GP has taken into account specific circularity criteria.

More in detail, the analysis referred to ECESP criteria, because the European Platform was considered more significant than the other collection criteria in terms of connection between circular economy and waste hierarchy principles.

Furthermore, to better analyse CE GP adoption, the classification of Emilia-Romagna CE GP takes into consideration of the following aspects:

- Geographical distribution: the province where the GP are implemented.
- Sectors: the type of productive area or service of the GP (i.e. agriculture, building/construction, bio-based materials, B2B services, etc.).
- Key area: the life cycle phase of the GP, which are already described in par. 2.4.
- Waste hierarchy: the priority concepts already described in Fig. 1.

Table 2 shows the results of the GP collection and classification. It includes a short description of each GP, the source, the geographical distribution, the key area, the sector and the waste hierarchy level.

3. Results and discussion

From the previous analysis, 33 CE GP from existing business have been identified in Emilia-Romagna Region. In Fig. 2, a distribution of good practices on the basis of the mapping and collection source is provided. The number describes the CE GP mapped by each collection described in paragraph 2.2 and 2.3.

Table 2. Emilia-Romagna CE GP collection and classification

Number of the good practice	*Short description*	*Source*	*Geographical distribution*	*Sector*	*Key area*	*Waste hierarchy level*
1	Art design with recovery materials - Eco-poetic necklaces and handcrafted home furniture	ECESP, Atlas of Circular Economy	Bologna	Repair, reuse, refurbishment; Clothing and fashion; Home furniture	Production	Reuse
2	Tomato production in hydroponic greenhouse - Greenhouse with closed production cycle	ECESP Atlas of Circular Economy, Symbola Fondation	Ferrara	Agriculture	Innovation and investments	Prevention
3	Valorisation of residues from wine production processes	ICESP	Reggio-Emilia	Agriculture	Production	Recycling
4	Co-housing processes - Development of communities based on the active cohabitation and mutual help	ICESP	Ferrara	Social business; Building/construction	Innovation and investments	Reuse
5	Sustainable urban drainage systems based on ceramics	ICESP	Modena	Sustainable development; Building and construction	Waste management	Reuse
6	Roveri smart Village - Industrial symbiosis practices application	ICESP	Bologna	Urban development; Sustainable development	Innovation and investments	Preparation for reuse
7	Valorisation of organic waste - Project to produce biomaterials with insects	ICESP	Reggio-Emilia	Recycling; Bio-based industries	Secondary materials	Recycling
8	Urban regeneration - Educational laboratories and job placement of disadvantaged people	ICESP	Forlì-Cesena	Social business	Production	Reuse
9	App for waste separate collection - Simplification of household collection by a barcode	ICESP	Bologna	Public services; Education; Digital technologies	Waste management	Recycling
10	Product and services for the territory - Waste management and compost and woodchip production	ICESP, ECESP	Bologna	Recycling	Waste management	Recycling
11	Waste prevention and reuse with the commitment of local community	ICESP, Atlas of Circular Economy	Bologna	Education; Repair, reuse, refurbishment	Innovation and investments	Prevention
12	Creative recovery - Accessories and furniture with scrap materials	ICESP, Symbola Fondation	Bologna	Clothing and fashion; Home furniture	Production	Reuse
13	Recovery of home furniture - Social cooperative with green projects	Atlas of Circular Economy	Bologna	Repair, reuse, refurbishment; Home furniture	Production	Reuse
14	Reuse, recycling and donation of second-hand goods	Atlas of Circular Economy	Forlì-Cesena	Repair, reuse, refurbishment	Production	Reuse
15	Recovery of wood waste - Production of particleboard panels for furniture industry	Atlas of Circular Economy	Piacenza	Recycling	Production	Recycling
16	100% recycled pellet - Pellet produced with coffee grounds or recovery wood	Atlas of Circular Economy	Bologna	Repair, reuse, refurbishment	Production	Recycling
17	Marketplace for production sraps - Sharing and commerce of production scraps	Atlas of Circular Economy	Bologna	Sharing economy; B2B services	Innovation and investments	Preparation for reuse
18	Home cleaning - Production of goods with post-consumption materials	Atlas of Circular Economy	Modena	Repair, reuse, refurbishment	Production	Preparation for reuse
19	Multi-utility digital services for citizens	Atlas of Circular Economy	Bologna	Public services	Innovation and investments	Prevention
20	Proposal for innovative ideas to improve the sustainaibility of services provided by multi-utility	Atlas of Circular Economy	Bologna	Public services	Innovation and investments	Prevention
21	Project for urban regeneration of city district	Atlas of Circular Economy	Reggio-Emilia	Urban development; Sustainable development	Innovation and investments	Reuse
22	Production of bioplastic from agricultural residues (sugar beets)	Atlas of Circular Economy, Symbola Fondation	Bologna	Recycling; Bio-based industries	Secondary materials	Recycling

23	Recovery and trasformation of textile residues from fashion industry by disadvantaged people	Atlas of Circular Economy, Symbola Fondation	Bologna	Social business; Clothing and fashion	Production	Reuse
24	Recovery of recycling materials from marble, earthenware tiles, nacre, glass, bottles, light bulbs - Production of eco-mortar for covering and flooring	Symbola Fondation	Rimini	Repair, reuse, refurbishment; Bio-based industries; Building/construction	Secondary materials	Recycling
25	Production of flooring with low environmental impact	Symbola Fondation	Modena	Sustainable development ; Building/construction	Production	Recycling
26	Environmental information technology consultancy - Restoration- of information technology devices informatici and toner recovery	Symbola Fondation	Bologna	Repair, reuse, refurbishment; Public services	Production	Preparation for reuse
27	Prevention of food waste, medicines, bulky goods and their recovery	Symbola Fondation	Bologna	Public services; Repair, reuse, refurbishment; Food and drink	Production	Reuse
28	Pallet reuse among different supply chains	Symbola Fondation	Ravenna	Sharing economy; Repair, reuse, refurbishment	Production	Reuse
29	Prevention of food waste, medicines, bulky goods and their recovery	Symbola Fondation	Modena	Public services; Repair, reuse, refurbishment; Food and drink	Production	Reuse
30	Innovative design goods from regenerated materials	Symbola Fondation	Ravenna	Repair, reuse, refurbishment; Home furniture	Production	Reuse
31	Recovery and recycle of wood packaging	Symbola Fondation	Forlì-Cesena	Recycling; Repair, reuse, refurbishment	Production	Recycling
32	Green Smart Technology for water: System for processing and communicating water consumption to managers and users	Symbola Fondation	Ferrara	B2B Services	Consumption	Prevention
33	Green Smart Technology for water: Systems for the management, recovery and reuse of rainwater and grey water at the building scale	Symbola Fondation	Bologna	B2B Services	Innovation and investments	Reuse

The most of Emilia-Romagna GP were collected by Atlas of Circular Economy (Ecodom and CDCA, 2019) and ENEL - Symbola Foundation, (2018). Other GP are present in ECESP and ICESP collections. Some GP are common to more collection sources, so the total number is larger than the CE GP real number.

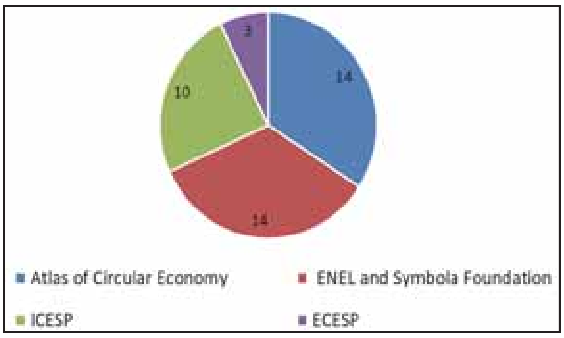


Fig. 2. Emilia-Romagna Region CE GP distribution on the basis of GP collection source

3.1. Good practice geographical distribution

The GP distribution in the Region is shown in Fig. 3. The Regional capital city of Bologna has the GP majority, followed by the provinces of Modena, Ferrara, Reggio Emilia and Forlì-Cesena, whereas the GP number located in the provinces of Piacenza, Rimini and Ravenna is lower.

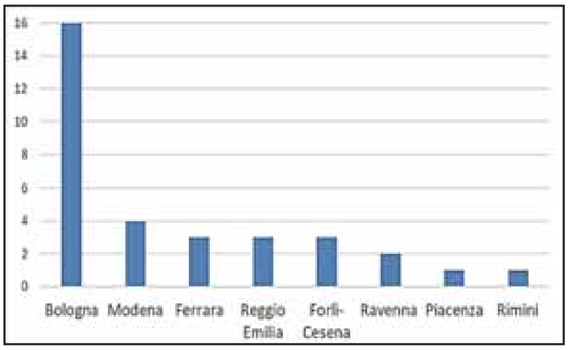


Fig. 3. CE GP geographical distribution in Emilia–Romagna Region

3.2. CE GP key area

Key areas are divided in production, consumption, innovation and investments, waste management and secondary materials, as already described in the paragraph 2.4.

Figure 4 highlights that most practices relate to production (17), including for example: the valorization of agri-food residues, the production of clothing and accessories and home furniture from waste materials, the production of recycled pellet and recycled wood panels, the prevention of food waste and medicines, the recycling of pallets and wood packaging.

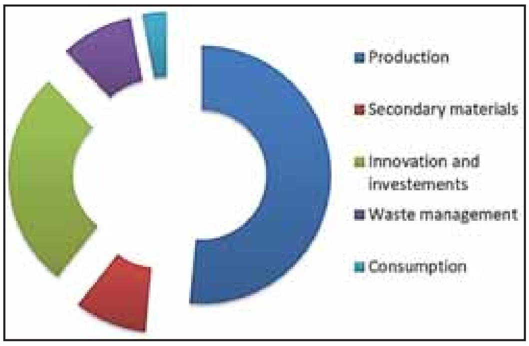


Fig. 4. CE GP key areas in Emilia-Romagna Region

Innovation and investments include nine GP, ranging from industrial symbiosis practice in urban areas, to urban restoration, green technologies for water management in buildings, waste prevention and reuse at local community scale. Both waste management and secondary materials contain three GP. The former includes IT applications for domestic waste collection, territorial waste management system and sustainable urban drainage system which uses ceramic tiles. At the moment, the application of circular economy principles to consumption models includes only one good practice.

3.3. CE GP sectors

The reference sectors of the Emilia-Romagna GP are very heterogeneous (Fig. 5).

The same good practice can refer to more than one sector. The repair, reuse and refurbishment sector include the majority of good practices (13), followed by public services, recycling (5), home furniture, sustainable development and building/construction (4 each). The remaining sectors have a lower amount of good practices.

3.4. CE GP and waste hierarchy

Fig. 6 shows the connections between CE GP and waste hierarchy. The prevention, including the reuse, has the majority of the good practices (19). Eight of them are related to repair, reuse and refurbishment, four to public services and home furniture, three to clothing and fashion and social business, two to B2B services, building and construction, food and drink and sustainable development, and finally one to agriculture, education and urban development.

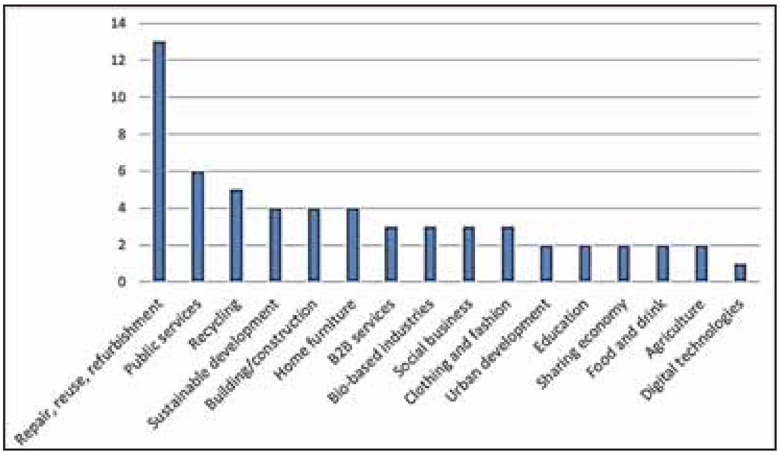


Fig. 5. CE GP Sectors in Emilia-Romagna Region

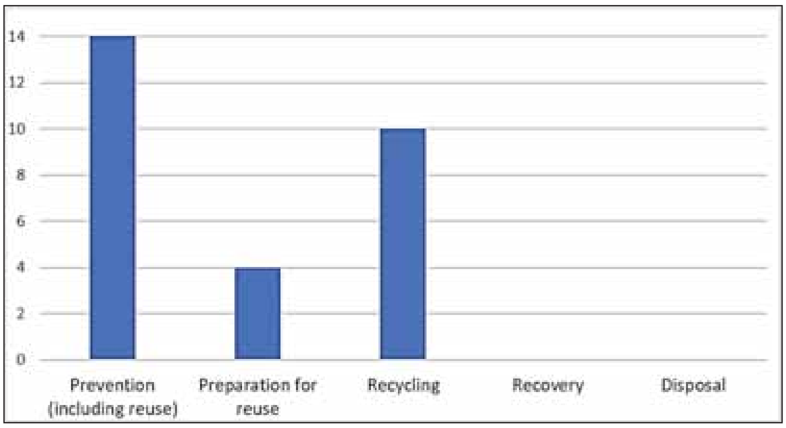


Fig. 6. CE GP and waste hierarchy in Emilia-Romagna Region

The preparation for reuse has four GP (two of them relate to repair, reuse and refurbishment), whereas the recycling presents ten GP, mainly related to repair, reuse and refurbishment, bio-based industries and building/construction. Finally, recovery, especially energy recovery and disposal do not have any GP.

The previous results highlight that the majority of Emilia-Romagna CE GP are connected to waste prevention. This confirms that there is a connection between circular economy and waste prevention. The introduction of a circular economy regional law has steered an innovation towards waste minimization. Moreover, Fig. 4 shows that CE GP are widespread distributed in different sectors. This result highlights the systemic innovation produced by the circular economy approach at production level. On the other hand, the majority of CE GP are distributed in the biggest regional economic cities, especially in Bologna, the Region's capital. Future direction in the implementation of CE in the region could be provided throughout a deeply analysis (i.e. SWOT or PESTLE) in order to show the barriers, drivers, benefits and challenges in the implementation of the GP in the region. This aspect could be included as future activities of the Regional Forum on circular economy or CE WG.

For a wider circular transformation of the whole regional system, all stakeholders must be further involved, such as: public authorities, businesses, trade unions and civil society. Actually, this analysis was limited to 2018 and the number of good practices is continuously growing and in evolution. It could be also recommended to introduce a Regional Circular Economy Observatory in order to map the real GP situation and to orient future regional policies.

Beyond the Emilia-Romagna case study, this work has introduced a new methodology for the CE GP classification. From a scientific point of view, this could be considered a first attempt to systematize circularity criteria for the CE GP identification. Future perspectives could concern the application of this methodology to other research studies for the analyis of the circular economy implementation.

4. Conclusions

This paper aims to investigate the connection between waste prevention and circular economy in the Emilia-Romagna Italian Region case study. To achieve this goal, this work carried out an analysis of regional CE GP resulting in a first attempt to systematize circularity criteria supporting the CE GP identification based on several good practice collections and in particular the European Circular Economy Stakeholder Platform criteria.

The analysis was realized in 2018 and was related to Emilia-Romagna Region which, in the last years, has implemented several policy actions to favour the circular economy transition according to a specific Regional law. Results show that the majority of the good practices are strongly related to waste prevention. In particular, the prevailing sectors are connected to repair, reuse and refurbishment initiatives and home furniture, thus favouring closed-loop process implementation and product lifetime extension, and public services addressed to consumers and citizens, supporting them towards more sustainable and circular consumption models and lifestyles.

This result confirmed therefore the strong connection between circular economy in Emilia-Romagna Region and waste prevention strategies. In conclusion, CE GP are also revealed a significant instrument to analyse public policy efficacy in terms of circular economy transition.

Abbreviation list:

CDCA: Documentation Centre on Environmental Conflicts
CE: circular economy
CE WG: Circular Economy working group
ECESP: European Circular Economy Stakeholder Platform
GP: good practices
ICESP: Italian Circular Economy Stakeholder Platform
WFD: Waste Framework Directive
WMP: Waste Management Plan
WPP: Waste Prevention Programme

Acknowledgements

The authors would like to acknowledge the Emilia–Romagna Circular Economy Regional Working Group members, ECODOM and also Italian Circular Economy Stakeholders Platform (ICESP) colleagues for the support in CE GP collection.

References

ART-ER, (2020), Accelerating the transition towards the circular economy in Emilia-Romagna, On line at: https://www.art-er.it/2020/05/economia-circolare-accelerare-la-transizione-verso-un-nuovo-modello/.

Cristobal G.J., Vila M., Giavini M., Torres De Matos C., Manfredi S., (2016), Prevention of Waste in the Circular Economy: Analysis of Strategies and Identification of Sustainable Targets - The food waste example, EUR 28422, Luxembourg (Luxembourg), Publications Office of the European Union, JRC105415, On line at: https://publications.jrc.ec.europa.eu/repository/bitstream/JRC105415/kj-na-28422-en-n.pdf.

Ecodom and CDCA, (2019), Italian Atlas of Circular economy (in Italian), On line at: http://www.economiacircolare.com/.

Cole C., Gnanapragasam A., Cooper T., Singh J., (2019), An assessment of achievements of the WEEE Directive in promoting movement up the waste hierarchy: experiences in the UK, *Waste Management*, **87**, 417-427.

EC Communication, (2020), Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, A new Circular Economy

Action Plan for a cleaner and more competitive Europe, COM(2020) 98 final, 11.3.2020, Brussels.

EC Communication, (2015a), Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Closing the loop - An EU action plan for the Circular Economy, COM(2015) 614 final, 02.12.2015, Brussels.

EC Communication, (2015b), Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Taking sustainable use of resources forward: A Thematic Strategy on the prevention and recycling of waste, COM(2005) 666 final, 21.12.2005, Brussels.

EC Communication, (2014), Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Towards a circular economy: A zero waste programme for Europe, COM(2014)0398 final, 02.07.2014, Brussels.

EC Directive, (2018), Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste, *Official Journal of the European Union*, L150/109/14.06.2018, Brussels.

EC Directive, (2008), Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives, *Official Journal of the European Union*, L312/3/22.11.2008, Brussels.

ECESP, (2018), Circular Economy Good Practices: guidelines for submissions to the ECESP website, On line at: https://circulareconomy.europa.eu/platform/sites/default/files/ecesp_-_website_-_gp_criteria_-_v3.pdf.

Ellen Mac Arthur Foundation, (2015), Growth Within: a Circular Economy Vision for a Competitive Europe, On line at: https://www.ellenmacarthurfoundation.org/assets/downloads/publications/EllenMacArthurFoundation_Growth-Within_July15.pdf.

Ellen MacArthur Foundation, (2012), Towards the Circular Economy: Economic and business rationale for an accelerated transition, On line at: http://www.ellenmacarthurfoundation.org/business/reports/ce2012

Emilia-Romagna Region, (2015), Regional Law 05th October 2015, n. 16. Regulation to support circular economy, the reduction of urban waste production, the reuse of end-of-life products, the separate collection and modification to the regional law 19th August 1996 n. 31 (Regulation of the special tax for landfill disposal of solid waste), 05.10.2005, Bologna, Italy.

ENEL and Symbola Foundation, (2018), 100 Italian Circular Economy Stories, On line at https://www.symbola.net/ricerca/100-italian-circular-economy-stories-la-ricerca-enel-symbola/.

Geissdoerfer M., Savaget P., Bocken N., Hultink E., (2017), The Circular Economy - A new sustainability paradigm?, *Journal of Cleaner Production*, **143**, 757-768.

Ghinea C., Gavrilescu M., (2010), Decision support models for solid waste management - An overview, *Environmental Engineering and Management Journal*, **9**, 869-880.

Ghisellini P., Ulgiati S., (2020), Circular economy transition in Italy. Achievements, perspectives and constraints, *Journal of Cleaner Productio*, **243**, 118360.

Iacovidou E., Millward-Hopkins J., Busch J., Purnell P., Velis C.A., Hahladakis J.N., Zwirner O., Brown A., (2017), A pathway to circular economy: Developing a conceptual framework for complex value assessment of resources recovered from waste, *Journal of Cleaner Production*, **168**, 1279-1288.

Kirchherr J., Reike D., Hekkert M., (2017), Conceptualizing the circular economy: An analysis of 114 definitions, *Resources, Conservation and Recycling*, **127**, 221-232.

Korhonen J., Nuur C., Feldmann A., Birkie S.E., (2018), Circular economy as an essentially contested concept, *Journal of Cleaner Production*, **175**, 544-552.

Lacy P., Rutqvist J., Lamonica B., (2016), Circular economy – From waste to value (Circular Economy – Dallo spreco al valore), EGEA, Milano, Italy.

Larsson M., (2018), *Circular Business Models, Developing a Sustainable Future*, 1st Edition, Palgrave Macmillan Publisher, Switzerland.

McDonough W., Braungart M., (2009), *Cradle to cradle: Remaking the Way We Make Things*, Vintage, North Point Press Publisher, London.

Mihajlov A., Stevanović-Čarapina H., (2015), Rethinking waste management within the resource-efficient concept, *Environmental Engineering and Management Journal*, **14**, 2973-2978.

Panaitescu C., Bucuroiu R., (2014), Study on the composition of municipal waste in urban areas of Prahova County, *Environmental Engineering and Management Journal*, **13**, 1567-1571.

Sposato P., Preka R., Cappellaro F., Cutaia L., (2017), Sharing economy and circular economy. How technology and collaborative consumption innovations boost closing the loop strategies, *Environmental Engineering and Management Journal*, **16,** 1797-1806

UNEP, (2006), Circular Economy: An Alternative Model for Economic Development. United Nations Environment Programme, Paris, France, On line at: http://www.unep.fr/shared/publications/pdf/DTIx0919xPA-circulareconomyEN.pdf.

WEF, (2014), Towards the Circular Economy: Accelerating the Scale-up Across Global Supply Chains, World Economic Forum, Geneva, Switzerland, On line at: http://www3.weforum.org/docs/WEF_ENV_TowardsCircularEconomy_Report_2014.pdf.

Zorpas A.A., Lasaridi K., Voukkali I., Loizia P., Chroni C., (2015), Promoting Sustainable Waste Prevention Strategy Activities and Planning in Relation to the Waste Framework Directive in Insular Communities, *Environmental Processes*, **2**, 159-173.

Environmental Engineering and Management Journal October 2020, Vol. 19, No. 10, 1711-1718
http://www.eemj.icpm.tuiasi.ro/; hiip://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

REGIONAL POLICIES FOR CIRCULAR ECONOMY IN ITALY AND AN EMPIRICAL ANALYSIS OF PAY-AS-YOU-THROW TAX EFFECTS IN EMILIA ROMAGNA

Marco Compagnoni

Area Science Park, Padriciano 99, Trieste, Italy and
PhD SUSTEEMS, University of Trento, Trento, Italy, E-mail address: marco.compagnoni@unitn.it; Phone: +39 3387064171

Abstract

A systematic transition towards circular economy (CE) explicitly became a major strategy at European Union level since 2015. Even though this EU-level boost is strong, a major role is played by regional implementation, since local needs and opportunities connected with CE may be very specific.
The aim of this article is twofold. On the one side it highlights which policy instruments are most frequently used by Italian regional policy makers to implement measures supporting the transition to more circular economic systems. The analysis highlights specific regional strategies as well as recurrent policies; these last focus on waste mainly. On the other side, as "pay-as-you-throw (*PAYT*)" is strongly supported by the EU within the set of policies in favour of EC, an empirical analysis of the effects of the introduction of this waste taxation scheme is conducted.
The case of excellence Emilia Romagna (ER) is considered, as it represents the first Italian Region imposing *PAYT* to all of its Municipalities by 2021. The effect of *PAYT* on the quantities of total and sorted urban waste generated is estimated, exploiting the difference-in-differences econometric technique with multiple treatment and time periods. Empirical results show that the effects of this policy in ER are coherent with the first best objective implied by EU Waste Hierarchy and therefore with the CE ones: the total quantity of waste generated decreases by 9.6%, with a non-significant increase of the sorted one.

Keywords: circular economy, difference-in-differences, pay-as-you-throw, regional policy, waste

Received: February, 2020; Revised final: June, 2020; Accepted: July, 2020; Published in final edited form: October, 2020

1. Introduction

The circular economy (CE) concept finds many definitions (e.g. Kirchherr et al., 2017), but a common twofold ultimate objective emerges among them: CE systems are economic systems aiming to minimize, on one hand, natural resources extraction and, on the other, any flow of waste generated by human activities going back to the environment (EEA, 2017).

This new paradigm started being support by some businesses (Zucchella and Urban, 2019), banks (EIB, 2019) and policy makers especially during the last decade. The EU committed itself in the design of a comprehensive transition strategy towards CE since 2015. Implementation at a local level started in the last few years. The action of regional and local policy makers is fundamental for the realization of the new paradigm, because it entails a transformation of the production systems and rooted consumption habits. Moreover, the barriers to and benefits of the transition may be locally very specific (OECD, 2019). For instance, agricultural regions could focus on the diffusion of bioeconomy activities, urban areas on practices of the kind "product as a service", and manufacturing regions on the support to product innovation through eco-design.

In this paper the European framework for CE transition is summarized. After that, we move to the Italian regional level, with particular attention to the kind of instruments used to introduce and apply CE principles in the regional policies.

From Section 3 the analysis focuses on a case study: the effects of "pay-as-you-throw (*PAYT*)" taxation on the types and quantities of urban waste generated in Emilia Romagna (ER) region. The case is relevant for at least two reasons. First, *PAYT* implementation is strongly supported by the EU and by a few Italian Regions, as a policy for CE. Second, ER comes out as the first Italian Region adopting a wide range of initiatives in favour of CE with effects on several economic sectors and on local public administration; *PAYT* is among these.

It is important to note that only a few empirical studies on the topic for cases in Europe exist; the case of ER is analysed for the first time. Moreover, both theoretical and empirical analyses actually provide mixed evidence on *PAYT* effects on households' waste production behaviour (Gradus et al., 2019).

This paper contributes to the empirical literature on *PAYT*, but it also provides a novelty investigating the effects of this measure in a CE perspective. Is *PAYT* effectively an instrument for the prevention of waste production? Does it entail a substitution of unsorted with sorted waste only? Or does it crowd out environmentally friendly attitudes, with a total increase of waste generated? The work is concluded by some policy recommendations.

2. Policies in favour of circular economy

2.1. The EU framework

The Circular Economy Action Plan (EC, 2015) represents the fundamental document for the EU strategy for a comprehensive transition of the European economic system towards an as-circular-as-possible model. This document presents the CE as the tool to achieve long run environmental and economic sustainability and, consequently, it is a starting point for a new EU innovation trajectory.

The EU strategy realizes with interventions in various economic scopes and along the whole resource use cycle: production (eco-design, facilitation of industrial symbiosis, support to bioeconomy practices), consumption (green labels for products, waste production prevention, driving public demand towards sustainable supply), waste management, secondary raw materials market. The EU already enacted 54 actions in favour of the CE (EC, 2019a; EC, 2019b). The EU legislative and regulatory action was intense, and the same was for its direct and indirect economic intervention to promote and support investments and innovations within the scope of CE. Indeed, a relevant part of Horizon 2020 funds were directed in this sense and the Commission also encouraged Member States to use EFSI (European Fund for Strategic Investments) and Cohesion Policy funds for green investments and resource efficiency projects.

The regulatory intervention in the field of waste at the EU level has an earlier origin. Indeed, the Waste Framework Directive (EC Directive, 2008) is particularly important, because it states the European waste management targets. These are summarized by the so called "Waste Hierarchy". The first best objective for environmental sustainability is represented by waste production reduction, followed by reuse, recycling, energy recover and disposal. Therefore, waste prevention represents the first best objective for waste policies. Moreover, the directive introduced the "polluter pays" principle and the extended producer responsibility one.

Afterwards, the Commission made more explicit the integration of the waste management objectives into the more recent and much wider strategy for the transition to CE (EC, 2014). With the "Circular Economy Package", approved by the European Parliament (EP) in May 2018, a first phase of normative reforms on waste is completed. The CE Package constitutes a modification of the six main directives in the field of waste (EC Directive, 1994; EC Directive, 1999; EC Directive, 2003; EC Directive, 2006; EC Directive, 2008; EC Directive, 2012), it promotes reuse and industrial symbiosis and it makes waste management targets more stringent: urban waste recycling at 65%, landfilling at 10%.

The European Green Deal has been launched in December 2019 and it emerges now as the "new growth strategy that aims to transform the EU into a fair and prosperous society, with a modern, resource-efficient and competitive economy where there are no net emissions of greenhouse gases in 2050 and where economic growth is decoupled from resource use" (EC, 2019d). The Green Deal is an integral part of this Commission's plan to implement the United Nation's 2030 Agenda and the Sustainable Development Goals. The Green Deal also introduces a new CE action plan (EC, 2020) which is hinged on the design and production phases, with the aim to ensure that the resources used are kept in the EU economy for as long as possible.

2.2. The Italian regional level

Local authorities play a very relevant role in implementing policies in favour of the CE, particularly at a regional government level, since local barriers and opportunities connected with CE may be very specific. This paragraph gives an overview of the most relevant initiatives for the CE at the Italian regional level, and how they introduced the CE principles in their normative system. The qualitative analysis of the Regions' actions to improve circularity highlights the use of three policy instruments mostly: Research and Innovation Strategies for Smart Specialisation (RIS3 or S3), single regional laws (RL) and Regional Waste Management Plans.

Regions are required to elaborate research and innovation strategies for a "smart specialization", in order to benefit from the EU Cohesion Policy (EC, 2012). The EU aim is to achieve a more efficient use of European Structural Investment Funds and to increase the synergies among Community, national and regional policies. The S3 identifies a regional innovation and industrial transformation trajectory starting from a medium-long run development vision shared by many stakeholders of various nature ("Entrepreneurial Discovery Process"). The S3 is also based on the analysis of the region's specific competitive advantages, resources and socio-economic structure. In practice, the S3 provides a multi-faceted policy mix for the allocation of Cohesion Policy funds (ERDF, EFS and EAFRD especially).

The analysis of Italian Region's S3 documents, which have been published between 2014 and 2016, with a planning horizon until 2020, highlighted just one case in which the CE concept have been explicitly integrated in the S3: Emilia Romagna Region.

This region's S3 specifies seven economic sectors of specialization, each of them corresponding to an industrial cluster, and four cross-sector thematic strategies: industry 4.0, big data, blue growth, circular economy. The document defines some strategic objectives for each specialization sector, 71 in total (ERR, 2018); of these, 22 are at least in part correlated with the cross-sectorial strategy "circular economy". Moreover, the CE is one of the trajectories of development of the specialization sector "Energy and sustainable development". Overall, Emilia Romagna Region chose a structure for its S3 in matrix form, in which the cross-sectorial strategies shape the innovation objectives of each economic specialization scope, with the aim to achieve a comprehensive transition.

Piedmont Region also developed a S3 clearly in favour to the circular transition, even though the concept of CE is not explicitly mentioned in the document. The policy maker defined six economic sectors of specialization, among which clean tech and green chemistry (PR, 2016). These sectors are supported in their expansion according to two "development trajectories": the smart trajectory and the resource efficiency one. The development trajectories influence the process of structural evolution of Piedmont economy. In particular, the resource efficiency trajectory is conceived as the promotion of competences and efficiency processes for a more sustainable regional economy and a reduction of natural resources use. For example, this trajectory realizes for the case of the cleantech/green chemistry sector in the following objectives: creation of biorefineries for chemical products, biofuels and bioplastics production; management and extraction of valuable resources from waste and wastewater; support to the secondary raw materials industry.

Eventually, Lazio Region doesn't mention CE in its S3, but it selected the "green economy" as a specialization sector. The sector development is supported through the promotion of research for eco-innovation, of industrial symbiosis projects, measures for waste reduction (LR, 2016).

In conclusion, the introduction of the CE concept into the regional S3 generally implies a rather comprehensive intervention on the various phases of products' life-cycle (R&D, production, commercialization, end-of-use) and it directs the incentives for innovation, public-private and interregional collaborations towards this paradigm. Formally, the S3 is structured in matrix form in the two main cases observed, with the aim to foster circular innovation and transition across the specialization sectors. In the cases of these regions, it emerges a clear long run development vision marked by environmental sustainability.

Some Regions introduced the CE principles in their own normative system through specific laws. This is the case of Friuli Venezia Giulia (FVGR, 2015; FVGR, 2017), Umbria (UR, 2009), Marche (MR, 2018), Basilicata (BR, 2018) and again Emilia Romagna (ERR, 2015). These laws are generally aimed to implement structural actions. These laws provide for eco-innovation incentives, targets and policies for waste management, the establishment of discussion forums for stakeholders of different nature in order to confront on practical CE barriers and projects.

However, regional policy makers focused their interventions on the waste scope mainly until now, defining measures and targets for waste management and for their prevention. Indeed, the guidelines of those policies are provided in the Regional Waste Management Plans. This approach is certainly inappropriate for a structural and comprehensive transition towards CE, because it is just focused the end-of-life phase. In other words, waste management policies aim to achieve environmental sustainability only, and neglect production and consumption phases. Nevertheless, waste management policies are fundamental to pursue two CE goals: waste reduction (first best goal); generating high-quality waste streams for recycling.

3. Case study: the effects of pay-as-you-throw taxation on waste production

Taking into account what emerged from the analysis of EU and regional policies for CE it is clear that most of the normative interventions are oriented to resources end-of-life phase. Taxation is one of the instruments considered as useful by the EU in order to direct households waste production behaviour towards the objectives defined by the Waste Hierarchy, especially *PAYT* taxation schemes (EC, 2014; EC Directive, 2008; EP, 2017). *PAYT* or Unit Pricing Systems (UPS) are urban waste taxation schemes in which the amount of the due fee depends, at least in part, on the quantity of unsorted waste generated by the single household. They are based on volume or weight criterion. Reviews of various collection systems practically implementing *PAYT* are given by e.g. Reichenbach (2008) and Skumatz (2008).

In this section an empirical analysis of the effects of *PAYT* introduction is conducted, in order to check if the results of this measure are effectively in favours of the CE ultimate objectives. Indeed, on the one side the support to this instrument within the scope of waste management/CE policies by the EU and a few Regions in Italy (see section 4) is strong, but, on the other, the literature on European cases shows a mixed evidence on the effectiveness of *PAYT* schemes and that a scarce number of empirical analyses is available.

More specifically, the case of Emilia Romagna region is considered here for the first time in the literature.

3.1. Theoretical background and literature review

PAYT taxation schemes belong to what is referred to as "benefit taxes". According to economic theory, an efficient decentralized financing system for local administrations should be based on the benefit principle: the burden of financing the services supplied by local governments should fall on the community benefitting of them and the burden should be proportional to the quantity of public good, i.e. service, received (Messina et al., 2018). Waste management should be suited for the application of a benefit tax, with positive outcomes both for local finance (Skumatz, 2008) and the environment. A tariff proportional to the amount of waste generated carries out the Pigouvian function of including in polluters' private costs the negative externalities bore by the whole community. In other words, UPS are coherent with the previously mentioned "polluter pays principle". The large majority of Italian Municipalities still implement the "Tassa sui rifiuti – Tax on waste" (Ta.Ri.), which is very far from the logic of the benefit tax. Ta.Ri depends on the house and family dimension and it is not conceived to measure the service effectively demanded by a single household.

Actually, even though the effects of this policy instrument have been investigated in the US since longtime (e.g. Fullerton and Kinnaman, 2000; Huang et al. 2011), very few empirical analysis were conducted for cases in Europe. Among these: Allers and Hoeben (2010), Dijkgraaf and Gradus (2009), Linderhof et al. (2001) deal with Dutch cases; Carattini et al. (2018) on Switzerland. Bucciol et al. (2015) and Valente and Bueno (2019) examined Italian case studies: the first used data for Treviso district; the second investigated the application of PAYT in the city of Trento. Therefore, both considered different geographical scopes with respect to this paper.

Importantly, results on PAYT effectiveness differ across studies and geographic areas, possibly because the policy effectiveness may vary across different social environments (see, e.g., Kipperberg, 2007) or because of different implementation systems. More specifically, two effects could be observed: an effort in waste prevention, acting in favour of total waste generated reduction; a substitution of unsorted (priced) waste with the sorted (unpriced) type, acting in favour of recycling but not of waste prevention (see Section 4). Depending on the magnitude of these two effects, very different consequences from a waste management point of view are expected. In principle, one may argue that only if a prevention effect is observed and combined with a non-positive variation of sorted waste quantity (in terms of weight) the policy can be considered really in favour of the CE ultimate goals: shrinkage in the use of raw materials, efficient use of resources and, consequently, waste production reduction.

Eventually, non-monetary incentives are also determinants of household waste generation behaviour: considering behavioural economics literature (e.g. Ariely et al. 2009; Gneezy and Rustichini, 2000) introducing a fee on unsorted waste may even crowd out the intrinsic motivation to sort and to avoid waste generation, associated with environmentally friendly attitudes.

3.2. PAYT in Emilia Romagna (ER) region

Here, the case of ER is more specifically considered, because it is the Italian Region that more strongly supports the implementation of this policy.

ER was the first Italian Region intervening to support the transition to *PAYT* systems, through the RL 16/2015 (ERR, 2015). This sets ambitious goals in terms of reduction of total waste generated and share of sorted over total waste. To achieve these objectives, the law provides for the implementation of *PAYT* schemes in all the Municipalities of the region by the end of 2020. *PAYT* started being applied in 2013. In 2019, the number of Municipalities enacting UPS was 81 out of 331 total Municipalities in ER.

The list of Municipalities adopting *PAYT* is available on ER Region website (https://ambiente.regione.emilia-romagna.it/it/rifiuti/temi/economia-circolare/tariffa-puntuale/elenco-dei-comuni-a-tariffa-puntuale). Data on urban waste are published by ISPRA (https://www.catasto-rifiuti.isprambiente.it/index.php?pg=downloadComune&width=1129&height=635&advice=si): this analysis considers annual data at municipal level, for all and only the Municipalities of the region (331), for the period 2010-2018 (latest available year). The number of municipalities implementing PAYT by 2018 is 53 (Fig. 1).

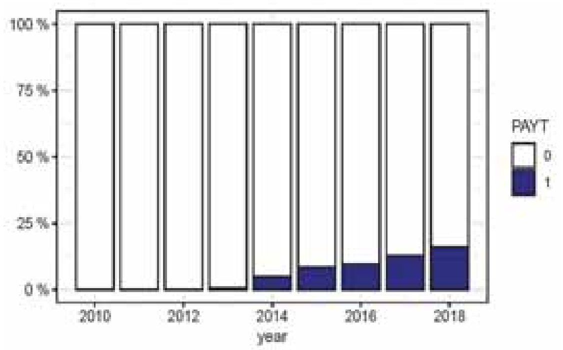


Fig. 1. Share of Municipalities implementing PAYT in Emilia Romagna between 2010 and 2018

3.3. Empirical methodology: difference-in-differences with multiple time and treatment periods

Differences-in-differences (DiD) strategies are panel-data, quasi-experimental methods applied to estimate the effect of a "treatment": sharp changes in the economic environment or changes in government policy, for example.

In DiD models, a treatment group, i.e. individuals for which the treatment is observed, and a comparison (control) group, not receiving the policy, are identified. The impact of the treatment is inferred from the (possible) different average variation of a certain variable of interest experienced by the two groups over time. This means that DiD estimators take into account both common trends and cross-sectional differences.

DiD models rely on the "common (or parallel) trends" assumption: this assumes that, in the absence of the treatment, the average variation of the outcome variable would be the same for the control and treatment groups. In this case, the control group provides a valid counterfactual for the time evolution of outcomes in the treatment group absent the treatment. Under this assumption, a DiD model is suited to control for time-invariant unobservable characteristics of the two groups.

The DiD methodology has been used to evaluate the effects of *PAYT* in Allers and Hoeben (2010); Bucciol et al. (2015); Carattini et al. (2018), for example.

Because Municipalities in Emilia Romagna started to implement *PAYT* in different years since 2013, our estimation is based on the following econometric model for a DiD on multiple time and treatment periods (Eq. 1):

$$Y_{it} = \alpha_0 + \alpha_1 PAYT_i + \sum_{t=2010}^{T=2017} \alpha_t year_t + \beta Policy_{it} + u_{it} \quad (1)$$

In this model: i indicates a Municipality in Emilia Romagna; t a year (2010-2018); *PAYT* is a dummy equal one for all Municipalities implementing *PAYT* somewhen between 2010 and 2018: this represents our treatment group; $year$ is a full set of year dummies: in this way we control for time trends, i.e. year fixed effects; $Policy_{it} = PAYT_i * year_t$ is a dummy equal one for treatment units in the post-treatment period: when this term is positive, the policy is actually implemented in a specific Municipality and year. Therefore, the average treatment effect of the policy is measured by $Policy_{it}$ coefficient, β.

Outcome variables Y_{it} are: logarithm of the quantity of per capita total waste generated; logarithm of the quantity of per capita sorted waste generated (kg*inh./year).

4. Case study results and discussion

According to the estimation generated by using (Eq. 1), the introduction of *PAYT* significantly reduced the annual amount of per capita total waste generated by 9.7%, while the policy does not have significant effects on sorted waste production (Table 1). The results of the analysis presented in this paper are very close to the ones predicted by Valente and Bueno (2019) for the Italian city of Trento, despite the use of a different methodology, with a non-significant increase of sorted waste and an average variation of total waste by -8.6%. As said, previous literature results on PAYT effects on total and sorted waste production are mixed. For example, Bucciol et al. (2015), Kipperberg (2007), Linderhof et al. (2001), and in part also Carattini et al. (2018) find that pricing unsorted waste leads to a reduction of total waste generated, but also to an increase of sorted waste. On the other side, Allers and Hoeben (2010); Dijkgraaf and Gradus (2009); Kinnaman and Fullerton (2000); Valente and Bueno (2019) find no significant effect of PAYT introduction on the quantities of recycling waste generated.

Table 1. Estimated effects of PAYT introduction on the (log) quantity of per capita (pc) total waste generated – col. 1 - and on the (log) quantity of per capita sorted waste generated – col. 2

	pc total waste (1)	*pc sorted waste (2)*
PAYT	-0.016 (0.017)	0.238*** (0.037)
year2010	-0.012 (0.018)	-0.383*** (0.040)
year2011	-0.018 (0.018)	-0.315*** (0.040)
year2012	-0.064*** (0.018)	-0.327*** (0.040)
year2013	-0.090*** (0.018)	-0.317*** (0.040)
year2014	-0.059*** (0.018)	-0.260*** (0.040)
year2015	-0.044* (0.017)	-0.196*** (0.039)
year2016	-0.028 (0.018)	-0.119** (0.040)
year2017	-0.048** (0.017)	-0.102** (0.040)
Policy	-0.097*** (0.024)	0.027 (0.055)
Constant	6.456*** (0.013)	5.874*** (0.029)
Observations	3070	3070
R^2	0.025	0.080
F Statistic	7.894***	26.483***
Note: * p<0.1; ** p<0.05; *** p<0.01; s.e. in brackets		

The econometric technique exploited in this paper may encounter some limitations. First of all, DiD methodology fails to include the possible effects of time-varying unobservable characteristics. Second, further analysis is required to ensure external validity: the results refer to the case of Emilia Romagna only; it must be considered that PAYT may be applied with different specificities in other regions.

Summarizing, the results of our empirical analysis suggest that the introduction of *PAYT* represents a policy instrument which is perfectly coherent with the EU Waste Hierarchy: a prevention of waste production is observed, while a substitution of unsorted waste with the sorted type is not.

If the policy would simply induce a substitution of unsorted with sorted waste, with a constant amount of total waste generated, this would represent a second best in terms of environmental benefits, as stated by the Waste Hierarchy. In the case of an increase of total waste production, the monetary incentive would have completely crowded out household's environmentally friendly attitudes. None of these situations is observed. Therefore, *PAYT* can be considered a good instrument for waste reduction and, consequently, a measure consistent with the circular economy objectives.

Unfortunately, in Italy this policy instrument has been introduced only in a small number of Municipalities. ISPRA estimates (ISPRA, 2018) that 13.2% of Italian Municipalities apply a taxation of the *PAYT* type. The figure tripled with respect to the 2015 census, but Ta.Ri remains largely prevalent. These municipalities are typically of small dimension, mainly located in Veneto, Emilia Romagna, Trentino Alto Adige and Lombardy.

Considering regional policies, the transition to *PAYT* tariffs is one of the objectives of Lombardy Region's Waste Management Plan (LoR, 2018). This sets the implementation target to the 20% of Lombard Municipalities within 2020. However, the Plan census found only 147 Municipalities with *PAYT* (9.7% of the total) in 2017. Also Sardinia (SR, 2016) and Friuli Venezia Giulia (FVGR, 2017) Regions incentivize the change to *PAYT*. Overall, Italian Regions' legislative efforts in favour of *PAYT* seem to be limited.

5. Conclusions

In this paper we go through the policies and the instruments in favour of the transition to the circular economy (CE) on different levels, from the EU to the Italian Regions. This last scope of analysis represents a novelty to the economic policy literature.

At the EU level, the transition is seen as a major strategy for sustainability and competitiveness in the medium-long run. The approach in terms of policies is multi-faceted and these intervene in many scopes: raw materials, production, consumption and waste management.

At the Italian regional level, the CE principles have been introduced into the regional authorities' interventions through three instruments, mainly: regional Smart Specialization Strategies (S3), regional laws or Waste Management Plans. The S3 approach is the most systematic one for CE implementation. Indeed, it is based on a medium-long run regional development vision shared by many stakeholders, it influences the innovation trajectories of various economic sectors and it usually presents a comprehensive policy mix for their implementation. Unfortunately, Emilia Romagna (ER) is the only Region explicitly mentioning the CE in its S3; a few other Regions inserted the CE principles or very closely related concepts, without mentioning CE itself.

The large majority of Regions mention CE only in their Waste Management Plans. Even if waste management policies are not enough for a whole CE implementation, these policies have been applied with the same objective (i.e. achieving EU Waste Hierarchy) and similar instruments across Europe. Among these policies, the diffusion of *PAYT* waste taxation schemes is supported by the EU and, among the Italian Regions, by Emilia Romagna especially, where it will be mandatory for all Municipalities before 2021.

Despite this support to *PAYT* implementation, only a few empirical researches examine its effects considering European case studies. Moreover, results on *PAYT* effectiveness differ across studies and geographic areas. More specifically, two effects on household behaviour could be observed: an effort in waste prevention, acting in favour of total waste generated reduction; a substitution of unsorted (priced) waste with the sorted (unpriced) type, acting in favour of recycling but not of waste prevention. Only if a prevention effect is observed with a non-positive variation of sorted waste (in absolute terms) the policy can be considered really in favour of the CE ultimate objectives, while substitution is just a second best. This paper analyses *PAYT* implementation from a CE perspective: this is also a novelty to *PAYT* literature.

For the first time, the Emilia Romagna case is investigated in order to check for the two effects mentioned above. The analysis relies on a difference-in-differences methodology with multiple time and treatment periods on ISPRA data. The aim is to compare Municipalities implementing the policy and not. Results show that *PAYT* significantly reduced the annual amount of per capita total waste generated by 9.7%, while the measure does not have significant effects on sorted waste production. This means that *PAYT* induces a prevention effect, without causing a substitution of unsorted waste with the sorted type, for the case of ER at least.

In conclusion, Italian Regions should adopt a more comprehensive approach in terms of scopes of interventions to support a systematic transition to CE. Regional S3s seem to be a coherent policy instrument for this. Nevertheless, waste management policies are crucial in order to close the loop of resources use in an efficient and sustainable way. Within this scope, *PAYT* taxation turns out to be, for the case of ER, a measure which is perfectly functional to the EU Waste Hierarchy first best goal, i.e. waste prevention, and therefore to the CE objectives.

Acknowledgements

This research was partially carried out during my experience as a guest researcher at DIW Berlin. Therefore, I thank Marica Valente (DIW Berlin) for the methodological support. I thank Stephen Taylor, Fabio Morea and Enrico Longato (Area Science Park) for the direct and indirect support, and Marinella Favot (Area Science Park) and Ilaria Gandin (University of Trieste) for the technical help.

References

Allers M., Hoeben C., (2010), Effects of unit-based garbage pricing: a differences-in-differences approach, *Environmental and Resource Economics*, **45**, 405-428.

Ariely D., Bracha A., Meier S., (2009), Doing good or doing well? Image motivation and monetary incentives in behaving pro-socially, *American Economic Review*, **99**, 544-555.

BR, (2018), Norms in implementation of part IV D. Lgs. 3 april 2006, n. 152, on waste management and polluted areas decontamination (in Italian), *Official Bulletin of the Basilicata Region* (*Bollettino ufficiale della Regione Basilicata)*, 35/2018, 16.11.2018, Potenza, On line at: https://www.regione.basilicata.it/giunta/files/docs/DOCUMENT_FILE_3053063.pdf.

Bucciol A., Montinari N., Piovesan M., (2015), Do not trash the incentive! Monetary incentives and waste sorting, *Scandinavian Journal of Economics*, **117**, 1204-1229.

Carattini S., Baranzini A., Lalive R., (2018), Is taxing waste a waste of time? Evidence from a Supreme Court Decision, *Ecological Economics*, **148**, 131-151.

Dijkgraaf E., Gradus R., (2009), Environmental activism and dynamics of unit-based pricing systems, *Resource and Energy Economics*, **31**, 13-23.

EC Directive, (1994), European Parliament and Council Directive 94/62/EC of 20 December 1994 on packaging and packaging waste, *Official Journal of the European Communities*, L 365, 31.12.1994, Brussels.

EC Directive, (1999), Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste, *Official Journal of the European Communities*, L 182, 16.7.1999, Brussels.

EC Directive, (2003), Directive 2003/53/EC of the European Parliament and of the Council of 18 June 2003 amending for the 26th time Council Directive 76/769/EEC relating to restrictions on the marketing and use of certain dangerous substances and preparations, *Official Journal of the European Communities*, L 178, 17.7.2003, Brussels.

EC Directive, (2006), Directive 2006/66/EC of the European Parliament and of the Council of 6 September 2006 on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC, *Official Journal of the European Communities*, L 266, 26.9.2006, Brussels.

EC Directive, (2008), Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives, *Official Journal of the European Communities*, L 312, 22.11.2008, Brussels.

EC Directive, (2012), Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE), *Official Journal of the European Communities*, L 197, 24.7.2012, Brussels.

EC, (2012), Guide to Research and Innovation Strategies for Smart Specialisations, European Commission, On line at: https://ec.europa.eu/regional_policy/sources/docgener/presenta/smart_specialisation/smart_ris3_2012.pdf.

EC, (2014), Towards a circular economy: A zero waste programme for Europe (COM(2014) 398), European Commission, On line at: https://ec.europa.eu/environment/circular-economy/pdf/circular-economy-communication.pdf .

EC, (2015), Closing the loop - An EU action plan for the Circular Economy (COM/2015/0614), European Commission, On line at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52015DC0614.

EC, (2019), Commission staff working document accompanying Report from the commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on the implementation of the Circular Economy Action Plan, European Commission.

EC, (2019), On the implementation of the Circular Economy Action Plan (COM(2019) 190), European Commission, On line at: https://ec.europa.eu/commission/sites/beta-political/files/report_implementation_circular_economy_action_plan.pdf.

EC, (2019), The European Green Deal (COM(2019) 640), European Commission, On line at: https://ec.europa.eu/info/sites/info/files/european-green-deal-communication_en.pdf.

EC, (2020), New Circular Economy Action Plan, European Commission, On line at: https://ec.europa.eu/environment/circular-economy/pdf/new_circular_economy_action_plan.pdf.

EEA, (2017), Circular by design. Products in the circular economy, *EEA Report*, **6,** Copenhagen, On line at: https://circulareconomy.europa.eu/platform/sites/default/files/circular_by_design_-_products_in_the_circular_economy.pdf.

EIB, (2019), The EIB Circular Economy Guide - Supporting the circular transition, European Investment Bank, On line at: https://www.eib.org/en/publications/the-eib-in-the-circular-economy-guide.

EP, (2017), Towards a circular economy–Waste management in the EU, European Parliament, On line at: http://www.europarl.europa.eu/thinktank/en/document.html?reference=EPRS_STU%282017%29581913.

ERR, (2015), Measures in support of the circular economy, of urban waste prevention, reuse, differentiated collection and RL 19/10/1996 (Italian), Emilia Romagna Region, *Bollettino ufficiale della Regione Emilia Romagna*, 16/2015, 05.10.2015, Bologna, On line at: https://bur.regione.emilia-romagna.it/dettaglio-inserzione?i=e08c3ac15eeb4fb1902978ea32f39a72.

ERR, (2018), Innovative orientations for the regional innovation strategy for the smart specialization (in Italian), Emilia Romagna Region, On line at: http://fesr.regione.emilia-romagna.it/s3.

Fullerton D., Kinnaman C.T., (2000), Garbage and recycling with endogenous local policy, *Journal of Urban Economics*, **48**, 419-442.

FVGR, (2015), "Rilancimpresa FVG" – industrial policies reform (in Italian), Friuli Venezia Giulia Region, *Bollettino ufficiale della Regione Friuli Venezia Giulia*, 3/2015, 20.02.2015, Trieste, On line at: https://www.regione.fvg.it/rafvg/cms/RAFVG/economia-imprese/rilancimpresa/argomento.html.

FVGR, (2017), Regional Law 34/2017 Waste management regulation and principles of circular economy (in Italian), Friuli Venezia Giulia Region, On line at: https://lexview-int.regione.fvg.it/fontinormative/xml/xmllex.aspx?anno=2017&legge=34.

Gneezy U., Rustichini A., (2000), A fine is a price, *Journal of Legal Studies*, **29**, 1-17.

Gradus R., Homsy G.C., Liao L., Warner M.E., (2019), Which US municipalities adopt Pay-As-You-Throw and curbside recycling?, *Resources, Conservation and Recycling*, **143**, 178-183.

Huang J.C., Halstead J., Saunders S., (2011), Managing municipal molid maste with Unit-Based Pricing: policy effects and responsiveness to pricing, *Land Economics*, **87**, 645-660.

ISPRA, (2018), Report on urban waste (in Italian), Istituto Superiore per la Protezione e la Ricerca Ambientale, On line at: http://www.isprambiente.gov.it/it/pubblicazioni/rapporti/rapporto-rifiuti-urbani-edizione-2018.

Kipperberg G., (2007), A comparison of household recycling behaviors in Norway and the United States, *Environmental and Resource Economics*, **36**, 215-235.

Kirchherr J., Reike D., Hekkert M., (2017), Conceptualizing the circular economy: An analysis of 114 definitions, *Resources, Conservation and Recycling*, **127**, 221-232.

Linderhof V., Kooreman P., Allers M.,Wiersma D., (2001), Weight-based pricing in the collection of household waste: the Oostzaan case, *Resource and Energy Economics*, **23**, 359-371.

LoR, (2018), Regional Waste Management Program–second monitoring report (in Italian), Lombardia Region, On line at: https://www.regione.lombardia.it/Secondo+Rapporto+monitoraggio+PRGR2019.pdf.

LR, (2016), Lazio smart specialization strategy (in Italian), Lazio Region, On line at: http://www.lazioinnova.it/wp-content/uploads/2017/05/Smart_Specialisation_Strategy_S3.pdf.

Messina G., Savegnago M., Sechi A., (2018), Local taxes on waste in Italy: benefit tax or (hidden) property tax? (in Italian), *Questioni di Economia e Finanza*, **474**, Bank of Italy.

MR, (2018), Industry 4.0: innovation, research and education (in Italian), Marche Region, *Bollettino ufficiale della Regione Marche*, 25/2018, 17.07.2018, Ancona. On line at: https://www.consiglio.marche.it/banche_dati_e_documentazione/leggi/dettaglio.php?arc=vig&idl=2025

OECD, (2019), Regions in Industrial Transition - Policies for People and Places, Organization for Economic Co-operation and Development, On line at: https://www.oecd.org/innovation/regions-in-industrial-transition-c76ec2a1-en.htm.

PR, (2016), Piedmont smart specialization strategy Piedmont Region, On line at: https://www.regione.piemonte.it/web/temi/sviluppo/sistema-ricerca-innovazione/s3-strategia-specializzazione-intelligente.

Reichenbach J., (2008), Status and prospects of pay-as-you-throw in Europe - A review of pilot research and implementation studies, *Waste Management*, **28**, 2809-2814.

Skumatz L.A., (2008), Pay as you throw in the US: Implementation, impacts, and experience, *Waste Management*, **28**, 2778-2785.

SR, (2016), Regional Waste Management Plan - update (in Italian), Sardinia Region, On line at: https://www.regione.sardegna.it/documenti/1_274_20161227144158.pdf.

UR, (2009), Integrated waste management norms and polluted areas decontamination (in Italian), Umbria Region, *Official Bulletin of the Umbria Region,* (*Bollettino ufficiale della Regione Umbria)*, 11/2009, 20.05.2009, Perugia. On line at: http://leggi.crumbria.it/mostra_atto.php?id=41979&&m=4

Valente M., Bueno M., (2019), The effects of pricing waste generation: A synthetic control approach, *Journal of Environmental Economics and Management*, **96**, 274-285.

Zucchella A., Urban S., (2019), Circular entrepreneurship – creating responsible enterprise, Palgrave Macmillan, On line at: https://www.palgrave.com/gp/book/9783030189983.

Websites:

https://ambiente.regione.emilia-romagna.it/it/rifiuti/temi/economia-circolare/tariffa-puntuale/elenco-dei-comuni-a-tariffa-puntuale.

https://www.catasto-rifiuti.isprambiente.it/index.php?pg=downloadComune&width=1129&height=635&advice=si

Environmental Engineering and Management Journal

October 2020, Vol. 19, No. 10, 1719-1729
http://www.eemj.icpm.tuiasi.ro/; hiip://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

OPEN SCIENCE AND ARTIFICIAL INTELLIGENCE SUPPORTING BLUE GROWTH

Gianpaolo Coro

Institute of Information Science and Technologies of the National Research Council of Italy (ISTI-CNR), Via Moruzzi 1, 56124 Pisa, Italy, E-mail address: gianpaolo.coro@isti.cnr.it; Phone: +39 0506218210; Fax: +39 0503152810

Abstract

The long-term EU strategy to support the sustainable growth of the marine and maritime sectors (*Blue Growth*) involves economic and ecological topics that call for new computer science systems to produce new knowledge after processing large amounts of data (Big Data), collected both at academic and industrial levels. Today, Artificial Intelligence (AI) can satisfy the Blue Growth strategy requirements by managing Big Data, but requires effective multi-disciplinary interaction between scientists. In this context, new Science paradigms, like Open Science, are born to promote the creation of computational systems to process Big Data while supporting collaborative experimentation, multi-disciplinarity, and the re-use, repetition, and reproduction of experiments and results. AI can use Open Science systems by making domain and data experts cooperate both between them and with AI modellers. In this paper, we present examples of combined AI and Open Science-oriented applications in marine science. We explain the direct benefits these bring to the Blue Growth strategy and the indirect advantages deriving from their re-use in other applications than their originally intended ones.

Keywords: artificial intelligence, big data, blue growth, marine science

Received: February, 2020; Revised final: June, 2020; Accepted: July, 2020; Published in final edited form: October, 2020

1. Introduction

Blue Growth is the long-term European strategy for the sustainable *growth* of the marine and maritime sectors. These sectors currently involve more than 5 million jobs with a gross added value of around 500 billion euros per year (EU Commission, 2019), and thus are integral parts of countries' economy. Blue Growth involves problems that include Big Data and requires Artificial Intelligence modelling (Steven et al., 2019). Extracting knowledge from these Big Data is essential to prevent severe consequences on sea resources alteration due to overfishing, climate change, invasive species, and other disasters.

Generally, the availability of Big Data in most fields of Science is strongly influencing the progress and evolution of Information Technology and consequently, the way Science is approached (Hey et al., 2009). Web and mobile applications and scientific and industrial experiments continuously produce Big Data and demand for new systems to process them, and extract information to produce new knowledge. Issues with Big Data, involve at least the following six "*V*" features: large *Volume*, high production *Velocity*, *Variability* of complexity, *Variety* of representational formats, untrustworthiness (*Veracity*) of the contained information, and high commercial or scientific *Value* of the extracted information. Managing and processing Big Data requires using non-conventional computer science architectures and models (Manyika et al., 2011). Indeed, in the last decade, new Science paradigms have been introduced to manage Big Data while supporting collaborative experimentation, multi-disciplinarity, and the open publication of scientific findings. These paradigms include Open Science, e-Science, and Science 2.0, which are rapidly converging towards the same objectives, i.e. (i) the open publication of results, findings and documents, (ii) the extraction of knowledge from Big Data through proper computational platforms and models, (iii) the implementation of collaborative approaches for services and users to solve complex scientific problems, and (iv) the application of the three *R*s of the scientific method: *R*eproducibility, *R*epeatability, and *R*e-usability of models and results (Andronico et al., 2011; EU Commission, 2016; Waldrop, 2008). In this paper, we will refer to Open Science (OS) as a representative of all the mentioned paradigms.

While new Science paradigms evolve, Artificial Intelligence (AI) is overcoming its traditional boundaries - of research on systems that simulate human intelligence - to meet industrial applications (Jeschke et al., 2017; Leitao et al., 2016). However, AI models often need domain/data experts to collaborate with machine learning experts to refine models and gain high performance. Indeed, a key to achieving high performance in AI modelling is that multi-disciplinary teams cooperate efficiently. In this view, Open Science-compliant systems are crucial to support AI modelling.

In this paper, we present examples of Open Science-oriented computer systems and AI approaches that have addressed and supported the Blue Growth strategy in several ways (summarised in Figs. 1-2). We also present how these systems, initially conceived for marine-science, have generated knowledge and methodologies that other scientists have re-used in other domains, thus extending their range of application. The paper is organised as follows: Section 2 describes standard features of Open Science-compliant platforms; Section 3 reports AI experiments - reported per application topic – supporting Blue Growth and Open Science; Section 4 draws the conclusions.

2. Open Science-oriented platforms

Processing Big Data requires distributed or parallel computing systems that execute computations on several processors/cores or machines in a computer network (Attiya and Welch, 2004). Today, most of the available computing systems do not meet Open Science requirements, because (i) they usually manage specific community requirements, (ii) are much tied to specific repositories and data formats, and (iii) do not support collaborative experimentation. Further, they seldom take into account the open publication of the results and the support of the three *R*s of the scientific method. However, examples of Open Science-oriented platforms are available, that have been developed in the context of marine science and have been extended to other domains (Candela et al., 2016; Coro et al., 2017; Hunter et al., 2012). These platforms include distributed computing systems that are economically sustainable and support flexible and quick import of community-provided processes.

They foster Open Science by embedding their computational platforms within an e-Infrastructure (e-I), i.e. a network of hardware and software resources (e.g. Web services, machines, processors, databases etc.) allowing users residing at remote sites to collaborate and exchange information in a context of data-intensive Science (Andronico et al., 2011; Assante et al., 2019a). An e-I can make a distributed/parallel processing platform (e.g. a High-Performance Computing, a Cloud/Grid Computing system etc.) interoperate with a distributed storage system and other services to manipulate, publish, harmonise, visualise, and access data.

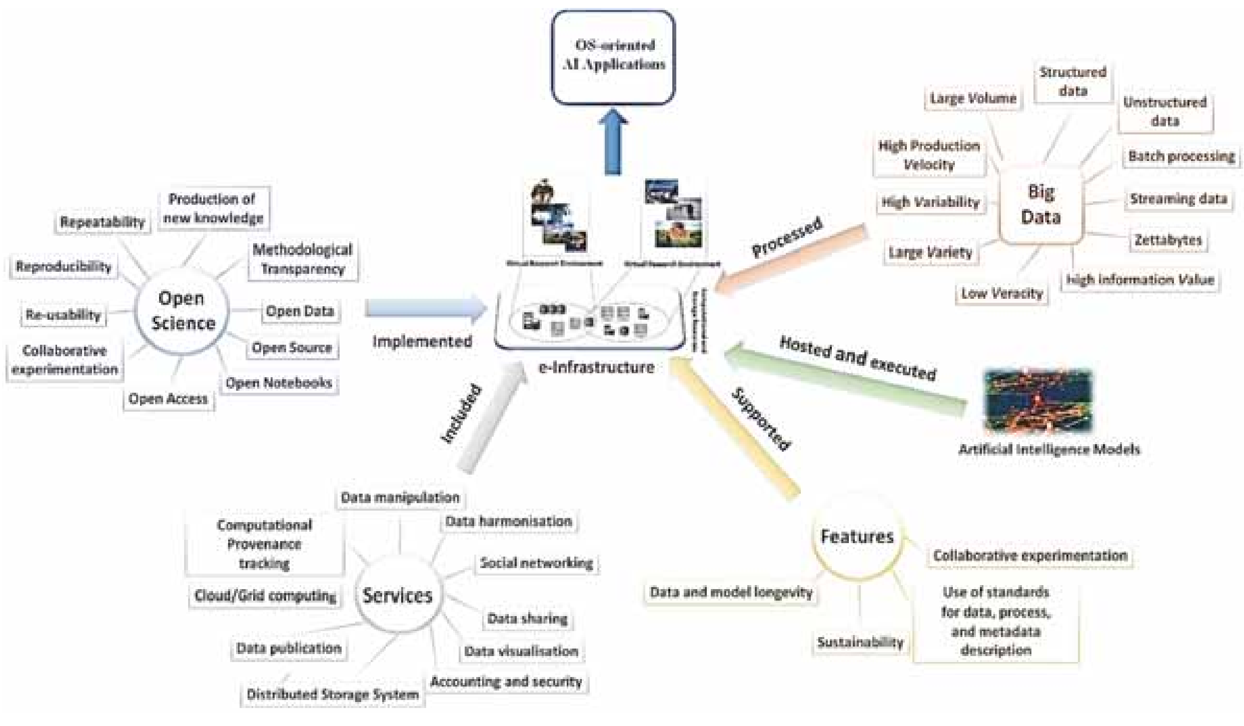


Fig. 1. Logic schema of e-Infrastructure features that support Open Science-oriented AI modelling and Big Data processing

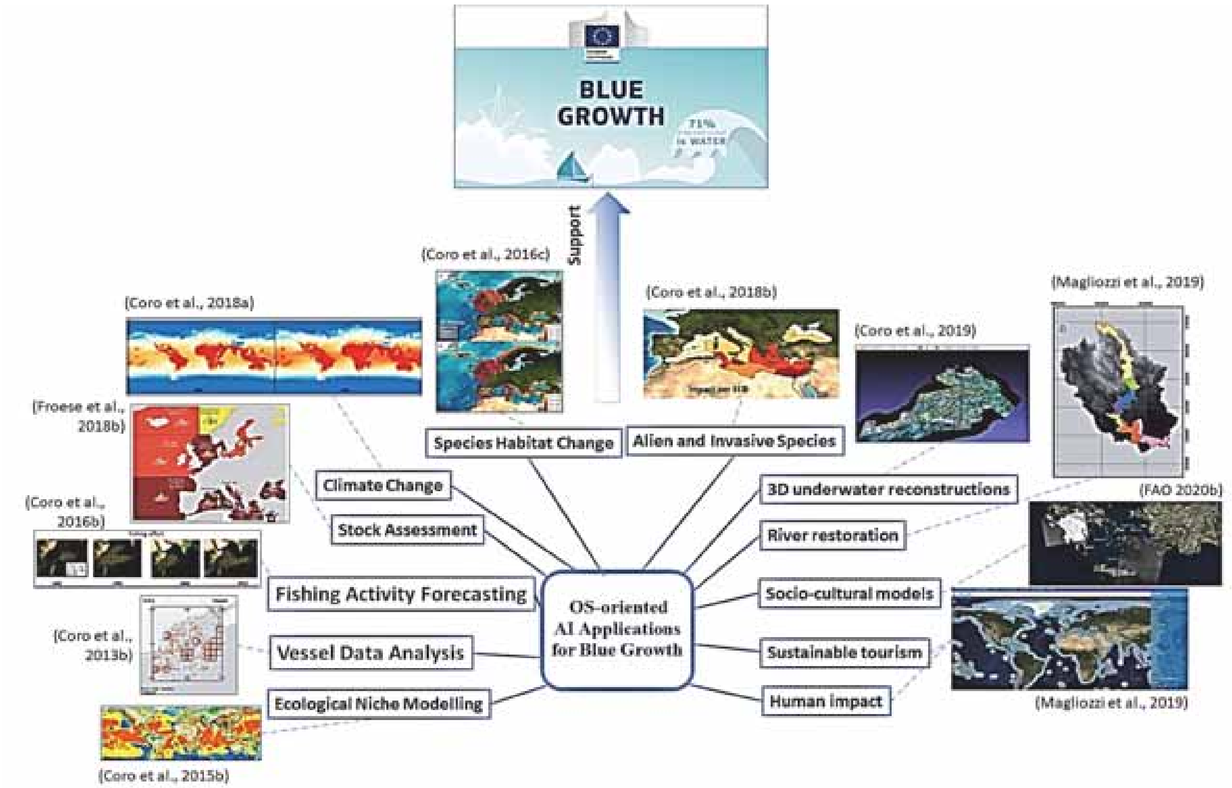


Fig. 2. Logic schema of the support to Blue Growth by Open Science-oriented AI applications

Also, an e-I can manage various access policies and formats for data payloads, data catalogues, security and accounting services, data sharing services, and social networking services.

The distributed computing systems used by e-Is mostly work in the same way as standard computing systems, but they also embed Open Science features. These features allow publishing processes (e.g. scripts, compiled programs etc.) as services that are invocable via a communication standard, and allow for their programmatic exploitation by other services, software, and workflows either provided by the e-I or by the communities using the e-I. Additional services enable quick integration of processes implemented under several programming languages to facilitate their usage and sharing. Usually, an e-I computational platform is also able to interoperate with other services of the e-I while tracking the *provenance* of an executed computation, i.e. the set of input/output data, parameters, and metadata that allow to precisely repeat the experiment. Finally, the platform should also support data and computational result sharing between users through collaborative online spaces.

There are many examples of Open Science-oriented platforms (Kramer and Bosman, 2016). However, few of them manage many of the mentioned properties with the same weight, e.g. D4Science (Assante et al., 2019b) and HubZero (McLennan and Kennell, 2010). Open-access platforms like Zenodo.org, Dataverse.org, and DataDryad.org, focus on the publication and re-use of documents, data, and software. Other platforms, e.g. Jupyter, focus on the reproducibility of processes and workflows (Kluyver et al., 2016), or foster the transparency of scientific workflows and collaborative multi-disciplinary experimentation (Staines, 2018; Thelwall and Kousha, 2015). Overall, a fragmented scenario exists across e-Infrastructures. Usually, scholars must use several platforms to reconstruct and repeat one experiment and retrieve results, documentation, and publications. The main reason is the high cost to manage all requirements of Open Science within one platform. Attempts to inter-connect several e-Infrastructures exist (Assante et al., 2019b; De Roure et al., 2008; Liew et al., 2016) that promote the introduction of standards for workflows' definition and re-use, and for service interactions and data exchange. However, these attempts have achieved minimal success so far.

Indeed, integral to Open Science compliance is the use of communication standards for all services and data that are integrated with the e-I. For example, the Web Processing Service standard (WPS) is commonly used to publish processes as-a-service and to enhance their interoperability with other services (Schut and Whiteside, 2007). The computational provenance can be described through the Prov-O XML-based standard (Lebo et al., 2013). The OAI-PMH standard (Lagoze and Van de Sompel, 2001) is commonly used to describe metadata. The standards defined by the Open Geospatial Consortium (OGC, 2019) are used for geospatial data description and access, and the Statistical Data and Metadata eXchange standard (SDMX, 2004) is used for time series search, retrieval, and inspection. The economic sustainability of Open Science platforms is usually managed by setting up fully automatic service deployment systems and by relying on multiple machine providers (Assante et al., 2016; Coro et al., 2015a).

One of the main advantages for marine scientists when using these platforms is the possibility to execute their processes much faster without developing specific code for the e-I computational platform. This goal is crucial also to run scientific experiments that would be computationally impractical otherwise (Coro et al., 2015b; Froese et al., 2014). Another advantage is the possibility to work collaboratively in a multi-disciplinary team made up of scientists residing very far from each other and having complementary competences. To this aim, Open Science e-Is usually offer virtual laboratories that provide collaboration tools and computational resources dedicated to a research focus group (Assante et al., 2016). For example, within a virtual laboratory, marine biologists can work together with AI experts and exchange data and experimental parameters, while mutually revising experiments and including biologically-oriented knowledge into AI models (Santana et al., 2006; Stockwell et al., 2006). In the next sections, we will show examples of experiments supporting Blue Growth, where multi-disciplinary teams have shared their competences through e-Is to build novel solutions.

Although the will to contribute to Open Science should naturally spur scientists to spend the effort required to share pre-processed data under recognised standards and to update these data continuously, the reality is that Open Science is still not practised spontaneously. This scenario is an open issue for OS-oriented e-Is. Some e-Is have introduced tools to help and accelerate e-I users to (i) standardise data, (ii) automatically import data from heterogeneous repositories, and (iii) make models available as standardised services (Assante et al., 2019a; Candela et al., 2015; Coro et al., 2018c). Other e-Is have proposed academic index calculation promoting open-access research (Thelwall and Kousha, 2015). However, the European Commission has a strategic implementation plan to foster Open Science practice (EOSC, 2019). Also, it has funded European projects to accomplish data/model sharing and standardisation within very large consortia (Blue-Cloud, 2019).

3. AI Applications for blue growth

3.1. Ecological niche modelling

Ecological niche modelling (ENM) refers to a set of computer-based approaches that predict the actual or potential distribution of a species across a geographic area and time. ENM is mostly based on environmental data and aims at identifying the abiotic and biotic conditions that favour a species' subsistence. ENM has been used in conservational biology and ecology, where approaches are categorised as *correlative* or *mechanistic* (Pearson, 2007). While correlative approaches model a species' niche as a function of the environmental parameters, mechanistic approaches use explicit information on the species' physiology. Correlative approaches have used AI techniques to model niche functions, in particular to (i) identify the most relevant environmental data to a species' ecological niche, (ii) simulate niche functions, and (iii) project these functions onto geographical spaces.

Identifying the environmental features correlated to a species' niche requires combining occurrence locations records (i.e. the *presence points* where the species was observed) - and possibly *absence* locations (where the species cannot subsist) - with the environmental parameters of those locations. Before simulating a niche function, the environmental features should be pre-processed and combined to maximise the correlation with the species' preferences. To this aim, processing techniques like Principal Component Analysis and machine learning (e.g. Maximum Entropy and cluster analysis) are commonly used (Coro et al., 2015b; Phillips and Dudík, 2008). Machine learning models are normally used to simulate a niche function, e.g. Generalised Linear Models, Artificial Neural Networks, Maximum Entropy, Support Vector Machines etc. (Coro et al., 2013a; Olden et al., 2008; Pearson, 2007). These models *learn* and simulate the correlation between presence (and sometimes absence) points and environmental parameters as a function with range [0,1]. This function is finally projected onto a geographical area at a specific spatial resolution by applying the learned function to the environmental parameters of that area.

In the context of Blue Growth, AI-based ENM (AI-ENM) approaches have been used in multi-disciplinary EU projects. For example, they have been used to detect the presence of rare species in a particular area as indicators of areas to be protected from fisheries and exploitation (Coro et al., 2013a; Owens et al., 2012). Further, AI-ENM has been used to assess species commonness and absence in marine areas as indicators of biodiversity change in time (Coro et al., 2015c; Pearman and Weber, 2007; Webb et al., 2012). In these cases, the use of AI, and in particular of pattern recognition techniques, was necessary to combine the expertise of conservation biologists with that of data scientists and AI modellers. Indeed, OS-oriented infrastructures have played an essential role in these experiments to (i) foster multi-disciplinary collaboration, (ii) produce results while publishing models as Web services, and (iii) disseminate results to decision-makers (Coro et al., 2016b; Vanden Berghe et al., 2010). AI-based ENM through OS-oriented e-Is is applicable as long as the e-I makes occurrence records - and the environmental parameters associated with these records - accessible to the models. Currently, the produced species distribution maps are of great support to taxonomic studies and are usually associated with species' descriptions in most large taxonomic collections (Froese, 1990).

3.2. Vessel data analysis and fishing activity forecasting

Vessel Monitoring Systems (VMSs) are either physical or virtual electronic systems that enhance maritime security and fishing activity monitoring. Tracking systems, based on information transmitted by on-board GPS (Vessel Transmitted Information, VTI), integrate different transmission technologies that are eventually processed by a computer system (Chang, 2003). These data have Big Data characteristics and require distributed storage systems to be managed and AI modelling for extracting valuable information. One common application based on VMSs is the monitoring of unreported, unregulated, and illegal (UUI) fishing activity (Davis, 2000). For this task, computer systems combine documents with time series information through AI models (e.g. Bayesian models and Artificial Neural Networks) to estimate the type of fishing activity performed by a group of vessels in a particular area and period (Joo et al., 2011; Walker and Bez, 2010). VTI has been used in AI models also to estimate the behavioural response of birds and marine species to commercial fisheries activity (Votier et al., 2010). Other applications have used AI to enhance the precision and reliability of VTI time series, which usually contain gaps and biases (Palmer and Wigley, 2009). Also, other models have combined AI-ENM with VTI to estimate locations with high fishing pressure (Campanis, 2008; Coro et al., 2013a). These methods help the Blue Growth strategy to regulate illegal activity and monitor the exploitation of marine resources. For example, tuna fisheries in the Pacific and Indian oceans produce several times the incomes of all other fisheries combined and involve frequent UUI fishing activity (Lymer et al., 2008). Thus, forecasting VTI time series is helpful to predict future exploitation rates and locations as well as illegal and piracy activity (Hollowed et al., 2011). Methods used in this context include Artificial Neural Networks combined with signal processing techniques (e.g. Fourier Analysis, Singular Spectrum Analysis), which decompose the time series of effort, longitudes, and latitudes into components that represent the essential structure of the time series and project them in the future (Coro et al., 2016a). Open Science technology has been used in these experiments also to gather and share data from VTI repositories (Coro et al., 2013b, Lee et al., 2010). AI-based VTI processing is being included in decision processes and management strategies. Large companies - like Google - are proposing open-access AI-based vessel monitoring systems, through online platforms (Merten et al., 2016). These platforms also promote VTI re-use in AI models to produce indicators for decision-makers. For example, monitoring authorities have used them to evaluate the success of the application of management strategies (Witkin et al., 2016).

Based on time series of annual catch statistics (at land or in the seas), AI methods are more and more used in fisheries to assess a stocks' status, e.g. to estimate the biomass still available for fishing and the yearly sustainable catch. These *stock assessment* techniques are becoming more and more crucial to safeguard the availability of food resources. One parameter estimated by the models is the Maximum Sustainable Yield (MSY), i.e. the maximum catch that can be taken from a commercial species in a specific area (i.e. a stock), so that catch corresponds to repopulation in the next year. Most stock assessment models are statistical models that require a large amount of prior information (Froese et al., 2017; Shepherd and Pope, 2002). However, data-poor models are emerging that rely just upon time series of catch, biomass, and fishing effort, and estimate MSY with comparable accuracy with respect to data-rich models (Froese et al., 2018a). These data-poor models increase the number of people and countries who can independently assess the status of their resources (Froese et al., 2018b). These models usually rely on population dynamics formulations and estimate *life-history* traits of the stock, e.g. the intrinsic rate of growth and the carrying capacity. They are generally computationally intensive, and high-performance models use exhaustive techniques like Markov Chain Monte Carlo methods (Cope, 2013; Froese et al., 2017; 2018a). Some of these models are available through Open Science platforms and support courses and scientists' assessments (Coro et al., 2015a; i-Marine, 2015). Stock assessment models are already considered in decision-making processes, and their results have been debated in political agendas (Oceana, 2017). Indeed, the suggestions deriving from scientific models are being actually considered in management strategies in Europe, with a decreasing compliance gradient from North to South (Froese et al., 2018b).

3.3. Climate change and effects on species' distribution

Climate change is currently one of the most discussed topics in public and scientific agendas. Ecological changes have potentially disruptive effects on many aspects of human life (Boon et al., 2011; Fritze et al., 2008). Climate change also influences species' habitat distributions, especially if coupled with anthropogenic pressure. This combination has already shown adverse effects on species' abundance and biodiversity at the global level (Cheung et al., 2009; SCBD, 2009). Climate change has severe consequences on many ecosystem services that are integral for human well-being, e.g. food, water, leisure, and recreation provisioning (Harley et al., 2006), and are taken into account by the Blue Growth strategy. ENMs have been used to measure the potential impact of climate change on species' habitat distribution. These approaches use forecasts of environmental parameters under different greenhouse gases emission scenarios (Coro et al., 2016c; Fernandes et al., 2013). However, reliable estimates require using complex models and massive computational resources. Thus, they are mostly limited to the near future and to a regional scale. High-quality forecasts of marine-related environmental parameters, combine information of air and ocean currents dynamics with socio-economic factors (under different greenhouse gases emission scenarios). They require high-performance computing systems even to produce regional-scale forecasts (Artale et al., 2010; Gualdi et al., 2013). However, the products of these models are Big Data that can be analysed with OS-compliant technologies and can be reused in ENMs and stock assessment models to analyse trends of ecological change due to climate change, and assess impact on habitat shift, fisheries, and food provisioning (Coro et. al., 2016b). For example, time series analysis and pattern recognition have been applied to environmental parameters forecasts focussing on different global marine areas and oceans (Coro et. al., 2018a). This application has revealed notable properties, for example that (i) the Mediterranean Sea has potentially a standalone "response" to climate change with respect to other areas, (ii) the trends of the Poles are the most representative of global change, and (iii) the current trends are generally negative and alarming in most oceans.

This information is crucial from the Blue Growth strategy point of view since the retreat of polar ice and the deterioration of tropical ecosystems - due to acidification - influence food availability, organism growth, and reproduction. Most of these considerations and reports have been taken into account by the Paris Climate Agreement in 2016.

Pattern recognition techniques have also been applied to extensive collections of ENM models' projections to extract global patterns of habitat shift and biodiversity change, and to assess the impact of climate change on fisheries (Otto et al., 2016; Uhe et al., 2016). OS-compliant technology has demonstrated effectiveness at combining different AI-ENM models with fisheries information while retrieving/harmonising parameters forecasts from extensive collections (Coro et al., 2018b). These models coarsely approximate very complex systems, but the extracted change rate indicators have a significant overlap with human expert assessments. For example, AI models have correctly predicted the increase of species richness of small-body fishes in the North Sea (Perry et al., 2005), a general shift of their latitudinal and depth ranges (Dulvy et al., 2008), and the probable replacement of calcareous corals by non-calcareous algae in high CO2 regions (Bellwood et al., 2004).

3.4. Alien and invasive species

Alien invasive species (AIS) are animals and plants that arrive *somehow* in a non-native natural environment and have severe consequences on the habitats their invade.

These species can settle in the new environment, increase in number, spread in the invaded area and threaten native species and countries' economy (Galil, 2008). High growth and reproduction rate, lack of natural predators, ability to exploit food resources, and tolerance to a wide range of environmental conditions are shared characteristics of the most dangerous species (Yaglioglu et al., 2011). Recent studies indicate that more than 5% of the marine species in the Mediterranean Sea are non-native (alien) and 13.5% are invasive (Galil, 2009; Golani, 2010; Zenetos et al., 2015). Supervising organisations spend considerable effort to monitor and predict AIS spread and avoid economic and ecological disasters. In the Mediterranean Sea, AIS especially enter through the Suez Canal, and their number is continuously increasing (Golani, 2010; Nader et al., 2012). For example, the silver-cheeked toad-fish *Lagocephalus sceleratus* (Gmelin, 1789) has begun the invasion around 2003 and has rapidly invaded all the eastern Mediterranean basin (Akyol et al., 2005; Peristeraki et al., 2006). This pufferfish is extraordinarily poisonous and lethal to humans if eaten, due to a high level of Tetrodotoxin (TTX) contained mainly in the liver and excreted from the skin (Nader et al., 2012; Yaglioglu et al., 2011). It is favoured by climate change because it prefers medium-high water temperature, which also increases its TTX production.

In Turkey, this species has caused a 5 million euros monetary loss between 2013 and 2014 and currently represents 4% of the weight of total artisanal catches (Nader et al., 2012). Further, since 2003 it has caused several episodes of death and severe illness after consumption since fishermen and ordinary people usually cannot identify it (Bentur et al., 2008; Kheifets et al., 2012). According to Blue Growth, it is crucial to detect, prevent, and eradicate this type of AIS. Selective fishing has been proposed as a solution but has not been effective. However, AI models have been used to forecast invasion patterns and thus to guide the development of preventive and corrective actions (Coro et al., 2018a; Pouteau et al., 2011; Sadeghi et al., 2012). In particular, AI-ENMs have been used to evaluate the differences between an AIS native habitat and the invaded region and have used climate forecasts to predict how climate change may facilitate the invasion (Sax et al., 2007; Thuiller et al., 2005). These AI-ENMs use machine learning and statistical models, e.g. Genetic Algorithms, Maximum Entropy, Artificial Neural Networks, and Support Vector Machines (Kulhanek and Bodur, 2011; Peterson, 2003; Sadeghi et al., 2012; West et al., 2016).

Also, they have been combined with economy-related information to assess the potential economic impact of the invasion (Coro et al., 2018b; Ünal et al., 2017). In this context, OS-oriented approaches have demonstrated efficiency in terms of reducing the time for integrating ENMs with economy-related data and effectiveness in building ensemble models (Assante et al., 2019b). Thanks to the reproducible and transparent methodologies implemented, the results have been included in international strategy documents and decision-makers' agendas (FAO, 2017).

3.5. Cross-domain Reuse of Models and Approaches

Open-Science AI models and approaches developed for ecological and climate modelling can be re-used for other scopes of the Blue Growth strategy. For example, they can be used in underwater habitats restoring and for sustainable tourism, through the implementation of tools for scuba-divers (Lucrezi et al., 2018; Palma et al., 2017). These applications can benefit from OS products such as GIS services, ENM species maps, AI-assisted applications, and collaboration tools. For example, OS services have been used to endow scuba-divers with ENM GIS maps in an explored area, and with processes for underwater photo sharing that rebuild an explored area as a 3D model through photogrammetry (Coro et al., 2019a; Palma et al., 2018a, 2018b). Additionally, Web services have been built to offer Virtual Reality tools to explore these reconstructions (Calvi et al., 2017; Coro et al., 2019). These OS services address both scientists who want to monitor the status of an ecosystem (e.g. a coral reef) in time, and tourists who want to plan the exploration of an underwater area and may use the 3D reconstructions to plan further visits. Thus, through OS-compliant platforms, it is possible to re-use models initially conceived for a specific scientific task on a new Blue Growth topic, such as citizen science, which may create financial gain and social benefits.

The Food and Agriculture Organisation of the United Nations (FAO) has sponsored Open Science platforms, and AI-enabled Virtual Research Environments, to support social analyses in marine science (FAO, 2020a, 2020b). In particular, these environments offer solutions to (i) visualise, analyse, and report essential ecological features within marine protected areas, (ii) study human-activity impact on these areas, (iii) monitor aquaculture activity through the automatic processing of Earth observations, (iv) understand aquaculture impact on protected areas, and (v) support maritime spatial planning. Generally, techniques conceived to process Big Data in social sciences have also been proposed to manage Blue Growth topics (Aronova et al., 2010; Palma et al., 2019). The idea behind these approaches is that the management of protected areas can benefit from the complementation of ecological information with social-science analyses regarding environmental economics, tourism, ecosystem-generated services, and the socio-cultural value of biodiversity (Bennett et al., 2017; Gruby et al., 2016; Mascia et al., 2003). Overall, integrating biodiversity conservation with human dimensions is an integral part of the concept of Digital Earth (Gore, 1998; Guo, 2017; Guo et al., 2014), i.e. a virtual representation of the globe that should allow accessing a vast amount of scientific and cultural information, and help people understand the Earth and human activities.

AI models for marine science have also been re-used through OS platforms in entirely different domains. For example, AI approaches assessing marine species commonness have been re-applied as-they-were to rivers restoration, e.g. to identify regions where groundwater mixes with a river's bed (*hyporheic* zone) (Magliozzi et al., 2019). Likewise, Maximum Entropy models for ENM have been re-applied to identify the most suitable sites for a geothermal energy plant installation by treating planting suitability as a species-presence function of environmental parameters (Coro and Trumpy, 2019). These applications were possible thanks to the re-usability guaranteed by the standardisation of data and processes provided by an OS platform, which allows re-applying the models to new data.

4. Conclusions

In this paper, we have presented technology and methods that support the Blue Growth strategy with economic, ecological, and sustainability assets. Artificial Intelligence, combined with Open Science-oriented platforms, can convince decision-makers to include results in their management strategies, thanks to the transparency of the supported methodologies. Thus, a sustainable management of marine and coastal ecosystems can be addressed by combining complementary competencies and approaches through collaborative online tools, and then by openly offering reproducible results to decision-makers. Important features brought by OS-compliant platforms to this context are (i) the transparency of the methodologies through the repeatability and reproducibility of the processes, (ii) the longevity guaranteed to data and processes through platform sustainability plans, (iii) the re-usability of the hosted models across different domains, (iv) the management of Big Data complexity and size, (v) the production of new knowledge as a consequence of the creation of new methodologies.

Overall, the reported examples indicate that AI is supporting Blue Growth in several ways: (i) to simplify complex problems through the discovery of an underlying analytical function defined on the input parameters, (ii) to select important information out of a large set of parameters related to a particular phenomenon, (iii) to estimate the parameters of a function that regulates a complex system, (iv) to produce and discover new knowledge out of Big Data, and (v) to find new virtuous combinations between datasets. One possible drawback is that most AI models do not reveal the rationale behind their outputs (e.g. Artificial Neural Networks, Long Short-Term Memory models, etc.), which often prevents explaining the mechanisms behind the modelled phenomenon. Further, the results are possibly driven by the prior knowledge of the modeller, who pre-selects particular input parameters or introduces *prior* information in variable initialisation (e.g. in Bayesian models). These shortcomings, together with the difficulty to make Open Science practised in every experiment, are hindrances also for Blue Growth development and will be a focus of future research in these sectors.

The future of OS-platforms will likely see AI also used as an e-Infrastructure *meta-model* to improve the cooperation between users. Indeed, an AI model working over an OS-platform can analyse the practices of the platform's users to inform other users about the possible cross-domain applications of their methods and data. This approach would create new collaborative laboratories and focus groups. New knowledge would come out not only from the data owned by the single scientists but also from their practice that – when repeatable and standardised – may be re-used for novel applications. This combination of AI and OS could also help to combine and harmonise the many topics addressed by the Blue Growth strategy itself.

References

Akyol O., Ünal V., Ceyhan T., Bilecenoglu M., (2005), First confirmed record of *Lagocephalus sceleratus* (Gmelin, 1789) in the Mediterranean Sea, *Journal of Fish Biology*, **66**, 1183-1186.

Andronico G., Ardizzone V., Barbera R., (2011), e-infrastructures for e-science: a global view, *Journal of Grid Computing*, **9**, 155-184.

Aronova E., Baker K.S., Oreskes N., (2010), Big science and big data in biology: from the international geophysical year through the international biological program to the Long Term Ecological Research (LTER) Network, 1957-Present, *Historical Studies in The Natural Sciences*, **40**, 183-224.

Artale V., Calmanti S., Carillo A., Dell'Aquila A., Herrmann M., Pisacane G., Bi X., (2010), An atmosphere–ocean regional climate model for the Mediterranean area: assessment of a present climate simulation, *Climate Dynamics*, **35**, 721-740.

Assante M., Candela L., Castelli D., Cirillo R., Coro G., Frosini L., Pagano P., Panichi G., Sinibaldi F., (2019a), The gCube system: delivering virtual research environments as-a-service, *Future Generation Computer Systems*, **95**, 445-453.

Assante M., Candela L., Castelli D., Cirillo R., Coro G., Frosini L., Sinibaldi F., (2019b), Enacting open science by D4Science, *Future Generation Computer Systems*, **101**, 555-563.

Assante M., Candela L., Castelli D., Coro G., Lelii L., Pagano P., (2016), Virtual research environments as-a-Service by gCube, *PeerJ Preprints*, **4**, e2511v1.

Attiya H., Welch J., (2004), *Distributed Computing: Fundamentals, Simulations, and Advanced Topics*, vol. 19, 1st Edition, John Wiley and Sons (Eds.), Hoboken New Jersey.

Bellwood D.R., Hughes T.P., Folke C., Nyström M., (2004), Confronting the coral reef crisis, *Nature*, **429**, 827.

Bennett N.J., Roth R., Klain S.C., Chan K., Christie P., Clark D.A., Greenberg A., (2017), Conservation social science: Understanding and integrating human dimensions to improve conservation, *Biological Conservation*, **205**, 93-108.

Bentur Y., Ashkar J., Lurie Y., Levy Y., Azzam Z.S., Litmanovich M., Golik M., Gurevych B., Golani D., Eisenman A., (2008), Lessepsian migration and tetrodotoxin poisoning due to lagocephalus sceleratus in the eastern Mediterranean, *Toxicon*, **52**, 964-968.

Blue-Cloud, (2019), Blue-Cloud: Piloting innovative services for Marine Research & the Blue Economy, EU Commission Web site, On line at: https://cordis.europa.eu/project/id/862409.

Boon H., Brown L., Clark B., Pagliano P., Tsey K., Usher K., (2011), Schools, climate change and health promotion: a vital alliance, *Health Promotion Journal of Australia*, **22**, 68-71.

Calvi L., Santos C.P., Relouw J., Endrovski B., Rothwell C., Sarà A., Pantaleo U., (2017), *A VR Game to Teach Underwater Sustainability While Diving*, Proc. 7th IFIP Conf. on Sustainable Internet and ICT for Sustainability, Funchal, Portugal, 1-4.

Campanis G., (2008), Advancements in VMS data analyses, NAFO Annual Report 2008, On line at: https://www.nafo.int/Library/General-Publications/Annual-Report/annual-report-2008.

Candela L., Castelli D., Coro G., Lelii L., Mangiacrapa F., Marioli V., Pagano P., (2015), An infrastructure-oriented approach for supporting biodiversity research, *Ecological Informatics*, **26**, 162-172.

Candela L., Castelli D., Coro G., Pagano P., Sinibaldi F., (2016), Species distribution modeling in the cloud, *Concurrency and Computation: Practice and Experience*, **28**, 1056-1079.

Chang S.J., (2003), *Vessel Identification and Monitoring Systems for Maritime Security*, IEEE Proceedings - 37th Annual 2003 International Carnahan Conference on Security Technology, 14-16 October, Taipei, Taiwan, 66-70, http://doi.org/10.1109/CCST.2003.1297537.

Cheung W.W., Lam V.W., Sarmiento J.L., Kearney K., Watson R., Pauly D., (2009), Projecting global marine biodiversity impacts under climate change scenarios, *Fish and Fisheries*, **10**, 235-251.

Cope J.M., (2013), Implementing a statistical catch-at-age model (Stock Synthesis) as a tool for deriving overfishing limits in data-limited situations, *Fisheries Research*, **142**, 3-14.

Coro G., Pagano P., Ellenbroek A., (2013a), Combining simulated expert knowledge with neural networks to produce ecological niche models for Latimeria chalumnae, *Ecological Modelling*, **268**, 55-63.

Coro G., Fortunati L., Pagano P., (2013b), *Deriving fishing monthly effort and caught species from vessel trajectories*, Proc. 2013 MTS/IEEE OCEANS, 10-14 June, Bergen, Norway, 1-5, http://doi.org/ 10.1109/OCEANS-Bergen.2013.6607976

Coro G., Candela L., Pagano P., Italiano A., Liccardo L., (2015a), Parallelizing the execution of native data mining algorithms for computational biology, *Concurrency Computation: Practice and Experience*, **27**, 4630-4644.

Coro G., Magliozzi C., Ellenbroek A., Pagano P., (2015b), Improving data quality to build a robust distribution model for Architeuthis dux, *Ecological Modelling*, **305**, 29-39.

Coro G., Webb T.J., Appeltans W., Bailly N., Cattrijsse A., Pagano P., (2015c), Classifying degrees of species commonness: North Sea fish as a case study, *Ecological Modelling*, **312**, 272-280.

Coro G., Magliozzi C., Berghe E.V., Bailly N., Ellenbroek A., Pagano P., (2016a), Estimating absence locations of marine species from data of scientific surveys in OBIS, *Ecological Modelling*, **323**, 61-76.

Coro G., Large S., Magliozzi C., Pagano P., (2016b), Analysing and forecasting fisheries time series: purse seine in Indian Ocean as a case study, *ICES Journal of Marine Science*, **73**, 2552-2571.

Coro G., Magliozzi C., Ellenbroek A., Kaschner K., Pagano P., (2016c), Automatic classification of climate change effects on marine species distributions in 2050 using the AquaMaps model, *Environmental and Ecological Statistics*, **23**, 155-180.

Coro G., Panichi G., Scarponi P., Pagano P., (2017), Cloud computing in a distributed e-infrastructure using the web processing service standard, *Concurrency and Computation: Practice and Experience*, **29**, e4219.

Coro G., Pagano P., Ellenbroek A., (2018a), Detecting patterns of climate change in long-term forecasts of marine environmental parameters, *International Journal of Digital Earth*, **13**, 1-19.

Coro G., Vilas L.G., Magliozzi C., Ellenbroek A., Scarponi P., Pagano P., (2018b), Forecasting the ongoing invasion of Lagocephalus sceleratus in the Mediterranean Sea, *Ecological Modelling*, **371**, 37-49.

Coro G., Scarponi P., Pagano P., (2018c), Enhancing ARGO floats data re-usability, *Bollettino di Geofisica Teorica e Applicata*, **53**, 53-55.

Coro G., Palma M., Ellenbroek A., Panichi G., Nair T., Pagano P., (2019), Reconstructing 3D virtual environments within a collaborative e-infrastructure, *Concurrency and Computation: Practice and Experience*, **31**, e5028.

Coro G., Trumpy E., (2019), Predicting geographical suitability of geothermal power plants, *Journal of Cleaner Production*, **266**, 121874.

Davis J.M., (2000), Monitoring control and surveillance and vessel monitoring system requirements to combat IUU fishing, FAO Web site, On line at: http://www.fao.org/docrep/005/Y3274E/y3274e0g.htm.

De Roure D., Goble C., Bhagat J., Cruickshank D., Goderis A., Michaelides D., Newman D., (2008), *myExperiment: Defining the Social Virtual Research Environment*, Proc. IEEE Fourth Int. Conf. on eScience, Indianapolis, USA, 182-189, http://doi.org/10.1109/eScience.2008.86

Dulvy N.K., Rogers S.I., Jennings S., Stelzenmüller V., Dye S.R., Skjoldal H.R., (2008), Climate change and deepening of the North Sea fish assemblage: a biotic indicator of warming seas, *Journal of Applied Ecology*, **45**, 1029-1039.

EOSC, (2019), European Open Science Cloud strategic implementation plan, EU Commission Web site, On line at: https://ec.europa.eu/research/openscience/index.cfm?pg=open-science-cloud.

EU Commission, (2016), European Commission, Open science definition, EU Commission Web site, On line at: https://ec.europa.eu/programmes/horizon2020/en/h2020-section/open-science-open-access.

EU Commission, (2019), European Commission, Blue Growth definition, EU Commission Web site, On line at: https://ec.europa.eu/maritimeaffairs/policy/blue_growth_en.

FAO, (2017), Report of the Expert Meeting on Climate Change Implications for Mediterranean and Black Sea Fisheries, FAO Web site, On line at: http://www.fao.org/family-farming/detail/en/c/1142401/.

FAO, (2020a), The Protected Areas Impact Maps Virtual Research Environment, i-Marine Gateway, On line at: https://i-marine.d4science.org/web/protectedareaimpactmaps.

FAO, (2020b), The Aquaculture Atlas Generation Virtual Research Environment, i-Marine Gateway, On line at: https://i-marine.d4science.org/web/aquacultureatlasgeneration.

Fernandes J.A., Cheung W.W., Jennings S., Butenschön M., de Mora L., Frölicher T.L., Grant A., (2013), Modelling the effects of climate change on the distribution and production of marine fishes: accounting for trophic interactions in a dynamic bioclimate envelope model, *Global Change Biology*, **19**, 2596-2607.

Fritze J.G., Blashki G.A., Burke S., Wiseman J., (2008), Hope, despair and transformation: Climate change and the promotion of mental health and wellbeing, *International Journal of Mental Health Systems*, **2**, 13.

Froese R., (1990), FISHBASE: an information system to support fisheries and aquaculture research, *Fishbyte*, ***8***, 21-24.

Froese R., Thorson J.T., Reyes Jr.R.B., (2014), A Bayesian approach for estimating length-weight relationships in fishes (Acknowledgments), *Journal of Applied Ichthyology*, **30**, 78-85.

Froese R., Demirel N., Coro G., Kleisner K.M., Winker H., (2017), Estimating fisheries reference points from catch and resilience, *Fish and Fisheries*, **18**, 506-526.

Froese R., Winker H., Coro G., Demirel N., Tsikliras A.C., Dimarchopoulou D., Scarcella G., Probst W.N., Dureuil M., Pauly D., (2018a), A new approach for estimating stock status from length frequency data, *ICES Journal of Marine Science*, **75**, 2004-2015.

Froese R., Winker H., Coro G., Demirel N., Tsikliras A.C., Dimarchopoulou D., Scarcella G., Quaas M., Matz-Lück N., (2018b), Status and rebuilding of European fisheries, *Marine Policy*, **93**, 159-170.

Galil B.S., (2008), Alien species in the Mediterranean Sea which, when, where, why?, *Hydrobiologia*, **606**, 105-116.

Galil B.S., (2009), Taking stock: inventory of alien species in the Mediterranean Sea, *Biological Invasions*, **11**, 359-372.

Golani D., (2010), Colonization of the Mediterranean by Red Sea fishes via the Suez Canal-Lessepsian migration, *Fish Invasions of the Mediterranean Sea: Change and Renewal*, **1**, 145-188.

Gore A., (1998), The Digital Earth: Understanding our planet in the 21st century, *Australian surveyor*, **43**, 89-91.

Gruby R.L., Gray N.J., Campbell L.M., Acton L., (2016), Toward a social science research agenda for large marine protected areas, *Conservation Letters*, **9**, 153-163.

Gualdi S., Somot S., Li L., Artale V., Adani M., Bellucci A., Déqué M., (2013), The CIRCE simulations: regional climate change projections with realistic representation of the Mediterranean Sea, *Bulletin of the American Meteorological Society*, **94**, 65-81.

Guo H., Wang L., Chen F., Liang D., (2014), Scientific big data and digital earth, *Chinese science bulletin*, **59**, 5066-5073.

Guo H., (2017), Big Earth data: A new frontier in Earth and information sciences, *Big Earth Data*, **1**, 4-20.

Harley C.D., Randall Hughes A., Hultgren K.M., Miner B.G., Sorte C.J., Thornber C.S., Williams S.L., (2006), The impacts of climate change in coastal marine systems, *Ecology Letters*, **9**, 228-241.

Hey A.J.G., Tansley S., Tolle K.M., (2009), *The Fourth Paradigm: Data-Intensive Scientific Discovery*, vol. I., 1st Edition, A.J. Hey (Ed.), Redmond, Washington, United States.

Hollowed A.B., Barange M., Ito S.I., Kim S., Loeng H., Peck M.A., (2011), Effects of climate change on fish and fisheries: forecasting impacts, assessing ecosystem responses, and evaluating management strategies, *ICES*

Journal of Marine Science, **68**, 984-985.
Hunter A.A., Macgregor A.B., Szabo T.O., Wellington C.A., Bellgard M.I., (2012), Yabi: An online research environment for grid, high performance and cloud computing, *Biology and Medicine*, **7**, 1, http://doi.org/10.1186/1751-0473-7-1.
i-Marine, (2015), The Stock Assessment Open Science Virtual Research Environment, i-Marine Gateway, On line at: https://i-marine.d4science.org/web/stockassessment.
Jeschke S., Brecher C., Meisen T., Özdemir D., Eschert T., (2017), *Industrial Internet of Things and Cyber Manufacturing Systems*, Industrial Internet of Things, vol. I, Springer, Cham, Switzerland, 3-19.
Joo R., Bertrand S., Chaigneau A., Niquen M., (2011), Optimization of an artificial neural network for identifying fishing set positions from VMS data: an example from the Peruvian anchovy purse seine fishery, *Ecological Modelling*, **222**, 1048-1059.
Kheifets J., Rozhavsky B., Girsh Solomonovich Z., Marianna R., Sorokský A., (2012), Severe tetrodotoxin poisoning after consumption of Lagocephalus sceleratus (pufferfish, fugu) fished in Mediterranean Sea, treated with cholinesterase inhibitor, *Case Reports in Critical Care,* **2012**, 782507.
Kluyver T., Ragan-Kelley B., Perez F., Granger B., Bussonnier M., Frederic J., Kelley K., Hamrick J., Grout J., Corlay S., Ivanov P., Avila D., Abdalla S., Willing C., (2016), *Jupyter Notebooks - A Publishing Format for Reproducible Computational Workflows*, Proc. 20th Int. Conf. on Electronic Publishing, Gottingen, Germany, 87-90, http://doi:10.3233/978-1-61499-649-1-87
Kramer B., Bosman J., (2016), Innovations in scholarly communication-global survey on research tool usage, *F1000Research*, **5**, 692.
Kulhanek S.A., Leung B., Ricciardi A., (2011), Using ecological niche models to predict the abundance and impact of invasive species: application to the common carp, *Ecological Applications*, **21**, 203-213.
Lagoze C., Van de Sompel H., (2001), *The Open Archives Initiative: Building A Low-Barrier Interoperability Framework*, Proc. 1st ACM/IEEE-CS joint Conf. on Digital libraries, New York, United States, 54-62.
Lebo T., Sahoo S., McGuinness D., (2013), Prov-O: the Prov ontology, W3C Recommendations' Web site, On line at: https://www.w3.org/TR/prov-o/.
Lee J., South A.B., Jennings S., (2010), Developing reliable, repeatable, and accessible methods to provide high-resolution estimates of fishing-effort distributions from vessel monitoring system (VMS) data, *ICES Journal of Marine Science*, **67**, 1260-1271.
Leitao P., Karnouskos S., Ribeiro L., Lee J., Strasser T., Colombo A.W., (2016), Smart agents in industrial cyber–physical systems, *Proceedings of the IEEE*, **104**, 1086-1101.
Liew C.S., Atkinson M.P., Galea M., Ang T.F., Martin P., Hemert J.I.V., (2016), Scientific workflows: moving across paradigms, *ACM Computing Surveys (CSUR)*, **49**, 1-39.
Lucrezi S., Milanese M., Palma M., Cerrano, C., (2018), Stirring the strategic direction of scuba diving marine Citizen Science: A survey of active and potential participants, *PloS One*, **13**, e0202484.
Lymer D., Funge-Smith S., Clausen J., Miao W., (2008), Status and potential of fisheries and aquaculture in Asia and the Pacific 2008, FAO Web site, On line at: http://www.fao.org/3/i1924e/i1924e00.pdf.
Magliozzi C., Coro G., Grabowski R.C., Packman A.I., Krause S., (2019), A multiscale statistical method to identify potential areas of hyporheic exchange for river restoration planning, *Environmental Modelling and Software*, **111**, 311-323.
Manyika J., Chui M., Brown B., (2011), Big data: The next frontier for innovation, competition, and productivity, McKinsey Global Inst. Web site, On line at: https://www.mckinsey.com/business-functions/mckinsey-digital/our-insights/big-data-the-next-frontier-for-innovation.
Mascia M.B., Brosius J.P., Dobson T.A., Forbes B.C., Horowitz L., McKean M.A., Turner N.J., (2003), Conservation and the social sciences, *Conservation biology*, **17**, 649-650.
McLennan M., Kennell R., (2010), HUBzero: a platform for dissemination and collaboration in computational science and engineering, *Computing in Science and Engineering*, **12**, 48-53.
Merten W., Reyer A., Savitz J., Amos J., Woods P., Sullivan B., (2016), Global Fishing Watch: Bringing transparency to global commercial fisheries, arXiv preprint, On line at: https://arxiv.org/abs/1609.08756.
Nader M., Indary S., Boustany L., (2012), The puffer fish Lagocephalus sceleratus (Gmelin, 1789) in the eastern Mediterranean, EastMed Technical Documents, On line at: http://www.fao.org/3/a-ap967e.pdf.
Oceana, (2017), EU Policy: Subsidies, Oceana Web site, On line at: https://eu.oceana.org/en/our-work/fishing-subsidies/overview.
OGC, (2019), Open Geospatial Consortium standards, OGC document repository, On line at: https://www.opengeospatial.org/docs/as.
Olden J.D., Lawler J.J., Poff N.L., (2008), Machine learning methods without tears: a primer for ecologists, *The Quarterly Review of Biology*, **83**, 171-193.
Otto F.E., Van Oldenborgh G.J., Eden J., Stott P.A., Karoly D.J., Allen M.R., (2016), The attribution question, *Nature Climate Change*, **6**, 813.
Owens H.L., Bentley A.C., Peterson A.T., (2012), Predicting suitable environments and potential occurrences for coelacanths (Latimeria spp.), *Biodiversity and Conservation*, **21**, 577-587.
Palma M., Rivas Casado M., Pantaleo U., Cerrano C., (2017), High resolution orthomosaics of African coral reefs: A tool for wide-scale benthic monitoring, *Remote Sensing*, **9**, 705.
Palma M., Rivas Casado M., Pantaleo U., Pavoni G., Pica D., Cerrano C., (2018a), SfM-based method to assess gorgonian forests (*Paramuricea clavata* (Cnidaria, Octocorallia)), *Remote Sensing*, **10**, 1154.
Palma M., Pavoni G., Pantaleo U., Rivas Casado M., Torsani F., Pica D., Benelli F., Nair T., Ccoletti A., Dellepiane M., Callieri M., Scopigno R., Cerrano C., (2018b), *Effective SFM-Based Methods Supporting Coralligenous Benthic Community Assessment and Monitoring*, Proc. 3rd Mediterranean Symp. on the conservation of Coralligenous and other Calcareous Bio-Concretions, Antalya, Turkey, 94.
Palma M., Magliozzi C., Rivas Casado M., Pantaleo U., Fernandes J., Coro G., Cerrano C., Leinster P., (2019), Quantifying coral reef composition of recreational diving sites: a structure from motion approach at seascape scale, *Remote Sensing*, **11**, 3027.
Palmer M.C., Wigley S.E., (2009), Using positional data from vessel monitoring systems to validate the logbook-reported area fished and the stock allocation of commercial fisheries landings, *North American Journal of Fisheries Management*, **29**, 928-942.
Pearman P.B., Weber D., (2007), Common species

determine richness patterns in biodiversity indicator taxa, *Biological Conservation*, **138**, 109-119.

Pearson R.G., (2007), Species' distribution modeling for conservation educators and practitioners, *Synthesis of American Museum of Natural History*, **50**, 54-89.

Peristeraki P., Lazarakis G., Skarvelis C., Georgiadis M., Tserpes G., (2006), Additional records on the occurrence of alien fish species in the eastern Mediterranean Sea, *Mediterranean Marine Science*, **7**, 61-66.

Perry A.L., Low P.J., Ellis J.R., Reynolds J.D., (2005), Climate change and distribution shifts in marine fishes, *Science*, **308**, 1912-1915.

Peterson A.T., (2003), Predicting the geography of species invasions via ecological niche modeling, *The Quarterly Review of Biology*, **78**, 419-433.

Phillips S.J., Dudík, M., (2008), Modeling of species distributions with maxent: new extensions and a comprehensive evaluation, *Ecography*, **31**, 161–175.

Pouteau R., Meyer J.-Y., Stoll B., (2011), A SVM-based model for predicting distribution of the invasive tree Miconia calvescens in tropical rainforests, *Ecological Modelling*, **222**, 2631-2641.

Sadeghi R., Zarkami R., Sabetraftar K., Van Damme P., (2012), Use of support vector machines (SVMs) to predict distribution of an invasive water fern Azolla filiculoides (lam.) in anzali wetland, southern Caspian Sea, Iran, *Ecological Modelling*, **244**, 117-126.

Santana F.S., Fonseca R.R., Saraiva A.M., Correa P.L.P., Bravo C., De Giovanni R., (2006), *OpenModeller - An Open Framework for Ecological Niche Modeling: Analysis and Future Improvements*, Proc. Computers in Agriculture and Natural Resources, Orlando, Florida, 787, http://doi.org/10.13031/2013.21974

Sax D.F., Stachowicz J.J., Brown J.H., Bruno J.F., Dawson M.N., Gaines S.D., Grosberg R.K., Hastings A., Holt R.D., Mayfield M.M., (2007), Ecological and evolutionary insights from species invasions, *Trends in Ecology and Evolution*, **22**, 465-471.

SCBD, (2009), Secretariat of the Convention on Biological Diversity, Review of the Literature on the Links between Biodiversity and Climate Change: Impacts, Adaptation, and Mitigation, UNEP/Earthprint, On line at: https://www.cbd.int/doc/publications/cbd-ts-42-en.pdf.

Schut P., Whiteside A., (2007), OpenGIS web processing service, OGC document repository, On line at: http://www.opengeospatial.org/standards/wps.

SDMX, (2004), The SDMX standard, SDMX Web site, On line at: https://sdmx.org.

Shepherd J.G., Pope J.G., (2002), Dynamic pool models I: Interpreting the past using virtual population analysis, *Handbook of Fish Biology and Fisheries*, **2**, 127-163.

Staines H., (2018), Digital open annotation with hypothesis: Supplying the missing capability of the web, *Journal of Scholarly Publishing*, **49**, 345-365.

Steven A.D., Vanderklift M.A., Bohler-Muller N., (2019), A new narrative for the Blue Economy and Blue Carbon, *Journal of the Indian Ocean Region*, **15**, 123-128.

Stockwell D.R., Beach J.H., Stewart A., Vorontsov G., Vieglais D., Pereira R.S., (2006), The use of the GARP genetic algorithm and Internet grid computing in the Lifemapper world atlas of species biodiversity, *Ecological Modelling*, **195**, 139-145.

Thelwall M., Kousha K., (2015), Research Gate: Disseminating, communicating, and measuring Scholarship?, *Journal of the Association for information Science and technology*, **66**, 876-889.

Thuiller W., Richardson D.M., Pysek P., Midgley G.F., Hughes G.O., Rouget M., (2005), Niche-based modelling as a tool for predicting the risk of alien plant invasions at a global scale, *Global Change Biology*, **11**, 2234-2250.

Uhe P., Otto F.E.L., Haustein K., van Oldenborgh G.J., King A.D., Wallom D.C.H., Cullen H., (2016), Comparison of methods: Attributing the 2014 record European temperatures to human influences, *Geophysical Research Letters*, **43**, 8685-8693.

Ünal V., Bodur H., (2017), The socio-economic impacts of the silver-cheeked toadfish on small-scale fishers: a comparative study from the Turkish coast, *Journal of Fisheries and Aquatic Sciences*, **34**, 119-127.

Vanden Berghe E., Halpin P.P., da Silveira F.L., Stocks K., Grassle F., (2010), *Integrating Biological Data into Ocean Observing Systems: The Future Role of OBIS*, Proc. OceanObs'09: Sustained Ocean Observations and Information for Society, Venice, Italy, 1-4.

Votier S.C., Bearhop S., Witt M.J., Inger R., Thompson D., Newton J., (2010), Individual responses of seabirds to commercial fisheries revealed using GPS tracking, stable isotopes and vessel monitoring systems, *Journal of Applied Ecology*, **47**, 487-497.

Waldrop M.M., (2008), Science 2.0, *Scientific American*, **298**, 68-73.

Walker E., Bez N., (2010), A pioneer validation of a state-space model of vessel trajectories (VMS) with observers' data, *Ecological Modelling*, **221**, 2008-2017.

Webb T.J., Freckleton R.P., Gaston K.J., (2012), Characterizing abundance–occupancy relationships: there is no artefact, *Global Ecology and Biogeography*, **21**, 952-957.

West A.M., Kumar S., Brown C.S., Stohlgren T.J., Bromberg J., (2016), Field validation of an invasive species maxent model, *Ecological Informatics*, **36**, 126-134.

Witkin T., Reyer A., Savitz J., (2016), Global Fishing Watch Reveals a Fisheries Management Success in the Phoenix Islands, Oceana Reports, On line at: https://usa.oceana.org/publications/reports/global-fishing-watch-reveals-fisheries-management-success-phoenix-islands.

Yaglioglu D., Turan C., Erguden D., Gurlek M., (2011), Range expansion of silverstripe blaasop, Lagocephalus sceleratus (Gmelin, 1789), to the northeastern Mediterranean Sea, *Biharean Biologist*, **5**, 159-161.

Zenetos A., Arianoutsou M., Bazos I., Balopoulou S., Corsini-Foka M., Dimiza M., Drakopoulou P., Katsanevakis S., Kondylatos G., Koutsikos N., (2015), Elnais: A collaborative network on aquatic alien species in Hellas (Greece), *Management of Biological Invasions*, **6**, 185-196.

Environmental Engineering and Management Journal

October 2020, Vol. 19, No. 10, 1731-1740
http://www.eemj.icpm.tuiasi.ro/; hiip://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

SEPARATE COLLECTION OF MUNICIPAL SOLID WASTE AND FATE OF THE RESIDUAL UNSORTED FRACTION: A SCENARIO ANALYSIS

Sabino De Gisi[1*], Alessandra Alberotanza[1], Francesco Todaro[1], Vincenzo Campanaro[2], Michele Notarnicola[1]

[1]Department of Civil, Environmental, Land, Building Engineering and Chemistry, Polytechnic University of Bari, Via Orabona n. 4, Bari, I-70125, Italy
[2]ARPA Puglia, corso Trieste 27, Bari, I-70126, Italy

Abstract

Three scenarios for the management of Municipal Solid Waste (MSW) produced in the study area of Bari (Southern Italy) were defined and evaluated in terms of separately collected material and fate of the residual fraction. The first scenario represented the bring points MSW separate collection system in the current configuration with a collection rate approx. 40%. The second scenario considered the study area in the optimal configuration, with a percentage of separate collection > 80% obtained through a door-to-door system. In both scenarios, the residual/unsorted fraction of MSW was destined for conventional mechanical-biological treatment. The third scenario was an intermediate one, with a separate collection percentage equal to the legal limit (65%); the residual/unsorted fraction of MSW was destined in a Secondary Raw Material Recovery (SRMR) plant. As described in the contribution, the SRMR plant can potentially produce Secondary Recovered Fuel (SRF), homogeneous sorted waste (PET, HDPE, PP, LDPE, ferrous materials, non-ferrous materials and mixed paper) and stabilized organic fraction to be landfilled. By means of mass balances that quantify the collected fractions, scenario 3 proved to be the most promising; the amount of potentially obtainable material was higher than that of the other two scenarios. With reference only to this aspect, the study shows how the optimal configuration for a large metropolitan area is not always the one with the highest percentage of separate collection. As the incoming waste to SRMR plant contains organic, the potentially recoverable homogeneous fractions could be of low quality, resulting in decreased economic quotation or market demand. This aspect needs to be further investigated together with a more accurate economic feasibility analysis.

Keywords: boost selection, bring points, door-to-door, mass balance, mechanical-biological treatments

Received: February, 2020; Revised final: June, 2020; Accepted: July, 2020; Published in final edited form: October, 2020

1. Introduction

Separate collection of single Municipal Solid Waste (MSW) fractions is a prerequisite to promote high quality recycling and high recycling rates in accordance with the Waste Framework Directive (EC Directive, 2018).

Collection methods vary according to the type of separate collection (SC) system adopted, which vary between two main types (Bertanza et al., 2018): (i) bring points system; (ii) door-to-door collection system.

With the bring points system, users deliver separate waste to one or more collection points, equipped with containers of various types, shapes and sizes. With the door-to-door system, users deposit the separated waste in containers or bags outside their homes. The door-to-door and the bring points system can be found under different configurations and can also be appropriately combined with each other. According to Giacetti et al. (2009), it is possible to schematize the main SC systems as follows: (i) bring points system without activation of organic SC (additional SC system); (ii) bring points system with

*Author to whom all correspondence should be addressed: e-mail: sabino.degisi@poliba.it; Phone: +39 0805963279

activation of organic SC (dry-wet bring points system); (iii) bring points system with activation of organic SC with elements of domiciliarization of some fractions such as cellulosic material, cardboard for non-domestic users; (iv) door-to-door system of dry residue and organic waste + bring points system for recyclable dry fractions (dry-wet door-to-door system); (v) high-performance door-to-door, consisting of household collection of dry residue, organic and recyclable dry fractions (full door-to-door system).

The above-mentioned SC systems show different performances in terms of SC percentage (Calabrò and Komilis, 2019). The most performing systems are full door-to-door and dry-wet door-to-door, with collection percentage values in the range 50-80%. The least performing system is the one with additional separate collection, with values in the range 5-15%; the other two bring points collection systems have performance in the range 20-35%. Intermediate values, 40-45%, can be obtained with the separate dry-wet bring points collection with domiciliarization elements (Giacetti et al., 2009).

The selection of the most appropriate SC system depends mainly on the percentage of separate collection to be achieved, a value that is generally set by the legislator, and on the quality (or purity) of the materials collected (Faraca et al., 2019). Further selection criteria are (i) the degree of citizen involvement (Babaei et al., 2015), (ii) the necessary equipment, simpler in the case of a door-to-door system, (iii) the cost of vehicles/equipment and personnel, high in the case of door-to-door system for personnel (De Feo and Malvano, 2012), (iv) user responsibility for waste disposal, higher in the case of a door-to-door system (Giacetti et al., 2009) and (v) environmental implications (Chàfer et al., 2019). In terms of quality of the waste collected, the most performing system is the high-performance door-to-door system.

The literature and case studies focusing on different aspects of SC clearly agree on the advantages of separate collection, although opinions on the optimal design of collection systems differ. First of all, there is agreement that it is essential both to extend the technical infrastructure and to inform/motivate users of collection systems (De Gisi et al., 2019). Secondly, the overall sorting of dry recyclables (and other fractions) increases when the separate collection of biodegradables is included in the door-to-door system (Giacetti et al., 2009). De Feo et al. (2019), evaluating the environmental and economic benefits of material recovery in a MSW management system, shows that the higher the level of waste separation at source, the lower were the overall impacts. On the other hand, Haupt et al. (2018) show that high recycling rates of collected waste do not always show an improvement from an environmental point of view; clearly this may place limitations on the collection phase, which does not always have to be maximised in terms of collected fractions. Hahladakis and Iacovidou (2018) observed that the recycled markets tend to require higher quality materials, as in the case of plastics, shifting the focus towards door-to-door collection systems. According to The EU report "Assessment of separate collection schemes in the 28 capitals of the EU" (EC Directive, 2015), countries that have introduced the mandatory SC of certain MSW fractions have high levels of waste recycling. However, the mechanical-biological treatment (MBT) of the residual/unsorted fraction, although it ensures the achievement of the landfill directive targets, alone does not allow the 50% recycling target to be reached. The recourse to plants that recover secondary raw material from residual/unsorted waste (labelled as Secondary Raw Material Recovery plant – SRMR) to replace traditional MBTs becomes an interesting option to explore.

From the above it is evident that the site-specific conditions of the study area, such as its tourist vocation (Mateu-Sbert et al., 2013), are fundamental. As well as it is important to reason both in terms of the SC percentage to be achieved and in terms of the final fate of the MSW residual fraction. The optimal waste management scenario is not always the one that maximizes the percentage of separate collection.

This study aims to compare, on the basis of mass balances, different scenarios of MSW management in a large metropolitan area, which vary according to: i) waste collection mode (bring point/door-to-door); ii) percentage of separate collection to be achieved; iii) final destination of the residual fraction of MSW (MBT plant/SRMR plant).

For the scope, a methodology has been defined and applied to the case study of the Municipality of Bari (Southern Italy), recently involved in the start-up of the door-to-door service. Three MSW management scenarios were defined as herein described.

2. Methodological approach

It was based on the following steps: (i) quantification and characterization, in terms of composition, of the MSW produced by the citizens of the Municipality of Bari; (ii) data acquisition on the functioning of the MSW SC services of the study area; (iii) definition of the scenarios for the management of separately collected waste; (iv) inventory analysis regarding the MBT plant and the SRMR plant; (v) implementation of the mass balance at the study area (boundaries of the system) and quantification of the waste to be destined to recovery of material, energy, landfilling and process losses, for the three management scenarios considered.

The main elements of the methodological approach were described below.

2.1. Study area and inlet waste characterization

The municipality of Bari is located in the Apulia Region, Southern Italy. It has an extension of 116 km^2 and a population in 2019 of 319,482 inhabitants. The city is characterized by a Mediterranean climate with mild winters and hot summers. The center of the city consists of the "old town" (*Città vecchia*, in Italian) and the Borgo Murattiano. These two districts are characterized by a high population density and scarce availability of areas, negative factors for the implementation of a door-to-door SC service. The old town is also an area with a strong tourist vocation. Regardng the period 2012-2016, the MSW per capita production varies in the range 1.55-1.61 kg/ab/d (ISPRA 2017).

The inlet MSW consists of compostable material (40%), recyclable (51.5%), WEEE (Waste Electrical & Electronic Equipment) and bulky items (2%), sanitary textile such as diapers (1.3%), hazardous material such as expired pharmaceuticals (0.2%) and collection residue (5%), previously reported in De Gisi et al. (2019).

The major component of the compostable waste (and in absolute terms) was the organic fraction from food waste (34%) while, for recyclables, were paper and cardboard (25%) and plastic (12%). Such a product composition was in line with that reported in ISPRA (2017) with reference to the period 2008-2017 (Table 1).

2.2. Description of the separate collection service

The MSW collection system is mixed, both bring points and door-to-door. The city of Bari was recently involved in the door-to-door SC project. The territory has been divided into eight Homogeneous Territorial Zones (HTZs) gradually interested in the start-up of the service (Fig. 1).

In the start-up area subject to door-to-door SC, performance in terms of waste collected separately was > 80% and in any case higher than the 65% limit set by the Italian legislator (LD, 2006). A description of the main elements of the separate collection system in the study area in terms of vehicles, operators and collection equipment is provided in De Gisi et al. (2019).

The HTZs still based on the pre-existing collection service include several collection points, which in turn consist of a fixed container for residual/unsorted waste, a container with wheels for multi-material and for paper, a green bell for glass, a container for used clothing and brown wheeled bins with a lock for organics.

Table 1. Characteristics of the investigated inlet MSW (from De Gisi et al., 2019)

Composition		***Unit***	***Value***	
			Our study	***Italy (ISPRA, 2017)***
Compostable	Organics	% w/w	34.0	35.7
	Cellulosic material	% w/w	6.0	-
Recyclable	Paper and cardboard	% w/w	25.0	22.6
	Plastic	% w/w	12.0	12.8
	Glass	% w/w	7.0	7.6
	Metals	% w/w	2.0	2.6
	Wood	% w/w	2.0	3.0
	Clothing and textiles	% w/w	3.5	3.6
Other	WEEE and bulky items	% w/w	2.0	0.9
	Sanitary textile (diapers)	% w/w	1.3	3.5
	Hazardous	% w/w	0.2	0.3
Residue	Unsorted fraction or mixed	% w/w	5.0	7.4

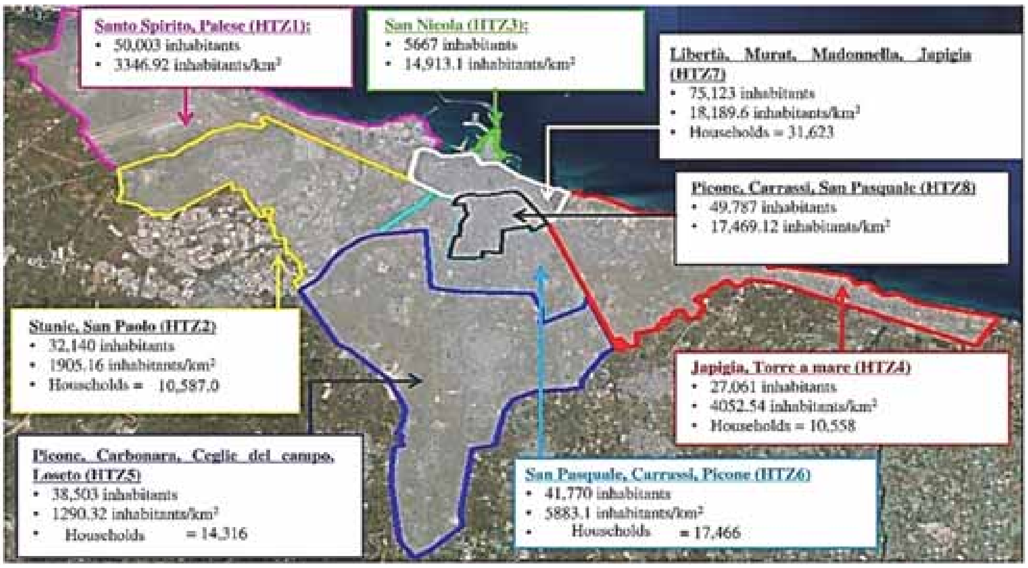


Fig. 1. Homogeneous territorial zones (HTZ) delimited within the start-up of the door-to-door MSW separate collection service for the municipality of Bari

The performance of the bring points system was much lower than 65%.

2.3. Waste management scenarios

Scenario 1 represents the MSW management system in its current configuration. It is characterized by a bring points system with collection percentage of 39.9%. The collection points consisted of a fixed container for undifferentiated residue (mixed waste), a container with wheels for multi-material, a container with wheels for paper, a green bell for glass, a container for used clothing and brown wheeled bins with a lock for organic. Once collected, the sorted dry fraction is delivered to the CONAI (Consorzio Nazionale Imballaggi) platform, the wet fraction to the composting plants and the residual/unsorted waste to MBT plants.

Scenario 2 was constructed based on the excellent performance in terms of separately collected waste achieved for the star-up zone 1 with the door-to-door system. The equipment was distributed to citizens in such a way as to collect the following fractions: (i) paper and cardboard; (ii) light multi-material (plastic, aluminium and ferrous materials packaging); (iii) glass packaging; (iv) organics; (v) dry residual fraction not differentiable; (vi) sanitary textiles (diapers, only to the users who have requested the service) (De Gisi et al., 2019). The SC percentage of 87%, achieved for the start-up zone 1, was extended to the entire municipal territory. Therefore, Scenario 2 represents a sort of *ideal scenario*, having maximized the percentage of MSW separately collected waste. As in the case of Scenario 1, the dry separated fraction is destined to the CONAI platform, the wet fraction to the composting plants and the residual/unsorted MSW to the MBT plants.

Starting from the assumption that in the areas with "lesser vocation" (it is the case of HTZ3 and HTZ7 visible in Fig. 1) bring points collection is to be preferred to a door-to-door one, a third scenario (Scenario 3) was defined. It was characterized as follows: (i) bring points system for the zones of the centre (with a greater vocation for tourism); (ii) door-to-door SC for all the remaining zones; (iii) SC percentage equal to the legal limit (65%). The bring point system of the historical centre was simplified in order to collect only the two macro-fractions dry and wet. This solution makes it easier to take into account the flow of tourists, whose behaviour is not always pro-environmental.

After collection, the separated dry fraction is delivered to the CONAI platform; the wet fraction to the composting plants. Differently from the other scenarios, the residual/unsorted waste is destined for the SRMR plant.

Table 2 shows the main characteristics of the three scenarios under investigation.

2.4. Inventory analysis for municipal solid waste treatment plants

A single-flow MBT plant and a more innovative SRMR plant are the two types of facilities considered in the study.

MBT plants are based on well-established technologies and have well known performance, although dependent on the characteristics of the incoming waste (De Gisi et al., 2018). SRMR plants implement more sophisticated technologies such as optical selectors; there are several examples of full-scale systems such as the case of the Romerike Waste Processing IKS (ROAF) plant in Oslo (Norway)(https://www.greenvisits.no/product/fully-automated-waste-sorting-facility-at-roaf/).

The two types of systems were chosen on the basis of the plants already present in the territory of the Apulia Region (of which Bari is the capital city) or being built in similar Italian contexts. The SRMR plant under study has recently been included in the MSW Management Plan of the Calabria Region (Southern Italy) and is being completed. The consulted documentation can freely be found on the website of the Calabria Region (http://old.regione.calabria.it/ambiente/index.php?option=com_content&task=view&id=898&Itemid=226). On the other hand, the MBT plant has been operating for years in the investigation territory as reported in De Gisi et al. (2018).

The SRMR plant involves the recovery of material from the residual/unsorted fraction of MSW according to the treatment scheme of Fig. 2a. After the opening phase of the bags, the inlet waste is subjected to a first screening to separate the coarse size flow. The under sieve is sent to a second separator which is aimed at intercepting the small material; following the removal of ferrous and non-ferrous metals, this material is sent to biostabilisation.

The over screen flow is sent to an optical selector with NIR (Near InfraRed) technology that will be able to intercept the polymers present in the flow indicated as "mixed plastic".

Table 2. Characteristic elements of the MSW management scenarios of the study area

Scenario	*Description*	*SC percentage (%)*
1	Bring-points SC for all the HTZs of the municipality (current scenario)	39.0[(a)]
2	Door-to-door SC for all the HTZs of the municipality	83.3
3	Door-to-door SC for suburban homogenous areas (HTZ1, HTZ2, HTZ4, HTZ5, HTZ6, HTZ8); unsorted bring-points system for HTZ in the city centre (HTZ3, HTZ7)	65.0

[(a)]: measured value referring to 2017.

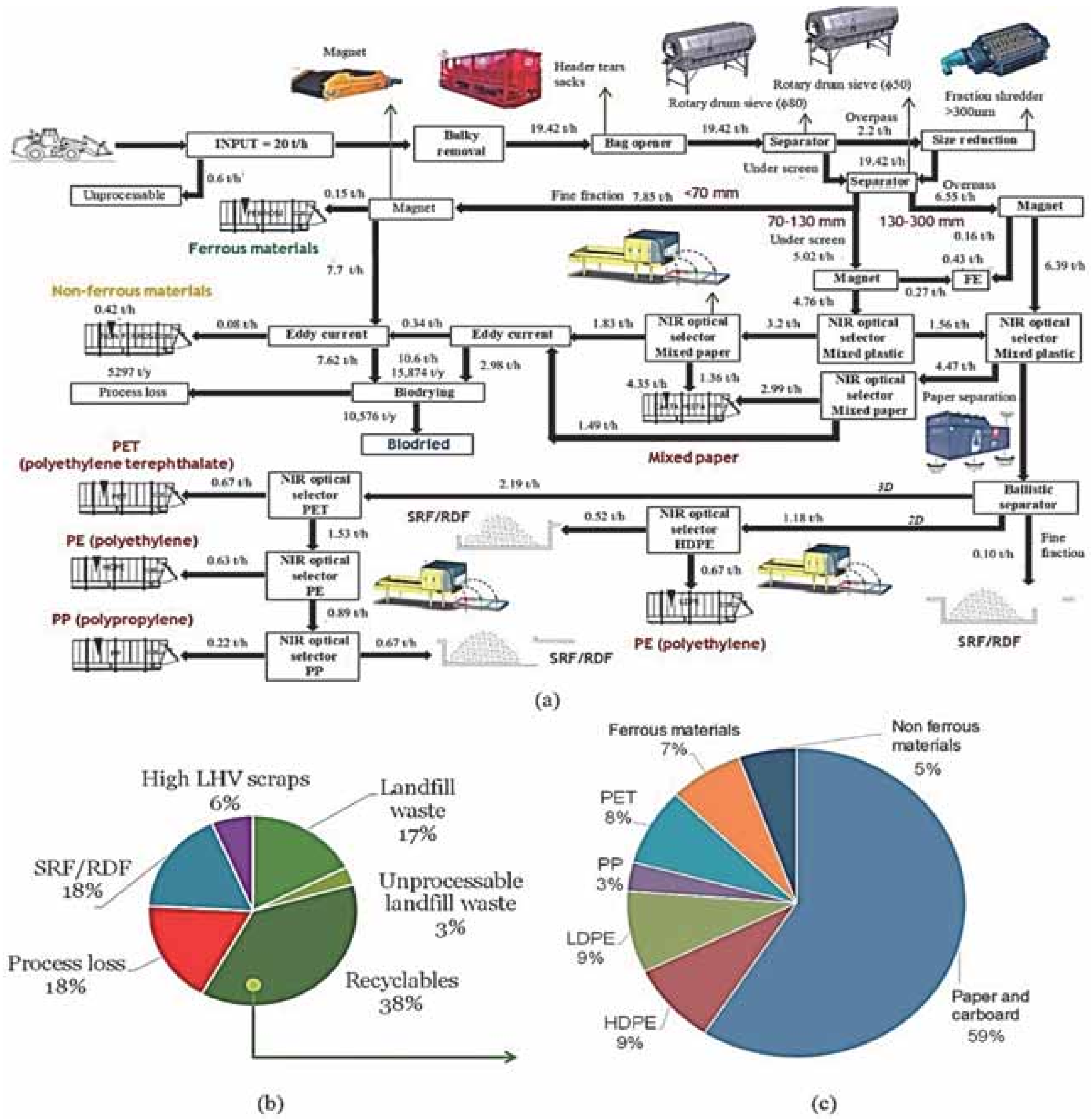


Fig. 2. SRMR plant: (a) process diagram with mass balance; (b) typical output composition; (c) potentially recoverable materials

The overflow is sent to a subsequent optical selector that will be able to select mixed paper/cardboard. The passing flow is also sent to the biostabilization phase. On the mixed plastics flow, a ballistic separator separates the flexible fraction (2D) consisting of plastic films from the rigid fraction (3D) consisting of plastic bottles. The subsequent optical selectors, always based on NIR technology, allow to intercept PET (polyethylene terephthalate), PE (polyethylene) and PP (polypropylene).

The SRMR plant under investigation is able to guarantee mainly recyclable material (38%) (Fig. 2b) although the percentages relative to SRF /RDF (18%) and process losses (18%) are not negligible. The percentage of waste destined for landfill is also significant, equal to 17%. The recoverable material consists mainly of paper and cardboard, followed by HDPE, LDPE (Low-Density PolyEthylene) and PET (Fig. 2c).

The MBT plant implements mechanical and biological treatments in order to separate recyclable fractions still present, stabilize the putrescible organic matter (biostabilization) and produce a dry fraction with energy content to be sent to energy recovery in Waste-to-Energy plants. The process scheme, visible in Fig. 3a, includes bag opening, shredding and size separation; the dry sieve is intended for SRF/RDF production and the wet sieve for aerobic biostabilisation.

The outlet flow from biostabilisation undergoes refining separation capable of separating the inert material and the plastics from the Stabilised Organic Fraction (SOF), which is smaller than the upper screen. With reference to the residual unsorted waste from the separately collected waste produced in Apulia Region and entering the MBT plant, Fig. 3b shows the distribution of outgoing products. SOF and scraps, to be disposed of in landfills, have a percentage of 45%, the SRF/RDF is equal to 30%. The process losses, consisting of process water and aeriforms produced in aerobic biostabilization, are equal to 22%. Plastics and metals present percentages of 1.5%, slightly lower than those expected in a typical MBT operating in the Apulia Region. The percentages reported in this inventory analysis were then applied in the feasibility study.

2.5. Mass balance

For each of the three scenarios, a mass balance was carried out with reference to the border of the territory of the municipality of Bari. The following homogeneous fractions of waste, leaving the MBT/SRMR plants and stored in the CONAI platform for the dry fraction (of MSW) and in the composting plants for the wet fraction, were considered: paper and cardboard, plastic, glass, metals, wood, clothing and textiles, WEEE and bulky items, sanitary textile (diapers), hazardous, organic, cellulosic material, SRF/RDF, SOF, process loss.

The three mass balances were conducted considering the year as a time unit.

3. Results and discussion

3.1. Composition of incoming waste to treatment plants

The amount of waste entering the MBT and SRMR plants was found to depend on the percentage of separate collection. The higher the percentage on a city scale, the lower the amount of unsorted waste to be sent to these plants.

With reference to Scenarios 1 and 2, characterized by a SC percentage of 39.0 and 83.3%, respectively, the amount of waste entering the MBT plant was 120.262 t/y and 32.929 t/y (Tab. 3). Scenario 3, being intermediate between the first two ones (%SC = 65%), showed an incoming waste to SRMR plant equal to 68,986 t/y. Also, in terms of waste composition, they presented different values. The unsorted waste in Scenario 1 was composed of organic matter (41.69%), plastics (17.14%) and paper and cardboard (10.13%). The unsorted waste in Scenario 2 (%SC = 83.3%) showed roughly similar percentage values for organic matter (29.03%) and paper and cardboard (25.88%), followed by plastics (15.89%). Scenario 3, while confirming the three components already shown above (organic, paper and cardboard, plastic), showed intermediate values to those of Scenarios 1 and 2.

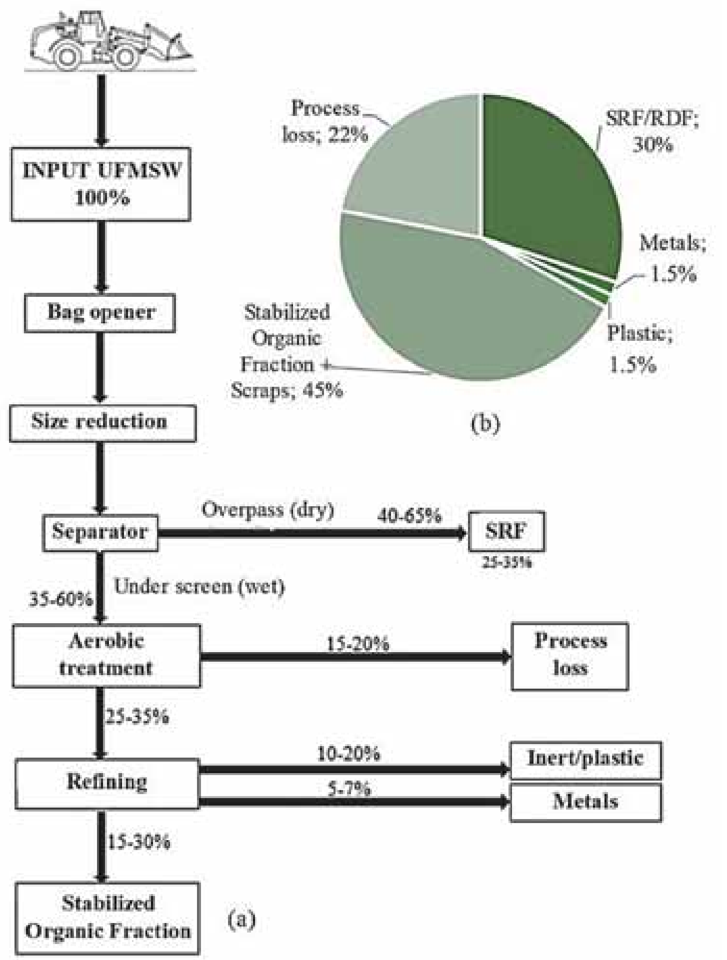


Fig. 3. MBT plant: (a) process diagram with mass balance; (b) typical output composition

It should be noted that the values obtained are difficult to compare with those of other similar cities reported in the EU report "Assessment of separate collection schemes in the 28 capitals of the EU" (EC Directive, 2015) because they differ in user behavior (which affects waste production) and collection methods.

3.2. Materials potentially recoverable from treatment plants

Scenarios 1 and 2, both based on MBT systems, allowed the potential recovery of 36,079 and 9879 t/y SRF/RDF, respectively (Table 4). The SOF was also the same while lower values were observed for scraps, plastics and metals. Process losses in bio stabilization were obviously lower for Scenario 2 compared to those in Scenario 1, due to the lower amount of waste entering the MBT plant. In percentage terms, the values were the same for both scenarios.

This was due because the same percentage removal values were considered during the MBT mass balance. This aspect appears to be a limitation of the study since the efficiency of unit processes, e.g. a separator, can vary depending on the feed mass flow and its waste composition.

Scenario 3, not subject to the limitation mentioned above, had a different percentage distribution compared to the case of MBTs; the percentage of produced SRF/RDF was lower while increasing the recovery rates of plastics (from 1.50 to 11.02%) and metals (from 1.50 to 4.56%). The amount of paper and cardboard recovered was high (15,466.7 t/y) and with a percentage (22.42%) roughly similar to that of SRF/RDF (Table 4).

3.3. Material potentially recoverable from separate collection

The total amount of materials collected separately was dependent on the percentage of separate collection.

The higher the value of such percentage, the greater the quantity recovered. The results in Table 5 show this trend for almost all recoverable fractions.

Table 3. Composition of incoming (residual/unsorted) waste to the MBT and SRMR plants

Composition		***Scenario 1***		***Scenario 2***		***Scenario 3***	
		(t/y)	*(% w/w)*	*(t/y)*	*(% w/w)*	*(t/y)*	*(% w/w)*
Compostable	Organics	50.142	41.69	9569	29.03	22.959	33.29
	Cellulosic material	12.187	10.13	3178	9.65	5543	8.04
Recyclable	Paper and cardboard	14.986	12.46	8522	25.88	18.374	26.63
	Plastic	20.607	17.14	5263	15.89	9992	14.48
	Glass	7115	5.92	2150	6.53	4908	7.11
	Metals	3780	3.14	839	2.55	1627	2.36
	Wood	3201	2.66	504	1.53	1293	1.87
	Clothing and textiles	6214	5.17	883	2.68	2262	3.28
Undersized <20mm		2029	1.69	2029	6.16	2029	2.94
Total		120.262	100.00	32.929	100.00	68.986	100.00

Table 4. Estimate of recovered materials from MBT and SRMR plants

Storage point at:	***Composition***	***Scenario 1***		***Scenario 2***		***Scenario 3***	
		(t/y)	*(% w/w)*	*(t/y)*	*(% w/w)*	*(t/y)*	*(% w/w)*
MBT/SRMR plant	SRF/RDF[(a)]	36.079	30.00	9879	30.00	16.557	24.00
	Stabilized organic fraction	36.079	30.00	9879	30.00	0.0	0.00
	Scraps	18.039	15.00	4939	15.00	13.797	20.00
	Plastic	1804	1.50	494	1.50	7602	11.02
	Metals	1804	1.50	494	1.50	3146	4.56
	Paper and cardboard	0.0	0.00	0.0	0.00	15.467	22.42
	Total waste out of the plant	93.804	-	25.684	-	56.569	-
	Process loss	26,458	22.00	7244	22.00	12.417	18.00
Total outflow from the plant		120.262	100.00	32.929	100.00	68.986	100.00

[(a)]*This item specifies the waste to be used for the production of SRF/RDF, and which will be further pre-treated before becoming SRF*

Table 5. Estimate of the waste collected separately and destined for material recovery

Storage point at:	***Composition***	***Scenario 1***		***Scenario 2***		***Scenario 3***	
		(t/y)	*(% w/w)*	*(t/y)*	*(% w/w)*	*(t/y)*	*(% w/w)*
CONAI collection centre	SC paper and cardboard	36.489	47.53	42,954	26.17	33,102	25.85
	SC plastic	5273	6.87	20,618	12.57	15,889	12.41
	SC glass	7061	9.20	12,027	7.34	9269	7.24
	SC metals	496	0.65	3436	2.09	2648	2.07
	SC wood	740	0.96	3436	2.09	2648	2.07
	SC clothing and textiles	682	0.89	6013	3.66	4634	3.62
	SC WEEE and bulky items	3941	5.13	3941	2.40	3941	3.08
	SC sanitary textile (diapers), Hazardous	2955	3.85	2955	1.80	2955	2.31
Composting plant	SC organic	17.835	23.23	58.417	35.60	45.019	35.16
	SC Cellulosic material	1300	1.69	10.309	6.28	7944	6.19
Total waste from SC to recovery		76.774	100.00	164.107	100.00	128.050	100.00

This was the case for plastics, glass, metals, wood, organic and cellulosic material. For WEEE and bulky items as well as for sanitary textile and hazardous waste the amount recovered was the same for the three scenarios; this is because the current collection system, corresponding to Scenario 1, was already able to intercept all these waste categories.

A different case, on the other hand, was the one corresponding to the collection of paper and cardboard; the quantity collected for Scenario 3, equal to 33,102 t/y was lower than in the current scenario, the latter equal to 36,489 t/y. In this regard, De Feo et al. (2017) highlighted this positive anomaly. Even with a bring points system, the percentage of paper and cardboard collected in the study area was higher than the typical value reported in ISPRA (2017).

3.4. Scenarios comparison and discussion

The implementation of mass balances considering the boundary of the municipality of Bari as a control volume allowed to quantify the different waste collected, visible in Table 6. First of all, the mass balance resulted "closed" since the difference between the total waste produced in the city and the outgoing waste was zero.

It is possible to observe how the fractions collected separately and destined to the CONAI platform and composting plant followed the percentage of separate collection. As the latter increased, the amount of waste collected and then stored increased. Compared to Scenario 2 (based on MBT), an increase in the amount of recovered material was observed for Scenario 3, from 32,929 to 68,986 t/y. With more evidence, the results in Fig. 4 show how Scenario 3 was capable of maximizing the recovery of plastics (Fig. 4a), paper and cardboard (Fig. 4b) and metals (Fig. 4c).

As far as the recovery of organic is concerned, Scenario 2 was found to maximize the amount of material recovered (Fig. 4d). However, this result did not affect the contribution of the SRMR plant, since the latter does not treat the organic fraction.

Analyzing Scenario 2 as a reference, assuming that the intention of the Bari Administration is - at least at the beginning - to maximize the percentage of waste collected by separate collection, it is possible to observe how overall the results of Scenario 3 differ slightly from those of Scenario 2 (Fig. 5).

A (slight) decrease in terms of recovered materials (from 1.40 to 1.31 kg/inhabitant/d) corresponds to an increase in SRF/RDF production (from 0.08 to 0.14 kg/inhabitant/d) and a decrease in waste to landfill (from 0.13 to 0.12 kg/inhabitant/d). At equal performance between Scenarios 2 and 3, it should be noted that the collection system of Scenario 3 has a more simplified operation than that of Scenario 2, having provided for the HTZ3 and HTZ7 (historical center) to use a system that only separates the wet and dry fractions.

It is a solution that can find broad consensus especially considering that the tourist presents a behavior not always pro-environment, as highlighted in Mateu-Sbert et al. (2013). A final discussion concerns the role of the quality of the homogeneous fractions of collected waste. The SRMR plant as it has been hypothesized can be fed with a waste also containing the organic fraction, as visible from Table 3 (the percentage of organics was 33.29%).

Under these conditions, each fraction recovered in the SRMR plant may have a lower degree of quality than that resulting from the door-to-door separate collection. As a consequence, the fee resulting from the collection of plastics, paper and cardboard and metals (from CONAI or its consortia to the municipality) may be lower than that resulting from the door-to-door sorting.

Accurate assessments of an economic nature cannot be overlooked in future feasibility investigations.

4. Conclusions

The study focused on the role of separate collection and fate of the residual/unsorted fraction of MSW for material recovery in a large metropolitan area. Three management MSW scenarios were considered to be characterized by different types and performance of separate collection and fate of the residual/unsorted fraction. Scenario 1 represented the current configuration with a bring points system; while, Scenario 2 was a sort of ideal scenario with door-to-door collection system and high performance in terms of separate collection percentage (>80%).

Table 6. Mass balance sheet verification on a city scale

Storage point at:	***Scenario 1***		***Scenario 2***		***Scenario 3***	
	(t/y)	***(% w/w)***	***(t/y)***	***(% w/w)***	***(t/y)***	***(% w/w)***
CONAI collection centre	57,638	29.25	95,381	48.41	75,086	38.11
Composting plant	19,135	9.71	68,726	34.88	52,963	26.88
MBT plant	120,262	61.04	32,929	16.71	-	-
SRMR plant	-	-	-	-	68,986	35.01
Assessment						
Total waste out of the city + process losses (OUT)	197,036	100.00	197,036	100.00	197,036	100.00
Total waste produced in the city (IN)	197,036 (t/y)					
Δ (IN-OUT)	0.0	-	0.0	-	0.0	-

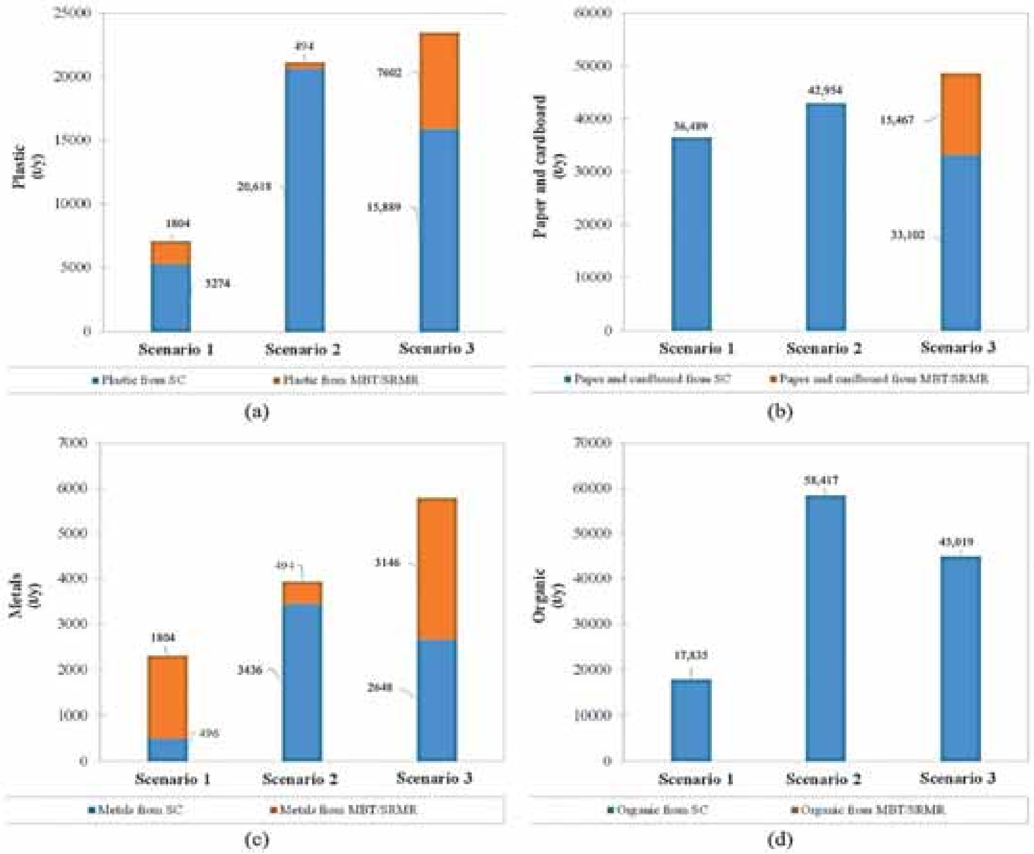


Fig. 4. Material recovery with reference to: (a) Plastic; (b) Paper and cardboard; (c) Metals; (d) Organic

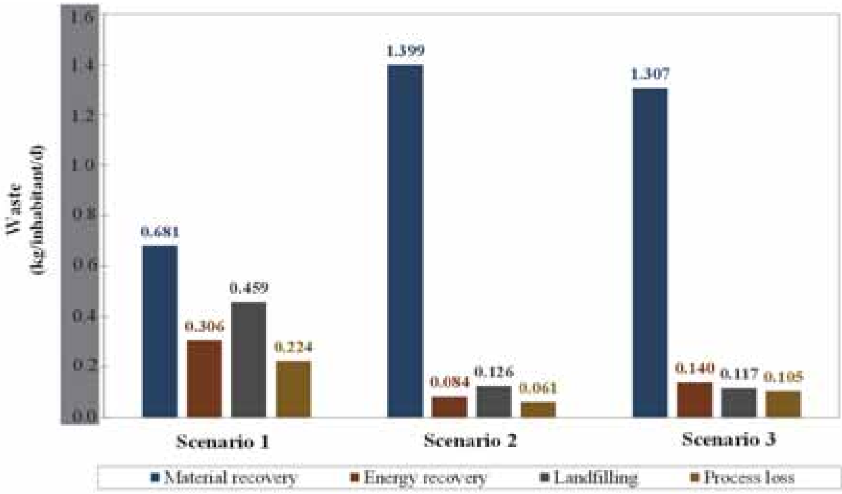


Fig. 5. Destination of the collected waste out of the city of Bari as a result of mass balance

Both systems were considered to send the residual fraction to mechanical-biological treatment plants. On the other hand, Scenario 3 was characterized by a percentage of separate collection equal to the legal limit (65%) and the fate of residual/unsorted fraction in a Secondary Raw Material Recovery (SRMR) plant. Such a collection percentage was considered having "lightened the constraint" on the areas of the historical centre with a greater tourist vocation, assuming the use of a simplified bring points system (dry and wet fractions) to replace door-to-door.

The results of the mass balances on the study area highlighted the technical feasibility of Scenario 3 as the overall materials potentially recoverable were roughly the same as in Scenario 2 (ideal scenario). Although preliminary, the study shows how the optimal configuration for a large metropolitan area was not always the one with the highest percentage of separate collection.

However, a negative aspect, which needs to be investigated, is the potentially lower quality of the fractions recovered from the SRMR plant such as paper and cardboard, plastic and metals, since the waste entering the plant contains a non-negligible percentage of organic from MSW.

Further studies need to be carried out together with a thorough economic feasibility assessment. The challenge is to improve the quality of materials recovered in SRSR plants fed with a stream that also contains the organic from MSW.

Abbreviations

CONAI = Italian national packaging consortium (in Italian, *Consorzio NAzionale Imballaggi*);
HDPE = High-Density PolyEthylene;
HTZ = Homogeneous Territorial Zone;
LDPE = Low-Density PolyEthylene;
MBT = Mechanical-Biological Treatment;
MSW = Municipal Solid Waste;
NIR = Near InfraRed;
PE = PolyEthylene;
PET = PolyEthylene Terephthalate;
PP = PolyPropylene;
SC = Separate Collection;
SOF = Stabilised Organic Fraction from MSW;
SRF/RDF = Secondary Recovered Fuel/Refuse Derived Fuel;
SRMR = Secondary Raw Material Recovery;
WEEE = Waste Electrical & Electronic Equipment.

Acknowledgements

The authors express their gratitude to the Environmental Protection Office of Municipality of Bari, A.M.I.U. Puglia and CONAI (Consorzio Nazionale Imballaggi).

References

Babaei A.A., Alavi N., Goudarzi G., Teymouri P., Ahmadi K., Rafiee M., (2015), Household recycling knowledge, attitudes and practices towards solid waste management, *Resources, Conservation and Recycling*, **102**, 94-100.

Bertanza G., Ziliani E., Menoni L., (2018), Techno-economic performance indicators of municipal solid waste collection strategies, *Waste Management*, **74**, 86-97.

Calabrò P.S., Komilis D., (2019), A standardized inspection methodology to evaluate municipal solid waste collection performance, *Journal of Environmental Management*, **246**, 184-191.

Chàfer M., Sole-Mauri F., Solé A., Boer D., Cabeza L.F., (2019), Life cycle assessment (LCA) of a pneumatic municipal waste collection system compared to traditional truck collection. Sensitivity study of the influence of the energy source, *Journal of Cleaner Production*, **231**, 1122-1135.

De Feo G., De Gisi S., Ferrara C., Notarnicola M., (2017), *Comparison Between the Waste Management of Two Southern Italy Regions: Lessons Learnt and Future Perspectives*, Proc. 16th Int. Symp. on Waste Management and Landfill (Sardinia), Santa Margherita di Pula (CA), Italy.

De Feo G., Malvano C., (2012), Technical, economic and environmental analysis of an MSW kerbside separate collection system applied to small communities, *Waste Management*, **32**, 1760-1774.

De Feo G., Ferrara C., Finelli A., Grosso A., (2019), Environmental and economic benefits of the recovery of materials in a municipal solid waste management system, *Environmental Technology*, **40**, 903-911.

De Gisi S., Todaro F., Fedele G., Carella C., Notarnicola M., (2018), Alternating pure oxygen and air cycles for the biostabilization of unsorted fraction of municipal solid waste, *Waste Management*, **79**, 404-414.

De Gisi S., Todaro F., Campanaro V., Notarnicola M., (2019), Start-up of the door-to-door municipal solid waste separate collection service in a large metropolitan area, *Environmental Engineering and Management Journal*, **18**, 2241-2252.

EC Directive, (2015), Assessment of separate collection schemes in the 28 capitals of the EU, Reference: 070201/ENV/2014/691401/SFRA/A2, On line at: http://ec.europa.eu/environment/waste/studies/pdf/Separate%20collection_Final%20Report.pdf.

EC Directive, (2018), Directive 2018/851/EC of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste (Text with EEA relevance), *Official Journal of the European Union*, L 150, 14.06.2018, Brussels.

Faraca G., Boldrin A., Astrup T., (2019), Resource quality of wood waste: The importance of physical and chemical impurities in wood waste for recycling, *Waste Management*, **87**, 135-147.

Giacetti W., Lepore P., Lanzotti M.A., (2009), *Start-up of Household Services with Particular Reference to Southern Italy: The Case of Salerno*, In: *Compost and Energy from Biowaste*, Vismara R., Centemero M., Grosso M. (Eds), Dario Flaccovio Publisher, Palermo, Italy, 135-170.

Hahladakis J.N., Iacovidou E., (2018), Closing the loop on plastic packaging materials: What is quality and how does it affect their circularity?, *Science of the Total Environment*, **630**, 1394-1400.

Haupt M., Waser E., Würmli J.C., Hellweg S., (2018), Is there an environmentally optimal separate collection rate?, *Waste Management*, **77**, 220-224.

ISPRA, (2017), Waste Register, Italian Higher Institute for Environmental Protection and Research, On-line at: http://www.catasto-rifiuti.isprambiente.it/.

LD, (2006), Legislative Decree No. 152/2006, regarding the environmental, *Italian Official Journal*, No. 88, 04.04.2006.

Mateu-Sbert J., Ricci-Cabello I., Villalonga-Olives E., Cabeza-Irigoyen E., (2013), The impact of tourism on municipal solid waste generation: The case of Menorca Island (Spain), *Waste Management*, **33**, 2589-2593.

Websites:

https://www.greenvisits.no/product/fully-automated-waste-sorting-facility-at-roaf/.

http://old.regione.calabria.it/ambiente/index.php?option=com_content&task=view&id=898&Itemid=226.

Environmental Engineering and Management Journal October 2020, Vol. 19, No. 10, 1741-1746
http://www.eemj.icpm.tuiasi.ro/; hiip://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

PROXY EXPOSURE INDICATORS FOR INDOOR AIR POLLUTION, HEALTH IMPACT AND DEPRIVATION IN THE MARCHE REGION, ITALY

Katiuscia Di Biagio[1*], Marco Baldini[1], Luca Formenti[2], Aurora Luciani[2], Lara Rita Napolitano[2], Iliana Sciarra[2], Jacopo Dolcini[2], Silvia Bartolacci[1], Thomas Valerio Simeoni[1], Emilia Prospero[3]

[1]Environmental Epidemiology Unit - Regional Environmental Protection Agency of Marche, 5 Ruggeri Luigi St., Ancona, Italy
[2]School of Hygiene and Preventive Medicine – Marche Polytechnic University, 10/A Tronto St., Ancona (AN)
[3]Department of Biomedical Sciences and Public Health, Section of Hygiene – Marche Polytechnic University, 10/A Tronto St., Ancona (AN)

Abstract

Literature supports the correlation between worse indoor air quality, lower socio-economic status and disease, such as asthma, Extrinsic Allergic Alveolitis (EAA) and Carbon Monoxide Intoxication (COI). In order to determine the extent of the phenomenon in the Marche Region, hospitalization risk for asthma, EAA and CO intoxication was assessed in association with Particulate Matter 2.5 ($PM_{2.5}$) air concentration and socio-economic Deprivation Index (DI).
Hospital discharge records of residents of the Marche Region with diagnosis of asthma, EAA and COI were analysed between 2006-2013. We then identified DI value and average $PM_{2.5}$ levels for each municipality, using atmospheric modelling systems. Association between these proxy indicators of indoor air quality and relative risk (Confidence Interval - CI 90%) of hospitalization for the considered health outcomes was evaluated.
Data analysis shows a higher number of hospitalizations for asthma with the increase of $PM_{2.5}$ concentration quintiles and suggests a possible correlation between socio-economic deprivation and EAA and CO intoxication.

Keywords: asthma, carbon monoxide, deprivation index, extrinsic allergic alveolitis, particulate matter

Received: February, 2020; Revised final: June, 2020; Accepted: July, 2020; Published in final edited form: October, 2020

1. Introduction

According to WHO, about 7 million people die every year by exposure to indoor and outdoor air pollutants (WHO, 2018a). In 2016 outdoor pollution caused 4.2 million deaths; in the same year indoor pollution, mainly produced by cooking flues and contaminants technologies, caused 3.8 million deaths. Recently, respiratory, cardiovascular diseases and cancers are attributable to ambient and household air pollution including chemicals that are also associated with neurological and mental disorders (Prüss-Ustün et al., 2019). Furthermore, over 90% of air pollution-related deaths occur in low- and middle-income countries, mainly in Asia and Africa, followed by low- and middle-income countries in the eastern Mediterranean region, Europe and America (WHO, 2018b).

In a recent study Burnett et al. (2018), using a new function for mortality hazard ratio calculation, estimated a number of attributable deaths to indoor and outdoor particulate matter with aerodynamic diameter <2.5 micron ($PM_{2.5}$), equal to 8.9 million (Burnett et al., 2018). Using the same statistical

*Author to whom all correspondence should be addressed: e-mail: katiuscia.dibiagio@ambiente.marche.it; Phone: +390712132756; Fax: +390712132740

model, other researchers have quantified for Europe a number of attributable events equal to 790,000 units [95% Confidence Interval (CI) 645,000-934,000]; this mortality excess would be responsible for a 2.2-year reduction in average life expectancy (Lelieveld et al., 2019). The EEA (2018) estimated that 5.5 million of years of life lost (YLL) are due to exposure to main air pollutants; within the European data relating to this epidemiological indicator, $PM_{2.5}$ showed a greater impact in Central and Eastern European countries.

Italian population spend most of its time (84%-93%) in indoor environments (Fuselli et al., 2013) where internal and external emissive sources determine air quality. Among the most important indoor sources there are burning process (cooking, heating, tobacco smoke), followed by pollution coming from building materials and furnishing, products for household cleaning/maintenance and cooling system (ISPRA, 2016). External sources of air pollution, particularly in urban areas, are mainly represented by vehicular traffic; their contribution to deterioration of indoor air quality is quantified with various parameters such as the indoor / outdoor ratio (I/O), the infiltration factor and the penetration factor. Several studies stressed the large variability of the I/O ratio which is linked to the size and chemical composition of the particles, volatilization of substances, room ventilation, outdoor temperature and the presence of indoor emissions (Chen and Zhao, 2011; Meier et al., 2015; Zauli et al., 2015). In Italy, the annual average standard on fine particulate matter concentrations for ambient outdoor is set on 20 $\mu g/m^3$, however no threshold or guideline values have been established inside buildings and homes (indoor air); an annual average concentration of 10 $\mu g/m^3$ (outdoor) was chosen as WHO Air quality guideline values for $PM_{2.5}$.

Some studies showed that indoor pollution levels are associated to family socio-economic status (SES) (Clark et al., 2013; Lewis and Pattanayak, 2012), that female gender and a higher education level promote a better indoor air quality while a lower economic status and housing in a rural area are generally related to an indoor air quality worsening (Ghimire et al., 2019). Results from a systematic review are in agreement with this (Hajat et al., 2015) identifying a relationship between low socio-economic status and high concentrations of air pollution in North America, New Zealand, Asia and Africa.

These evidences are confirmed by a more recent systematic review that showed how, in Europe too, a low socio-economic level is associated with a greater environmental pollution exposure (Fairburn et al., 2019). Furthermore, it should be noted that the presence of high SES in high polluted areas doesn't correspond to a greater individual exposure because better economic conditions enable implementation of protective measures against harmful atmospheric exposures, such as buildings constructed with low-emission materials and equipped with ventilation and air purification systems (Hajat et al., 2015). Concerning specific effects on human health, some studies indicated that indoor pollution caused an increase of asthma cases and a deterioration of respiratory functions (Gordon et al., 2014; Jie et al., 2013; Li et al., 2019; Mentese et al., 2015); regarding indoor air pollution there is evidence of possible links both with chronic diseases, such as extrinsic allergic alveolitis (EAA), and with acute diseases such as carbon monoxide (CO) intoxication (Fuselli et al. 2013; ISPRA 2010; Toscany Region, 2013).

The aim of this study is to evaluate in our Marche region possible association between hospitalization for asthma, EAA and CO intoxication and two proxy indicators of the exposure to indoor air pollution, such as $PM_{2.5}$ concentration and socio-economic deprivation index (DI).

2. Material and methods

This study has been conducted in the Italian Region of Marche. Average annual municipal air concentrations of $PM_{2.5}$ were determined from the estimates provided by the atmospheric modelling system of Italian National Integrated Assessment Model (AMS-MINNI) carried out throughout the Italian territory to a spatial resolution of 4 x 4 km for year 2010.

The MINNI project is funded by Italian Ministry for Environmental and Territory and Sea to support the international negotiation on atmospheric pollution and is developed by ENEA (Mircea et al., 2014). The main components of AMS-MINNI are the three-dimensional Eulerian model FARM (Flexible Air Quality Regional Model) that includes transport and multiphase chemistry of pollutants in the atmosphere, the meteorological model RAMS (Regional Atmospheric Modelling System) and the emission processor EMMA (Emission Manager); input emissions were prepared from a combination of the national emission inventory for Italy and the EMEP inventory (European Monitoring and Evaluation Programme) for the surrounding countries. The validation with measured data, extracted from the national database, shows that PM concentrations are generally underestimated for all station types, in particular at the urban ones.

The gradient of exposure to air pollution was defined on the basis of the quintiles of $PM_{2.5}$ municipalities distribution values.

Socio-economic disadvantage was measured at macro-level unit (municipalities) through the DI (Caranci et al., 2010). This index is built considering five features of the resident population which were chosen on the basis of the literature and sociological considerations and were recorded during the Permanent Census of population and housing in 2001 conducted by the Italian National Institute of Statistics (ISTAT, 2018). The five characteristics used to describe the concept of social and material deprivation are: low level of instruction, unemployment or first job-employment, living on rent, being part of a single-parent family and high population density that has been codified as number of occupants for 100 m^2. The DI provides, considering distribution quintiles, a municipalities classification in five categories: very wealthy, wealthy, middle, deprived, very deprived.

$PM_{2.5}$ concentration value and DI class, based on residency address, were assigned to each subject at the time of hospitalization. We included subject's hospital admissions residing in the Marche region between 2006 and 2013, selected from the regional archive of hospital discharge records (HDR) using the International Classification Disease - ninth revision (ICD9) codes for the primary and secondary diagnosis. Ordinary and Day-Hospital admissions of residents of all ages were considered.

The population residing in the municipalities of the Marche region during the study period was derived from the ISTAT archives, classified by gender and age. Association between proxy indicators of indoor air quality and risk of hospitalization for asthma (ICD-9 493), EAA (ICD-9 495) and CO intoxication (ICD-9 986) was investigated. Estimation of rate ratio (RR) of hospitalization for subjects belonging to the highest DI and exposure to $PM_{2.5}$ categories were calculated by applying a multi-level Poisson regression model with normally distributed random intercept for municipalities, to account for potential within-cluster correlation between subjects, the natural logarithm of the person-years contributed by population in each covariate pattern as the offset term and a log-link function. The RR was adjusted for potential confounding factors like gender and age and its 90% confidence interval (CI) was calculated.

Statistical analyses were performed with the SAS System software ver.9.4.

3. Results and discussion

Quintiles of $PM_{2.5}$ concentrations has been divided according to the following cut-offs: 8.51 μg/m^3 (20th percentile), 9.79 μg/m^3 (40th percentile), 10.83 μg/m^3 (60th percentile) and 11.85 μg/m^3 (80th percentile). The minimum concentration of $PM_{2.5}$ detected was 5.03 μg/m^3. The maximum value identified was 13.88 μg/m^3 and the median was 10.36 μg/m^3. All measurements are in compliance with the Italian annual average standards of 20 μg/m^3; however, it is universally recognized that there is no evidence of a safe level of exposure to PM below which no adverse health effects occur (WHO, 2013).

Regarding socio-economic deprivation index, in the Marche region there aren't municipalities categorized as "very deprived". Table 1 shows the distribution by gender, age, socio-economic deprivation index and $PM_{2.5}$ quintiles of the person-years and patients hospitalized for asthma, EAA and CO intoxication between the years 2006 and 2013.

Most of the population was resident in municipalities categorized as "wealthy" and with an average concentration of fine particulate matter higher than 11.85 μg/m^3. Hospital admissions for asthma were a total of 7,864 for 6,583 subjects. Among these 52% were female and 43% aged between 0 and 19 years. Hospitalization events for EAA amounted to 128 for 105 subjects, 60% of whom were men and 65% were over the age of 65. 116 hospitalizations were recorded for CO intoxication and occurred in 114 different subjects, of which 51% were males and 35% aged between 20 and 44 years.

Table 2 displays results from association analysis between municipal deprivation index, concentration of fine particulate matter estimated by atmospheric modelling and hospitalization for asthma, EAA and CO intoxication. Number of events and relative risk of hospitalization by DI and $PM_{2.5}$ concentrations, compared to the reference category (DI: very wealthy; $PM_{2.5}$: I quintile), with the relative 90% confidence intervals are reported for each pathology.

Table 1. Descriptive characteristics of hospitalized subjects by pathology

		Person-years		***Asthma***		***EAA***		***CO intoxication***	
		N	***%***	***N***	***%***	***n***	***%***	***n***	***%***
	Total	12.256.524	100%	6.583	100%	105	100%	114	100%
Gender	Male	5.944.676	49%	3.191	48%	63	60%	58	51%
	Female	6.311.848	51%	3.392	52%	42	40%	56	49%
Age	0-19	2.182.872	18%	2.811	43%	5	5%	33	29%
	20-44	4.033.318	33%	945	14%	9	9%	40	35%
	45-64	3.248.406	27%	1.026	16%	23	22%	19	17%
	>65	2.791.929	23%	1.801	27%	68	65%	22	19%
DI	Very wealthy	4.345.873	35%	2.299	35%	41	39%	46	40%
	Wealthy	7.381.290	60%	4.072	62%	57	54%	57	50%
	Middle	489.865	4%	193	3%	6	6%	8	7%
	Deprived	39.496	<0.5%	19	0%	1	1%	3	3%
$PM_{2.5}$	I quintile	561.665	5%	221	3%	6	6%	8	7%
	II quintile	1.681.800	14%	847	13%	22	21%	16	14%
	III quintile	1.539.743	13%	817	12%	13	12%	12	11%
	IV quintile	1.540.744	13%	851	13%	12	11%	13	11%
	V quintile	6.932.573	57%	3.847	58%	52	50%	65	57%

Table 2. Number of events, crude rate and rate ratio of hospitalizations for asthma,

EAA and CO intoxication by deprivation index class and $PM_{2.5}$ quintiles

	Asthma				***EAA***				***CO intoxication***			
	N	***CR****	***RR*****	***90% CI†***	***N***	***CR***	***RR***	***90% CI***	***N***	***CR***	***RR***	***90% CI***
DI												
Very wealthy	2,737	63.0	1.00		48	1.1	1.00		48	1.1	1.00	
Wealthy	4,880	66.1	0.95	0.84-1.06	72	1.0	1.07	0.61-1.90	57	0.8	0.72	0.38-1.37
Middle	227	46.3	0.82	0.64-1.04	7	1.4	1.21	0.40-3.62	8	1.6	1.25	0.38-4.11
Deprived	20	50.6	1.01	0.59-1.72	1	2.5	2.27	0.22-23.10	3	7.6	7.68	1.32-44.63
$PM_{2.5}$												
I quintile	251	44.7	1.00		7	1.3	1.00		8	1.4	1.00	
II quintile	1,015	60.4	1.19	0.96-1.48	25	1.5	1.77	0.61-5.14	18	1.1	0.90	0.27-3.01
III quintile	950	61.7	1.35	1.09-1.66	16	1.0	1.04	0.34-3.13	12	0.8	0.65	0.18-2.27
IV quintile	1,010	65.6	1.34	1.09-1.65	18	1.2	0.99	0.33-2.97	13	0.8	0.81	0.25-2.66
V quintile	4,638	66.9	1.30	1.07-1.59	62	0.9	1.08	0.39-2.97	65	0.9	1.19	0.40-3.53

** CR: Crude Rate per 100,000 person-years*

***RR Adjusted Rate Ratio*

†90% CI - Confidence Interval of 90%

Variance component estimates of random effect were positive and significant different from zero for asthma ($\sigma^2_{int} = 0.10$, p<0.001), EEA ($\sigma^2_{int} = 1.19$, p<0.001) and CO ($\sigma^2_{int} = 1.20$, p<0.001), indicating that there are some variations among municipalities; moreover, the explicit modelling of multilevel data nature achieves correct inference for DI and $PM_{2.5}$ coefficients.

Regarding asthma, results show a higher risk of hospitalization with the increasing of $PM_{2.5}$ concentration quintiles. The risk increases by 35% (90% CI 1.09-1.65) for the third and fourth quintile compared to the first, 30% (90% CI 1.07-1.59) for the highest quintile (Table 2). There aren't significant associations between hospitalization for asthma and socio-economic DI. This result seems to confirm data reported in literature, namely that high indoor and outdoor concentration of aeroallergens and pollutants play a key role in the etiopathogenesis of allergic respiratory disease (Cecchi et al., 2018). Studies suggest that reduction in $PM_{2.5}$ air concentration leads into chronic respiratory diseases' symptoms reduction and prevention; using air cleaners and filters is one of the suggested strategies to improve indoor air quality (Vijayan et al., 2015).

For EAA and CO intoxication there is a risk gradient of hospitalization as the socio-economic deprivation increases, with a high variability of the estimates due to the reduction of cases. Risk excesses for EAA and CO intoxication are respectively 21% and 25% in the "middle" DI class compared to the "very wealthy" class, with an even higher risk in the "deprived" class compared to the reference one (Table 2). This, despite the low statistical power, provides evidence in favour of possible association between these two diseases and indoor pollution. This might be also supported by results from other studies which state that indoor air quality is directly correlated with the different categories of the familiar socio-economic state (Clark et al., 2013; Lewis and Pattanayak, 2012).

Exposure to fine particulate matter is not associated with a greater risk of hospitalization for EAA and CO intoxication (Table 2). This could be explained by the fact that other elements and environmental pollutants, different from $PM_{2.5}$, could be implicated in the etiopathogenesis of EAA (Park and Cox-Ganser, 2011). Particularly, excessive moisture in buildings represents a critical factor for fungal and bacterial proliferation and determines an increased and repeated exposition to fungal spores, cellular fragments or toxins for people who live in particularly damp indoor environments. This may cause different respiratory disease such as hypersensitivity pneumonitis, also called EAA, in genetically predisposed individuals. In fact, the incidence of this disease, although low in the general population, becomes higher in water-damaged building.

Moreover, the EAA has been associated to the chronic exposition to indoor/outdoor avian antigens (Kuramochi et al., 2010) and to other indoor pollutants such as fungal antigens coming from dehumidifiers where the internal conditions of high temperature and high humidity are optimal for fungal proliferation (Carrer and Moscato, 2004; Otsuka et al., 2008). Finally, CO intoxication is caused by exposition to toxic gas derived by the incomplete combustion of hydrocarbons (Prockop and Chichkova, 2007). In literature, only few studies investigate the association between CO intoxication and urban air pollution.

Among them, a cross-sectional study conducted in two African cities described a high air pollution in terms of CO and benzene concentration and the presence of elevated rate of carboxyhaemoglobin in the blood of more than 66% of the recruited taxi drivers (Fourn and Fayomi, 2006).

Another study conducted in Turkey highlighted how traffic policemen on duty at cross-sections of the capital city are affected by CO chronic intoxication since they are exposed to high levels of CO for at least 6 hours a day (Atimtay et al., 2000).

4. Conclusions

This work confirms that $PM_{2.5}$ concentration has a major impact in increasing hospital admissions due to asthma and suggests a possible correlation between lower socio-economic status and increased risk of hospitalization due to EAA and CO intoxication.

Moreover, it represents the first study of this kind to be conducted in our region.

The use of outdoor $PM_{2.5}$ as proxy for indoor exposure is due to the lack of ambient measurements; the outdoor PM penetrates into indoor environments and is added to fine particulate from typically indoor sources, as combustion (e.g. cooking, cigarette smoke), heating and allergens, then the personal exposure and the health effect of indoor air pollution may be biased. We would like also to underline that penetration of outdoor PM2.5 may be also eased by the fact that in Marche region, which is mainly a rural reality with small-medium municipalities, a lot of housing buildings have been built in the past 40-50 years without materials or modern ventilations systems that are able to isolate indoor from outdoor environment. This is particularly true if compared to modern buildings like skyscrapers in much more bigger cities.

From a methodological point of view, it should be highlighted that the availability of data about $PM_{2.5}$ concentrations and socio-economic deprivation only on a municipal basis could represent an ecological bias of the study, since a collective measure of exposition is attributed to the individual. Therefore, further studies are necessary to investigate the association between asthma, EAA, CO intoxication, $PM_{2.5}$ air concentration and socio-economic DI.

Air pollution is a risk factor for those with a history of respiratory disease, such as asthma. Subjects with higher socio-economic deprivation are most vulnerable to potential indoor air pollution health effects.

Local and national authorized institutions should take necessary measures to control indoor emissions and give top priority to further regulatory interventions, aiming to reduce health loss, associated with air pollution exposures.

Moreover, they need to support the importance of promoting information campaigns among the population to raise awareness about risk factors regarding air pollution associated diseases. More investigation is needed to understand the exposure to indoor air pollution and the relationship with health effects.

Finally, considering the amount of old buildings in our country, this study may allow to better improve knowledge about how much Italian population's health worsening is due to lack of renovation of these buildings and it could help to define strategies of national economic incentives that should be used to renovate them. This may improve, among many things, also indoor air quality.

References

Atimtay A.T., Emri S., Bagci T., Demir A.U., (2000), Urban CO exposure and its health effects on traffic policemen in Ankara, *Environmental Research*, **82**, 222-30.

Burnett R., Chen H., Szyszkowicz M., Fann N., et al., (2018), Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter, *Proceedings of the National Academy of Sciences USA*, **115**, 9592-9597.

Caranci N., Biggeri A., Grisotto L., Pacelli B., Spadea T., Costa G., (2010), The Italian deprivation index at census block level: definition, description and association with general mortality (in Italian), *Epidemiology and Prevention* (*Epidemiologia e Prevenzione)*, **34**, 167-76.

Carrer P., Moscato G., (2004), Biological pollution and allergic diseases (in Italian), *Italian Journal of Occupational Medicine and Ergonomics* (*Giornale Italiano Medicina del Lavoro ed Ergonomia)*, **26**, 370-4.

Cecchi L., D'amato G., Annesi-Maesano I., (2018), External exposome and allergic respiratory and skin diseases. *Journal of Allergy and Clinical Immunology*, **141**, 846-57.

Chen C., Zhao B., (2011), Review of relationship between indoor and outdoor particles: I/O ratio, infiltration factor and penetration factor, *Atmospheric Environment*, **45**, 275-288.

Clark M.L., Peel J.L., Balakrishnan K., Breysse P.N., Chillrud S.N., Naeher L.P., Rodes C.E., Vette A.F., Balbus J.M., (2013), Health and household air pollution from solid fuel use: the need for improved exposure assessment, *Environmental Health Perspectives*, **121**, 1120-8.

EEA, (2018), European Environment Agency Air quality in Europe - 2018 report. EEA Report No 12/2018, On line at: https://www.eea.europa.eu/publications/air-quality-in-europe-2018.

Fairburn J., Schüle S.A., Dreger S., Karla Hilz L., Bolte G. (2019), Social inequalities in exposure to ambient air pollution: a systematic review in the WHO European Region, *International Journal of Environmental Research and Public Health*, **16**, 3127.

Fourn L., Fayomi E.B., (2006), Air pollution in urban area in Cotonou and Lokossa, Benin, *Bulletin de la Société de Pathologie Exotique*, **99**, 264-8.

Fuselli S., Musmeci L., Pilozzi A., Santarsiero A., Settimo G., for the National Working Group on indoor air (2013), Workshop. Issues related to indoor air pollution: current situation in Italy. National Health Institute. Rome, June 25, 2012. Proc. (in Italian), Report ISTISAN 13/39, On line at: http://old.iss.it/binary/publ/cont/13_39_web.pdf.

Ghimire S., Mishra S.R., Sharma A, Siweya A., Shrestha N., Adhikar B., (2019) Geographic and socioeconomic variation in markers of indoor air pollution in Nepal: evidence from nationally-representative data, *BioMed Central BMC Public Health*, **19**, 195.

Gordon S.B., Bruce N.G., Grigg J., et al., (2014), Respiratory risks from household air pollution in low and middle income countries, *The Lancet Respiratory medicine*, **2**, 823-60.

Hajat A., Hsia C., O'Neill M.S., (2015), Socioeconomic disparities and air pollution exposure: a global review, *Current Environmental Health Reports*, **2**, 440-450.

ISPRA, (2010), Indoor pollution: general aspects and case-study in Italy (in Italian), Report 117/2010, ISBN 978-

88-448-0451-0, On line at: http://www.isprambiente.gov.it/contentfiles /00010300/10392-rapporto-117-2010.pdf/.

ISPRA, (2016), XII Report on Urban Environment Quality - 2016 edition (in Italian), State of the Environment 67/16, On line at: http://www.isprambiente.gov.it/public_files/XII_ RAPPORTO_AREE_ URBANE/XII_RAU_Volume_completo.pdf.

ISTAT, (2018), Demography in Figures (in Italian), On line at: http://demo.istat.it/.

Jie Y., Isa Z.M., Jie X., Ismail N.H., (2013), Asthma and asthma-related symptoms among adults of an acid rain-plagued city in Southwest China: Prevalence and risk factors, *Polish Journal of Environmental Studies*, **22**, 717-26.

Kuramochi J., Inase N., Takayama K., Miyazaki Y., Yoshizawa Y., (2010), Detection of indoor and outdoor avian antigen in management of bird-related hypersensitivity pneumonitis, *Allergology International*, **59**, 223-8.

Lelieveld J., Klingmüller K., Pozzer A., Poschl U., Fnais M., Daiber A., Munzel T., (2019), Cardiovascular disease burden from ambient air pollution in Europe reassessed using novel hazard ratio functions, *European Heart Journal*, **40**, 1590-1596.

Lewis J.J., Pattanayak S.K., (2012), Who adopts improved fuels and cookstoves? A systematic review, *Environmental Health Perspectives*, **120**, 637-45.

Li S., Xu J., Jiang Z., Luo Y., Yang Y., Yu J., (2019) Correlation between indoor air pollution and adult respiratory health in Zunyi City in Southwest China: situation in two different seasons, *BioMed Central BMC Public Health*, **19**, 723.

Meier R., Eeftens M., Phuleria H.C., Ineichen A., Corradi E., Davey M., Fierz M., Ducret-Stich R.E., Aguilera I., Schindler C., Rochat T., Probst-Hensch N., Tsai M.Y., Künzli N., (2015), Differences in indoor versus outdoor concentrations of ultrafine particles, $PM_{2.5}$, PMabsorbance and NO_2 in Swiss homes, *Journal of Exposure Science and Environmental Epidemiology*, **25**, 499-505.

Mentese S., Mirici N.A., Otkun M.T., Bakar C., Palaz E., Tasdibi D., Cevizci S., Cotuker O., (2015), Association between respiratory health and indoor air pollution exposure in Canakkale, Turkey, *Building and Environment*, **93**, 72-83.

Mircea M., Ciancarella L., Briganti G., Calori G., Cappelletti A., Cionni I., Costa M., Cremona G., D'Isidoro M., Finardi S., Pace G., Piersanti A., Righini G., Silibello C., Vitali L., Zanini G., (2014), Assessment of the AMS-MINNI system capabilities to simulate air quality over Italy for the calendar year 2005, *Atmospheric Environment*, **84**, 178-188.

Otsuka M., Akiyama T., Saikai T., Tanaka Y., Saizen H., Murakami S., Yamada G., Tanaka H., Takahashi H., (2008), A case of hypersensitity pneumonitis due to the contamination of a dehumidifier by Thermoactinomyces vulgaris, *Nihon Kokyūki Gakkai zasshi*, **46**, 39-43.

Park J.H., Cox-Ganser J.M., (2011), Mold exposure and respiratory health in damp indoor environments, *Frontiers in Bioscience (Elite Edition)*, **3**, 757-71.

Prockop L.D., Chichkova R.I., (2007), Carbon monoxide intoxication: an updated review, *Journal of the Neurological Sciences*, **262**, 122-130.

Prüss-Ustün A., Van Deventer E., Mudu P., Campbell-Lendrum D., Vickers C., Ivanov I., Forastiere F., Gumy S., Dora C., Adair-Rohani H., Neira M., (2019), Environmental risks and non-communicable diseases, *British Medical Journal*, **364**, l265.

Toscany Region, (2013), Practical Guide to prevention of adverse effects of vapours and smokes from combustion process in the areas of life (in Italian), On line at: http://www.regione.toscana.it/-/salute-negli-ambienti-di-vita.

Vijayan V.K., Paramesh H., Salvi S.S., Dalal A.A., (2015) Enhancing indoor air quality - The air filter advantage, *Lung India*, **32,** 473-479.

WHO, (2018a), Burden of disease from the joint effects of household and ambient air pollution for 2016, On line at: https://www.who.int/airpollution/data/AP_joint_effect _BoD_results _May2018.pdf.

WHO (2018b), 9 out of 10 people worldwide breathe polluted air, but more countries are taking action, On line at: https://www.who.int/news-room/detail/02-05-2018-9-out-of-10-people-worldwide-breathe-polluted-air-but-more-countries-are-taking-action.

WHO, (2013), Regional Office of Europe, Health effects of particulate matter, On line at: https://www.euro.who.int/__data/assets/pdf_file/0006/ 189051/Health-effects-of-particulate-matter-final-Eng.pdf?ua=1.

Zauli Sajani S., Ricciardelli I., Trentini A., Bacco D., Maccone C., Castellazzi S., Lauriola P., Poluzzi V., Harrisond R.M., (2015), Spatial and indoor/outdoor gradients in urban concentrations of ultrafine particles and $PM_{2.5}$ mass and chemical components, *Atmospheric Environment*, **103**, 307-320.

Environmental Engineering and Management Journal *October 2020, Vol. 19, No. 10, 1747-1753*
http://www.eemj.icpm.tuiasi.ro/; hiip://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

AUTOMOTIVE RECYCLING: A CIRCULAR ECONOMY CENTRE

Luca Pomili*, **Alessio Fabrizi**

Pomili Demolizioni Speciali S.R.L. – End-of-life vehicle (ELV) treatment plant,
Via Salaria km 26.300 snc, 00015 Monterotondo (RM), Italy

Abstract

Every year 93 billion tonnes of raw materials are consumed, but only 9% of them are reused: a potential of about 3 trillion dollars worldwide, 88 billion in Italy, according to *Growth Within: A Circular Economy Vision for a Competitive Europe* by Ellen MacArthur Foundation with McKinsey.
A vehicle is potentially recoverable, in its components for more than 95%, an industrialised process of treatment of end-life vehicles (ELVs). Optimising raw material recovery is currently possible and advantageous.
The aim of this work is to increase the knowledge regarding the ideal dimensioning of an automotive recycling plant. Indeed, it is possible to find out the maximum capacity of both the number of the incoming vehicles to handle and the amount of produced and treatable waste material through a correct division of space of a plant for the end-of-life vehicles. Therefore, it is possible to foresee and programme the typology of the outgoing waste materials and the secondary raw materials that can be obtained from these.
The questions based on this document are: (1) Is it possible to have guidelines for the creation and the correct dimensioning of an automotive recycling plant that would allow reaching European circular economy goals? (2) Is it possible to know the treatment capacity of an automotive recycling plant? (3) Is it possible to create a calculation method for the correct dimensioning of a plant for ELVs treatment?
The authors were able to create the formula for the ideal dimensioning of a automotive recycling plant by using the data analysis of the "Guidelines on the treatment of end-of-life vehicles. Technological and managing aspects" ("Linee guida sul trattamento dei veicoli fuori uso. Aspetti tecnologici e gestionali") developed by the High Institute for the Protection and the Environmental Research (ISPRA–Istituto Superiore per la Protezione e la Ricerca Ambientale).
The correct dimensioning of a plant of this kind is configurated as base to carry out the optimisation of working processes within a plant, guaranteeing the complete traceability of the vehicle, subject of process, from the initial stage of acceptance to the complete recover-disposal of all its parts, the advanced education of the sector operators in mechanical, logistical, and warehouse competence, the certification of quality, environment and security process.

Keywords: automotive recycling, circular economy, end-of-life vehicles (ELVs), treatment plant

Received: February, 2020; Revised final: June, 2020; Accepted: July, 2020; Published in final edited form: October, 2020

1. Introduction

Every year a large number of internal combustion engine vehicles reach the end of their cycle of usage because of their age, incidents or accidents that have compromised their functions and also because they are no longer adequate for the usage in the urban areas that are increasingly attentive to maintaining air quality, good for people's health and the liveability of the cities (Findomestic, 2019; Levizzari, 2001). The disposal of all these vehicles generates between 8 and 9 million tonnes of special waste each year in the European Union (EU). This waste must be managed in such a way as to minimise the impact on the environment and to ensure the best and utmost reuse of the materials of which the vehicles themselves are composed (Laraia et al., 2007). The subject of the current article is the discipline of a

*Author to whom all correspondence should be addressed: e-mail: direzione@pomilids.it; Mobile: +39 3279918485; Phone: +39 06 9060232; Fax: +39 06 9060437

correct and ideal dimensioning of a plant of end-of-life vehicles according to regulations in force and aiming at being able to optimize the process of their transformations according to the circular economy principles.

It is clear that the ELVs treatment is only one of the aspects that have an impact on the environment: the overall balance of impacts generated by a vehicle throughout its life cycle would also include effects, not covered in this document, of pollution from the very production of the vehicles and the pollution caused by keeping them running and functioning during their use.

In order to ensure a proper treatment of waste end-of-life vehicles, there are several actions to take with high responsibility both of the automotive recycling plants and of the other protagonists of the automotive sector. For example, in order to improve recycling, European Union legislation establishes how new vehicles should be designed to improve downstream reuse, considering a second use of the materials of which they are composed. Therefore, it is necessary to establish measures and actions to limit the use of substances and materials for which the only form of final management is disposal in the construction process.

2. Material and methods

The method used in the current document was the analysis of the data produced by ISPRA and the target area is Italy, an EU member country. The model used for studying the innovation of system of vehicle recycling in Italy is a reworking of the model used in Sweden in 1910-2010 (Fig. 1). The fundamental technology is analytically outlined on the capacity of transforming the ELVs in valuable products and iron containing raw materials (FF, 2020). The directly operational responsibility for the end-of-life vehicles management therefore takes place within an ELVs treatment plant, known as automotive recycling.

The design of these plants must be based on an industrial approach ensuring a process with a “dis-assembly” chain (Fig. 2), from the initial stage in which the “good-vehicle” that becomes waste, until the recovery of the waste of vehicles that become resources or second raw materials (*end of waste*) for new production processes.

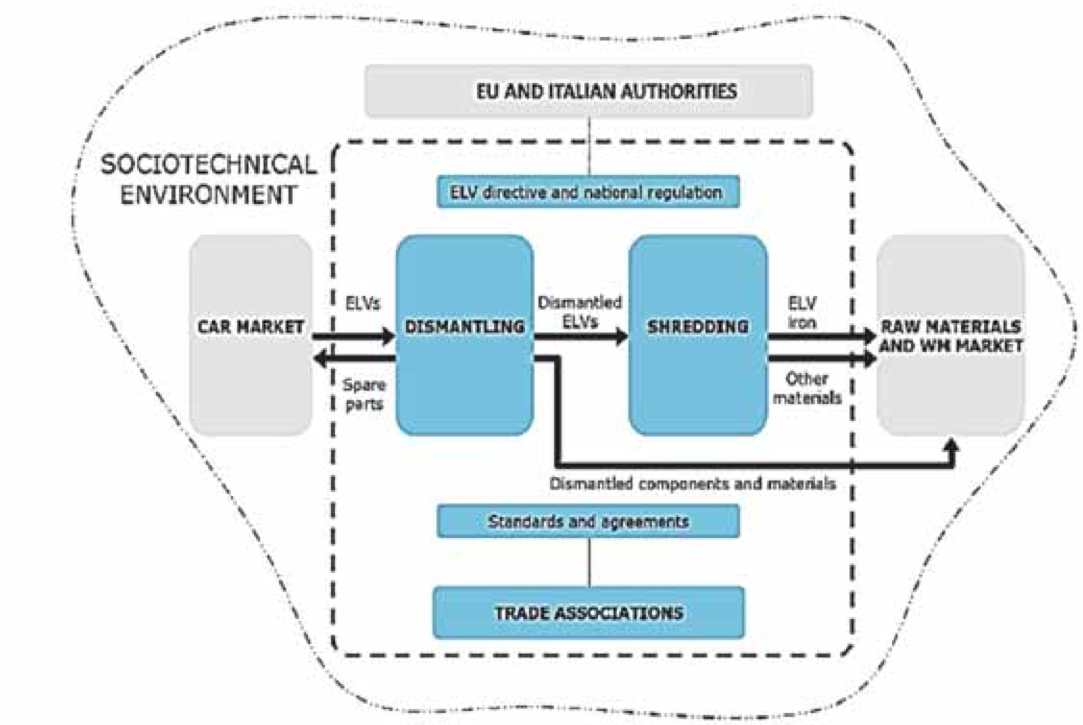


Fig. 1. The model used for studying the innovation of system of vehicle recycling in Sweden in 1910-2010, then re-elaborated for Italy. WM = waste management (Andersson, 2016; Bergek et al., 2008; Hekkert et al., 2007)

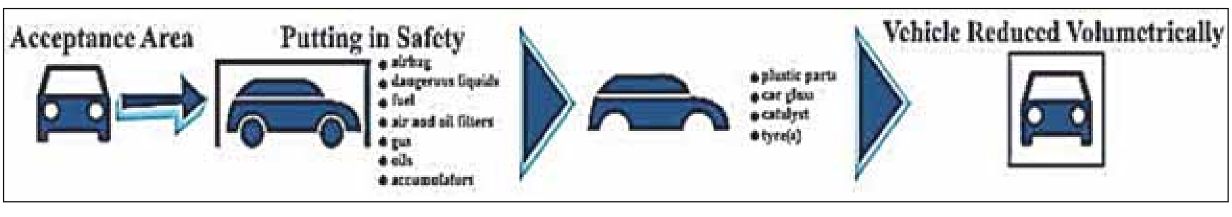


Fig. 2. “Dis-assembly” chain (EC, 2007a; 2003; GHK, 2006)

Automotive recycling must essentially be based on two main production lines:

1. *waste management and treatment line* (Fig. 3), for recycling and recovery of materials;

2. *valorisation line of spare parts* (Fig. 4), finalised to a second use of material.

To ensure these processes, every plant must be adequately equipped in terms of surface and technologies.

In particular, the dimensioning of a plant type of demolition must consider the surface available as input in which to imprint the treatment site, that is to say: *L = Ground area of an industrial complex* .

Within each batch the following management areas must be identified as the following:

• Treatment Areas – A – (Table1);

• Functional accessory Areas – P – (Table 2);

• Waste and material storage Areas – S – (Table 3);

• Buildings – E – (Table 4).

It can be summarised by the Eqs. (1-5):

$$L=A+P+S+E \quad (1)$$

Eq. (1) means:

$$A=Aa+Amis+Ads+Ap \quad (2)$$

$$P=Pc+Pamis+Pads+Pap+Pm \quad (3)$$

$$S=Svmis+Srnp+Srp+Svp \quad (4)$$

$$E=Eu+Er \quad (5)$$

Once the areas are identified, it is necessary to combine linear and volumetric measures to make them suitable for the individual operational phases. *Guidelines on the treatment of end-of life vehicles. Technological and management aspects* (*Linee guida sul trattamento dei veicoli fuori uso. Aspetti tecnologici e gestionali)* (ISPRA, 2004), a document of ISPRA – Italian Higher Institute for Environmental Protection and Research (Istituto Superiore per la Protezione e la Ricerca Ambientale) has been considered as a national legislative reference for the internal dimensional and thematic subdivision of a standard automotive recycling area (500 vehicles/year). This document presents a type subdivision of an automotive recycling plant of about 2525 m².

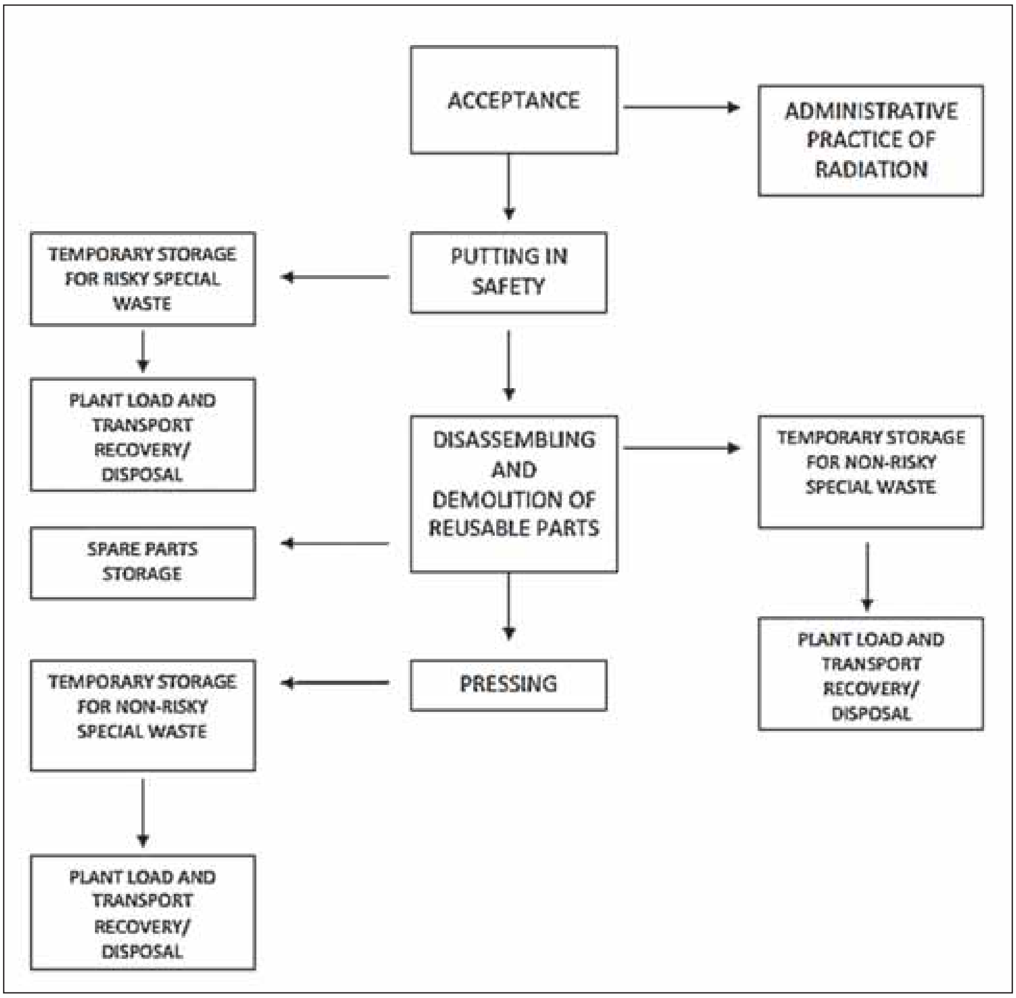


Fig. 3. Flow chart of the operating cycle: End-of-Life Vehicle (ELV) Management and Treatment (EC, 2007b; 2003; GHK, 2006)

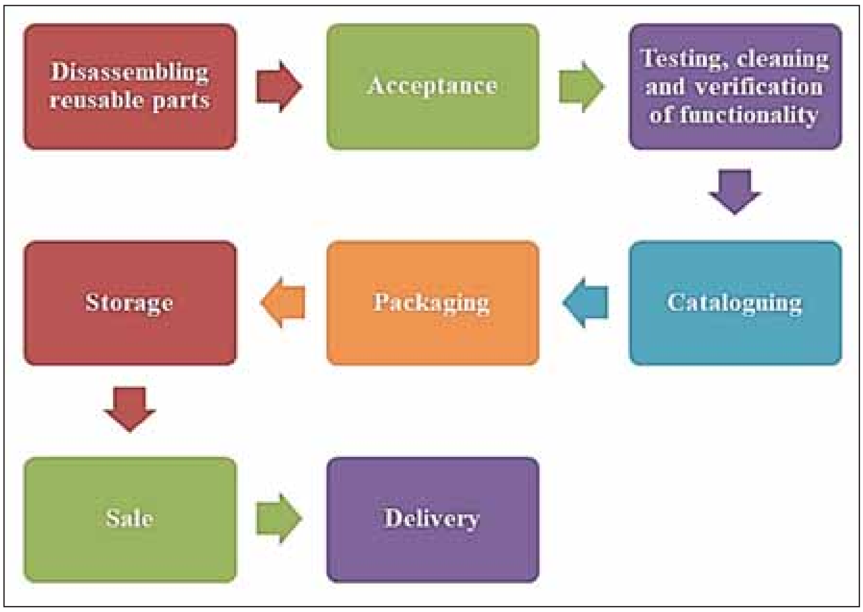


Fig. 4. Flow chart: original used spare parts line

Table 1. Treatment areas – A –

A_a	*Acceptance Area*	Identification, marking and preparation of the vehicle for treatment.
A_{mis}	*Area for the putting in safety of end-of-life vehicles*	The end-of-life vehicle changes state from hazardous special waste to non-hazardous special waste. The hazardous components are removed off the vehicle.
A_{ds}	*Area for the demolition and the dissembling operations*	All the spare parts that can be valorised in the second-hand market are taken out of the vehicle and transformed into non-hazardous special waste for recycling.
A_p	*Area for pressing on end-of-life vehicles (ELV)*	The vehicles, without the primary components that can be reused and recovered, are adjusted volumetrically to optimise the following phase of transfer towards the crushing plants.

Table 2. Functional accessory areas – P –

P_c	Parking space for clients
$P_{a\text{-}mis}$	Parking space for vehicles waiting for the putting in safety
$P_{a\text{-}ds}$	Parking space for vehicles waiting for the dismantling and the disassembling operations
$P_{a\text{-}p}$	Parking space for vehicles waiting for the pressing operations
P_m	Manoeuvring and general traffic areas

Table 3. Waste and material storage areas – S –

$S_{v\text{-}mis}$	Storage of vehicles put in safety
S_{rnp}	Storage of non- hazardous waste produced from the treatment
S_{rp}	Storage of hazardous waste produced from the treatment
S_{vp}	Storage of volume-reduced end-of-life vehicles (ELVs)

Table 4. Buildings – E –

E_u	Administrative offices building
E_r	Spare parts warehouse

The subdivision, taken as data, allowed to determine the percentage of breakdown of the individual areas within a site which are listed below (Table 5). These percentages are taken as a reference and applied to the parameter available to the project engineer (Eq. 6):

$$L = \text{Ground area of an industrial complex} \quad (6)$$

You can associate to a numeric value to the individual parameters (Eq. 7):

$$A+P+S+E \quad (7)$$

The linear distribution of the different areas makes (Eq. 1) it possible to determine the central parameter of a process of construction of an automotive recycling plant that is the processing capacity (Eq. 8):

$$Ct = number\ of\ vehicles\ that\ can\ be\ managed \quad (8)$$

Through the number above (Eq. 6) and assuming an average product composition of a vehicle (Fig. 5b) (Table 6), it is possible to determine the quantities of special waste, hazardous and non-hazardous, which can be generated by treatment and which must be stored and managed within a production site, and the quantity of spare parts obtainable from the disassembling of vehicles.

Table 5. Car demolition areas proportions

Typology	*Proportions (%)*
Acceptance Area	18
Treatment Area	4
Spare Parts Warehouse	4
Hazardous Waste Storage Area	2
Recoverable Waste Storage Area	8
Volumetric Reduction Sector	49
Storage for the Vehicle Safety Process	5
Offices and Services	2
Traffic Area	8
Total Area for the Automotive Recycling Plant	**100**

3. Results and discussion

The results of the current document are an ideal formula, presented on a spreadsheet that allows sizing a plant of treatment of end-of-life vehicles from the actual data of extension of the lot that an operator has available. The sizing allows obtaining the production capacity of the site in terms of the number of the end-of-life vehicles that can be treated safely and, in an environment, -friendly way within a site. The assessment of the treatment capacity ensures that the project engineer can analytically determine the quantities of waste produced during treatment.

Based on the production of special waste that allows the study the most suitable dimensions of the appropriate keeping areas, the size of various storage areas can be determined. Once the storage areas are identified, it is possible to determine the quantities of special waste, hazardous and non-hazardous, which can be stored instantaneously, in compliance with the criteria of safety and environmental impact during a calendar year. These data are the fundamental numbers of the management of a plant. They become requirements and limits of the management of a plant and they are precisely described in the authorizing decree for each plant.

4. Conclusions

The transformation from automotive recycling into a “centre” of circular economy is fundamental for the innovative processes of a country system and such proposed formula can be a key instrument:

to make available to Public Administration and Institutions that are competent to issue authorized titles through which it is aimed to find out and agree in a prompt but punctual way for each treatment plant, its operative flow and then simulating environmental impact that is produced.

• The latter can be verified in various configurations of plant engineering for various modifiable input data in order to be able to create the best configuration possible;

• to make available to companies and their project engineers for the analytic determination of the above-mentioned presentation/point and the managing costs of a plant.

The proposed treatment allows, for each treatment plant, the achievement of the Logistics, Legislation, Future objectives (“LLF”):

• Logistics: creating and setting up a database of digital information that allows to trace back from the recovered spare parts or the waste product of the originally treated vehicle, and vice versa;

• Legislation: ensuring and documenting the recovery rates in line with the European norms;

• Future: organising the plants with specific lines targeted for the treatment of internal combustion end-of-life vehicles and electric and hybrid vehicles. These, currently, represent the waste of the future.

The treatment lines will have to be built to manage the electrical risk that arises with the putting in safety operations and disassembly of these vehicles, also the new types of waste produced, destined to the recovery and recycling.The Italian Senate set the goal to 2040 for the elimination of cars with internal combustion, also by providing a technological solution such as electric and hybrid vehicles.

Table 6. Average composition of a vehicle (MATREC, 2003)

Material	**%**	**Mass (kg)**
Steel	59	619.5
Zinc, Copper, Magnesium, Lead	2	21
Tyre	5.6	58.8
Cast iron	6.4	67.2
Aluminium	8	84
Plastic	9.3	97.65
Adhesives and Paints	3	31.5
Glass	2.9	30.45
Textile	0.9	9.45
Fluid	0.9	9.45
Miscellaneous	2	21
Total (Vehicle)	**100**	**1050**

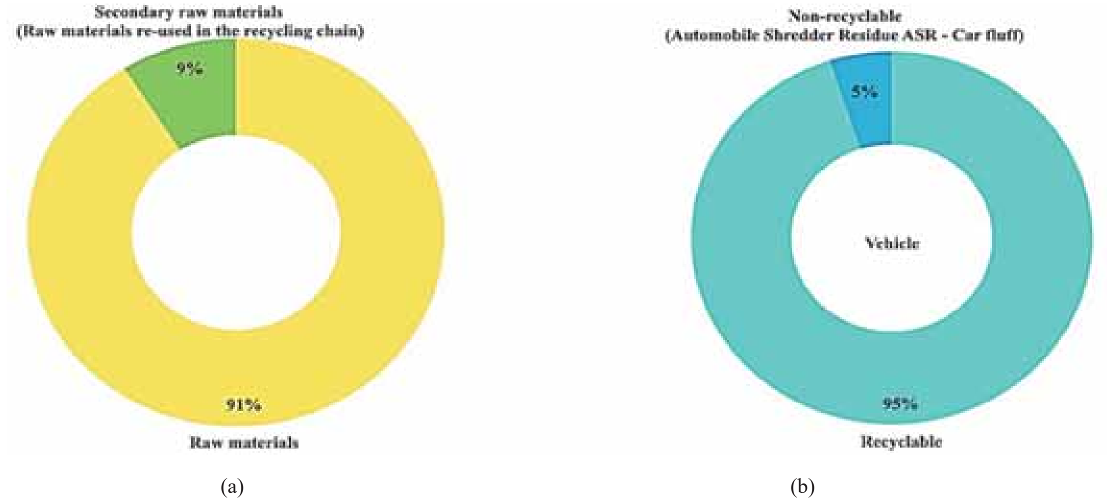


Fig. 5. Raw materials and vehicles: (a) percentage of raw materials usage and second raw materials in the world (EMA, 2015); (b) percentage of Recyclable and Non-recyclable Components (MATREC, 2003)

This innovation can really be sustainable only by completing, with its last phase, the "circle" of the automotive industry: providing facilities for automotive recycling in which it is possible to deal with the electrical risk generated by an end-of-life vehicle. The automotive recycling centre could be an instrument and operational source for the society against temperature rise and exhaust emissions of vehicles.

References

Andersson M., (2016), Innovating Recycling of End-of-Life Cars, Technical report no 2016:7 - Department of Energy and Environment - Chalmers University of Technology, Gothenburg, Sweden, On line at: http://publications.lib.chalmers.se/records/fulltext/235671/235671.pdf.

Bergek A., Jacobsson S., Sandén B.A., (2008), 'Legitimation' and 'development of positive externalities': two key processes in the formation phase of technological innovation systems, *Technology Analysis and Strategic Management*, **20**, 575-592.

EC, (2003), Report compiled for the Directorate General Environment, Nuclear Safety and Civil Protection of the Commission of the European, Reference document on best available techniques for the waste treatments industries -Heavy Metals in Vehicles II; Communities Contract No B4-3040/2000/300649/MAR/E.3, On line at: https://ec.europa.eu/environment/waste/studies/elv/heavy_metals.pdf.

EC, (2007a), Impact Assessment accompanying the Report on the Targets contained in article 7(2) of Directive 2000/53/EC on end-of-live vehicles –SEC (2007)14. 16/01/2007, On line at: https://secure.ipex.eu/IPEXL-WEB/dossier/document.do?code=SEC&year=2007&number=14&extension=FIN.

EC, (2007b), Report of the Commission of the European Council and the European Parliament on the aims referred in the art 7, paragraph 2, letter b), of the directive 2000/53/CE about end-of-life vehicles, COM 5. European Commission, 16/01/2007, On line at: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32000L0053.

EMA, (2015), Ellen MacArthur Foundation and the McKinsey Center for Business and Environment, Growth Within: A Circular Economy Vision for a Competitive Europe, On line at: https://www.ellenmacarthurfoundation.org/publications/growth-within-a-circular-economy-vision-for-a-competitive-europe.

FF, (2020), Sustainable Development Foundation and FISE UNICIRCULAR - Union of Circular Economy Companies, On line at: https://www.fondazionesvilupposostenibile.org/wp-content/uploads/dlm_uploads/L%E2%80%99Italia-del-Riciclo-2019.pdf.

Findomestic, (2019), The Findomestic Observatory 2019, On line at: http://www.osservatoriofindomestic.it/media/OSSERVATORIO_AUTO_2019_AGG_Singole2.pdf.

GHK, (2006), GHK-Bio Intelligence Service, A study to examine the benefits of the End of Life Vehicles Directive and the costs and benefits of a revision of the 2015 targets for recycling, re-use and recovery under the ELV Directive – Final report to DG Environment, On line at: https://ec.europa.eu/environment/waste/pdf/study/final_report.pdf.

Hekkert M.P., Suurs R.A.A., Negro S.O., Kuhlmann S., Smits R.E.H.M., (2007), Functions of innovation systems: A new approach for analysing technological change, *Technological forecasting and social change*, **74**, 413-432.

ISPRA, (2004), ISPRA-Higher Institute for Environmental Protection and Research ex-APAT – Agency for Environmental Protection and for Technical Services, Guidelines on the treatment of end-of life vehicles. Technological and management aspects (Linee guida sul trattamento dei veicoli fuori uso. Aspetti tecnologici e gestionali), On line at: http://www.isprambiente.gov.it/files/pubblicazioni/manuali-lineeguida/Linee_guida_Veicoli_fuori_Uso_Fonte_APAT_20051.pdf.

Levizzari A., (2001), The end of life of the car: technological and environmental perspectives-FIAT Research Center, Turin, Italy.

Laraia R., Foschini F., Frittelloni V., (2007), *Management of End-of-Life Vehicles: Current Status and Perspectives*, Ecomondo seminar, Ecomondo Conf. 2007-11th International trade fair for material and energy, Rimini, Italy.

MATREC, (2003), MATREC – Sustainable Materials and Trends, Material Recycling, Report Jun 2003, Ancona, Italy, On line at: https://www.reportlinker.com/market-report/Recycling/8162/Recycling?utm_source=adwords1&utm_medium=cpc&utm_campaign=Energy_And_Environment&utm_adgroup=Recycling_Trends&gclid=EAIaIQobChMIk8r_kJfr7AIVIwZ7Ch1W9QoyEAAYASAAEgIfavD_BwE.

Environmental Engineering and Management Journal October 2020, Vol. 19, No. 10, 1755-1763
http://www.eemj.icpm.tuiasi.ro/; hiip://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

DEVELOPMENT OF A SELECTION SYSTEM BASED ON HYPERSPECTRAL IMAGING FOR PLASTIC WASTE WITH BROMINATED FLAME RETARDANTS

Giuseppe Bonifazi[1], Ludovica Fiore[1*], Pierre Hennebert[2], Silvia Serranti[1]

[1]*Department of Chemical Engineering, Materials & Environment (DICMA), Sapienza – University of Rome, Via Eudossiana 18, 00184, Rome, Italy*
[2]*INERIS, French National Institute for Industrial Environment and Risks CS 10440, 13592, Aix-en-Provence Cedex 03, France*

Abstract

Brominated flame retardants (BFRs) are used in different types of products such as plastic, textiles and electronic circuits with the aim to increase fire resistance and to avoid or to delay the propagation of accidental combustion. However, high concentrations of bromine in waste from electrical and electronic equipment (WEEE) hinder the possibility of their use as secondary raw materials. Furthermore, the possibility that BFRs can be released during mechanical recycling processes, imposes the need for *ad hoc* separation processes through an appropriate selection system.

In order to adopt solutions based on the circular economy, it is necessary to develop an efficient strategy for selecting plastic waste containing BFRs from waste flow addressed to recycling. In this perspective, the use of a rapid and non-destructive technique, such as hyperspectral imaging (HSI), represents a powerful solution for the identification and to perform quality control of plastics waste. The study aims to develop a new methodology based on HSI in the short-wave infrared range (SWIR: 1000-2500 nm) coupled with chemometrics and X-ray fluorescence analysis in order to discriminate plastic waste with BFRs into two classes (low Br <2000 mg/kg and high Br> 2000 mg/kg) in agreement with the limits recommended by technical specification for WEEE. The promising results achieved suggest that this methodology may be applicable for the separation of plastics containing BFRs in recycling plants.

Keywords: hierarchical PLS-DA analysis, Plastic recycling, SWIR hyperspectral imaging, X-ray fluorescence

Received: February, 2020; Revised final: June, 2020; Accepted: July, 2020; Published in final edited form: October, 2020

1. Introduction

Waste from electrical and electronic equipment (WEEE) is very complex and rich in materials that can be recycled after specific treatments. They mainly consist of ferrous metals (45%), plastics (20%), copper (7%), aluminum (5%), glass (5%) and other materials like ceramics and wood (Huisman et al., 2008). The greatest difficulty in WEEE plastics recycling is the variety of types of polymers and additives. WEEE plastics including acrylonitrile-butadiene-styrene (ABS), polystyrene (PS), high-impact polystyrene (HIPS), polyethylene (PE), polypropylene (PP), styreneacrylonitrile (SAN), polyesters, polyurethane (PU), polyamide (PA), blends of polycarbonate (PC/ABS) and blends of HIPS/poly (p-phenylene oxide) (PPO) (Ma et al., 2016). Also, WEEE plastics are usually mixed whit additives as well as flame retardants, colorants, stabilizer and others (Buekens and Yang, 2014). About 5% of WEEE plastic contains brominated flame retardants (BFRs) (Huisman et al., 2008) and therefore must be removed from WEEE. Some BFRs have been banned by the European Union because they can cause serious risks to human health and environment such as endocrine disruption, damage to the thyroid, development and reproduction. Furthermore, if manual or automatic sorting phases are not correctly

*Author to whom all correspondence should be addressed: e-mail: ludovica.fiore@uniroma1.it; Phone: +39 0644585360

implemented during the recycling process, these hazardous substances could be released (EC Directive, 2011a).

BFRs are frequent in Europe in plastics from vehicles, construction products, textiles and non-food packaging (EC Directive, 2011b). In a recent review of literature data, all these plastics have at least one BFR with a mean concentration above the EU regulatory concentration limit for substances, products or hazardous waste (Hennebert, 2020). The proportion of data below these concentration limits extends to 84% for plastics from electrical and electronic equipment, 88% for plastics from vehicles, 92% for plastics from construction and demolition materials, 84% for plastics from textiles and upholstery, and 91% for plastics from non-food packaging. These plastic fractions must be sorted to ensure the quality of the secondary material in the circular economy (EC, 2017; EC, 2019). The distribution of the reported concentrations of these additives is skewed by some large values. The last centile (i.e. most concentrated centile) of the population largely multiplies the mean concentration of a set of particles. It is necessary to identify these last centiles and separate them. For batches, special provisions for representative sampling by numerous measurements are necessary.

For characterization, prior to expensive and time-consuming laboratory analysis, screening methods are recommended to identify the parts or scraps of brominated plastics (UNEP, 2017). The standard method today is portable XRF for field campaign. For sorting, a technical specification (CENELEC CLC/TS 50625-3-1, 2015) recommends the separation of WEEE plastic with a concentration limit of 2000 mg/kg for Br. The methods currently used for are:

- density by flotation in a liquid (dense non-brominated plastics are lost);
- density by in-line X-ray transmission (XRT) (less sensitive and subject to deviations in practical use in sorting centers; dense non-brominated plastics are lost);
- elements by X-ray fluorescence (XRF): this standardized method quantifies the elements and exists in portable mode and recently in sorting machine mode.

The present work explores the possibility of identifying bromine above and below 2000 mg/kg of plastic samples using HSI working in the SWIR range. In recent years, such an approach has been applied to various fields and in particular to plastic waste classification (Bonifazi et al., 2018; Bonifazi et al., 2019; Serranti et al., 2019). The advantages of this approach are cheaper device, on-line automatic sorting, use of harmless light (no special X-ray permit or habilitation necessary) and potential combination with polymer identification, for a complete sorting to produce high purity secondary material.

One of the disadvantages of SWIR spectroscopy is that black polymers cannot be identified. The black color is obtained by adding 0.5 to 3 mass percent soot or black master batch in the polymer melt during the extrusion process (Becker et al., 2017). Black plastic waste absorbs all light, therefore polymer recognition by SWIR spectroscopy is difficult. For this reason, an HSI model was built in order to first identify light and dark colored plastics and then to classify the light ones based on their Br content, setting the threshold at 2000 mg/kg, according to the limit set by technical specifications.

2. Material and methods

2.1. Material

The analyzed samples are plastic scraps from mixed large household appliances (e.g. washers, dryers, dishwashers, etc.) and end-of-life vehicles and were provided by Galloo Plastics, a company specialized in plastic recycling located in Hallu (France). Overall, 66 plastic samples characterized by different polymers (ABS and PS), bromine content, color and weight were selected (Fig. 1).

The scraps were first analyzed by XRF using a portable X-ray fluorimeter (XRF) in order to measure their Br content and then, based on the results, they were divided into two datasets for the construction of the HSI classification model. More in details, 37 scraps were selected for the training set and 29 scraps for the validation set.

2.2. Methods

2.2.1. X-ray fluorescence

The scraps were analyzed for total bromine by portable X–ray fluorescence (XRF) spectrometer. A hand-held XRF Niton XL2 with benchtop stand and software dedicated for plastics (with automatic thickness correction) was used for Br measurements.

2.2.2. Hyperspectral imaging analysis

The hyperspectral images of plastic waste samples were acquired by SISU ChemaXL™ Chemical Imaging Workstation (Specim, Finland) equipped with ImSpector™ N25E imaging spectrograph, working in the SWIR range (1000-2500 nm). A 31 mm lens with a field of view of 50 mm was adopted. The spectral resolution was 6.3 nm.

The spectrometer captures a line image of a target and disperses light from each line image pixel to spectrum. Each spectral image contains line pixels in spatial axis and spectral pixels in spectral axis. Through the hyperspectral pushbroom imaging device, a three-dimensional data cube is obtained, where the two-dimensional image contains spatial information in one dimension and spectral information in the other (Harsanyi, 1994; Polder and van der Heijden, 2001). HSI acquisitions were carried out at RawMaLab (Raw Materials Laboratory) of the Department of Chemical Engineering, Materials & Environment. The spectral data were processed using PLS-Toolbox™ (Version 8.8 Eigenvector Research, Inc.) working into Matlab® environment (Version 7.11.1, The Mathworks, Inc.).

Fig. 1. The investigated plastic scraps from mixed large household appliances and end-of-life vehicles

2.2.2.1. Spectra preprocessing and Principal Component Analysis (PCA)

Regions of Interest (ROI) were selected on the acquired images of plastic samples to obtain the average raw reflectance spectra. Subsequently, data were preprocessed in order to emphasize the different spectral features using scatter correction methods and spectral derivatives. Standard Normal Variate (SNV) was used in order to decrease the effect of light scattering, 1st Derivative to heighten both additive and multiplicative effects in the spectra. Derivation technique uses smoothing in order to reduce the signal-to-noise ratio and, therefore, to emphasize spectral ranges.

Finally, Mean Centering (MC) was applied to center the data with respect to their average in order to eliminate the data offset not important for the analysis (Rinnan et al., 2009). Moreover, in order to describe the multivariate nature of the data, Principal Component Analysis (PCA) was utilized. PCA is an unsupervised method allowing to reduce the size of data keeping as much as possible the variation present in the data set (Bro and Smilde, 2014; De Juan et al., 2009). PCA consists of mathematical decomposition of data matrix X obtained from two smaller matrices T (score matrix) and P (loading matrix). The residue matrix (E) identifies the noise component. The columns in the P matrix are also called principal components (PCs) and are determined to be mutually orthogonal (Cordella, 2012; Wold et al., 1987). The PCA can be formulated as (Eq. 1):

$$X = TP^T + E = t_1p_1^T + \cdots + t_Rp_R^T = \hat{X} + E \quad (1)$$

where: $T=[t_1, \ldots, t_R]$ (I×R) and $P=[p_1, \ldots, p_R]$ (J×R) being I and J the number of samples and variables, respectively, and R the significant retained components in the PCA model.

The original data are plotted on an X-axis and a Y-axis, PCA rotates the original X and Y-axes so that the new axis X' is in the direction of the maximum variation in the data. Since the axes are perpendicular, the choice of the X will automatically determine Y'. For more than two dimensions, the first axis is in the direction of most variations; the second, in the direction of the closest variation and so on (Wallisch, 2014). Each PC describes a specific amount of contained variance of the data matrix X and a maximum of variance which has not yet been achieved by the precedents. Through the PCA, it is possible to obtain the distribution in subgroups of the data because this method detects spectral similarities between the samples (Jolliffe, 2002).

2.2.2.2. Classification by Hierarchical Partial Least Squares Discriminant Analysis (HI-PLSDA)

Plastic sample classification was performed using HI-PLSDA modelling. PLSDA is a linear classification method capable of detecting the sources of data variability by combining the properties of partial least squares regression with classification techniques. The classification method is performed by selecting samples belonging to known classes (training dataset) on which a classification rule is built. The model obtained is validated using an unknown data set (validation dataset) (Barker and Rayens, 2003). The classification of the samples is estimated by choosing the class that has the highest probability; the membership threshold of a class is calculated on the basis of the Bayes theorem. In this way, the samples are always classified in one of the classes. Venetian Blinds was used as cross–validation method for evaluating the complexity of the predictive model and to select the number of Latent variables (LVs) (Ballabio and Consonni, 2013). In this case, 4 LVs were chosen for the model.

The HI-PLSDA model was built to discriminate plastic scraps from mixed large household appliances and end-of-life vehicles. Through the hierarchical model, the classification problems were broken down into sub-groups with single PLS-DA models handling the detail of the problem (Bonifazi et al., 2018). In Fig. 2 it is shown the developed HI-PLSDA model. It is based on two discrimination rules. In "*Rule 1*", samples are divided by color in two classes: light color (white and light grey) and dark color (black and dark grey).

In "*Rule 2*", samples with light color are divided in two classes characterized by values of bromine content above (Br> 2000 mg/kg) and below (Br < 2000 mg/kg) the limits recommended by the technical specifications for WEEE. The parameters used to evaluate the model performance are *Sensitivity* and *Specificity*; the first estimates the model ability to avoid false negatives while the second estimates the model ability to avoid false positives (Amigo et al., 2015). They assume values between 0 and 1, where 1 is the ideal value for the model.

3. Results and discussion

3.1. X-ray fluorescence

The bromine concentration of the samples was measured by XRF. The samples were then divided in two groups based on the Br content: above (High Br > 2000 mg/kg) or below (Low Br < 2000 mg/kg) the limit set by the legislation. Color, weight and bromine content for each investigated sample are reported in Table 1.

3.2. Hyperspectral imaging

3.2.1. Spectral analysis and Principal Component Analysis (PCA)

The average raw reflectance spectra of plastics characterized by light and dark color for "*Rule 1*" of HI-PLSDA model are shown in Fig. 3a. The spectral signature of dark plastic is flat, confirming that it cannot be utilized for polymer recognition, due to the absorption of all light.

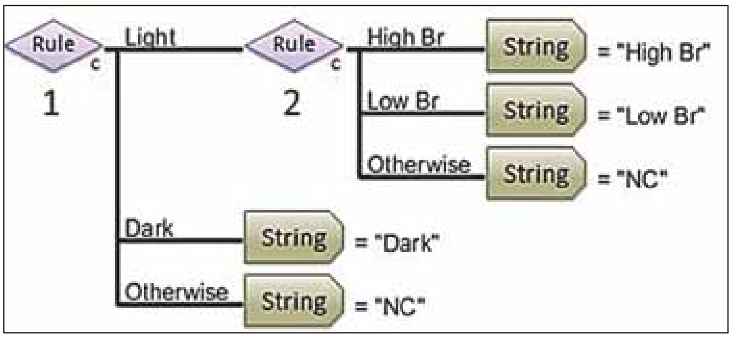


Fig. 2. HI-PLSDA model built to classify the samples based on colour and bromine content

In order to highlight the differences between the two selected classes for "*Rule 1*", spectral data were preprocessed using Mean Center (MC) (Fig. 3b).

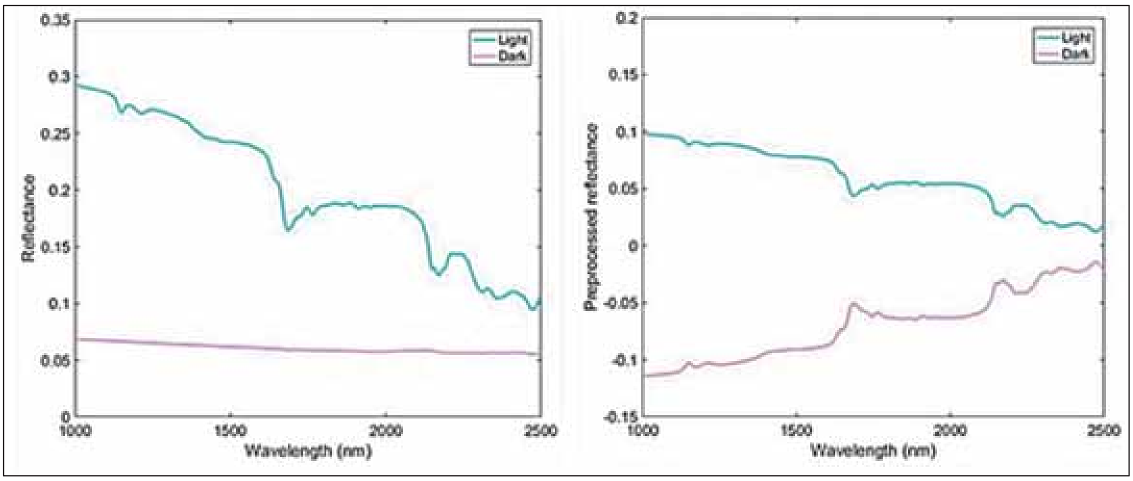
Projection of the samples on the space spanned by the first and second principal components is reported in Fig. 4. Most of the variance was captured by the first two PCs, PC1 and PC2 explain 54.12% and 14.12% of the variance, respectively. The spectral data of the polymer samples are clustered in two groups according to their spectra. More in detail, the PC1 negative values identify the samples with light color while the PC1 positive ones identify those characterized by dark color.

Concerning "*Rule 2*", Fig. 5a shows the average raw reflectance spectra of the two classes of plastics characterized by values above and below the Br threshold. The SWIR range is very useful to identify the polymer type because the spectral features are related to the overtone bands of fundamental groups containing C–H and O–H bonds (Workman and Weyer, 2012).

The spectra of the investigated plastic samples are characterized by absorptions around 1200 nm due to the first overtone of O–H and N–H stretching and by absorptions around 1450 nm due the combination bands of the C–H stretching (Stuart, 2004).Spectral data were pre-processed using a combination of the following algorithms: Standard Normal Variate (SNV), 1st Derivative (11pt), and Mean Center (MC) (Fig. 5b). .

Table 1. Main characteristics of plastic waste from mixed large household appliances and end-of-life vehicles

Sample	*Color*	*Weight (g)*	*Br (mg/kg)*	*Sample*	*Color*	*Weight (g)*	*Br (mg/kg)*
S1	White	12.09	7	S34	Grey	9.70	109424
S2	Grey	13.05	7	S35	White	3.28	4
S3	Grey	3.14	118349	S36	White	8.56	21
S4	Black	7.86	6	S37	Black	10.85	3909
S5	Grey	4.07	11	S38	Grey	4.03	145300
S6	Grey	8.51	90890	S39	White	1.30	76448
S7	Black	24.95	15	S40	White	9.41	95227
S8	Grey	8.72	32	S41	Grey	7.11	106624
S9	White	16.25	23	S42	White	6.56	3
S10	Grey	17.4	121726	S43	Grey	2.92	126758
S11	Grey	8.87	60	S44	Grey	4.48	5
S12	Black	3.66	6	S45	Black	7.51	59803
S13	Grey	5.72	107544	S46	Black	7.12	72572
S14	Black	6.51	8	S47	Grey	3.97	8
S15	White	5.06	5	S48	Grey	9.44	124981
S16	White	3.81	53	S49	Black	7.59	100884
S17	Black	5.43	12	S50	Black	3.41	5536
S18	Black	2.10	6	S51	Grey	8.72	6
S19	Grey	1.72	56033	S52	Grey	9.81	33
S20	Black	7.51	5	S53	Grey	9.09	7
S21	Grey	8.15	8	S54	White	7.68	82575
S22	Grey	1.07	66206	S55	White	3.93	85969
S23	Grey	8.26	6	S56	White	9.23	94670
S24	Grey	3.53	88203	S57	Grey	2.58	100119
S25	Grey	6.59	6	S58	Grey	3.58	69242
S26	Grey	3.15	5	S59	White	2.70	73127
S27	Grey	6.80	105946	S60	Grey	3.43	109025
S28	Black	3.58	7	S61	Black	3.76	57990
S29	White	7.66	4	S62	Black	3.81	79757
S30	Black	4.76	4	S63	White	1.71	109007
S31	Grey	1.07	77443	S64	Black	4.53	2761
S32	Black	3.01	11	S65	Grey	8.81	26860
S33	Grey	8.70	12	S66	Black	4.36	11279



(a) (b)

Fig. 3. Average raw reflectance spectra (a) and average pre-processed reflectance spectra (b) of plastic waste samples acquired by HSI in the wavelength range 1000-2500 nm, representative of the two classes characterized by light colour (white and light grey) and dark colour (black and dark grey)

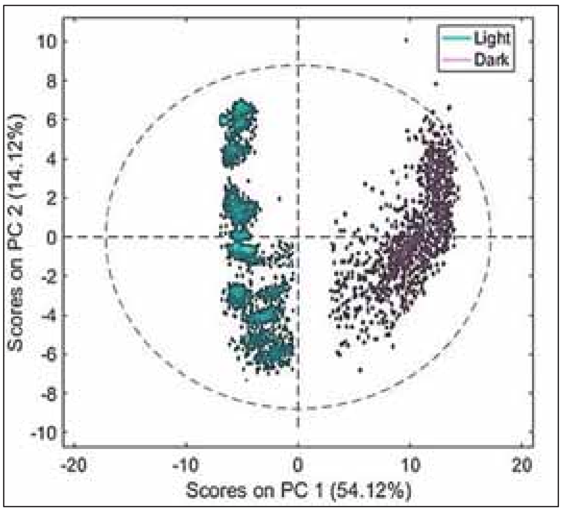
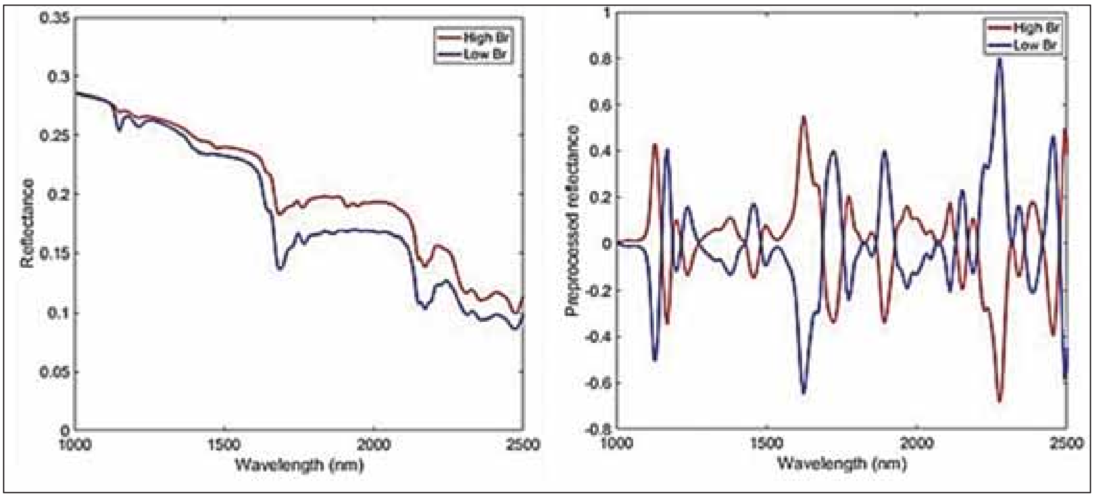


Fig. 4. PC1-PC2 score plot of the plastic samples constituting the training set for the two groups characterized by light and dark colour



(a) (b)

Fig. 5. Average raw reflectance spectra: (a) and average pre-processed reflectance spectra; (b) of the plastic waste samples acquired by HSI in the wavelength range 1000-2500 nm, representative of the two classes characterized by high (Br> 2000 mg/kg and low (Br < 2000 mg/kg) bromine content

The results of PCA are reported in Fig. 6. Most of the variance was captured by the first two PCs, in fact PC1 and PC2 explain 59.47% and 13.78% of the variance, respectively. The PC1 positive values identify samples with high bromine content (Br> 2000 mg/kg) while the PC1 negative ones identify those with low content (Br < 2000 mg/kg).

3.2.2. Classification by Hierarchical Partial Least Squares Discriminant Analysis (HI-PLSDA)

The HI-PLSDA model was built and applied to the validation dataset. The results of the classification are reported in Fig. 7, in terms of prediction image, showing that most of the samples were correctly identified and classified (green: light samples with high Br, blue: light samples with low Br and red: dark samples).

Only three samples with values of bromine content above the limit set by technical specifications were incorrectly classified as low bromine samples while in some other samples wrong predictions occur at the boundaries of the plastics. The *Sensitivity* and *Specificity* values, ranging from 0.996 to 1.000 (Tables 2-3), confirm the quality of the developed model

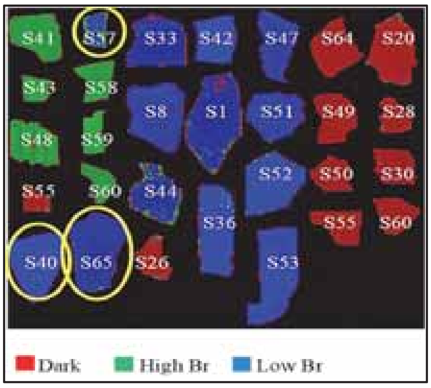


Fig. 7. Prediction map of the plastic validation set obtained after the application of the HI-PLSDA model. The plastic classes are dark colored, light colored with high Br (Br> 2000 mg/kg) and light colored with low Br (Br < 2000 mg/kg), corresponding to the red, green and blue particles, respectively. Samples circled in yellow (S40, S57 and S65) are incorrectly identified.

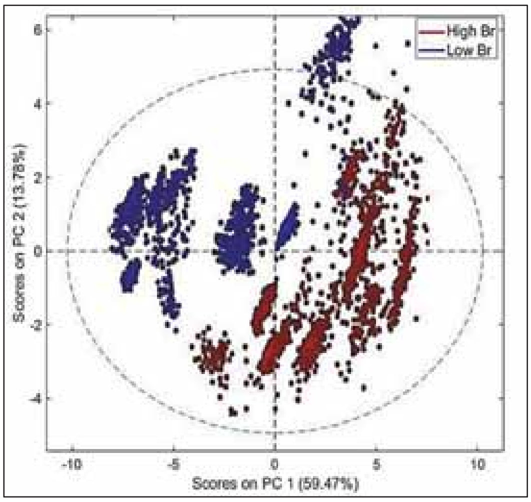


Fig. 6. PC1-PC2 score plot of the plastic samples constituting the training set for the two groups characterized by the presence of high (Br> 2000 mg/kg) and low (Br < 2000 mg/kg) bromine content

Table 2. *Sensitivity* and *Specificity* values for "*Rule 1*" of HI-PLSDA model built for the recognition of waste plastic samples characterized by light and dark color (black and dark grey)

		Light	***Dark***
Sensitivity	Calibration	0.996	1.000
	Cross validation	0.996	1.000
Specificity	Calibration	1.000	0.996
	Cross validation	1.000	0.996

Table 3. *Sensitivity* and *Specificity* values for "*Rule 2*" of HI-PLSDA model built for the recognition of waste plastic samples characterized by the presence of high (Br> 2000 mg/kg) and low (Br < 2000 mg/kg) bromine content

		High Br	***Low Br***
Sensitivity	Calibration	0.999	0.999
	Cross validation	0.999	0.999
Specificity	Calibration	0.999	0.999
	Cross validation	0.999	0.999

4. Conclusions

A procedure based on HSI in the SWIR region (1000-2500 nm) coupled with chemometrics methods was developed to demonstrate the high potentialities of such strategy in order to classify plastic waste based on their bromine content, according to the limit set by technical specifications.

Plastic scraps from mixed large household appliances and end-of-life vehicles were classified building and applying a HI-PLSDA model, in a fast and non-destructive way. The developed strategy allowed to identify first dark plastics, characterized by a flat spectrum, and light-colored ones. The latter samples were subsequently discriminated according to their bromine content (above or below 2000 mg/kg). The results shown that samples with bromine quantities exceeding the technical specification for WEEE, that cannot be recycled, were correctly classified. More in details, a good identification was achieved with 90% of samples correctly classified.

The proposed approach is very promising and could be further implemented at industrial level, contributing to solve a problem actually present in recycling plants for separation of plastic waste with high levels of BFRs, according to the limit set by regulation.

References

Amigo J.M., Babamoradi H., Elcoroaristizabal S., (2015), Hyperspectral image analysis. A tutorial, *Analytica Chimica Acta*, **896**, 34-51.

Ballabio D., Consonni V., (2013), Classification tools in chemistry. Part 1: linear models. PLS-DA, *Analytical Methods*, **5**, 3790-3798.

Barker M., Rayens W., (2003), Partial least squares for discrimination, *Journal of Chemometrics*, **17**, 166-173.

Becker W., Sachsenheimer K., Klemenz M., (2017), Detection of black plastics in the Middle Infrared Spectrum (MIR) using photon up-conversion technique for polymer recycling purposes, *Polymers*, **9**, 1-9.

Bonifazi G., Capobianco G., Serranti S., (2018), A hierarchical classification approach for recognition of low-density (LDPE) and high-density polyethylene (HDPE) in mixed plastic waste based on short-wave infrared (SWIR) hyperspectral imaging, *Spectrochimica Acta Part A*, **198**, 115-122.

Bonifazi G., Gasbarrone R., Palmieri R., Serranti, S., (2019), *Plastic Identification from End of Life Flat Monitors by Hyperspectral Imaging Methods*, The 17th Int. Waste Management and Landfill Symp., Sardinia 2019, 1-9.

Bro R., Smilde A.K., (2014), Principal component analysis, *Analytical Methods*, **6**, 2812-2831.

Buekens A., Yang J., (2014), Recycling of WEEE plastics: a review, *Journal of Material Cycles and Waste Management*, **16**, 415-434.

CENELEC CLC/TS 50625-3-1 (2015), Requirements for collection, logistics and processing for Waste Electrical and Electronic Equipment (WEEE) - Part 3-1: Specifications for depollution, CENELEC, Brussels.

Cordella C.B.Y., (2012), PCA: The Basic Building Block of Chemometrics, *Analytical Chemistry*, Ira S. Krull, Intech Open.

De Juan A., Maeder M., Hancewicz T., Duponchel L., Tauler R., (2009), Chemometric tools for image analysis, *Infrared and Raman Spectroscopic Imaging*, 65-109.

EC Directive, (2011a), Directive 2011/65/EC of the European Parliament and of the Council of 8 June 2011, on the restriction of the use of certain hazardous substances in electrical and electronic equipment (recast), *Official Journal of the European Union*, L 174/88/01.07.2011, Brussels.

EC Directive, (2011b), European Commission, Service request under the framework contract No ENV.G.4/FRA/2007/0066, Study on waste related issues of newly listed POPs and candidate POPs, 25 March 2011 (Update 13 April 2011), Consortium ESWI Expert Team to Support Waste Implementation, by Umweltbundesamt, BiPRO, Enviroplan.

EC, (2017), Strategy on Plastics in a Circular Economy, 26.01.2017, On line at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2018%3A28%3AFIN.

EC, (2019), Study to support the review of waste related issues in Annex IV and V of Regulation (EC) 850/2004, final report by Ramboll Environment and Health GmbH, January 2019.

Harsanyi J.C., (1994), Hyperspectral image classification and dimensionality reduction: an orthogonal subspace projection approach, *IEEE Transactions on. Geoscience and Remote Sensing*, **32**, 779-785.

Hennebert P., (2020), Concentrations of brominated flame retardants in plastics of electrical and electronic equipment, vehicles, construction, textiles and non-food packaging: a review of occurrence and management, *Detritus, Multidisciplinary Journal for Waste Resources and Residues*, doi 10.31025/2611-4135/2020.13997.

Huisman J., Magalini F., Kuehr R., Maurer C., Ogilvie S., Poll J., (2008), Review of directive 2002/96 on waste electrical and electronic equipment (WEEE), United Nations University, Bonn On line at: https://ec.europa.eu/environment/waste/weee/pdf/final_rep_unu.pdf.

Jolliffe I.Y., (2002), *Principal Component Analysis*, 2nd Edition, Springer Series in Statistics, Berlin-Heidelberg-New York.

Ma C., Yu J., Wang B., Song Z., Xiang J., Hu S., Su S., Sun L., (2016), Chemical recycling of brominated flame retarded plastics from e-waste for clean fuels production: A review, *Renewable and Sustainable Energy Reviews*, **61**, 433-450.

Polder G., van der Heijden G.W.A.M., (2001), Calibration and characterization of spectral imaging systems, *Proc. SPIE 4548*, 10-17.

Rinnan Å., van den Berg F., Engelsen S.B., (2009), Review of the most common preprocessing techniques for near-infrared spectra, *TrAC Trends in Analytical Chemistry*, **28**, 1201-1222.

Serranti S., Fiore L., Bonifazi G., Takeshima A., Takeuchi H., Kashiwada S., (2019), *Microplastics Characterization by Hyperspectral Imaging in the SWIR Range, SPIE Future Sensing Technologies*, Proc. of SPIE 11197, Tokyo, Japan.

Stuart B.H., (2004), Infrared spectroscopy: fundamentals and applications, *Analytical Techniques in the Sciences (AnTS)*, Wiley.

UNEP, (2017), Draft Guidance on Sampling, Screening and Analysis of Persistent Organic Pollutants (POPs) in Products and Articles, On line at:

http://chm.pops.int/Implementation/NIPs/Guidance/guidanceonsampling,screeningetcofPOPs/tabid/5333/Default.aspx.

Wallisch P., (2014), Principal Components Analysis, *MATLAB for Neuroscientists, An Introduction to Scientific Computing in MATLAB*, 2nd Edition, **19**, 305-315.

Wold S., Esbensen K., Geladi P., (1987), Principal Component Analysis, *Chemometrics and Intelligent Laboratory Systems*, **2,** 37-52.

Workman Jr.J., Weyer L., (2012), *Practical Guide and Spectral Atlas for Interpretive Near-Infrared Spectroscopy*, CRC Press.

Environmental Engineering and Management Journal

October 2020, Vol. 19, No. 10, 1765-1771
http://www.eemj.icpm.tuiasi.ro/; hiip://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

SFS-H PHYTOTREATMENT OXI-NITRO RATE TESTED IN STEADY-STATE ON ENGINEERING-UNIBO PILOT PLANT

Carmine Fiorentino*, Maurizio Mancini

Department of Civil, Chemical, Environmental and Materials Engineering – DICAM,
University of Bologna, Viale Risorgimento, 2 - 40136, Bologna Italy

Abstract

Natural wastewater treatment systems can represent a smart solution in small communities (50-2000 Population Equivalent) as they are very low-cost technologies in terms of energy consumption and maintenance. Moreover, those systems could be implemented as clean processes for wastewater reuse in the frame of circular economy applications. In this context the present study examines the main features of Subsurface Flow System - horizontal (SFS-H) phyto-treatment process. To this aim a pilot plant was built at University of Bologna in School of Engineering campus. The plant was equipped with an inlet water storage tank and two SFS-H tanks in parallel. Tanks are filled with the same sand/gravel medium while only one is equipped by *Phragmites australis*, commonly used in phyto-treatment applications. The study was developed in two main phases: firstly, we analysed the hydraulic behaviours, Hydraulic Retention Time (HRT) and conductivity, in steady state conditions and secondly, we focused on the treatment capacity in various HRT conditions. Measurement campaigns were conducted over around one year in order to compare Summer and Winter conditions. Results show an interesting ammonium removal efficiency (66%) when HRT is 30h, also in worst weather conditions during winter. Finally, we evaluated organic matter and nitrogen compounds removal capacity comparing the Oxygen Consumption Rate (OCR) with similar pilot treatment plants in wetland literature. OCR values result consistent, anyway we noted that they are strongly influenced by initial transitory time (around 3h).

Key words: irrigation, nitrification, SFS-H phyto-treatment, small plants, wastewater reuse

Received: February, 2020; Revised final: June, 2020; Accepted: July, 2020; Published in final edited form: October, 2020

1. Introduction

The increasing use of natural wastewater treatment systems in the last years is mainly due to their features: no energy and chemicals consumption or it is very low. Indeed, those systems represent an interesting solution for sewage treatment coming from small communities (50-2000 Population Equivalent). In the last years their use is increasing as clean processes for wastewater reuse, in the frame of circular economy applications. Wastewater reuse has a key role within the wider context of water reuse that becomes increasingly necessary due to water resources scarcity. Moreover , smart implementation of natural wastewater systems in association with agricultural uses could be a very interesting solution in the near future as the agricultural sector is responsible for about 70% of annual global freshwater withdrawals (BIO by Deloitte, 2015) (Sanz and Bernd, 2014).

From a regulatory perspective, a specific directive for wastewater reuse has not been implemented yet at European level. There are several European environmental directives and member states and regional regulations. This regulations heterogeneity, in terms of uses and permitted threshold values, represents one of the barriers to wastewater reuse development at European level. To overcome this barrier the European Commission (EC) is discussing about a Regulation proposal on minimum requirements for water reuse (EC, 2018). Table 1 shows the legal thresholds values for water reuse in

* Author to whom all correspondence should be addressed: e-mail: carmine.fiorentino2@unibo.it; Phone: +39 051 2093751

four European countries compared to EC Regulation proposal (EC, 2018), referred to six main parameters: Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Ammonium Nitrogen (NH_4^+), Total Nitrogen (TN), Total Phosphorus (TP), Total Suspended Solids (TSS).

Existing Wastewater Treatment Plants (WWTPs) have been designed to respect the threshold for discharge in natural water bodies so their adaptation to irrigation reuse will be an important challenge in the near future. Moreover, natural treatments have also been implemented for industrial and agro-industrial wastewater treatment. The full-scale implementation of Subsurface Flow System - horizontal (SFS-H) phyto-treatment systems in irrigation channels is recently studied (Tatoulis et al., 2017) (Andreo-Martínez et al., 2017).

In this context this study examines the main features of SFS-H phyto-treatment processes. We studied the oxidization performance in a submerged flow phyto-treatment bed, defined "natural appropriate system" by the Italian Laws on discharge, with the aim to test design criteria in order to obtain, in output, nitrogen values which guarantee onsite and neighbouring reuse. High values of NH_4^+-N, due to the related toxic NH_3–N equilibrium phase, can limit drastically the grow of crops, but also Total Nitrogen discharge in the soils must be taken into account because high concentrations can reduce the crops quality due to overstimulation, lodging or maturity delay (Lazarova and Bahri, 2004). Besides, a reduction of Nitrogen concentration enables discharging effluent wastewater after irrigation in water bodies, with a high tendency for eutrophication phenomena (Mancini, 2004).

The final aim of the study is to evaluate the oxygen transfer capability of roots to filtering bed in order to permit higher Hydraulic Retention Time (HRT) able to force nitrification and consequently to increase TN removal by denitrification. We study more particularly real HRT permitted by the filtering flow within the bed in function of very different steady-state alimentation conditions and we have paid attention to transitory times required to balance oxygen demand and rate transfer to the bed and to reach steady oxygen concentration.

A pilot plant has been designed and realised in "Bertalia campus" area of Engineering School of Bologna University in order to study the natural treatment aerobic processes of a SFS-H phyto-treatment plant charged with a similar domestic wastewater coming from bathrooms and bar activities of the school buildings.

The study was developed in two main phases. The first phase was necessary to set the experimental plant, looking for the HRT, Hydraulic conductivity (K) in different plant configurations as they were comparable to similar real plants. In the second phase Dissolved Oxygen (DO), pH and NH_4^+ were measured in each tank in different hydraulic conditions, developed during the first phase.

2. Material and methods

Experimentations have been carried out in existing pilot plant located in "Bertalia campus" of Engineering School of Bologna University. The main features of the SFS-H phyto-treatment process have been examined (Fig. 1). The pilot plant is fed by clean water and raw sewage from campus sewage system and is divided into two lines, named 0 and 1, consisting in two SFS-H tanks (Fig. 2). The tanks contain the same filling of sand (diameter = 2-4 mm), the first is used as blank (SFSh - 0) and in the second were planted *Phragmites australis* (SFSh - 1).

A sedimentation tank is placed before the tanks because the path is short and, as often happens in biofiltering beds, suspended solids could clog the following tanks gravel bed, after this pre-treatment phase the sewage is directly sent to the two (0,1) SFS-h tanks (Fig. 2).

The study was developed in two main phases:

- Phase A: Hydraulic steady state conditions: HRT and conductivity;
- Phase B: Process steady conditions: balance of oxygen and nitrification rate**.**

2.1. Phase A: Hydraulic steady state conditions: HRT and conductivity

The first phase was necessary to set the experimental plant looking for HRT, Hydraulic conductivity (K) in various plant configurations as they were comparable to similar real plants. Measurements have been executed using clean water in tests conducted from 25 May 2016 to 24 June 2017. Steady flow conditions were reached and controlled by calibration of valves openness which regulate input and output flow rates. In/out flow rates and openness degree of valves were compared until the achievement of each test condition. Three HRT conditions were studied: HRT = 1.5h-12h-30h (Fig. 3).

Table 1. BOD, COD, NH_4^+, TN, TP, TSS legal thresholds for water reuse in four European countries compared to the EC Regulation proposal

	BOD (mg/L)	*COD (mg/L)*	*NH_4^+ (mgN/L)*	*TN (mgN/L)*	*TP (mgP/L)*	*TSS (mg/L)*
Italy (DM, 2003)	20	100	2	15	2	10
France (AM, 2014)	-	60*	-	-	-	15*
Spain (RD, 2007)	-	-	-	10*	2*	5-35*
Greece (CMD, 2011)	10-25*	-	-	30*	1-2*	2-35*
EC Regulation proposal (EC, 2018)	10-25*	-	-	-	-	10-35*

**The limit is referred to several uses*

(a) (b)

Fig. 1. Buildings of the UNIBO School Engineering in the Bertalia Campus with identification of pilot plant location with red arrow (a). Front view of Phyto-treatment Pilot Plant based on subsurface flow (b)

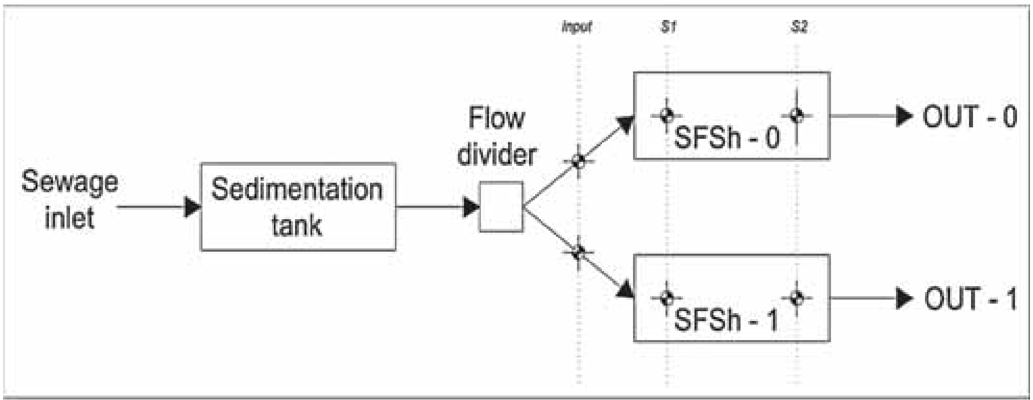


Fig. 2. Flow scheme implemented in the pilot plant during measurements campaigns

We measured input and output flow rate until the values were similar so it means that steady flow conditions were established. Experimental conditions were verified with the equation for SFS-h systems by Çakir et al., 2015 (Eq. 1) in each HRT condition:

$$HRT = \frac{L \cdot W \cdot n \cdot d}{Q} \quad (1)$$

where: *HRT* = Hydraulic Retention Time (h), *L*= bed length (cm) =75 cm, *W*= bed width (cm) = 45 cm, *n*= porosity (-) = 30%, *d*= filling high (cm) = 27cm, *Q* = flow rate (l/min).

Therefore, we calculate k using the usual formulation by Darcy Law (Eq. 2) in three flow rate conditions established before:

$$v = k \cdot i \quad (2)$$

where: *v* = velocity (cm/h), *i* = hydraulic gradient (-)

The hydraulic gradient (i) in hydraulic head has been verified by controls of water level within the sampling tubes (shown in Fig. 3b) inserted inside the filtering bed in correspondence to input/output sections.

2.2. Phase B: Process steady conditions: balance of oxygen and nitrification rate

During the second phase Dissolved Oxygen (DO), pH and Ammonium Nitrogen (NH4+-N) were measured in each tank in the different hydraulic conditions, investigated during the first phase, using the multiparameter system YSI 556, for DO and pH, and the Ion Selective Electrod Crison 9663C, for NH4+-N. Data have been collected during measurement campaigns conducted from 26 June 2016 to 24 July 2017.

DO, pH, NH4+-N and NO3-N were monitored by time step varying from 30 to 180 min in each scenario (HRT = 1.5h - 12h - 30h) (Fig. 4).

Second phase aims to study the aerobic conditions in the system as oxygen allows to remove organic matter and nitrogen compounds. More in details, we will compare oxygen trends with nitrification/denitrification capacity of the system with different HRT values, in order to obtain the output concentration respecting the legal thresholds.

In this context, oxygen transfer is one of the main rate-limiting processes in subsurface-flow treatment wetlands.

The prominent pathways of oxygen transfer in subsurface flow treatment wetlands are atmospheric diffusion, plant-mediated oxygen transfer, and convective flow of air within the pore space of the media (Nivala et al., 2013).

3. Results and discussion

3.1. Phase A: Hydraulic steady state conditions: HRT and conductivity

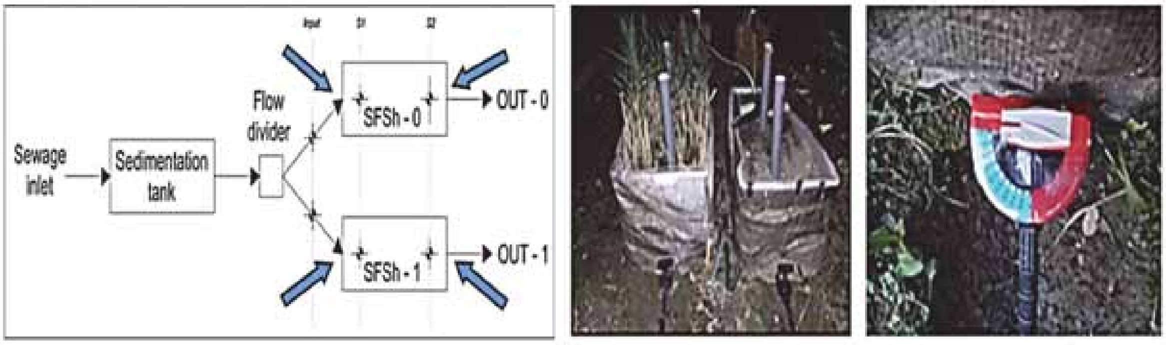
Experimental results reported in Table 2 represent the ingoing and outgoing flow rate calibration required to obtain and maintain steady flow conditions. Flow parameters into the biofiltering bed are reported in Table 3. Hydraulic conductivity resulting from Darcy law implementation and flow parameters into the biofiltering bed, in each HRT condition, are reported in Table 3.

Table 2. Openness calibration of IN/OUT hydraulic valve for each tested HRT

HRT (h)	*Q (l/min)*	*Hydraulic Valve Openness (°)*
	IN	
1.5	0.267	10 (without flow reducer)
12	0.038	50 (with flow reducer)
30	0.016	10 (with flow reducer)
	OUT	
1.5	0.300	20 (without flow reducer)
12	0.036	90 (with flow reducer)
30	0.016	20 (with flow reducer)

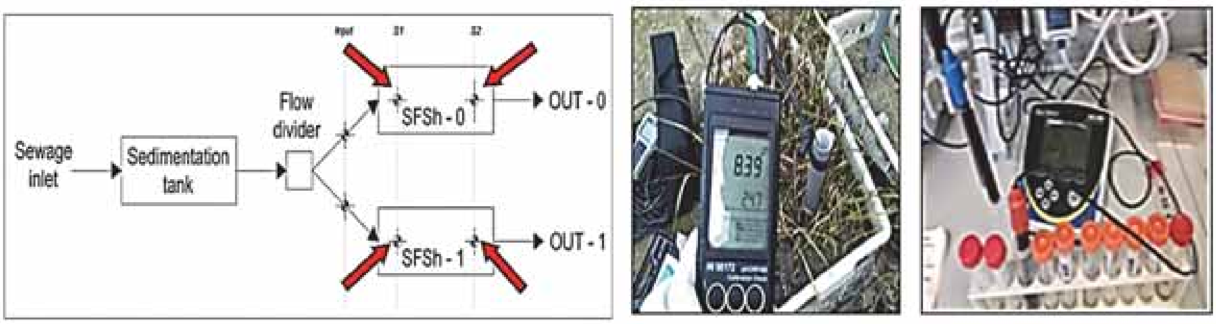
Table 3. Hydraulic parameters of the flow internal to the filtering bed related to each HRT condition

HRT (h)	*Q (cm³/min)*	*v (cm/h)*	*ΔH (cm)*	*i (-)*	*K (cm/h)*
1.51	300	37.04	1.1	0.0141	2626.74
12.65	36	4.44	0.10	0.0016	2629.85
29.53	16	1.98	0.05	0.0007	2645.50



(a) (b) (c)

Fig. 3. Pilot plant scheme with flow rate measurements points identified with blue arrows (a). SFSh-0 and SFSh-1 tanks view from the output (b). Detail of the regulation valves(c)



(a) (b) (c)

Fig. 4. Pilot plant scheme with measurement points for DO and pH and water level identified with red arrows (a). pH measurement system (b); Ion-Selective electrode for NH_4^+-N measurement (c)

3.2. *Phase B: Process steady conditions: balance of oxygen and nitrification rate*

The following graphs (Figs. 5-10) represent the initial transitory for DO, NH_4^+-N and NO_3^--N parameters respectively for HRT= 1.5 h, HRT= 12 h, HRT= 30 h.

Data in Fig. 5 show as not completely outraced the transitory from the initial conditions. It's detectable a clear oxygenation effect by roots of plants. The input rate in water maintains the DO level higher than the one measured in the reference bed without plants around 1 mg/L).

The registered trends of NH_4^+-N and NO_3^--N concentrations, as traced in Fig. 6, indicates as not outraced the initial transient phase for both parameters. The final efficiency in Ammonium Nitrogen removal, evaluable around 15 %, attests a very limited nitrification effect. As reported in Fig. 7, at the beginning of the test, it has been noted an oxygen consumption rate prevalent on the rate of oxygenation in wastewater of both filtering bed, with a decreasing trend for DO in outlet.

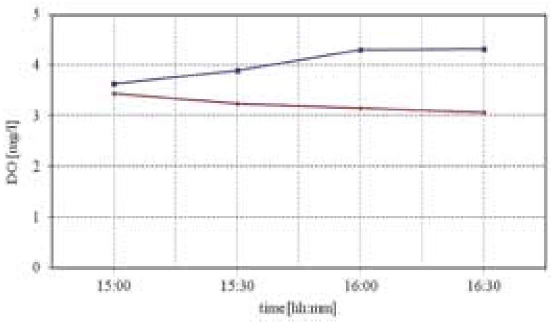


Fig. 5. HRT = 1.5 h - Dissolved Oxygen concentrations measured by YSI probe in S2 sampling tubes with plants (blue line) and without plants (red line)

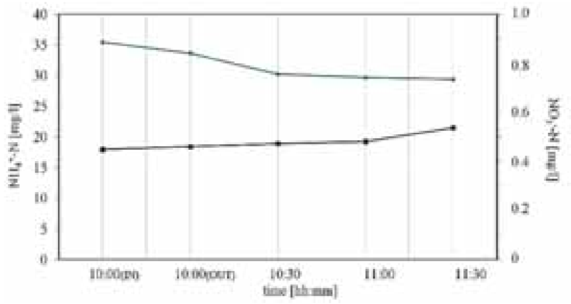


Fig. 6. HRT= 1.5 h - Ammonium (green line) and Nitrate (black line) concentrations in samples from S2 tubes

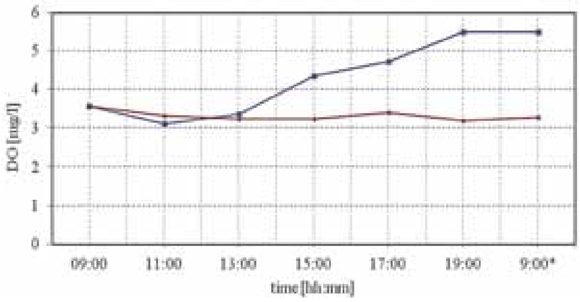


Fig 7. HRT= 12 h - DO concentration measured by YSI probe in S2 sampling tubes with plants (blue line) and without plants (red line).*day after

The phenomenon is due to the kinetic of carbonaceous BOD and to the conditions of the medium at starting of flow, which initially presents high oxygen demand for the release to the sewage of organic substances cumulated during the time of out-of-service. This transient phase appears to be limited to around two hours from start. The final steady condition shows a DO level equal to e 5.5 mg/L (about 2 mg/L higher than the not planted bed) and it is reached approximately after 10 h.

The transitory trend of the outlet concentration of ammonium nitrogen is complementary to that of dissolved oxygen and the regime condition, equally reached after about 10 hours, reveals an ammonium concentration of 19.5 mg/L (about 15 mg/L less than that of the not planted bed). The nitrification efficiency, after 12 hour of retention time, is evaluated around 43% (Fig. 8).

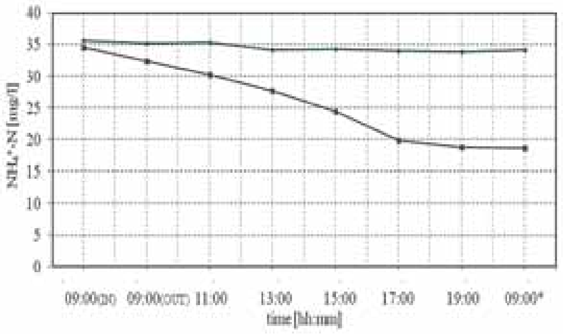


Fig. 8. HRT= 12 h - Ammonium concentration (NH_4^+-N) analysed in samples from S2 sampling tubes without plants (green line) and with plants (grey line).*day after

The graph in Fig. 9 shows that the regime condition for dissolved oxygen is reached after about 24 h and is characterized by a concentration of about 5 mg/L (also in this case about 2 mg/L higher than that of the not planted bed). The initial transient phase of oxygen demand due to the bed is included within the initial 3 hours.

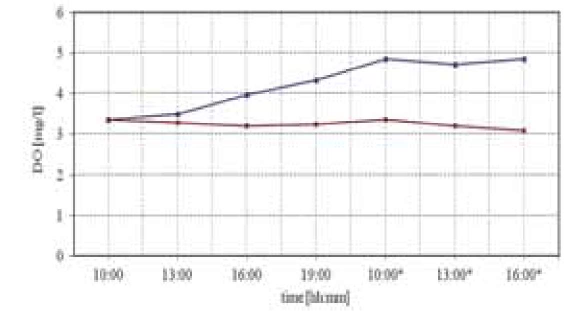


Fig. 9. HRT= 30 h - DO measured by YSI probe in S2 sampling tubes with plants (blue line) and without plants (red line).*day after

Also, the steady condition for nitrification is reached after about 24 h and it is characterized by an initial stretch with high slope during around 6 hours from start. The output regimen NH4+-N concentration becomes around 11 mg/L (in this case 20 mg/L less than not planted bed NH4+-N concentration).

Results of measurements carried out with HRT equal to 30 h show an interesting NH4+-N removal efficiency (66%)(Fig. 10).

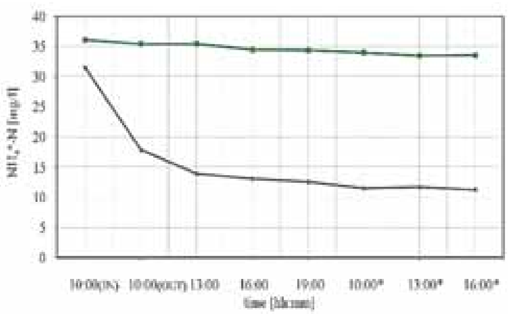


Fig. 10. HRT= 30 h - Ammonium concentration (NH_4^+-N) analysed in samples from S2 sampling tubes without plants (green line) and with plants (grey line).*day after

Anyway, ammonium output concentration does not guarantee yet the respect of the Italian legal threshold for reuse in irrigation (2 mg/L). To estimate the oxygen consumption in relationship with pollutants degradation in wetland processes the approach based on Oxygen Consumption Rate (OCR) estimation is commonly used. The equations proposed in wetland literature for OCR are related to surface of bio-filtering bed and estimation generally include: mass removed for a specific parameter as Biochemical Oxygen Demand, Chemical Oxygen Demand, NH4+-N and Total Kjeldahl Nitrogen (TKN) calculated by flow rate and input/output concentration.

In this study we consider the equation proposed by (Kadlec and Wallace, 2009) that takes into account the ratio between BOD and TKN mass removed and surface area. Implementing the data collected in our case, the OCR values result 12.8 g/m2-d and 7.6 g/m^2-d with HTR equal to 12 h and 30 h respectively.

Moreover, OCR values are around 55 $g/m^2 \cdot d$ during a transitory initial period (3h) when the process behaviour is transitory and appear more similar to a vertical flow wetland system. Consequently the final OCR values are strongly influenced by this transitory time so we recalculate the values excluding the transitory initial time, founding values equal to 1.9 g/m2-d and 4.4 g/m2-d with HTR equal to 12h e 30 h respectively. The higher value, in HRT=12 hours test, represents OCR conditions still affected by the transitional oxy/nitro phase. Those OCR values are consistent with literature values in wetland treatment plants with similar conditions (Nivala et al., 2013).

4. Conclusions

This study deals with the possibility to adopt, for reuse in irrigation, SFS phyto-treatment systems for wastewater treatment of small communities or for finishing treated effluents from WWTPs. The measurements campaigns have been carried out in order to obtain information about applicability and design criteria with reference to the legal thresholds from the Italian regulation for wastewater reuse.

The operating conditions of a SFS-h phyto-treatment pilot plant have been studied in different HRT and Flow Rate scenarios aiming to verify the operational conditions of a real scale plant working in steady state. In the hypothesized test conditions: HRT = 1.5h - 12h - 30h the experimentations show hydraulic conductivity values around 2600 cm/h in accordance with the references available in scientific literature.

In terms of oxygen balance and oxidation capability, in a transient phase limited to the first two/three hours it has been noted a decreasing trend for DO probably due to the kinetic of carbonaceous BOD and to the conditions of the medium at starting of flow, enriched of organic substances cumulated during the time of out-of-service.

Good values of DO within the filtration flow (around 5 mg/L) are guaranteed in all test conditions and steady process conditions are reached both with HRT=12 and with HRT =30. In the first case, nitrification rate brings the concentration of ammonium nitrogen to 19.5 mg/L with a nitrification efficiency around to 43 %. In the second case (HRT= 30 h), the output regimen concentration of NH_4^+-N decrease to 11 mg/L (20 mg/L less than that of the not planted bed).

It's possible to conclude that results obtained operating with HRT equal to 30 h show an interesting removal efficiency (66%) but output concentration of ammonium doesn't guarantee yet the respect of bounds of 2 mg/L of the Italian legal threshold for reuse in irrigation. For this further experiment is forecasted and planned with HRT 36-48 h.

Finally, the organic matter and nitrogen compounds removal capacity was evaluated comparing the OCR with similar pilot treatment plants in wetland literature. OCR values result 1.9 g/m^2-d and 4.4 g/m^2-d with HTR equal to 12h e 30 h respectively, and they are consistent compared to similar pilot plants. Anyway, we noted that it is strongly influenced by initial transitory time (around 3h).

References

AM, (2014), Ministerial Decree on Use of water from the treatment of urban wastewater for the irrigation of crops or green spaces, JORF No 01553, 04 July 2014 page 11059 texte No 29, (In French), On line at: https://www.legifrance.gouv.fr/affichTexte.do?cidTexte=JORFTEXT000029186641&categorieLien=id.

Andreo-Martínez P., García-Martínez N., Quesada-Medina J., Almela L., (2017), Domestic wastewaters reuse reclaimed by an improved horizontal subsurface-flow constructed wetland: A case study in the southeast of Spain, *Bioresource Technology*, **233**, 236-246..

BIO by Deloitte, (2015), Optimising water reuse in the EU – Final report prepared for the European Commission (DG ENV), Part I. In collaboration with ICF and Cranfield University, On line at: https://op.europa.eu/en/publication-detail/-/publication/7d25585a-99a8-452e-9cf3-d1e388bec46a/language-en.

Çakir R., Gidirislioglu A., Çebib U., (2015), A study on the effects of different hydraulic loading rates (HLR) on pollutant removal efficiency of subsurface horizontal-flow constructed wetlands used for treatment of domestic wastewaters, *Journal of Environmental Management*, **164**, 121-128.

CMD, (2011), Common Ministerial Decision No 145116 on Measures, Limits and Procedures for Reuse of Treated Wastewater, Ministry of Environment, Energy and Climate Change, Athens, Greece, On line at: https://rm.coe.int/16805c7703.

DM, (2003), Ministerial Decree Number 185/2003 of the Ministry of Environment and Protection of Land, Gazzetta Ufficiale Number 169, 23-7-2003, Rome, Italy, On line at: https://www.ilo.org/dyn/natlex/natlex4.detail?p_lang=en&p_isn=69760.

EC, (2018), Proposal for a regulation of the european parliament and of the council on minimum requirements for water reuse, COM/2018/337 final - 2018/0169 (COD), On line at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52018PC0337.

Kadlec R.H., Wallace S.D. (2009), *Treatment Wetlands*, 2nd Edition, CRC Press, Boca Raton, New York.

Lazarova V., Bahri A., (2004), *Water Reuse for Irrigation: Agriculture, Landscapes, and Turf Grass*, 1st Edition, CRC PRESS, New York, 1-432.

Mancini M.L., (2004), *Discharge in Coastal Seawater of Treated Wastewater from Riccione WWTP by Estuarine Transition Flow*, Int. Symp. on Sanitary and Environmental Engineering – SIDISA 23-26 June 2004, 1-69.

Nivala J., Wallace S., Headley T., Kassa K., Brix H., van Afferden M., Müller R., (2013), Oxygen transfer and consumption in subsurface flow treatment wetlands, *Ecological Engineering*, **61**, 544-554,

RD, (2007), Royal Decree No. 1620 of Health Ministy on Wastewater reuse, BOE-A-2007-21092. (In Spanish). On line at: https://www.boe.es/eli/es/rd/2007/12/07/1620/con.

Sanz L.A., Bernd M.G., (2014), Water Reuse in Europe - Relevant guidelines, needs for and barriers to innovation, Publications Office of the European Union, On line at: https://www.researchgate.net/publication/321998325_Water_Reuse_in_Europe_-_Relevant_guidelines_needs_for_and_barriers_to_innovation#fullTextFileContent

Tatoulis T., Akratos C.S., Tekerlekopoulou A.G., Vayenas D. V., Stefanakis A.I., (2017), A novel horizontal subsurface flow constructed wetland: Reducing area requirements and clogging risk, Chemosphere, **186,** 257-268.

Environmental Engineering and Management Journal

October 2020, Vol. 19, No. 10, 1773-1780
http://www.eemj.icpm.tuiasi.ro/; hiip://www.eemj.eu

“Gheorghe Asachi” Technical University of Iasi, Romania

BIOWYSE: A SOLUTION FOR REAL-TIME, AUTOMATED AND INTEGRATED BIOCONTAMINATION CONTROL

Vincenzo Guarnieri*, Ilaria Locantore, Giovanni Marchitelli, Giorgio Boscheri, Cesare Lobascio, Antonio Saverino

Thales Alenia Space Italia Strada Antica di Collegno, 253 - 10146, Torino, Italy

Abstract

Space exploration requires reliable, rapid, significant and safe methods for preventing, monitoring and controlling biocontamination risk in water loops and humid areas in manned Space habitats. Water is one of the most important resources of our everyday life. Its microbiological control in houses, public water dispensers and special conditions (e.g.: epidemics, catastrophes, isolation) is crucial. The presented solution is automated, compact and portable, and above all “integrated” – i.e.: composed of modules working in synergy (prevention, monitoring, control and decontamination). It was designed for space applications, thus microgravity-compatible. BIOWYSE integrated system combines biostatic/biocide action with real-time biomonitoring and almost instantaneous UV-based disinfection. It is an automated and compact system, meaning low crew time need and suitable transportability. In an automated way, the Prevention Module prevents biofilm formation and the Decontamination Module immediately counteracts water microbial load increment upon checks by the Monitoring Module. BIOWYSE has full potential for exploitation for ISS and future manned Space Exploration missions and represents an innovative tool with a wide application potential in a large number of situations on Earth.

Key words: ATP-metry, biocide, bioluminescence, biomass, biostatic, decontamination, microbial contamination, monitoring, prevention, spacecraft, UV-C LED

Received: February, 2020; Revised final: June, 2020; Accepted: July, 2020; Published in final edited form: October, 2020

1. Introduction

Space exploration requires reliable, rapid, significant and safe methods for preventing, monitoring and controlling biocontamination risk within human confined environments (THESEUS Consortium, 2012). There is a rich literature on advanced life support, crew health risks, microbial contamination, biofilm formation etc. in spacecraft. A considerable number of relevant publications have been taken into consideration and cited in one of the scientific articles resulting from the BIOWYSE project (Amalfitano et al., 2020).

On Earth, water is among the most important resources of our everyday life, its microbiological control is crucial - in houses, public water dispensers and special conditions (e.g.: epidemics, catastrophes, isolation).

Our solution is BIOWYSE (Biocontamination Integrated Control of Wet Systems for Space Exploration) - an automated, compact and portable system, and above all *"integrated"* - that is, composed by modules working in synergy. For space it must also be compatible with the weightlessness conditions.

BIOWYSE development approach is shown in Fig. 1. Starting from our space and terrestrial technologies concerning prevention, monitoring and mitigation we concentrated on the realization of a prototype and on the design of a flight demonstrator. These studies are the core of a future overall space

* Author to whom all correspondence should be addressed: e-mail: vincenzo.guarnieri@thalesaleniaspace.com; enzoguarnieri@gmail.com; Phone: +39 011 7180689; Fax: +39 011 7180

system that can be developed in the future. The portable prototype, used in the field, would bring know-how for commercial products. The main objective was the validation of prevention monitoring and mitigation technologies for human exploration of Space.

2. BIOWYSE flight concept

Since project beginning, BIOWYSE was conceived to be installable as an Experimental Insert of the EDR2 rack in Columbus module of the International Space Station (Fig. 2). In fact, Breadboard & Flight system have same/similar requirements for:

- Functions and performances;
- Design (e.g.: mechanical, power, cooling);
- Reliability, Availability, Maintainability, and Safety.
- Operations.

3. Outline of the BIOWYSE terrestrial system (breadboard)

The integrated BIOWYSE breadboard is the main hardware output of the BIOWYSE project. The breadboard was designed with the aim to test the system functionality behind the concept using commercial components, though equivalent to those qualified for flight whenever possible.

The breadboard schematic and subsystems were described in previous papers, in particular ICES-2018-178 (Detsis et al., 2018) and ICES-2019-63 (Guarnieri et al., 2019).

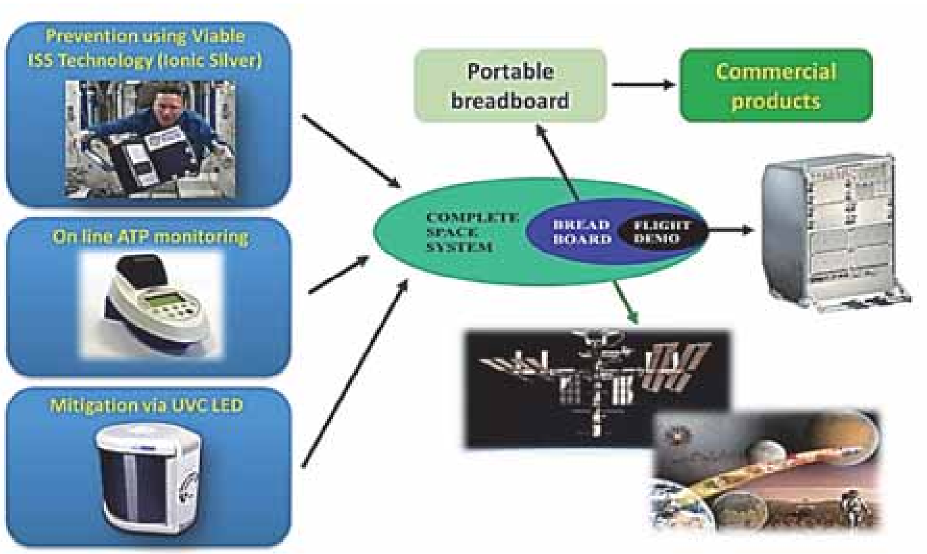


Fig. 1. BIOWYSE development approach

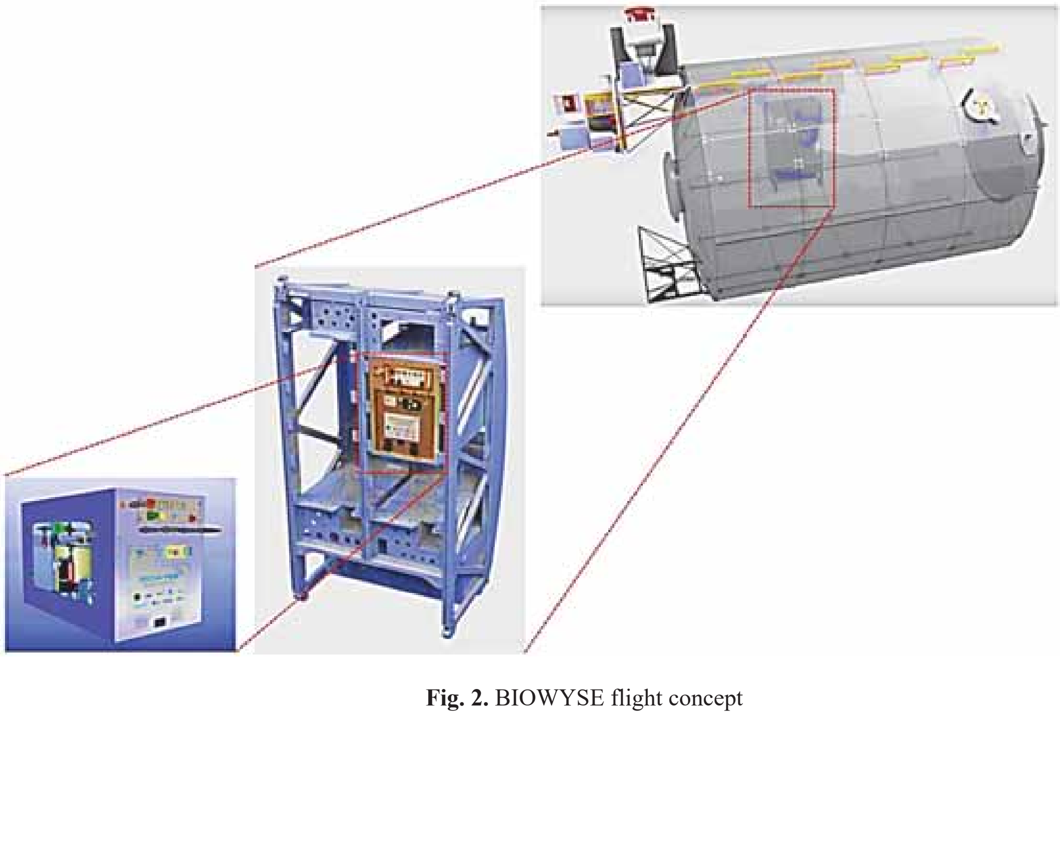


Fig. 2. BIOWYSE flight concept

During operations, the User has access to the BIOWYSE front side interfaces. The CM front panel provides the electrical interfaces, while the rest of the front panel provides hydraulic and mechanical interfaces for maintenance and operations. The breadboard "as designed" *vs*. "as built" is shown in Fig. 3.

Dimensions (460 mm x 525 mm x 720 mm) and mass requirements (56 kg) were fulfilled by the "as built system", and the power requirement (267 watt) was largely fulfilled – even for all the items and support equipment running simultaneously.

4. Microbiological control in BIOWYSE

The following sections sketch out the modules in BIOWYSE that deal directly with microbiological control, namely the PM, MM, DM, CM and HAS. Details of these modules were provided in ICES-2018-178 (Detsis et al., 2018) and ICES-2019-63 (Guarnieri et al., 2019).

4.1. Prevention Module - PM

Starting from the results of the VIABLE-ISS experiment and the up-to-date available ISS data, the Prevention Module technology is based on silver (Birmele et al., 2011). The PM (Fig. 4), developed by TAS in Italy, can be already considered the precursor of a Space product. It can also become a self-standing payload for manned spacecraft. The "double disks" PM solution proved good performance in the lab and field tests, together with strong synergy of the silver charged ceramic filter "coupling" with the PM solution.

Fig. 3. BIOWYSE breadboard "as designed" a) vs "as built" b)

Fig. 4. BIOWYSE Prevention Module

4.2. Monitoring Module - MM

The Monitoring Module (Fig. 5) is based on ATP-metry (Hammes et al., 2010; Venkateswaran et al., 2003), for *total* viable microorganism's quantification. It was developed by GL Biocontrol. The MM is automated, rapid, compact, not using toxic or flammable chemicals, applicable to multiple sources and with low requirements for energy, consumables and maintenance. The MM allows prompt biorisk detection for consequent rapid counteraction, so reducing the necessity of decontamination from "constant" to "if needed" intervention. The analysis of the samples is based on *"thresholds"*. Four thresholds (Amalfitano et al., 2018) were defined for water:

- safe (drinkable, <0.5 pgATP/ml),
- warning (drinkable, 0.5-3 pgATP/ml),
- alarm (drinkable, 3-10 pgATP/ml), and
- not drinkable (10 pgATP/ml).

The measurement is online, in real time and with a high detection sensitivity. In fact, the required detection limit (0.1 ATP pg/ml) and accuracy (<10%) were both verified by analysis and tests. The Monitoring Module is also compatible with weightlessness. It secures the use of water for the astronaut by daily monitoring the total biomass and triggering disinfection cycles.

4.3. Decontamination Module - DM

The DM is based on UV-C LED technology (Fig. 6). Mercury lamps cannot be used in space, and this technology has the advantages of reaching full intensity within nanoseconds, excluding chemicals, minimizing energy consumption. LED utilisation allowed realization of a compact and reliable system, which favored the development of a highly competitive commercial product. The DM was developed by Aquisense.

The DM has fulfilled a "fluid compatibility" specific requirement, listing a number of characteristics typical of the ISS, including a maximum turbidity of 8 NTU.

As for UV-C disinfection effectiveness, please refer to (Simons et al., 2018).

Fig. 5. BIOWYSE Monitoring Module

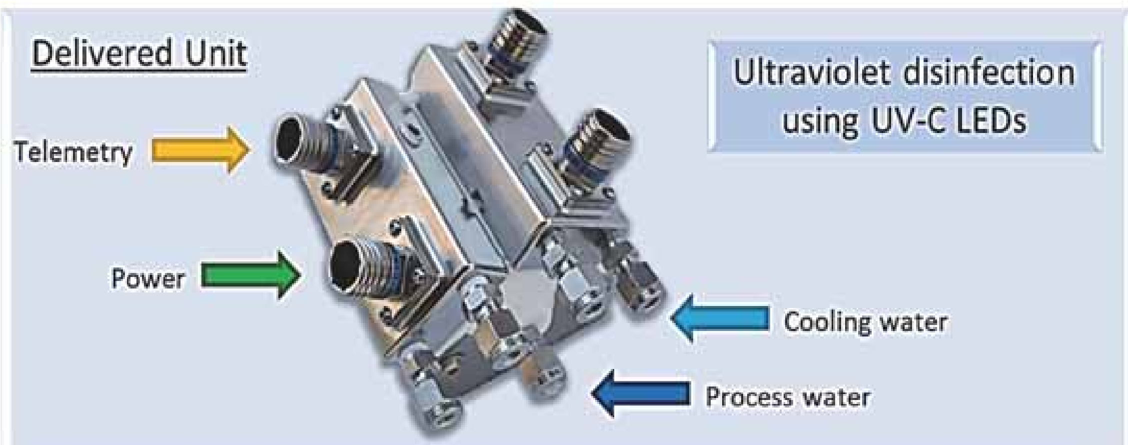


Fig. 6. BIOWYSE Decontamination Module

4.4. Humid Area Sampler - HAS

As part of BIOWYSE, an innovative surface sampling and analysis system was also developed. For all current methods of analysis (e.g.: culture, ATP-metry, PCR), the microbiological sampling of the surfaces is done manually, using swabs and wipes. These techniques require Operator's skill and time, are poorly repeatable and prone to cross contamination. Our HAS (Fig. 7) offers a semi-automatic surface sampling that eliminates the systematic error of the Operator. The measurement, very sensitive, takes place by inserting the cartridge into the reader on the MM panel and pressing a button.

We have a patent pending on this kit (ref. 102018000009137 extended to PCT).

4.5. Control Module - CM

The Control Module (Fig. 8) hardware and software were specially designed from scratch by Liewenthal. It allows automatic and manual control of the system, telemetry data collecting and storing for further analysis, and provide user interface for most system functions.

5. Testing

To validate the functional and performance requirements, we carried out tests on the integrated breadboard in laboratory and on the field: TAS Clean Room and SMAT in Turin, and in the cave "Grotta del Vento" in Tuscany. Our scientific partners CNR-IRSA and SMAT also applied different types of comparative microbiological analyzes (culture-based, portable flow cytometry, molecular methods) to better understand ATP measurements applied to our system.

The tests on the breadboard have led to fine-tuning of the BIOWYSE integrated System and consolidation of the key elements for future flight demonstration and utilisation, as well as terrestrial applications.

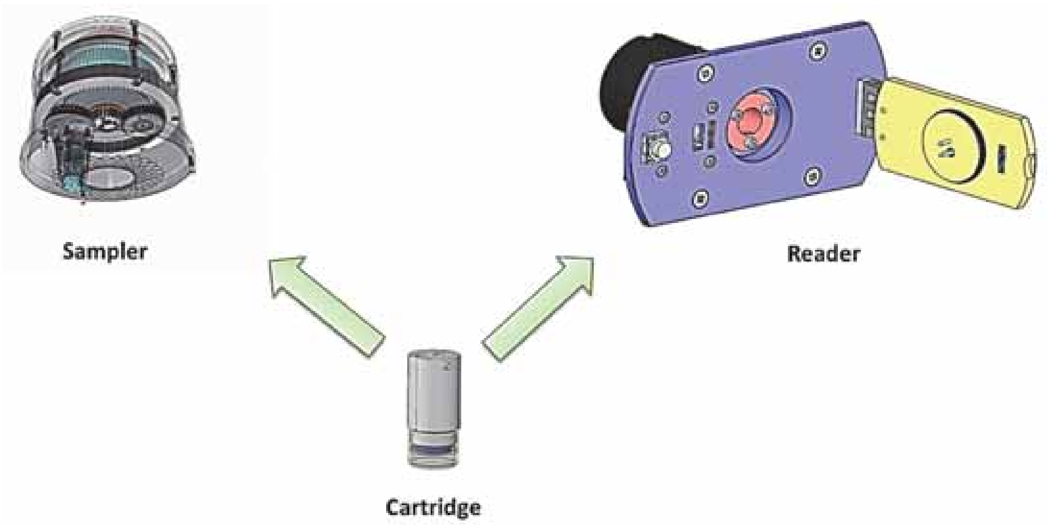


Fig. 7. BIOWYSE Humid Area Sampler

Fig. 8. BIOWYSE Control Module

The BIOWYSE breadboard configuration for transportation and field testing is depicted in Fig. 9. The PC tool software and the laptop were provided together with the CM. As support equipment there are four main subsystems: Mechanical, off-the-shelf trolley for transportation of BIOWYSE and support equipment; Electrical, customized AC/DC power supply; Fluidic, for start-up (priming) and final operations; Thermal, COTS compact chiller (to simulate EDR-2 liquid cooling system).

Among the many caves in Italy, the “Grotta del Vento” (Fig. 10) was chosen for its characteristics of humidity, condensation and representativeness of confined environment, where the only source of pollution is given by human presence, just like on board the ISS. This test was also aimed at demonstrating the successful BIOWYSE utilisation in a particularly challenging environment, which also exceeded the humidity and temperature requirements of the system.

Fig. 11 reports the results of the integrated laboratory tests to validate the contamination control strategy (July/August 2018). Normally, the water from our home taps is generally between the warning and alarm thresholds. Over 10 pgATP/ml the water is not drinkable. During the tests, the alarm threshold was exceeded on the 21st day, and the system reported it below the alarm threshold with the application of the UV rays. The PM/DM coupling has been proved to be synergistic, since the PM ensures no biofilm formation on surfaces and DM is active on the planktonic microorganisms: ATP concentration values remain well below the first threshold for a long time, and when a threshold is exceeded, water recirculation thru DM with UV lights ON readily lowers such values. Fig. 11 is intended to give a "practical" information, highlighting the synergy among the modules of BIOWYSE. For instance, it evidences that the PM/DM couple is an effective and reliable system for water biocontamination risk control.

Fig. 9. BIOWYSE support equipment for field tests. a) PC tool, b) power supply, chiller and fluidic panel

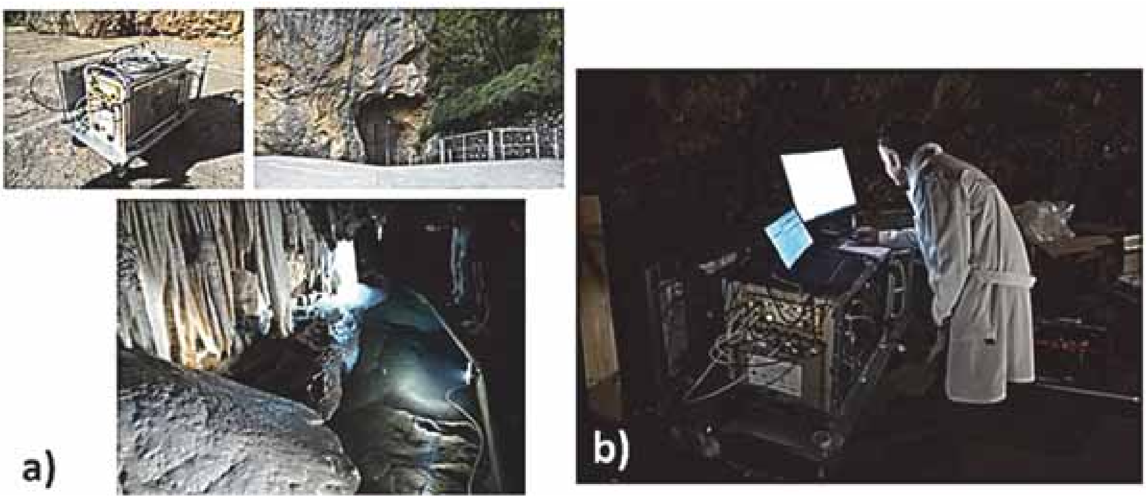


Fig. 10. “Grotta del Vento” field tests (12-14 September 2018); a) BIOWYSE breadboard, cave entrance and sampling site “Laghetto dei Cristalli”; b) operations inside the cave

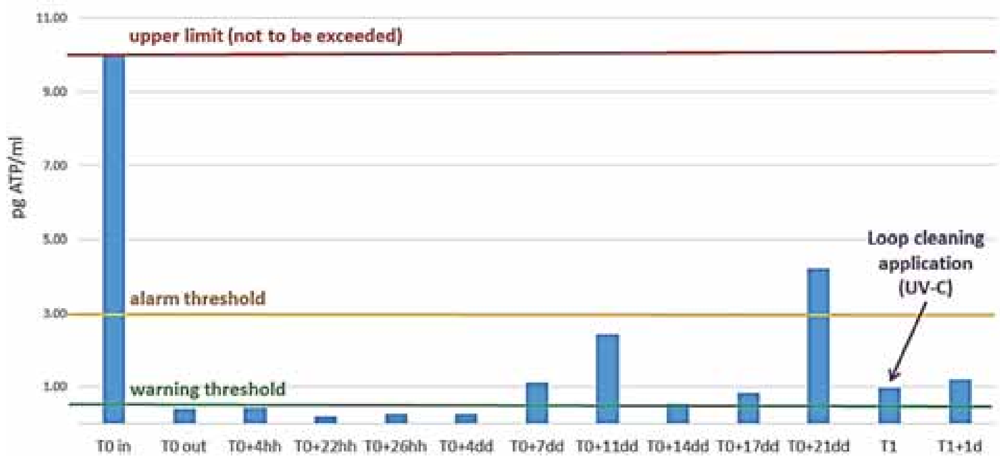


Fig. 11. PM/DM lab tests results (July/August 2018)

Beside the *"water"* test, also *"surface monitoring"* was performed - by sampling five significant locations inside the cave (Figs. 12 and 13). High expected biocontamination was detected in the sampling spots.

Fig. 12. "Grotta del Vento" field tests. Surface sampling by the HAS sampler

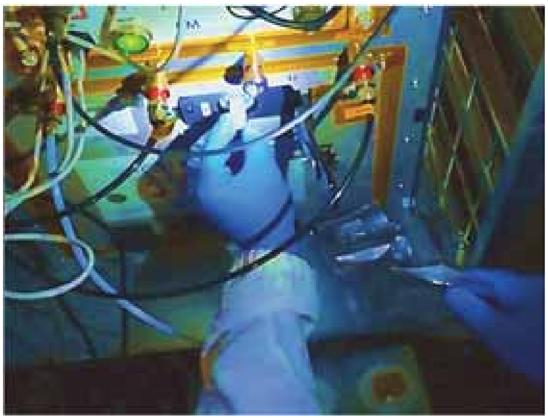


Fig. 13. Surface sample analysis. Cartridge insertion in HAS housing on the MM front panel

Results were cross-checked and validated with a variety of conventional (e.g.: HPC) and innovative methods (e.g.: NGS, flow cytometry). Some problems were encountered with the third sample, due to the extreme roughness of the sampled surface. The problem was solved for the last two samples by using manually the sole cartridge for punctual sampling of the surface included in the standard sampling frame. This mode of operation can be extended to sample any surface (also very rough and irregular), thus it represents a positive outcome resulting from a technology limit.

At the end, HAS testing, which was the primary objective of this first field test, although displaying some technical limits to be overcome in view of possible space and/or terrestrial developments of the system, can reasonably be considered as successful.

9. Exploitation

Major strengths to take into consideration for future development, spin-off strategy and industrial exploitation of the BIOWYSE breadboard are: modularity and scalability of the system, low power consumption, no use of chemicals (e.g.: chlorine) to disinfect water, limited water sample need for analysis, instantaneous response (real-time water analysis and immediate restoration of quality standards).

BIOWYSE has full potential to be exploited in *all manned space programs* (space stations, planetary exploration), and in *many terrestrial applications*: water distribution, industry (food & beverage, pharmaceutical, cosmetics), hospitals, swimming pools, domotics, mountain huts, tourism, boats, submarines, off-shore platforms, underwater bases, isolated bases like in Antarctica, emergency scenarios like floods and earthquakes, war scenarios.

10. Conclusions

Many teams work on prevention, monitoring and decontamination fields, but no team is dealing with an "integrated" system. BIOWYSE combines biostatic and biocide action with real-time biomonitoring and almost instantaneous UV-based disinfection. In automated way, the PM prevents biofilm formation and the DM immediately counteracts water microbial load upon check vs thresholds by the MM. BIOWYSE is an automated and compact system, meaning low crew time and suitable transportability.

BIOWYSE has full potential for exploitation for the International Space Station and future manned Space Exploration missions and represents an innovative tool with a wide application potential in a large number of situations on Earth.

Acknowledgements
BIOWYSE was financed by the European Commission Horizon 2020 SPACE initiative (project no. 687447). The authors of this paper would like to thank the whole BIOWYSE team:

- E. Detsis, P. Cabezas Padilla, J.C. Worms & Z. Dustalova of European Science Foundation
- C. Faye L. Garrelly, C. Martinez, C. François, A.L. Buisson of GLBiocontrol
- R. Simons and J. Pagan of AquiSense Technologies
- F. Bersani, D. Giacosa, G. Bocina, L. Meucci of SMAT Torino
- Mengoni & E. Perrin from University of Florence
- R. Tamm, T. Jantson, E. Pehtla, A. Laansoo, M. Koiv & J.Rosin from Liewenthal Electronics
- S. Rossetti , C. Levantesi & S. Amalfitano of CNRS - IRSA
- Tomas &Veronika Rousek from A-Etc).

References

Amalfitano S., Levantesi C., Garrelly L., Giacosa D., Bersani F., Rossetti S., (2018), Water quality and total microbial load: a double-threshold identification procedure intended for space applications, *Frontiers in Microbiology*, https://doi.org/10.3389/fmicb.2018.02903

Amalfitano S., Levantesi C., Copetti D., Stefani F., Locantore I., Guarnieri V., Lobascio C., Bersani F., Giacosa D., Detsis E., Rossetti S., (2020), Water and microbial monitoring technologies towards the near future space exploration, *Water Research*, **177**, 115787, https://doi.org/10.1016/j.watres.2020.115787.

Birmele M., McCoy L., Roberts M., (2011), *Disinfection of Spacecraft Potable Water Systems by Passivation with Ionic Silver*, ICES 2011, AIAA 2011-5278, On line at: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20110014435.pdf.

Detsis E., Guarnieri V., Lobascio C., Saverino A., Boscheri G., Locantore I., Garrelly L., Simons R., (2018), *Biocontamination Integrated Control of Wet Systems for Space Exploration (BIOWYSE)*, 48th Int. Conf. on Environmental Systems, 8-12 July, Albuquerque, New Mexico, 1-10, On line at: https://ttu-ir.tdl.org/bitstream/handle/2346/74150/ICES_2018_178.pdf?sequence=1&isAllowed=y

Guarnieri V., Marchitelli G., Boscheri G., Locantore I., Lobascio C., (2019), *Biocontamination Integrated Control of Wet Systems for Space Exploration (BIOWYSE) – Test campaign results*, 49th Int. Conf. on Environmental Systems, 7-11 July, Boston, Massachusetts, On line at https://ttu-ir.tdl.org/bitstream/handle/2346/84748/ICES-2019-63.pdf?sequence=1&isAllowed=y.

Hammes F., Goldschmidt F., Vital M., Wang Y., Egli T., (2010), Measurement and interpretation of microbial adenosine tri-phosphate (ATP) in aquatic environments, *Water Research*, **44**, 3915-3923.

Simons R., Pagan J., Lawal O., (2018), *Low-Maintenance Consumable Free Disinfection by UV-C LEDs*, 48th Int. Conf. on Environmental Systems, Albuquerque, New Mexico, 8-12 July, 1-11.

THESEUS Consortium, (2012), Towards Human Exploration of Space: a EUropean Strategy - Roadmap, On line at: https://www.essc.esf.org/fileadmin/user_upload/essc/RoadMap_web_2012.pdf.

Venkateswaran K., Hattori N., La Duc M.T., Kern R., (2003), ATP as a biomarker of viable microorganisms in clean-room facilities, *Journal of Microbiological Methods*, **52**, 367-377.

Environmental Engineering and Management Journal

October 2020, Vol. 19, No. 10, 1781-1789
http://www.eemj.icpm.tuiasi.ro/; hiip://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

FULL-SCALE APPLICATION OF MABR TECHNOLOGY FOR UPGRADING AND RETROFITTING AN EXISTING WWTP: PERFORMANCES AND PROCESS MODELLING

Giuseppe Guglielmi[1*], Daniel Coutts[1], Dwight Houweling[2], Jeff Peeters[2]

[1]*Suez Water Technologies and Solutions Italy Srl, Via Benigno Crespi, 57, 20159 Milano, Italy*
[2]*Suez Water Technologies and Solutions, 3239 Dundas Street West, Oakville, ON, Canada*

Abstract

MABR (Membrane Aerated Biofilm Reactor) consists in an attached-growth process in which a gas permeable membrane is used as a biofilm carrier, and bubble-less oxygen transfer allows for a counter-diffusional mechanism where the electron donor (NH_4^+, biodegradable organics) and electron acceptor (O_2) reach the biofilm from opposing sides. The paper reports results form the largest MABR installation in the world, demonstrating the beneficial impact of the technology in terms of improved process resilience under different operational conditions, through the key performance indicator oxygen transfer rate (OTR), which ranged between 7 and 16 $gO_2/m^2/d$. The OTR monitoring over the considered operational period shows (i) a weak impact of sludge temperature on the oxygen transfer within the considered range (9-22 degC) and also (ii) proves the reliability of OTR as an indicator of the improved resilience of the entire wastewater plant in the new MABR configuration, under peak loading conditions. Finally, a mathematical model was developed in the BioWin software platform, to evaluate its use as support tool for model-aided process optimization. The model was calibrated in terms of hydrodynamic behaviour of the MABR zone and seeding effect on the nitrifying biomass, which was expressed as solids retention time (SRT) of the attached growth biomass; the calibrated mathematical tool was then successfully validated in terms of prediction of ammonia concentration in the MABR zone.

Keywords: modelling, Membrane Aerated Biofilm Reactor (MABR), resilience, upgrading

Received: February, 2020; Revised final: June, 2020; Accepted: July, 2020; Published in final edited form: October, 2020

1. Introduction

Climate change and continuing population growth pose new challenges to wastewater management and make it necessary to adopt new technological solutions to achieve sustainability while guaranteeing reliable performance in a variety of operating conditions, which are more significant than in the past. With the aim of improving efficiency in water, land and energy utilization in a framework of circular economy, the need for smarter technological solutions in wastewater engineering is widely recognized as a top-priority challenge (EEA, 2019). The overall social-economical impact of these aspects have been pointed out by Daigger (2007) who suggests a holistic view of water management in which water supply, wastewater collection and treatment and storm water management are interconnected components of broader picture.

Drivers such as (i) energy efficiency, (ii) performance reliability, (iii) optimized used of existing infrastructures and (iv) operational resilience become therefore crucial criteria when developing new technologies and optimizing their application at full-scale. In such context Membrane Aerated Biofilm Reactor (MABR) technology offers unique advantages which are intrinsically related to the technology working principle.

The great potential of coupling a gas-permeable membrane with a biofilm process in a so-

*Author to whom all correspondence should be addressed: e-mail: giuseppe.guglielmi@suez.com; Phone: +39 342 1287963

called Membrane Biofilm Reactor (MBfR) has been deeply discussed by Rittmann (2007), who introduces possible applications of the technology with either O_2 or H_2 as gaseous substrate, for both drinking- and waste-water applications. In the MABR technology a gas-permeable membrane is used to transfer the electron acceptor (O_2) to a biofilm naturally growing on the membrane. The complementary substrates (i.e. ammonia NH_4^+, biodegradable organics) typically diffuse from the bulk into the biofilm. This counter-diffusional mechanism results in significant differences compared to the traditional biofilm processes in which both electron donor and acceptor reach the attached-growth biomass from the bulk. Nerenberg (2016) reports a thorough description of the advantages of MABR, including.

- development of unique microbial community with most favourable conditions for nitrifying microrganisms, which are also protected against possible inhibitors since they mainly growth in the inner layer of biofilm;
- lower susceptibility to liquid diffusion layer resistance compared to traditional biofilm processes. In a counter-diffusional process, the layer actually tends to contrast the loss of internal substrate from the biofilm to the liquid bulk, whereas in a co-diffusional mechanism a high bulk concentration is necessary to overcome the liquid diffusion layer resistance;
- much higher energy efficiency compared to conventional technologies, thanks to the bubble-less molecular diffusion of O_2. The above-mentioned pros result in an overall more stable, efficient and environmental-friendly solution for wastewater treatment.

More specifically, the process intensification and improved process stability of the MABR technology under a wide range of operational conditions have been discussed in the literature, with a special focus on the hybrid configuration. A hybrid MABR-activated sludge (MABR-AS) system is where the attached-growth MABR is coupled with a conventional suspended-growth process. Starting from early studies (*inter alia* Brindle and Stephenson, 1996; Brindle et al., 1998), the achievement of consecutive nitrification and denitrification in the biofilm was demonstrated over a 300-days trial by Shin et al (2008) on a bench-scale CSTR system fed with synthetic wastewater, with a maximum nitrification rate of 2.06 $gN\text{-}NH_4^+/m^2/d$ and a denitrification rate of 1.76 $gN\text{-}NO_3^-/m^2/d$. Hu et al. (2008) reported steadily high removal efficiencies for both ammonia nitrogen, total nitrogen and COD at hydraulic retention time varying between 12 and 20 hours. The same research group investigated the technology potential in achieving simultaneous nitrification denitrification (SND) under different COD/N ratios. The application of FISH (*Fluorenscence In-Situ Hybridization*) and confocal laser scanning microscopy techniques to biofilm samples collected from two bench -scale reactors revealed a strong prevalence of *Nitrosomonas* and *Nitrospira*, mainly distributed in the inner layer of biofilm (Liu et al., 2010), thus confirming the beneficial effect of the counter-diffusional mechanism on the growth of nitrifying organisms over heterotrophs. Performances of a bench-scale MABR in a long-term continuous operation study have been recently presented by Lin et al. (2016), who demonstrate stable nitrification and total nitrogen removal efficiency in a COD/N ratio in the influent ranging between 3 and 5; also in this case, the application of microbiological techniques such as PCR-DGGE prove the impact of the counter-diffusional mechanism on the microbial diversity in the biofilm. The beneficial impact of MABR for retrofitting existing operational systems, by reducing the sludge age even below the washout SRT value for nitrifying biomass, has been demonstrated by Houweling et al. (2018) on demo-scale plants fed with real wastewater.

Using bubble-less oxygen transfer to the biofilm also allows for a better control of the electron acceptor for unconventional nitrogen removal pathways. Early investigations on the utilization of MABR to control nitration have been reported Lackner et al. (2008; 2010). A bench-scale study carried out by Gilmore et al. (2013) proves that a biofilm grown ex-novo with continuous aeration can combine nitratation and anaerobic ammonia oxidation in a single-stage MABR. A synthetic wastewater free of organic carbon was fed to the system, using relative loading ratios of oxygen and nitrogen as control tool for the suppression of NOB (*Nitrite Oxidizing Bacteria*). Removal rate of 1.7 $gN/m^2/d$ were demonstrated, the total removal efficiency of nitrogen being up to 85% through anaerobic ammonium oxidation. Experimental studies have proven that MABR can increase flexibility, be an energy efficient upgrade, and can be retrofitted in existing conventional activated sludge systems, thus making the technology a reliable alternate for the current and future wastewater treatment challenges. Sunner et al. (2018) have published results from a one-year study on a pilot unit fed with real sewage, reporting high efficiencies for BOD_5 removal and nitrification (90% and 96% respectively), improved sludge settleability and aeration efficiency of 4 kgO_2/kWh.

Despite the great potential that the technology has shown at both bench- and pilot/demo-scale level, there is a lack of reporting from full-scale installations proving the actual reliability of the process. This paper focuses on more than two years of operations of the site which is, based on authors' knowledge, the largest hybrid MABR currently running worldwide. More specifically, the work focuses on:

1. the Key Performance Indicator (KPI) Oxygen Transfer Rate (OTR) and its capability to describe the process development and behaviour;

2. the benefits derived from the implementation of MABR in terms of overall stability and resilience of the nitrification process;

3. the use of mathematical modelling as advanced tool for optimization of process design and operation.

2. Material and methods

2.1. The Yorkville MABR

The wastewater treatment plant of Yorkville-Bristol Sanitary District (YBSD) was originally built on 1957, and it has been progressively modified and upgraded to handle the loading increase and the changes in environmental regulation. Until 2016 the YBSD facility consisted of:

- mechanical pre-treatment (coarse screening 6 mm, fine screening 1 mm wedge wire);
- fully aerobic biological process, in two lines which can be operated either in series or in parallel depending on the weather conditions. Each line is configured as an in-series scheme with five plug-flow reactors, equipped with fine bubble diffuser. The overall installed volume for the biological process is 5122 m^3;
- three secondary clarifiers;
- UV disinfection.

In 2017, YBSD projected increased influent loading due to new industrial streams entering the facility and learned of the introduction of a new discharge limit for total phosphorus. The utility decided to implement a biological phosphorus removal process, by converting one of the two treatment lines into a hybrid MABR-AS system. Therefore, an anaerobic compartment was created within the volume of Line 1 and, in order to retain the overall nitrification capacity of the system under the new loading conditions, twelve ZeeLung cassettes were installed in an anoxic compartment immediately downstream the anaerobic zone. Therefore, the modification implemented for Line 1 from the original configuration to the upgraded one is shown in Fig. 1.

ZeeLung is the MABR solution developed by Suez Water Technologies Solutions. Each cassette consists of forty-eight modules, which in their turn are formed by cords. The cord structure consists of a braided polyester support, surrounded by a number of filaments (lumens). Each lumen is coated with a dense gas-permeable membrane. Air, at pressure higher than the hydrostatic pressure of the water level, is supplied to the module top header. The air passes inside of the lumens and oxygen diffuses through the membrane where it is consumed by bacteria that have formed a biofilm on the outer wall of the lumen. The braided polyester structure of the cord makes it virtually unbreakable and suitable for installation in activated sludge.

Each membrane module accounts for 40 m^2 of media available for biofilm growth, thus resulting in an overall media surface of 1920 m^2 per cassette and 23,040 m^2 in total. The process air flowrate ranges between 96 and 192 Nm^3/h (8-16 Nm^3/h/cassette) with a median value of 9.2 Nm^3/h/cassette over the considered monitoring period. The pressure value at the air inlet of each cassette is approximately 480 mbar, whereas the outlet pressure is 270 mbar. The pressure loss across the media is partially due to headloss and to the loss of oxygen that has been transferred to the biofilm. Exhaust air at the bottom of each cassette is collected and sent to a sensor measuring oxygen concentration and then is expelled to the environment. An ejector is installed to allow for removal of condensate from each cassette. An addition coarse bubble aeration grid, designed around SUEZ's membrane bioreactor LEAP aeration, is installed beneath the cassette and is fed with air that is scalped from the YBSD aerobic blower system. This installed coarse bubble aeration grid is used for substrate renewal within the cassette and biofilm thickness management.

Average data about influent feed water characteristics are summarised in Table 1.

Over the whole monitoring period considered for this study, MLSS concentration in the biological process tanks and overall SRT in the systems were 3000 ± 500 gMLSS/m3and 12 days respectively; dissolved oxygen concentration in the aerobic section of the plant was kept at the set-point of 2 gO_2/m^3.

2.2. Key Performance Indicators for the MABR technology

The typical KPI's for the MABR process are those parameters which summarize biofilm activity through the consumption of oxygen and the overall media efficiency in delivering oxygen. The Oxygen Transfer Efficiency (OTE) can be calculated as per Eq. (1):

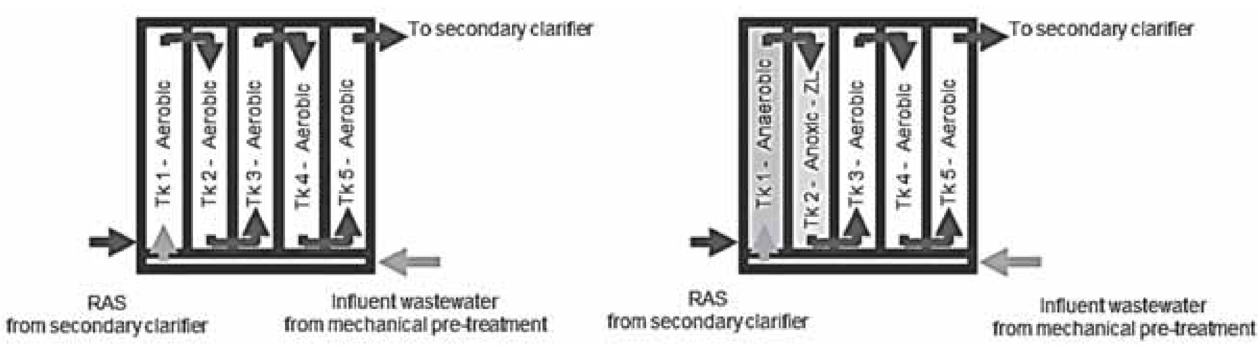


Fig. 1. Original configuration (on the left) and upgraded configuration (on the right) of biological process scheme in Line 1 at the YBSD wastewater treatment plant

Table 1. Average flowrate and feedwater composition during the considered monitoring period

Parameter	*Unit*	*Value*
Average Daily Flowrate	m3/d	10400
COD	g/m3	422
BOD5	g/m3	190
TSS	g/m3	164
TKN	g/m3	32
N-NH4	g/m3	22.5
Total P	g/m3	4.8

$$OTE = \frac{20.9\,\% - O_2\%_{exhaust\ air} \cdot \frac{1 - 20.9\,\%}{1 - O_2\%_{exhaust\ air}}}{20.9\%} \tag{1}$$

The Oxygen Transfer Rate (OTR) represents the mass of O_2 delivered per unit of biofilm surface per unit of time. It is dimensionally expressed as $gO_2/m^2/d$, and can be calculated as per Eq. (2):

$$OTR\left(\frac{g_{O2}}{m^2 \cdot d}\right) = \frac{OTE \cdot Q_{air}\left(\frac{L_{air}}{h}\right) \cdot 20.9\%\left(\frac{mol_{O2}}{mol_{air}}\right) \cdot 32\,\frac{g_{O2}}{mol_{O2}} \cdot 24\,\frac{h}{d}}{22.4\,\frac{L}{mol_{air}} \cdot A_{biofilm}\ (m^2)} \tag{2}$$

where: Q_{air} is the process air flow rate fed to the ZeeLung cassettes; $A_{biofilm}$ is the biofilm surface covering the membrane media, which is assumed to be equal to the installed membrane surface area.

2.3. Mathematical modelling of the full-scale MABR

Modelling is a tool in the wastewater industry to test the hypothesis of new processes, understand the current operation of full-scale processes, and effectively communicate to a variety of audiences. At YBSD modelling was used as a communication and education tool to empower the operations team with a deeper understanding of the installed MABR-Activated Sludge hybrid system. A calibrated model would demonstrate how specific decisions made in the field would impact the overall process. Also, modelling would provide the operations team at YBSD a platform to probe operational approaches to various situations and see how the hybrid MABR-Activated Sludge system would react.

Modelling a biofilm process has two major phases for analysis: a solids phase and a liquid phase. There is no constant transport of materials in the solids phase and the liquid phase transfers soluble material into the biofilm where reaction occurs (Tartakovsky and Guiot, 2004); also, the rate of soluble material transfer to the biofilm is a function of diffusion characteristics of each soluble component (sCOD, sTKN, sNH4-N, etc) (Dzianach et al., 2019). There is a transfer of particulate components from the biofilm, which is modelled as a wasting process from the biofilm into the suspended growth system (Houweling and Daigger, 2019). The model of biofilm brings together the physical chemistry and the biological reaction components of the process to understand impact the biofilm has on the hybrid MABR-AS system (Tartakovsky and Guiot, 2004).

Modelling the MABR in BioWin requires a combination of a few process modules to achieve the transport of materials through the liquid phase and restrict the transfer of materials in the solids phase. The conceptual framework of MABR modelling in BioWin eliminates the solids transfer from the bulk solution to a side-stream reactor, which represents the biomass attached to the membrane media. The model of the MABR process at YBSD was calibrated based on two main parameters: i) the hydrodynamic behaviour of the cassette, which determined the substrate renewal within the cassette; and ii) The biofilm solids retention time, which determined the treatment rate of the MABR biofilm.

In BioWin the transport of materials from the bulk solution to the “virtual” side-stream reactor is achieved through a “splitter tool”. The BioWin splitter represents the MABR mixing system, which is analogous to an air lift system. To understand the rate of exchange between the bulk solution and the MABR cassette volume a tracer study was completed onsite and a mathematic model calibrated to determine the hydraulic residence time (HRT) of the cassette. The results of the tracer study concluded that the rate of exchange between the MABR cassette and bulk solution was 24.9 m3/h, which meant that the MABR cassette had a 19-minute retention time (Underwood et al., 2018). The hydrodynamics of the anoxic zone at YBSD were also experimentally assessed through tracer tests. It was determined that the MABR anoxic zone was described as three continuous stirred tank reactors (CSTRs), with four cassettes in each CSTR. The BioWin splitter flow was calibrated based on the output of the hydrodynamic tests, thus providing an accurate model of the MABR operation within the anoxic tank.

When modelling a MABR process in BioWin, the seeding effect is modelled by wasting solids from the side-stream biofilm reactor into the bulk suspended growth system. The calibration of the seeding effect occurs by comparing the measured and modelled values of the aerobic bulk specific nitrification rate (SNR) for the suspended-growth biomass. Three biofilm SRT’s were calibrated: 25 days, 30 days, 35 days. The sum of squared differences (SSD) was used to determine which biofilm SRT best suited the measured SNR data of 2.57 gN/kgVSS/h, which was determined by completing a nitrogen mass balance around the aerobic system. A 30-days SRT resulted as best fitting value for the actual SNR, and was carried forward to model validation, which is summarized in the Results section.

3. Results and discussion

3.1. Process KPIs: OTR, OTE and NR

Real-time calculations of OTE and OTR was carried out from the online measurement of oxygen concentration in the exhaust air and air flow from the process air blower. The trend of daily OTR and average daily temperature measured during the first year of operation are reported in Fig. 2. Over the entire considered period, daily OTR ranged between 7.1 and 15.9 $gO_2/m^2/d$, with an average value of 11.6 ± 1.5 $gO_2/m^2/d$. OTE measured during the same period was steadily higher than 25%, with peak values up to 50% during high loading conditions.

Two statistical tests were performed to determine the OTR dependency on temperature: Chi-squared and Cramer's V (see Table 2). The results of the Chi-squared (216 on 365-data series of T and OTR) and Cramer's V (0.28 on the same data series) showed a relatively weak relationship between the two variables was observed. This weak relationship between temperature and OTR suggests that other factors (e.g. the bulk ammonia concentration) influence OTR more than temperature itself.

A dedicated monitoring campaign was also carried out to correlate OTR and nitrification rate (NR). Composite samples were collected at the inlet and the outlet of the MABR zone to calculate NR and, over the entire monitoring campaign the observed nitrification rate on the biofilm was 2.1 gN-$NH_4^+/m^2/d$, with peaks up to 3.1 gN-$NH_4^+/m^2/d$. The average value OTR/NR ratio was 5.4 gO_2/gN-$NH_{4nitrified}$, which is higher than the stoichiometric ratio of 4.57 gO_2/gN-$NH_{4nitrified}$, thus suggesting that yet a part of oxygen was depleted by heterotrophic micro-organisms for oxidation of biodegradable organics. As far as it concerns the ammonia removal efficiency onto the biofilm, an average daily removal of 52 kgN-NH_4^+/d was observed, approximately corresponding to 22% of the influent ammonia nitrogen loading.

The removed loading of soluble COD (after 0.45 micron filtration) around the MABR zone over the same monitoring period was 232 kgCOD/d, due to both reactions occurring onto the biofilm (aerobic oxidation and denitrification) and simultaneous denitrification in the bulk sludge of the anoxic tank.

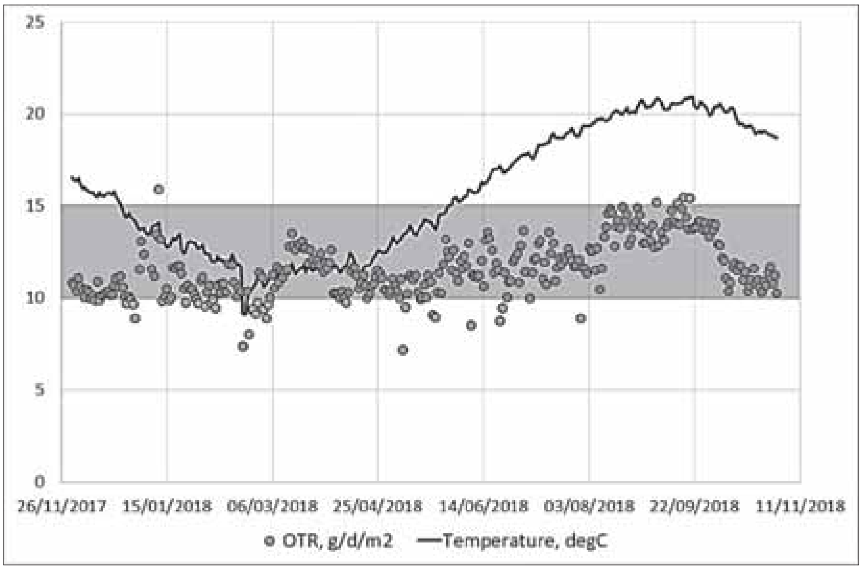


Fig. 2. Trend of average daily values for OTR and temperature during the considered monitoring period

Table 2. Absolute frequency of OTR values for different temperature values over the considered monitoring period

		Temperature (°C)												
		9-10	***10-11***	***11-12***	***12-13***	***13-14***	***14-15***	***15-16***	***16-17***	***17-18***	***18-19***	***19-20***	***20-21***	***Total***
OTR (gO2/m2/d)	***7-8***	1	0	0	1	1	0	0	0	0	0	0	0	**3**
	8-9	0	2	0	1	1	1	1	1	1	0	1	0	**9**
	9-10	0	5	5	7	5	3	3	1	1	0	2	0	**32**
	10-11	0	5	17	21	6	8	14	7	3	7	6	2	**96**
	11-12	1	3	18	9	13	3	10	3	4	9	12	3	**88**
	12-13	2	6	12	0	1	1	4	2	6	7	7	9	**57**
	13-14	0	3	2	0	3	1	1	3	1	2	4	21	**41**
	14-15	0	2	2	3	2	1	0	1	2	1	2	18	**34**
	15-16	0	0	0	0	0	1	0	0	0	0	0	4	**5**
	Total	**4**	**26**	**56**	**42**	**32**	**19**	**33**	**18**	**18**	**26**	**34**	**57**	**365**

3.2. MABR resilience

In general terms, the concept of resilience refers to the ability to overcome upsets and return to previous performance levels. When applied to wastewater engineering processes, resilience is synonymous to robustness, flexibility and ability of a system to promptly react to conditional changes. Fig. 3 demonstrates the resiliency of MABR with respect to changes in ammonia concentration within the bulk solution. In fact, Fig. 3 shows a counter-phase relationship between the MABR exhaust oxygen and the bulk ammonia concentration, thus proving that the biofilm is more active, and using more oxygen, when subject to higher ammonia concentrations in the bulk solution. The adaptive biofilm self-regulates its activity based on the demand created by the bulk ammonia concentration. Likewise, what is typically observed in respirometric tests for the assessment of nitrifying biomass activity through Ammonia Utilization Rate (*inter alia* Spanjers and Vanrolleghem, 2016), OTR reflects the "*breathing*" capability of the biofilm.

Fig. 3 also demonstrates a biofilm that is subject to an ammonia limited environment. A biofilm that is not ammonia limited will demonstrate no correlation or a weak correlation between bulk ammonia concentration and exhaust MABR oxygen concentration. By employing the Chi-squared (438.9 in a 288 data series) and Cramer's V (0.87 in the same data series) tests, a strong correlation was found between bulk ammonia concentration and MABR exhaust oxygen concentration, thus supporting the YBSD MABR is an ammonia limited biofilm. The strong correlation between bulk ammonia and MABR exhaust oxygen concentration provides a more reliable alternative for performance and operation monitoring with minimal maintenance. The gas-phase MABR exhaust oxygen sensor requires less maintenance, replacement parts, and calibration than the liquid-phase ammonia probes. The liquid sensors are more susceptible to drift and foreign material affecting the data. Therefore, by establishing a relationship of OTR and nitrogen removal, the MABR can use the oxygen balance to gain insights into the performance and operation of the system with minimal maintenance.

Fig. 4 demonstrates how the self-regulating biofilm activity in an ammonia limited biofilm is beneficial to the downstream aerobic suspended growth system. The introduction of the MABR at YBSD provides a self-regulating biofilm upstream of the aerobic suspended growth biomass, reducing the fluctuations in ammonia load on the downstream aerobic tanks. Therefore, the counter-phase relationship shown in Fig. 3 develops into the reduced amplitude in ammonia load taxing the downstream aerobic tanks, as shown in Fig. 4. The ability of the MABR biofilm to reduce the amplitude of the diurnal ammonia concentration pattern on the aerobic suspended growth makes the overall hybrid system more resilient to influent streams that have highly variant ammonia concentrations.

The YBSD MABR has also demonstrated hydraulic peak loading resilience. Peak hydraulic loads are known to cause biomass washout and, consequently, drop in performance of conventional activated sludge systems. Fig. 5 reports a wet weather event that occurred at YBSD in February 2019. The OTR trend observed before the wet weather event shows a regular behaviour, with an average OTR of (8.7 ± 1.1) $gO_2/m^2/d$. Wet weather in the area results in an influent flow increase of 2.4 times the average daily flow for 24 hours. During the time of the wet weather event the OTR maintains an average of (7.5 ± 1.3) $gO_2/m^2/d$, greater than 85% of the trend leading up to the wet weather event.

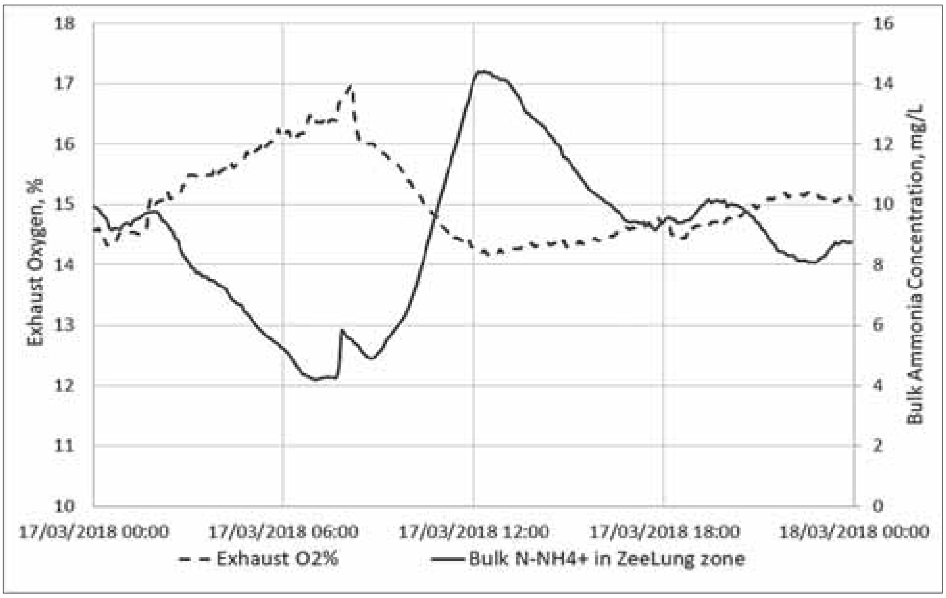


Fig. 3. Typical daily pattern of oxygen concentration in the exhaust air and ammonia concentration in the mixed liquor in the MABR zone

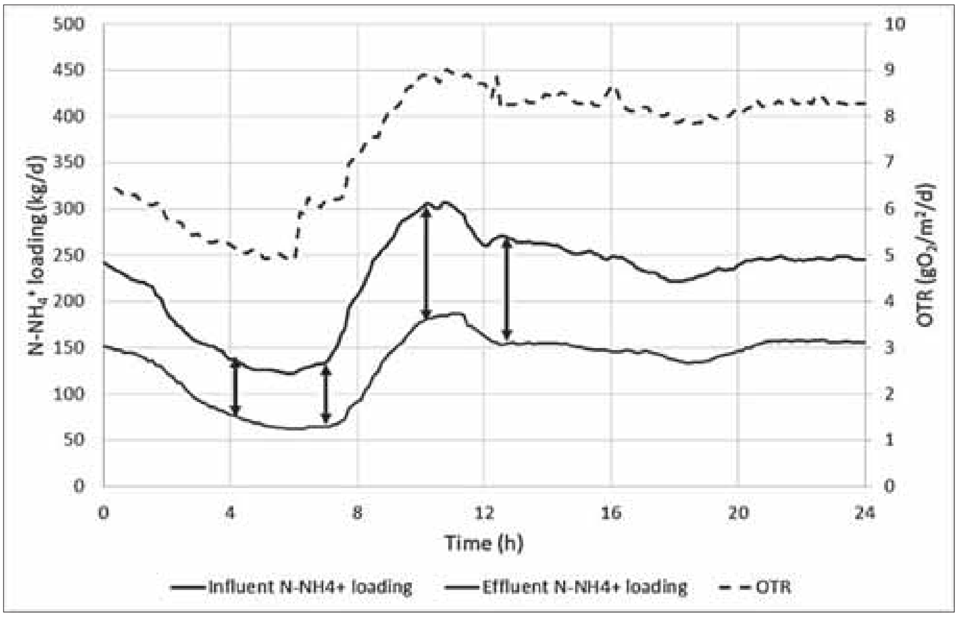


Fig. 4. Calculated OTR and influent and effluent ammonia loading to/from the MABR zone

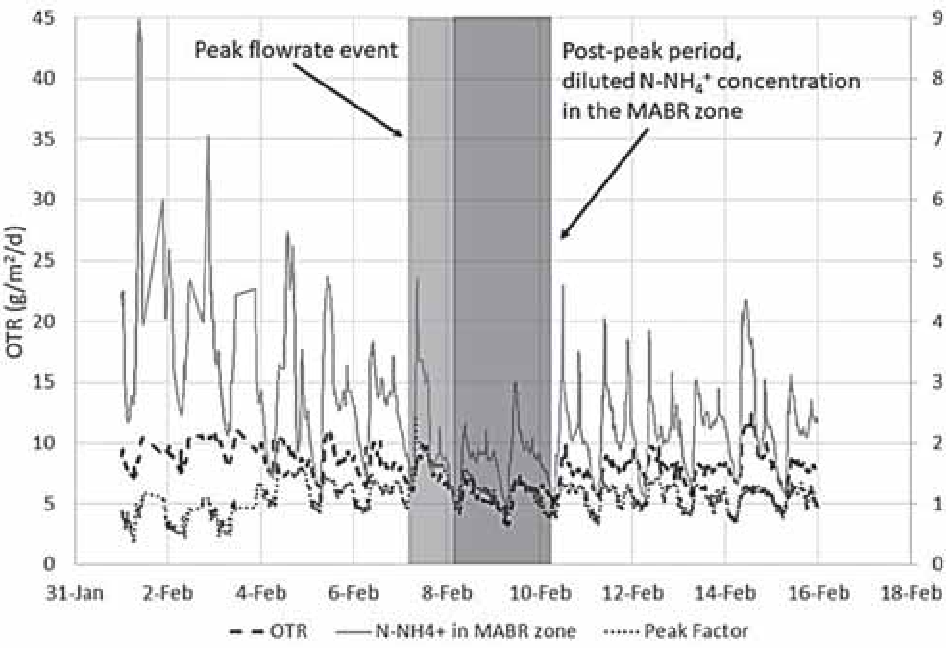


Fig. 5. Impact of rainy weather conditions on the OTR. The peak event (flow up to 2.4 times the average flow value) in the light grey area, the ammonia dilution effect in the MABR zone in the dark grey area

There is a clear impact of the dilution of ammonia bulk concentration in the MABR zone reflected in the OTR trend during the 48 hours following the peak event. Leading up to the wet weather event, the ammonia ISE sensor showed a bulk ammonia concentration of (10.4 ± 3.9) gN-NH_4^+/m3, which drops to (4.5 ± 1.3) gN-NH_4^+/m^3 in the next two days after the rainfall. During this same timeframe, the OTR decreases with the ammonia concentration down to (5.6 ± 0.9) $gO_2/m^2/d$. Nonetheless, once the ammonia concentration is restored to a normal operating range the biofilm promptly returns to the performance seen before the wet weather event, with OTR values back to (7.9 ± 1.4) $gO_2/m^2/d$.

3.3. Process modelling

A model calibration for YBSD was completed around data collected in May of 2018. This model calibration was later validated with data from August through September 2018. Online data provided the diurnal flow, RAS flow, wasting flow, and diurnal ammonia concentration calibration. A daily inlet composite sample was used to get the daily average of the inlet total COD, soluble COD, total BOD, TSS, TKN, total phosphorus, ortho-phosphate and ammonia. Composite samples were used to get the ammonia removal across the MABR zone. Grab samples were used to check the MLSS concentration.

The influent model used COD, TKN, total phosphorus, and ISS as inputs and based on the fractionation of species the BOD, ammonia, ortho-phosphate and TSS were calculated. Based on MLSS concentration from collected samples the sludge production of the model was matched to achieve a representative model. Input values for wastewater characterisation and main biokinetic and stoichiometric parameters are summarised in Table 3. The ammonia removal of the biofilm was validated based on the composite samples that were collected around the MABR zone (Fig. 6).

Model capability to fit the experimental data was determined by means of absolute and relative error, as per Eq. (3) and Eq. (4) respectively.

$$\%\, err._{absolute} = \frac{\sum_{i=1}^{n} \left| x_{i,model} - x_{i,measured} \right|}{\sum_{i=1}^{n} x_{i,measured}} \tag{3}$$

$$\%\, err._{relative} = \frac{\sum_{i=1}^{n} \left(x_{i,model} - x_{i,measured} \right)}{\sum_{i=1}^{n} x_{i,measured}} \tag{4}$$

While the absolute error calculated over the modelled period was 6.6%, the relative error was 1.1%. The difference in between the absolute error and relative error points to times of overestimation and underestimation. That said, both the absolute and relative error are less than 10% suggesting that the model is a good fit for the data collected from site, which is subject to noise due to sample collection and processing.

The model developed a relationship of oxygen transfer rate to the biofilm, which was compared to the empirical data collected from online measurement of air flow to the media and exhaust gas concentration. The model does accurately represent the activity of the biofilm at a bulk ammonia concentration between 10-15 g/m^3 but overestimates the OTR at higher bulk ammonia concentrations and underestimates the OTR at lower bulk ammonia concentrations. The discrepancy between the two values could be explained by the lack of modelling around the diffusion characteristics and the impact that has on the biofilm composition when employed in an ammonia limiting environment. One possible solution to overcome this would be the implementation of an additional model able to describe the physical properties on the diffusion rates of various soluble materials.

This BioWin model approach still does provide a platform for communication for how the biofilm system would respond to changes in the process. The trend is similar: as the ammonia concentration in the bulk goes up the OTR to the biofilm increase, and the opposite is true too. With this information, operators understand the impact of major wet weather events, impacts of how they manage the RAS flow, and the impact of acute increase in ammonia concentration from centrate returns from the sludge dewatering section.

Table 3. Input data used in the BioWin model for the validation period

Parameter	*Unit*	*Value*
Average Daily Flowrate	m^3/d	7220 ± 1710
COD	g/m^3	395 ± 58
BOD5	g/m^3	170 ± 25
TSS	g/m^3	166 ± 40
TKN	g/m^3	30.2 ± 3.6
N-NH4	g/m^3	24 ± 2.9
Total P	g/m^3	4.8 ± 1
Ortho-phosphate	g/m^3	2.9 ± 0.6

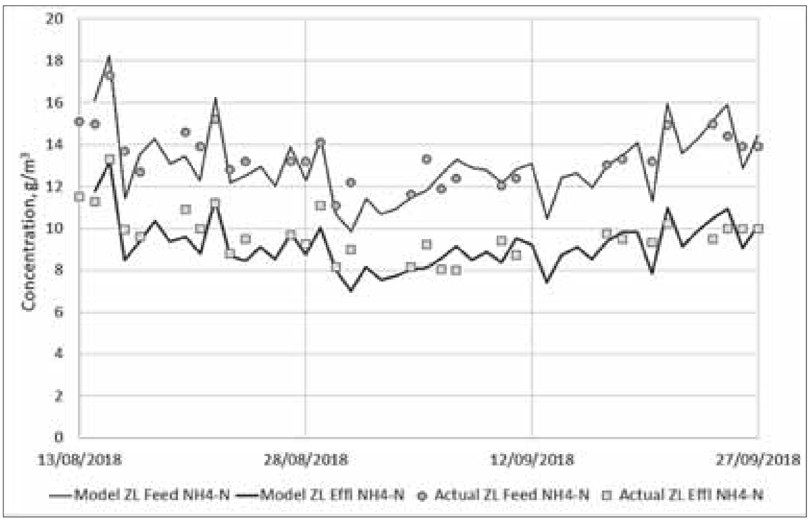


Fig. 6. Validation of the YBSD MABR model in Biowin on influent and effluent ammonia concentration in the MABR zone

This model also confirms the MABR peak trimming effect discussed in paragraph 3.2, where the large fluctuation of ammonia concentration is passively dampened by the MABR response to the ammonia concentration in the bulk. This phenomenon requires no control but provides an extra level of safety factor from breakthrough at the daily peak ammonia concentrations.

4. Conclusions

Field data from a full-scale membrane aerated biofilm reactor in hybrid configuration have been presented and discussed, to demonstrate the reliability of MABR to intensify the nitrification process in existing wastewater treatment plants. The main outcomes from the collected data can be summarized as follows:

1. real-time monitoring of the MABR exhaust oxygen concentration provides a reliable, repeatable and affordable assessment of the overall process performance, through the calculated key performance indicator OTR;

2. OTR well correlates with ammonia removal rate on the biofilm, thus proving the favourable conditions for nitrifying micro-organisms in MABR;

3. impact of temperature on OTR shows a weak correlation, thus confirming the great potential of the technology under the most challenging conditions for nitrification (cold climates);

4. MABR technology has demonstrated overall process resilience, to handle both nitrogen and hydraulic peak events. The OTR trend observed during influent N peak loading events demonstrates that MABR has a self-regulating biofilm that reduces fluctuations in nitrogen loading to the downstream aerobic system. Similarly, OTR data collected during a wet weather event proves the technology ability to recover performance when regular conditions are restored;

5. a mathematical model built and calibrated in Biowin, was able to adequately describe the full-scale performance in terms of ammonia removal in the MABR zone and can now be used as support tool for process optimization.

References

Brindle K., Stephenson T., (1996), Nitrification in a bubble-less oxygen mass transfer membrane bioreactor, *Water Science and Technology*, **34**, 261-267.

Brindle K., Stephenson T., Semmens M., (1998), Nitrification and oxygen utilisation in a membrane aeration bioreactor, *Journal of Membrane Science*, **144**, 197-209.

Daigger G.T., (2007), Wastewater Management in the 21st Century, *Journal of Environmental Engineering*, **133**.

Dzianach P.A., Dykes Gary A., Strachan Norval J.C., Forbes Ken J., Pérez-Reche Francisco J., (2019), Challenges of biofilm control and utilization: lessons from mathematical modelling, *Journal of the Royal Society Interface*, **16**.

EEA, (2019), European Environment Agency, Urban waste water treatment for 21st century challenges, Briefing No 5/2019, On line at: https://www.eea.europa.eu/publications/urban-waste-water-treatment-for.

Gilmore K.R., Terada A., Smets B.F., Love N.G., Garland J.L., (2013), Autotrophic nitrogen removal in a membrane-aerated biofilm reactor under continuous aeration: a demonstration, *Environmental Engineering Science*, **30**, 38-45.

Houweling D., Daigger G.T., (2019), *Intensifying Activated Sludge Using Media-Supported Biofilms*, CRC Press, Taylor and Francis Group.

Houweling D., Long Z., Peeters J., Adams N., Côté P., Daigger G.T., Snowling S., (2018), Nitrifying below the "washout" SRT: experimental and modelling results for a hybrid MABR/Activated Sludge Process, *Proceedings of the Water Environment Federation*, **16**, 1250-1263.

Hu S., Yang F., Sun C., Zhang J., Wang T., (2008), Simultaneous removal of COD and nitrogen using a novel carbon-membrane aerated biofilm reactor, *Journal of Environmental Sciences*, **20**, 142-148.

Lackner S., Terada A., Smets B.F., (2008), Heterotrophic activity compromises autotrophic nitrogen removal in membrane-aerated biofilms: results of a modeling study, *Water Research*, **42**, 1102-1112.

Lackner S., Terada A., Horn H., Henze M., Smets B.F., (2010), Nitratation performance in membrane-aerated bifilm reactors differs from conventional biofilm systems, *Water Research*, **44**, 6073-6084.

Lin J., Zhang P., Li G., Li J., Zhao X., (2016), Effect of COD/N ration on nitrogen removal in a membrane-aerated biofilm reactor, *International Biodeterioration and Biodegradation*, **113**, 74-79.

Liu H., Yang F., Shi S., Liu X., (2010), Effect of substrate COD/N ratio on performance and microbial community structure of a membrane aerated biofilm reactor, *Journal of Environmental Sciences*, **20**, 540-546.

Nerenberg R., (2016), The Membrane-Biofilm Reactor (MBfR) as a Counter-Diffusional Biofilm Process, *Current Opinion in Biotechnology*, **38**, 131-136.

Rittmann B.E., (2007), The membrane biofilm reactor is a versatile platform for water and wastewater treatment, *Environmental Engineering Research*, **12**, 157-175.

Shin J.-H., Sang B.-I., Chung Y.-C., Choung Y.-K., (2008), A novel CSTR-type of hollow fiber membrane biofilm reactor for consecutive nitrification and denitrification, *Desalination*, **221**, 526-533.

Sunner N., Long Z., Houweling D., Monti A., Peeters J., (2018), MABR as a low-energy compact solution for nutrient removal upgrades – results form a demonstration in the UK, *Proceedings of the Water Environment Federation,* doi: 10.2175/193864718825137908.

Underwood A., Mc Mains C., Coutts D., Peeters J., Ireland J., Houweling D., (2018), Design and start-up of the first full-scale Membrane Aerated Biofilm Reactor in the United States, *Proceedings of the Water Environment Federation*, **16**, 1282-1296.

Tartakovsky B., Guiot S.R., (2004), *Biofilm Modelling*, In: *Fundamentals of Cell Immobilisation Biotechnology, (Focus on Biotechnology)*, Nedović V., Willaert R. (Eds.), vol. 8, Springer, Dordrecht.

Environmental Engineering and Management Journal October 2020, Vol. 19, No. 10, 1791-1796
http://www.eemj.icpm.tuiasi.ro/; hiip://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

FIELD APPLICATION OF A REAGENT FOR IN SITU CHEMICAL REDUCTION AND ENHANCED REDUCTIVE DICHLORINATION TREATMENT OF AN AQUIFER CONTAMINATED WITH TETRACHLOROETHYLENE (PCE), TRICHLOROETHYLENE, 1,1-DICHLOROETHYLENE, DICHLOROPROPANE AND 1,1,2,2-TETRACHLOROETHANE (R-130)

Alberto Leombruni*, Michael Mueller, Alan Seech, Daniel Leigh

PeroxyChem LLC, 2005 Market Street, Philadelphia, PA, USA

Abstract

Groundwater at an abandoned industrial area near Bergamo, Italy, was historically contaminated by tetrachloroethylene (PCE) (>100 µg/L) and, to a lesser extent, by trichlorethylene (TCE), dichloropropane (DP) and 1,1,2,2-tetrachloroethane (R-130). A liquid reagent (EHC® Liquid) was selected for remediation of groundwater at the site. The reagent is provided in two parts: EHC® Liquid Mix (a soluble organo-iron salt), and ELS® Microemulsion (a lecithin-based carbon substrate), and is designed to promote both *in situ* chemical reduction (ISCR) and enhanced reductive dechlorination (ERD) to destroy chlorinated organic compounds. The two components are mixed with water and injected into the subsurface. Once in groundwater, EHC® Liquid rapidly generates highly reduced conditions, favouring both biotic and abiotic dechlorination reactions. Less than 6 months after the injection of EHC® Liquid in the main source area, concentrations of the target contaminants had reached the site-specific remediation target values (CSC Legislative Decree 152/06) in the main monitoring piezometers present in the area, thus demonstrating the effective establishment of enhanced biotic and abiotic reducing conditions and degradation of the target compounds.

Keywords: aquifer, chlorinated solvents, enhanced reductive dichlorination, lecithin microemulsion, treatment

Received: February, 2020; Revised final: June, 2020; Accepted: July, 2020; Published in final edited form: October, 2020

1. Introduction

Enhanced *in situ* anaerobic bioremediation can be an efficient method of degrading various chlorinated solvents dissolved in groundwater, including some dissolved metals (e.g., hexavalent chromium) (Bradley, 2000; Lee et al., 2000). Advantages of enhanced anaerobic bioremediation include complete mineralization of the contaminants in groundwater with limited impacts on infrastructures and relatively low cost compared to other common engineered remedial systems (Borden, 2006; Lewis et al., 2000). However, the addition of organic carbon into saturated zones is a well-known technology to promote conventional enzymatic reductive dechlorination reactions (Hartmans et al., 1985; Vogel, 1994). This happens because the organic carbon substrate in the subsurface will support the growth of indigenous microbes in the aquifer (Aulenta et al., 2006). As bacteria feed on the soluble carbon media, they consume dissolved oxygen and other electron acceptors, thereby reducing the redox potential in groundwater (Bradley et al., 1998). In particular, as bacteria ferment the ELS® (Emulsified

*Author to whom all correspondence should be addressed: e-mail: alberto.leombruni@dgextern.com; Phone: +39 3895121600

Lecithin Substrate) component (Leombruni et al., 2020), they release a variety of volatile fatty acids.

(VFAs) such as lactic, propionic and butyric, which diffuse from the site of fermentation into the saturated contaminated plume, and serve as electron donors for other bacteria, including dehalogenators. Enhanced anaerobic bioremediation may fit sites where site-specific data indicate that the contaminants can be readily degraded by native microbial populations under anaerobic conditions (Lee et al., 1999; Newell et al., 2003). Moreover, the use of microemulsion such as ELS should be strongly recommended where subsurface conditions (e.g., aquifer permeability) are conducive to adequate emplacement and distribution, and creation of an in situ reactive zone conducive to anaerobic degradation of the targeted contaminants.

Treated area: background

Groundwater at an abandoned industrial area near Bergamo, Italy, was historically contaminated by tetrachloroethylene (PCE) (>100 µg/L) and, to a lesser extent, by trichlorethylene (TCE), dichloropropane (DP) and 1,1,2,2-tetrachloroethane (R-130), as shown in Fig. 1 and Fig. 2. Based on the results of a characterization analysis, the contaminated source area aquifer subject to intervention consisted of a saturated area approximately 400 m^2 wide and 18 meters of thick. The piezometric surface is located at approximately 20 meters below ground level, while the base of the investigated aquifer, represented by a stratification of thick silty sand, is approximately 38 m from the ground level (Fig. 3). The surficial contaminated aquifer is constituted by a fine sand with hydraulic conductivity in the order of 1.2 x 10^{-3} cm/s, considering a hydraulic gradient of about 7% and an effective porosity of the saturated medium of about 34%. Linear interstitial velocity of the groundwater flow is calculated to approximately 76 m/year. Before treatment, the aquifer showed natural aerobic conditions (Eh ≈ 150 mV, DO ≈ 4 mg/L), an average sulphate content of about 1 mg/L, and pH values in the neutral range (pH ≈ 6.7). In April 2019, limited evidence of anaerobic degradation catabolites (e.g. Trichloroethylene, 1,1-Dichloroethylene, Vinyl chloride) together with DP and R-130 concentrations were present in solution. Moreover, multi-levels monitoring data have shown a clear uniform distribution of the main contaminant levels along the saturated treatment zones.

Therefore, in consideration of the asymptotic trend of the contaminant concentrations in the solution, with values above the GD 152 (2006), it was considered appropriate to apply the EHC® Liquid technology; an innovative *in situ* treatment able to favour the establishment of both biotic and abiotic reductive dechlorination processes. The distribution of PCE and 1,1-DCE concentrations in the source area groundwater pre- treatment are shown, respectively, in the following maps.

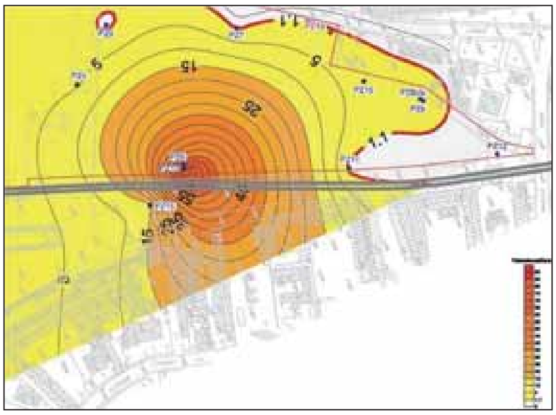


Fig. 1. PCE concentrations (µg/L) in the source area before treatment (April 2019)

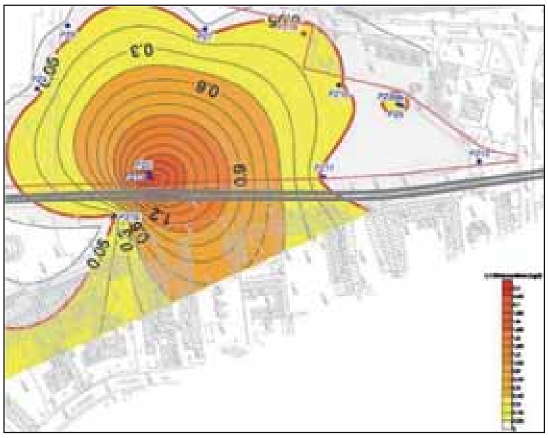


Fig. 2. 1,1-DCE concentrations (µg/L) in the source area before treatment (April 2019)

2. Material and methods

2.1. The science behind EHC® Liquid ISCR Reagent

EHC® Liquid is composed primarily of ELS® Microemulsion; a slow-release organic carbon substrate, and EHC® Liquid Mix; an organo-ferrous compound (both food-grade). Key characteristics include,

- The ELS® component is based on soy lecithin, which is comprised of a high weight molecular phospholipid organic substrate ideal for the slow and sustained release of electron donors. ELS® also contains polysaccharides that are easily fermented to rapidly establish reducing conditions *in situ*. ELS® concentrate is shipped in 200 litre/204 kg steel drums and has a honey-like appearance with viscosity of about 3,700 N-s/m^2, at 20°C (Fig. 4).
- The iron in EHC® Liquid Mix is an organo-ferrous iron compound, provided as a soluble dry powder packaged in 11.7 kg bags (Fig. 4).

The EHC® Liquid formulation has been specially engineered for easy on-site handling, and can be applied through fixed well injection systems, hydraulic injection systems or via "direct push technologies”.

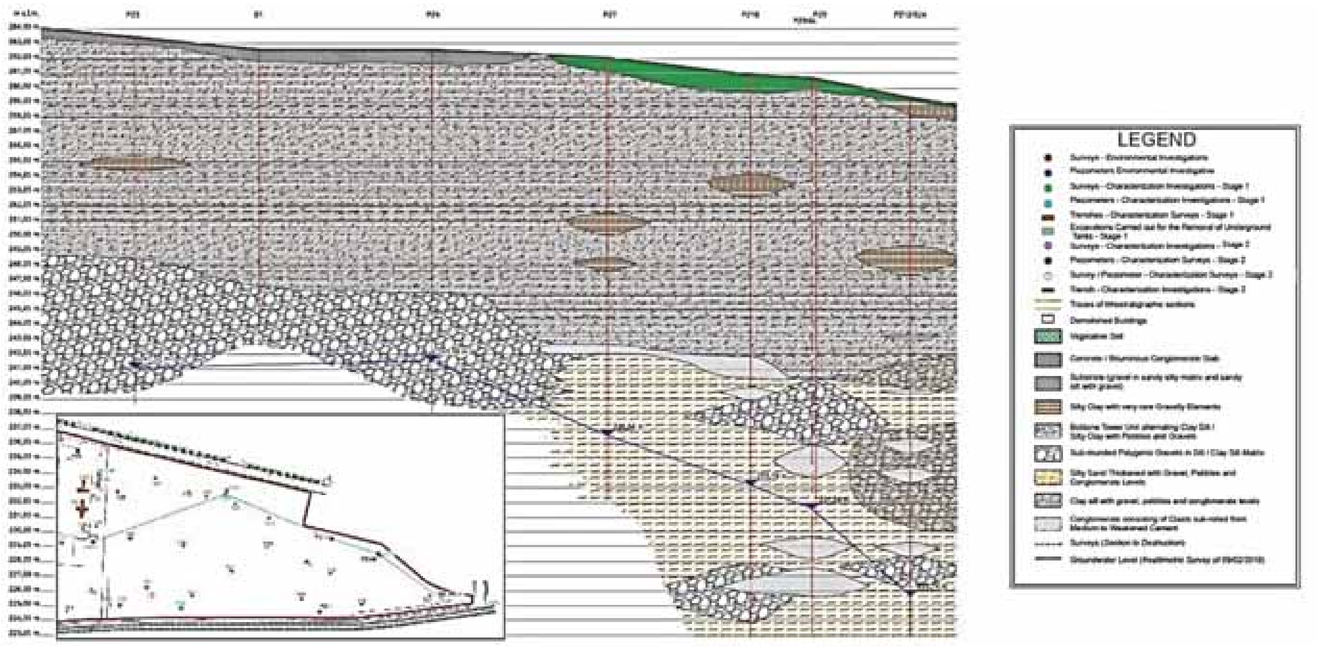


Fig. 3. Geological section aquifer being treated

(a) (b)

Fig. 4. ELS® Microemulsion barrel (a) and pails with the EHC® Liquid Mix compound (b)

The components are readily mixed in water on site prior to injection. Once in the aquifer, the EHC® Liquid components rapidly generate reducing conditions and act as an electro-donor, favouring enhanced reductive dechlorination processes (ERD). Furthermore, through fermentation of the ELS® Microemulsion, bacteria release a variety of volatile fatty acids (VFAs) such as lactic, propionic and butyric acid. These then spread from the injection zone throughout the contaminated plume, acting as electron donors for other bacteria, including dehalogenators (Fennell and Gossett, 1998; Maymo-Gatell et al., 1997). The lecithin molecule itself is composed mainly of phospholipids. It is also a zwitterion, which has a positively charged head and a negatively charged tail. Consequently, the ELS® Microemulsion has both hydrophilic and hydrophobic properties, which tend to be more stable and long-lasting in the subsurface compared to compounds consisting of only a hydrophobic part (e.g. emulsified vegetable oils). Furthermore, in addition to serving as a long-lasting carbon source, phospholipids promote bioremediation in groundwater by providing highly bioavailable organic nutrients, including nitrogen and phosphorous: essential elements for bacterial growth (Leombruni et al., 2020).

2.2. Full scale implementation

In May 2019, approximately 8,160 kg of ELS® Microemulsion were first emulsified with water at 10% dilution (approximately 1 kg of ELS® Microemulsion mixed into 10 L of water), together with 1,872 kg of the EHC® Liquid Mix organo-ferrous compound. The solution was then injected under pressure (≈7 bar) into the impacted groundwater zone between 20 m and 38 m bgl through 8 fixed injection points distributed in the source area (Fig. 5). The main objective established in the reclamation plan was to obtain compliance with GD 152 (2006) limits (PCE = 1.1 µg/L, TCE = 1.5 µ/L, 1,1-DCE = 0.05 µ/L, 1,2-DP = 0.15 µ/L, R-130 = 0.05 µ/L) at monitoring points present in the treatment area (Pz6, Pz1, MLS1). The injection phase lasted approximately 7 working days and included the use of specific injection tools.

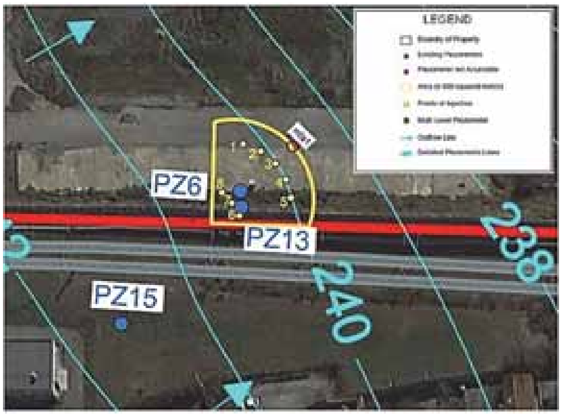


Fig. 5. Injection points grid (yellow) and monitoring points (blue and red) together with the GW flow direction

The ELS® Microemulsion component is easily emulsified directly on site, using a common high-speed centrifugal pump. Before mixing, a receptacle tank is filled with the appropriate amount of water needed to dilute the concentrate; this water is often pre-conditioned in order to remove the dissolved oxygen present. Afterwards, the ELS® Microemulsion and EHC® Liquid mix are added in sequence to the pre-mixing tank, and then transferred to a main mixing tank. A recirculation system with a centrifugal pump is then placed in-line, to provide continuous agitation of the reagents inside the main mixing tank (Fig. 6).

3. Results and discussion

Less than 6 months following EHC® Liquid injections, the remedial objectives were achieved in all monitoring piezometers present in the treatment area, except for a few downstream points where some degradation catabolites were still slightly above target limits (<0.3 µg/L). The concentrations in downgradient wells decreased but may still be above target limits. This may be due to matrix diffusion downgradient of the treatment area. It is anticipated that further treatment, or time, will result in achieving the goals in the highlighted wells. Fig. 7, for example, shows how the PCE concentrations and the respective biological daughter-products are reduced below clean-up goals (GD 152, 2006) in all the main piezometers, thus showing a reduction greater than the 95% in just 5 months of treatment.

Concentrations of individual degradation catabolites, such as DCE and VC, have remained substantially below detection limits in almost all monitoring points located within the treatment area. This data confirms the establishment of complete reductive dichlorination processes in the entire aquifer being treated (Fig. 8). Furthermore, the degradation processes in different portions of the treated aquifer were verified by sampling at different depths and observing the same degradation trends (Fig. 9). Finally, complete abatement of 1,2-DP and R-130 concentrations in solution was also observed at all monitoring points located in the enhanced anaerobic treatment zone (Figs. 10-11). No rebound in PCE, DP or R-130 concentrations was observed subsequent to treatment, demonstrating the effectiveness of the reductive dichlorination process and indicating treatment of both dissolved and adsorbed phase contaminants.

Fig. 6. ELS® Microemulsion component in 200 L steel drums, and EHC® Liquid mix component in 11.7 kg bags delivered in plastic pails

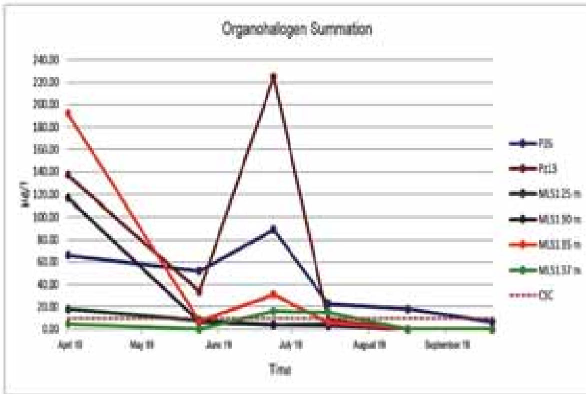


Fig. 7. Concentration trends for chlorinated ethylenes in groundwater at monitoring points in the treatment area, before and after EHC® L injections performed in May 2019

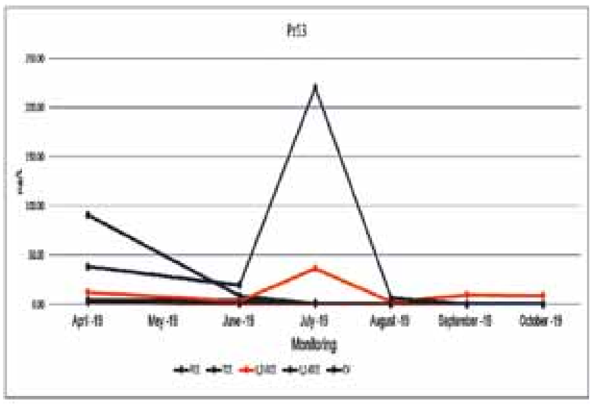
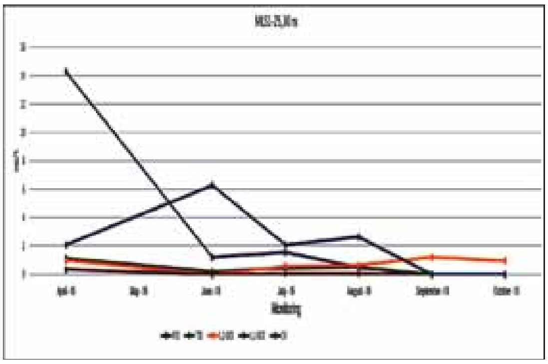
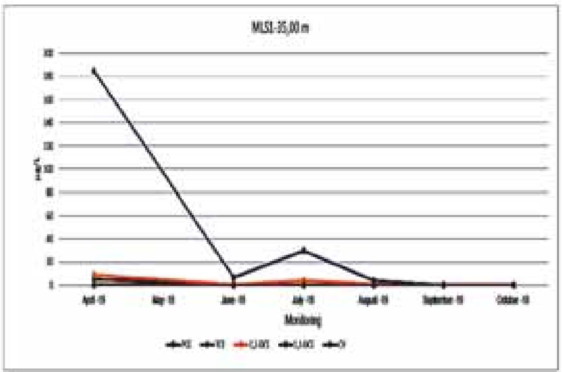


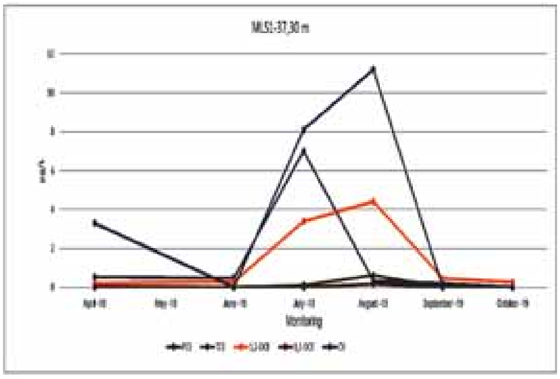
Fig. 8. Concentration trends for chlorinated ethylene in groundwater at monitoring point Pz13 in the treatment area before and after injection of EHC® L performed in May 2019



(a)



(b)



(c)

Fig. 9. Concentration trends for chlorinated ethylenes in groundwater at the MLS1 multi-level monitoring point: (a) 25 m bgl; (b) 35 m bgl; (c) 37 m bgl

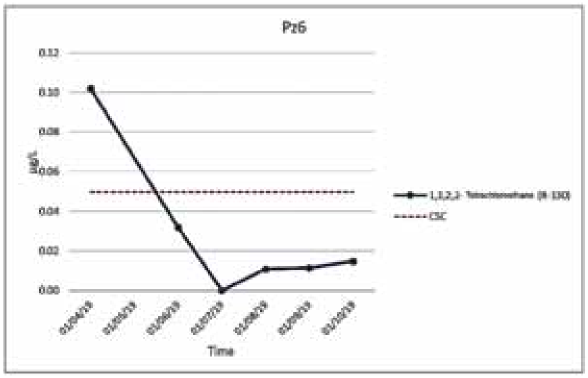


Fig. 10. Trend in R-130 concentrations in groundwater at the Pz6 monitoring point in the treatment area before and after EHC® L injection performed in May 2019

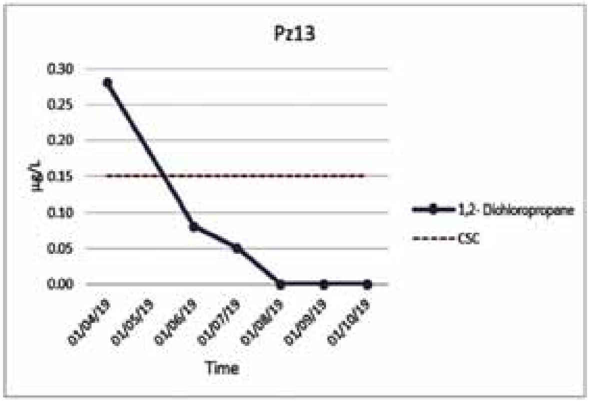


Fig. 11. Trend in 1,2-DP concentration in groundwater at the monitoring point Pz13 in the treatment area before and after EHC® L injection performed in May 2019

3.1. Evaluation parameters of EHC® Liquid effectiveness

In order to determine if the piezometers were effectively under the influence of the EHC® Liquid reagent and, therefore, to demonstrate the effective distribution of the reagent in all the treated areas, aquifer field parameters including total organic carbon (TOC), dissolved oxygen (DO), hydrogen ion activity (pH), and oxidation-reduction potential (ORP) were measured. The extent of reducing conditions was also assayed by analysis of dissolved iron Fe (II), manganese Mn (II) and sulphate (SO_4). Along with DO, ORP, and pH as field parameters, Fe (II) and Mn (II) are viewed as good indicators of substrate effectiveness in establishment of reducing conditions.

A decreasing trend in DO was observed following substrate injection, indicating rapid establishment of anaerobic conditions necessary for biological reductive dechlorination. A significant increase in the concentrations of Fe (II) and Mn (II) in solution was observed in all the monitoring piezometers present in the treatment area, confirming the correct distribution of the reagent in the groundwater and the establishment of enhanced anaerobic conditions. Maximum concentrations of Mn (II) and Fe (II) of 4 and 13 mg/L were observed.

A decrease in the concentrations of sulphate in solution was observed, on average, equal to an order of magnitude compared to the pre-treatment values ranging from 0.5 to 1 mg/L, thus demonstrating the establishment of sulphate-reducing conditions, necessary for the achievement of complete biological reductive dichlorination.

4. Conclusions

In 2019, the ISCR and ERD treatment of an aquifer historically contaminated with tetrachlorethylene, 1,2-dichloropropane and 1,1,2,2-tetrachloroethane was successfully performed in Italy using EHC® Liquid. Following injection of EHC® Liquid into the treatment zone, highly reduced conditions were established in the aquifer as indicated by the reduction in ORP, and geochemical changes including an increase in soluble manganese and ferrous iron and a decrease in sulphate concentrations. As reducing conditions were being established, a rapid decrease of the PCE, DP and R-130 was observed in all treatment area monitoring wells. Less than six months after application, PCE, DP and R-130 concentrations were reduced up to 95% compared to pre-treatment concentrations.

As anticipated by sequential reductive dichlorination processes, a temporary increase of daughter products including DCE and VC was observed. These daughter products were rapidly reduced to below the method detection limit in all the monitoring wells, except for some downstream wells where EHC® Liquid had not been distributed. No rebound in PCE, DP or R-130 concentrations was observed subsequent to treatment, demonstrating the effectiveness of the reductive dichlorination process and indicating treatment of both dissolved and adsorbed phase contaminants.

References

Aulenta F., Majone M., Tandoi V., (2006), Enhanced anaerobic bioremediation of chlorinated solvents: environmental factors influencing microbial activity and their relevance under field conditions, *Journal of Chemical Technology and Biotechnology*, **81**, 1463-1474.

Borden R., (2006), Protocol for Enhanced in situ Bioremediation Using Emulsified Edible Oil, Air Force Center for Environmental Excellence (AFCEE), On line at: https://frtr.gov/costperformance/pdf/remediation/Final-Edible-Oil-Protocol-October-2007.pdf.

Bradley M., Chapelle F., Lovley D., (1998), Humic acids as electron acceptors for anaerobic microbial oxidation of vinyl chloride and dichloroethene, *Applied and Environmental Microbiology*, **64**, 3102-3105.

Bradley M., (2000), Microbial degradation of chloroethenes in groundwater systems, *Hydrogeology Journal*, **8**, 104-111.

Fennell E., Gossett J., (1998), Modeling the Production of and Competition for Hydrogen in a Dechlorinating Culture, *Environmental Science and Technology*, **32**, 2450–2460

GD 152, (2006), Governmental Decision No. 152/2006 Annex 5 Part IV, regarding the groundwater quality limits, On line at: https://www.camera.it/parlam/leggi/deleghe/06152dl2.htm.

Hartmans S., De Bont J., Tramper J., Luben K., (1985), Bacterial degradation of vinyl chloride, *Biotechnology Letteres*, **7**, 383-388.

Lee C.H., Lewis T.A., Paszczynski A., Crawford R.L., (1999), Identification of an extracellular agent [correction of catalyst] of carbon tetrachloride dehalogenation from Pseudomonas stutzeri strain KC as pyridine-2, 6-bis(thiocarboxylate), *Biochemical and Biophysical Research Communication*, **261**, 562-6.

Lee M.D., Buchanan R., Ellis D., (2000), *Laboratory Studies Using Edible Oils to Support Reductive Dechlorination*, Proc. 2nd Int. Symp. on Remediation of Chlorinated and Recalcitrant Compounds, Monterey, vol.1, 77-84.

Leombruni A., Morlacchi F., Collina L., Leigh D., Mueller M., (2020), Full-scale application of ELS® microemulsion technology for the treatment of an aquifer contaminated with perchloroethylene and trichloroethylene via enhanced reductive dechlorination, *Acque Sotterranee - Italian Journal of Groundwater*, **9**, 19-26.

Lewis T.A., Cortese M.S., Sebat J.L., Green T.L., Lee C.H., Crawford R.L., (2000), A Pseudomonas stutzeri gene cluster encoding the biosynthesis of the CCl4-dechlorination agent pyridine-2,6-bis (thiocarboxylic acid), *Environement Microbiology*, **2**, 407-16.

Maymo-Gatell X., Zinder S.H., Anguish T., (1997), Reductive dechlorination of chlorinated ethenes and 1,2-dichloroethane by “Dehalococcoides ethenogenes” 195, *Applied and Environmental Microbiology*, **65,** 3108-3113.

Newell C.J., Rifai H.S., Wilson J.T., Connor J.A., Aziz J.A., Suarez M., (2003), *Calculation and Use of First-Order Rate Constants for Monitored Natural Attenuation Studies*, In: *Ground Water Issue*, U.S. Environmental Protection Agency.

Vogel T., (1994), *Natural Bioremediation of Chlorinated Solvents*, In: *Handbook of Bioremediation*, Lewis Publishers, Boca Raton, 201-225.

Environmental Engineering and Management Journal *October 2020, Vol. 19, No. 10, 1797-1805*
http://www.eemj.icpm.tuiasi.ro/; hiip://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

EXPLOITING THE POTENTIAL OF POLYETHYLENE MECHANICAL RECYCLING: ECONOMIC AND SUSTAINABILITY ANALYSIS

Leonardo Mita

Department of European and Mediterranean Cultures: Architecture, Environment, Cultural Heritage (DiCEM) University of Basilicata, University Campus of Matera, 75100, Matera (Italy),
E-mail address: leonardomita@hotmail.com; Phone: +39 329 1244180

Abstract

Plastic and circular economy are key words that characterize our present and seek to address the future of the global social economic system. Plastic, on the one hand, is the emblem of modern times, a low cost material with unparalleled functional properties. Circular economy, on the other hand defines an alternative model to traditional economy that focuses on sustainability. In this work, the author presents a case study relating to a virtuous example of circular economy applied to the industrial plastic sector used in the packaging field. The study was conducted through a cost-benefit analysis to evaluate the profitability of internal mechanical recycling of polyethylene and a sustainability analysis to characterize the circularity of the production process introduced. The benefits of introducing a production waste mechanical recycling line have been studied by comparing them to external recycling. The evaluation of the presented case is positive, from both an environmental and a business point of view in relation to the economic, energy and production efficiency factors.

Key words: circular economy, polyethylene, recycle

Received: February, 2020; Revised final: June, 2020; Accepted: July, 2020; Published in final edited form: October, 2020

1. Introduction

Starting from the circular economy definitions of various authors such as Dupont-Inglis (2015), EMAF (2012), Schut et al. (2016), , coded and collected in previous reviews papers (i.e. Ghisellini et al., 2016; Kirchherr et al., 2017;) this study presents a plastic circular economy case study in which the value attributable to plastic is rethought, extending its life cycle and proposing new application scenarios. Circular business models are economically viable ways to continually reuse products and materials especially for plastic that is a fully recycable one (Bocken et al, 2016).

Plastic represents one of the most used materials all over the world. It is characterized by a medium - short life cycle and by a mostly improper disposal which causes significant environmental problems (ICESP, 2018). Consequently, in December 2015 the European Commission adopted a Union action plan for a circular economy (EC, 2015) identifying plastic as a key priority and committing to prepare a strategy to address the challenges posed by plastics taking into account the whole life cycle.

Plastic production in Europe in 2015 was around 60 million tons (PE, 2015). Specifically European demand for plastics was around 48 million tons, of which 14% (around 7 million tons) concentrated in Italy. A summary of the main production and demand quantities is shown in Fig. 1.

According to Eurostat calculations (Eurostat, 2015), in the same year the production of plastic waste in Europe was 26 million tons, of which approximately 1.7 million tons generated in Italy with a recycling rate for packaging between 40% and 50%.

In this context, it is clear that a change is necessary starting at the beginning: from the production of plastic (Paletta et al., 2019) and from the prevention of plastic waste through circular solutions. The return logistics for packaging or the contemporary recycle of production scraps, joined with the development of the production digitalization processes are virtuous examples able to optimizing the packaging production and reducing the production of polymeric waste from the beginning (Niero and Hauschild, 2017).

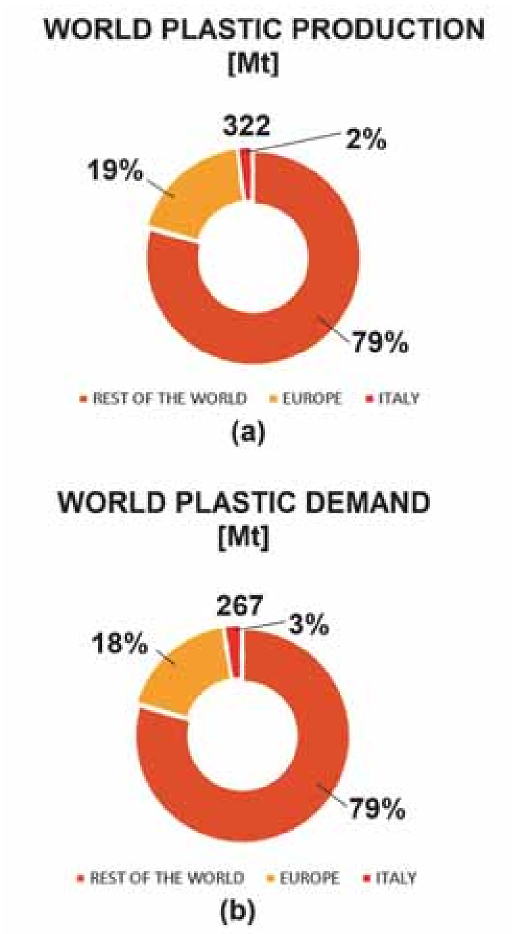


Fig. 1. World plastic production versus world plastic demand (adapted from Nkwachukwu et al., 2013): (a) represents the world plastic production in million tons, (b) represents the world plastic demand in million tons. The quantities are expressed as a percentage of the total shown above the graph

The increase in the world population estimated by 2030 indicates that 8.5 billion people (UN, 2019) will be livingon the Earth. The linear economy model used to date, by which resources run out and end up becoming waste and emissions, appears unsustainable and lays the foundation for an economic transition towards the circular economy, i.e. using waste and scraps as a resource (Van Eygen et al., 2018, Schiopu et al., 2007).

Polyethylene is the simplest of polymers, it is a fully recyclable material, but only a small part of the plastic waste is currently recycled (Sulyman et al, 2016). A sustainable supply chain management ensure recyclability and enlarged recycling capability (Comăniță et al, 2016). The recycle of plastic, in particular of polyethylene, has been studied by several authors (i.e. Hopewell et al, 2009; Jnr et al, 2018; Loultcheva et al., 1997; Luijsterburg and Goossens, 2014; Radusin et al., 2020; ;) highlighting costs, benefits and useful applications.

For example, Dahlbo et al. (2018) show the the recycling potential of plastic packaging waste in Finland; the mechanical and rheological test results indicated that even plastic wastes, can be useful second raw materials. Soto et al. (2018) investigated the possibility of recycling the film obtained from municipal solid wastes to showing that recycled material presents good properties close to virgin polyethylene. Maris et al. (2018) reported an overview of different techniques for compatibilization used for mechanical recycling. Gu et al, (2017) investigated the life cycle environmental impacts of mechanical plastic recycling practice of a plastic recycling company in China. Datta and Kopczyńska (2016) presented a review in which describe the main methods of recycling plastic waste, Hamad et al. (2013) reviewed the progress on recycling of polymeric waste form some traditional polymers and their systems, Ragaert et al. (2017) presented a comprehensive description of the current pathways for polymers recycling, via mechanical and chemical recycling. According to Grigore (2017) this study investigates the environmental and economic potential of polyethylene recycling. The application reports a secondary or mechanical recycling of polyethylene. Polyethylene wastes and scraps will be formed by shredding or grinding into pellets, and then melted to make the new product by extrusion (Francis, 2016). Regranulated polyethylene will be used as input to the production cycle as a second raw material.

This application represents a simple strategy for product design and business model innovation in businesses that want to pursue a circular economy model.

2. Material and methods

This section reports the results of a production, energy and economic efficiency project developed within a polyethylene packaging production company (Mita, 2019). Isopack, promoter of this project, is a plastic packaging manufacturer located between the regions of Puglia and Basilicata, in the south of Italy. It is specialized in extruding and marketing polyethylene film, bubble and foam for packaging.

The company extrudes both low density polyethylene (LDPE) and high density polyethylene (HDPE). Polyethylene is one of the most important thermoplastic polymer. It is elastic, non-toxic and is created through the polymerization of ethylene. LDPE appears semi-rigid, translucent, very tough, weatherproof, with good chemical resistance and low water absorption. HDPE is flexible, translucent/waxy, weatherproof with a good low temperature toughness (Brazel and Rosen, 2012).

For the purposes of the investigation was used:

● high density polyethylene (HDPE) TIPELIN 7000F (MOLGROUP, 2020), produced by Mol Petrochemicals. The material has density 0.955 g/cm^3

(23°C) and melt flow index 0.08 g/10min (190° and 2.16 kg);

- low density polyethylene (LDPE) LOTRÈNE FD0270 (QAPCO, 2020), produced by Qatar Petrochemical company. The material has density 0.923 g/cm^3 (23°C) and melt flow index 2.40 g/10min (190° and 2.16 kg).

As part of the efficiency improvement project, particular attention was paid to the recycling and recovery of waste from the manufacturing processes through the introduction of a new production sector aimed at the recycling of production waste.

The production sector for the mechanical recycling of the second raw material was designed and built between 2017 and 2018 and consists of:

- Continuous pneumatic conveying system of production scraps from each line to the grinding station;
- Grinding line;
- Storage station;
- Shredding line for production waste;
- Granulation line.

The recycling compartment shown in Fig. 2 is fed by two different types: while on the one hand the grinding line receives the production scraps of the extrusion lines operating simultaneously, on the other hand the shredding line is fed by the waste of production of the material produced. Grinder had installed an horizontal rotor with a diameter of 250 that rotates at 340 rpm. The rotor has 3 rotating knives and two fixed ones. The grinding line is continuously fed by an automatic pneumatic conveying system consisting of centrifugal fans (450 m^3/h) and circular section channels. The shredder, however, is manually fed as a function of the waste products. Product waste is preliminarily subjected to a quality control at the end of which the non-compliant material to be shredded is selected. The quality control also, allows the selection of the polymer which is differentiated according to density, typology and color. Shredder had installed an horizontal rotor with a diameter of 220 mm and a length of 900 mm. The rotor has 23 knives that rotates at 82 rpm. The shredded polyethylene is sorted according to the polymer type High Density (HDPE) - Low Density (LDPE) and the color, later is processed by means of speed programs differentiated according to the density, thickness and surface mass.

The shredded or ground material is subsequently stored in a silo that allows the accumulation of polyethylene in order to provide a constant flow rate to the granulation line. The size of the pellets output from grinding and shredding, of about 200 mm, makes them suitable for processing in the subsequent granulation.

The last step of the recycling process consists of the granulation line by means of a reverse extrusion: it melts the material, cools it and forms it into granules. The granulator had installed a single screw extruder (L/D 35) with degassing system. Polyethylene was extruded at screw rotation of 120 rpm, and processing temperature of 240 °C with a throughput between 140 and 160 kg/h. Fig. 3 shows the polyethylene in the different recycling phases, the first phase (1) involves the polyethylene in the form of production waste and scraps, the second phase (2) regards the shredded and ground polyethylene, while in the last phase (3) polyethylene is in the form of granules of second raw material.

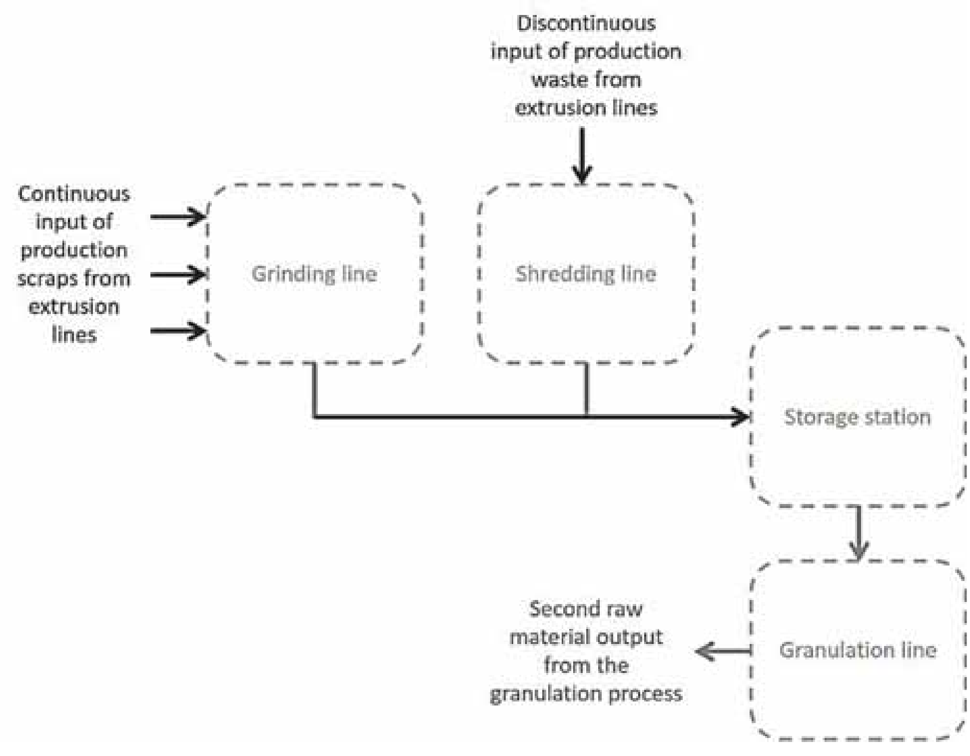


Fig. 2. Block diagram of the recycling compartment.
Inputs are shown in black; processes are dotted and outputs are shown in gray

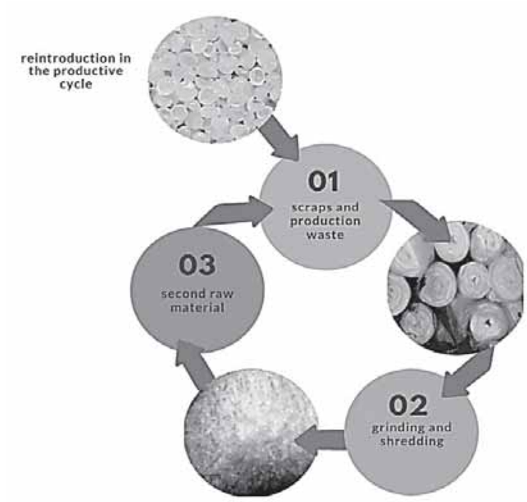


Fig. 3. Explanation of recycling process

The granules produced constitute second raw material, which is useful to feed the company's extrusion lines reducing the quantity of virgin polymer to be purchased. Both the shredding and the granulation lines are equipped with an innovative Programmable Logic Control (PLC) system with synoptic panel to keep production constant and self-regulating. The PLC is equipped with a real-time operating system that manages flash memories and allows to exchange data without having to put your hand to the machine code, in order to avoid unnecessary production stoppages. This system allows to control and act directly on the parameters and commands of each phase.

In addition, the supervision of the system allows the automatic setting of the starting procedures with parameters and temperatures recalled from pre-set recipes, based on the material to be worked, and greatly simplifies the start-up operations and exchange processing. Table 1 summarizes the characteristics of the recycling system.

Table 1. Main characteristics of the sector's recycling lines

Station	*Capacity*	*Measure unit*	*Note*
Grinding	100	kg/h	Amount of ground polymer per hour
Shredding	150	kg/h	Amount of shredded polymer per hour
Storage	300	kg	Amount of stored polymer
Granulation	150	kg/h	Amount of granulated polymer per hour

The recycling line is comparable to a production line. It does not produce any finished product, but it allows making the entire polyethylene production system efficient by enhancing the waste product and minimizing the economic losses associated with waste.

The visual inspection of the regenerated polymer represents a proof of the product quality; in particular, the more the coloration of the regenerated granule tends to the white shade of the virgin polymer, the more quality polyethylene has been regenerated by the process.

2.1. Production, energy and economic efficiency

The entire redevelopment project has, technically and functionally, modified the production department allowing productive, energy and economic efficiency. The introduction of the recycling process has allowed the real-time granulation of the production waste to be transported through an automatic and continuous aeraulic system.

The granulation of the polyethylene, following its extrusion allows a faster enhancement, a recovery of warehouse space and a saving in the handling of the product. In addition, there is a reduction in the fire risk related to the flammability of the polymer.

Energetically, the introduction of the new production sector constitutes an increase in dissipated electrical power; however, each component of the system was chosen to optimize energy consumption.

Lastly, the economic aspect, which represents an important issue linked to commercial and competition strategies on the market, has allowed the recycling to give the waste a higher market value than other scenarios as detailed. For a preliminary assessment in relation to the project carried out, an alternative scenario has been defined to the introduction of the recycling sector following the extrusion and production process of scraps and waste. Table 2 shows the essential elements of each scenario for comparison purposes. Table 2 reports two different scenarios. The first one is called Project and represents the realized one. The second is called Mixed and represents an alternative scenario of comparison.

Table 2. Comparison scenarios

Scenario	*Type*
Project	inside the company
Mixed	inside and outside the company

The alternative scenario has provided that the recycling process of the waste is outsourced polyethylene takes the name of processing account material; in this case, the external company is paid a fee per kg for the recycling process. The alternative scenario provides the recycling of the waste by third parties company. In this scenario, the company producing the waste obtains a value in terms of second raw material.

The project scenario, carried out internally through the previously described technologies, provides that the discarded material, which correspond to about 16% of the polyethylene initially introduced into the production cycle, is fully re-inserted within the new production process in the form of a second material. In the project scenario, the polyethylene containing prints and / or colored is treated separately and intended to be reused only in the production of industrial covering material (i.e. bags for waste collection), both for aesthetic reasons (color) and because of regulatory obstacles (Siciliano and Verdesca, 2001).

It should be noted that the recycled material poses aesthetic and odor problems, besides to a loss of productivity caused by the presence of particles that are not perfectly melted during the recycling process (Bessant, 1974). Based on the previous specifications, the convenience and value of recycling can be analyzed by referring to the average costs specified in Table 3.

Table 3. Average polyethylene costs referring to the year 2018. By virgin polymer we mean the first choice polyethylene, while by regenerated polymer we mean a recycled polymer of medium quality (BVSE, 2018; IMF Report, 2018)

Type of material	*Virgin polymer cost [€/kg]*	*Regenerated polymer cost [€/kg]*
HDPE	1.332	0.861
LDPE	1.324	0.762

To the listed costs must be added the operating costs related to the polymer recycling processes. Considering the project scenario and analyzing company's consumption and energy costs, along with the productivity of lines and processes by the data extracted from each line designed according to the standards of the Industry 4.0 program (MISE, 2018), it turns out that the benefit deriving from the recycling system B_R can be computed according to (Eq. 1).

$$B_R = C_{MR} + C_R \tag{1}$$

where: C_{MR} represents the cost of the regenerated material and C_R is the sum of recycling costs extracted from the company's internal energy and production monitoring. In particular, C_R includes costs related to loss times, maintenance costs, process water treatment costs, energy costs.

The cost of the regenerated material derives from the market data explained in Table 3, while the recycling costs amount to 0.210 €/kg for a total benefit equal to 1.071 €/kg for HDPE and 0.972 €/kg for LDPE. According to Eq. (2), the company profit **G,** is obtained with the difference between the benefit and the cost of the raw material C_{MP} (Eq. 2).

$$G = C_{MP} - B_R \tag{2}$$

The gain corresponds to 0.261 for HDPE and 0.352€/kg for LDPE. Referring to the same costs, it can be deduced that in the mixed scenario both the benefit and the gain are linked to the cost of processing by third parties; the latter can be considered equal to about € 0.3/kg.

2.2. Environmental efficiency and sustainability

The circular approach is based on the use of renewable energies or technologies and recyclable inputs capable of supporting a production system that avoids the waste of resources and that is capable of self-recycling, at least partially. This model is focused on recovery and recycling to recover part of the value of the product and insert it into a new production cycle maintaining quality and functionality.

Product recycling and use of recycled raw materials are two of the best practices of circular economy among the most implemented by Italian companies (Biancato, 2018). This study analyzed the recovery of waste directly from the production process to enhance waste and obtain new resources at zero cost for the management of a new production.

One of the main problems related to circular economy is the evaluation of actions in terms of sustainability. As reported in the Italian environmental code (DLGS, 2006), waste management is carried out according to criteria of effectiveness, efficiency and economy.

The first parameters that allow measuring the circularity of the processes are related to:

- Monitoring of energy consumption;
- Monitoring of water consumption;
- Counting of waste for treatment, reuse, recycling.

All the above parameters were monitored and analyzed in this study. In particular, all production lines were equipped with energy data loggers, chiller that thermoregulates the water input was equipped with a volumetric and energy meter, waste and scraps produced were counted and characterized before being sent to subsequent treatments.

In addition to sustainability, the measurement of the circularity is an essential requirement in order to allow pursuing concrete actions and achieving measurable results (MATTM Report, 2018). There are methods and databases at European and national level for measuring circularity (i.e. Resource Efficiency Scoreboard or Environmental Indicator).

In this paper a company circularity indicator developed by the Ellen MacArthur Foundation called Material Circularity Indicator (EMAF, 2015a, 2015b) was used. The Material Circularity Indicator (MCI) suggests the transition from the linear flow to the circular flow by its components. Moreover, the MCI compares the product's intensity and usage time to a similar industry-average product. The MCI is the combination of virgin raw material, unrecoverable waste and a utility factor that accounts for the length and intensity of the product's use.

In most cases, the MCI will be calculated using detailed knowledge of a product's component parts and materials. Fig. 4 shows the quantities involved in the calculation of the Material Circularity Indicator applied in this study.

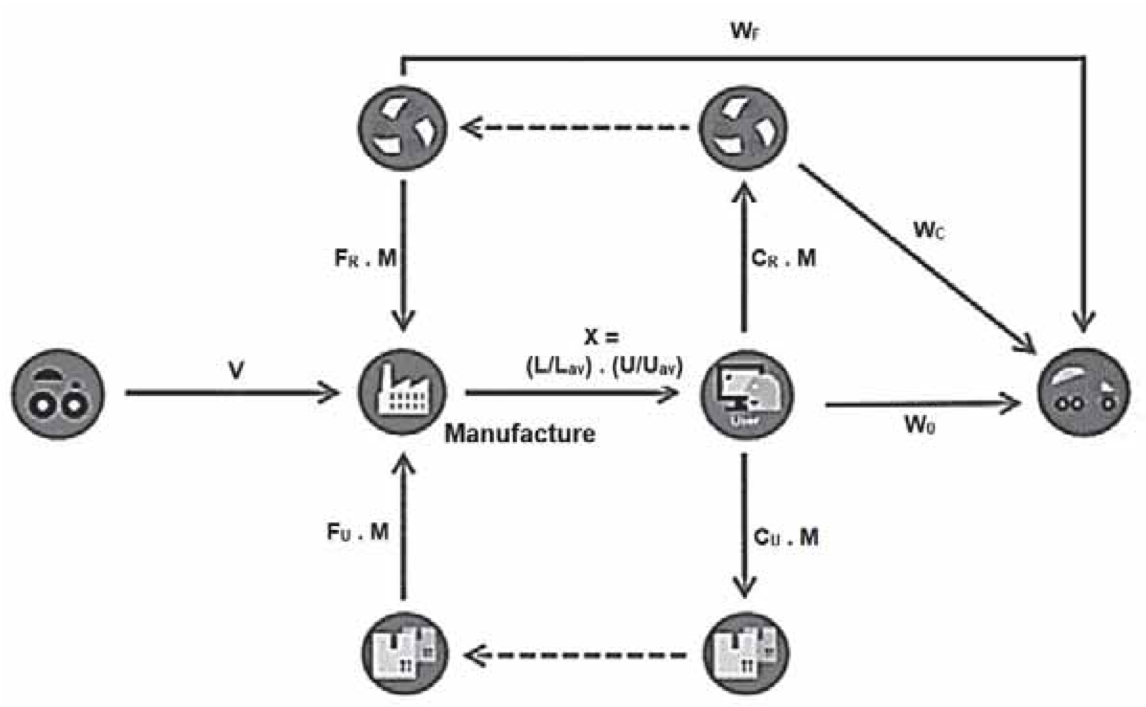


Fig. 4. Representation of material flows (from EMF, 2015a)

The calculation of MCI starts from the calculation of the virgin raw material used *V*. The part of virgin raw materials is calculated through the subtraction between the mass of the product produced and the mass of raw materials deriving from recycling F_R and / or reuse F_U processes (Eq. 3).

$$V = M(1 - F_R - F_U) \quad (3)$$

The overall amount of unrecoverable waste *W* is given by Eq. (4).

$$W = W_0[(W_F + W_C)/2] \quad (4)$$

where: W_0 represents the Unrecoverable Waste, W_F indicate the amount of waste generated to produce recycled contents used as feedstock and W_C is the amount of wast related of recycling process.

Eq. (4) considers that the efficiency of the raw material recycling process necessary for the calculation of W_F is equal to the efficiency of the product recycling process necessary for calculation of W_C.The Linear Flow Index *LFI* measures the proportion of material flowing in a linear fashion, that is, sourced from virgin materials and ending up as unrecoverable waste. Here its simplified version is used (Eq. 5).

$$LFI = [(W + W)/2M] \quad (5)$$

The closer the index approaches zero, the more the company is inclined to adopt circularity practices and carry them out correctly. The last variable to consider is the utility factor **X**. It is composed of the duration of the life cycle of a product U and the intensity of use L (Eq. 6).

$$X = (U/U_{mean}) + (L/L_{mean})$$

(6)

The Material Circularity Indicator of a product can now be defined by considering the Linear Flow Index of the product and a factor F(X), built as a function F of the utility X (Eq. 7).

$$MCI * p = 1 - [LFI\ F(X)] \quad (7)$$

F tates the form (Eq. 8):

$$F(X) = X/0.9 \quad (8)$$

This assumption allows to consider a reduction of the MCI; the index will be smaller and will quickly approach zero.

A summary of the values used in the calculation of the MCI is shown in Table 4.

Table 4. Values of parameters adopted in MCI calculation

Parameters	*Values*
V	0.85
W	0.30
W_0	0.20
W_F	0.04
W_C	0.16
X	1
F(X)	0.9

The simplifying hypothesis that was adopted in the calculation of the MCI concerned the utility factor. Since no comparative studies were available regarding the intensity and duration of the product life cycle, F was set equal to the unit avoiding the influence in the calculation of the MCI.

3. Results and discussion

The results confirm that the introduction of recycling line is a good choice for the recovery of production waste. The analisys are discussed separately: in the first part are reported the result related to economic perspective, in the second part are presenter those referred to environmental sustainability. After the activation of the line, the company generated a mean profit (or savings) of about thirty cents per kilogram of recycled polymer. The results obtained from the comparison are summarized in Table 5.

As can be seen from the obtained results, the internal recycling of polymer allows a greater gain compared to recycling at third parties (mixed scenario), the amount of gain represents about 23% of the value of the raw material with a higher value for HDPE. In the mixed scenario, in which the polymers are recycled externally, the gain of the company is around of 16% of the value of the raw material with a higher value for HDPE. In addition, to the costs analyzed it is necessary to add the transport costs which represent an important part especially in the polymery sending phase in which there are more voluminous than heavy rolls. The proposed cost benefit assessments are relative to the current state. Changes in the quantity of production and/or changes in the prices of the raw material would lead to different economic benefits.

Table 5. Benefit and profit for the scenarios analyzed. Advantages and gains are shown for each type of polymer: the results for HDPE are shown outside the brackets, in brackets those referred of LDPE

Scenario	*Benefit [€/kg] HDPE (LDPE)*	*Gain [€/kg] HDPE (LDPE)*
Project	1.071 (0.972)	0.261 (0.352)
Mixed	1.161 (1.062)	0.171(0.262)

The circularity indicator used here allows a quick and concise evaluation of the transition strategy undertaken. The main indicator adoptes wat the MCI. It has a score between 0 and 1 to a product assessing how linear is the flow of the product compared to similar industryaverage products.

The linear flow of a product represent the part of a product that comes from virgin materials and ends up as landfill related to a linear economy model. It is measured by LFI and takes a value between 1 and 0, where 1 is a completely linear flow and 0 a completely circular flow. As can be seen from Table 6 both indeces are close to 0.5. In particular for LFI the achivied value has been of 0.59 and for MCI has been a value of 0.47. These values indicate the transition from a linear flow to a sustainable circular flow, providing positive feedback to the heads of the departments on the strategy adopted.

Table 6. Results of Material Circularity Indicator approach

Index	*Value*
MCI	0.47
LFI	0.59

As shown by the indices, both close to 50%, a substantial increase in the circularity of the process would be obtained by increasing the fraction of raw materials deriving from recycling and the efficiency of recycling.

The limitations of the present study naturally include the lack of mechanical performance tests in relation to relation to the composition of recycled polymers. However, as suggested by Meran et al. (2008) and Jin et al. (2012), the mechanical performance decrease about 10% compared with the pure material for rates of recycled polymer until 20%. Considering the low percentages of use of recycled polymer, around 10%, and considering the use of the polymer as industrial packaging, it represents a good technical, economic and environmental compromise.

4. Conclusions

The introduction of a new production sector suitable for the recycling of scraps and production waste of polyethylene has allowed a change of perspective considering waste not as an environmental problem, but as an economical resource.

In fact, although seemingly unrelated, economic and environmental aspects are interconnected with each other about business strategies. On the one hand, the enhancement of scraps and production waste generates economic benefits in terms of cost reduction; on the other hand, it leads to an increase in environmental sustainability by reducing unrecoverable waste.

The proposed case study represents a virtuous example of circular economy applied to the plastic sector which in recent years represents the main enemy of the environment and sustainable development. In particular, this analysis, based on practical experience in the packaging sector, allowed a preliminary quantification regarding the circularity of a product and its environmental sustainability.

To date, plastic, and in particular polyethylene, is a very popular and difficult replacing material in daily life for its costs and its multiplicity of use. In this context, the application presented above shows how properly managed and recycled plastic, can be considered sustainable in environmental and economic terms.

This application provides a parallel view of the economic and environmental benefits resulting from the transition from traditional economy (linear) to circular. The preliminary results show the economic convenience of the company's internal recycling treatment proving that path taken has a significant potential to reduce the environmental impact of the current production system.

The shift to circular economy requires the replacement of the present production strategy. Analyzed action represents the first and most complex step for the transition from a linear economy model to a circular and sustainable economy model.

Future production technologies will be based on the integration of recycle in the producyion phase. The introduction of recycling lines inside the production could be the starting point for a supply chain of selected second raw material.

References

Bessant K.H.C., (1974), Subject: some environmental aspegts of won-returnable packaging with partiguur reference to pagkagiwb of dairy products in plastics: environmental aspects and disposal, *International Journal of Dairy Technology*, **27**, 156-159.

Biancato L., (2018), *Company management through the circular economy model: efficiency analysis*, MSc Thesis, Ca'Foscari University, Venice, Italy.

Bocken N.M., De Pauw I., Bakker C., Van Der Grinten B., (2016), Product design and business model strategies for a circular economy, *Journal of Industrial and Production Engineering*, **33**, 308-320.

Brazel C.S., Rosen S.L., (2012), *Fundamental Principles of Polymeric Materials*, 4th Edition, John Wiley & Sons, Hoboken, New Jersey.

BVSE, (2018), BVSE market report: plastics, German Federal Association on Secondary Raw Materials and Waste Management, On line at: https://plasticker.de/preise/marktbericht_en.php.

Comăniță E.D., Hlihor R.M., Ghinea C., Gavrilescu M., (2016), Occurrence of plastic waste in the environment: ecological and health risks, *Environmental Engineering & Management Journal*, **15**, 675-685.

Dahlbo H., Poliakova V., Mylläri V., Sahimaa O., Anderson R., (2018), Recycling potential of post-consumer plastic packaging waste in Finland, *Waste Management*, **71**, 52-61.

Datta J., Kopczyńska P., (2016), From polymer waste to potential main industrial products: Actual state of recycling and recovering, *Critical Reviews in Environmental Science and Technology*, **46**, 905-946.

DLGS, (2006). Environmental Standards, (in Italian), Legislative Decree 152/2006, Italian Government, On line at: https://www.camera.it/parlam/leggi/deleghe/06152dl.htm.

Dupont-Inglis J., (2015), Circular Economy: All Eyes on the Juncker Commission's Next Move, Renewable Matter. International Magazine on the Bioeconomy and the Circular Economy, On line at: http://suschem.blogspot.com/2015/04/circular-economy-all-eyes-on-juncker.html.

EC, (2015), The missing link - European Union action plan for the circular economy, (in Italian), Action plan, European Commition, 614, On line at: https://eur-lex.europa.eu/resource.html?uri=cellar:8a8ef5e8-99a0-11e5-b3b7-01aa75ed71a1.0009.02/DOC_1&format=PDF.

EMAF, (2015b), MCI Product-Level Dynamic Modelling Tool, Tool, Ellen MacArthur Foundation, On line at: https://www.ellenmacarthurfoundation.org/assets/downloads/insight/Circularity-Indicators_MCI-Product-Level-Dynamic-Modelling-Tool_May2015.xlsx.

EMAF, (2012), Towards the Circular Economy: Economic and Business Rationale for an Accelerated Transition, Report, Ellen MacArthur Foundation, On line at: https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Ellen-MacArthur-Foundation-Towards-the-Circular-Economy-vol.1.pdf.

EMAF, (2015a), Circularity Indicators: An Approach to Measure Circularity, Report, Ellen MacArthur Foundation, On line at: https://www.ellenmacarthurfoundation.org/assets/downloads/Circularity-Indicators-Methodology.pdf.

Eurostat, (2015), Waste statistics, Eurostat pubblication 2443-8219, Eurostat, On line at: http://ec.europa.eu/eurostat/statistics-explained/index.php/Waste_statistics.

Francis R., (2016), *Recycling of Polymers: Methods, Characterization and Applications*, John Wiley & Sons, Hoboken, New Jersey.

Ghisellini P., Cialani C., Ulgiati S., (2016), A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems, *Journal of Cleaner Production*, **114**, 11-32.

Grigore M.E., (2017), Methods of recycling, properties and applications of recycled thermoplastic polymers, *Recycling*, **2**, 24, doi:10.3390/recycling2040024

Gu F., Guo J., Zhang W., Summers P.A., Hall P., (2017), From waste plastics to industrial raw materials: A life cycle assessment of mechanical plastic recycling practice based on a real-world case study, *Science of The Total Environment*, **601-602**, 1192-1207.

Hamad K., Kaseem M., Deri F., (2013), Recycling of waste from polymer materials: An overview of the recent works, *Polymer Degradation and Stability*, **98**, 2801–2812.

Hopewell J., Dvorak R., Kosior E., (2009), Plastics recycling: challenges and opportunities, *Philosophical Transactions of the Royal Society B: Biological Sciences*, **364**, 2115-2126.

ICESP, (2018), Measuring tools for the circular economy, (in Italian), Report, Italian Circular Economy Stakeholder Platform, On line at: https://www.icesp.it/landing/docs/gdl/gdl3/REPORT_GdL3%20Strumenti%20per%20la%20misurazione%20dell%E2%80%99economia%20circolare.pdf.

IMF Report, (2018), Price trend of thermoplastic materials, (in Italian), International Monetary Fund, Washington D.C., On line at: https://data.imf.org/?sk=388dfa60-1d26-4ade-b505-a05a558d9a42

Jin H., Gonzalez-Gutierrez J., Oblak P, Zupancic B., Emri I., (2012), The effect of extensive mechanical recycling on the properties of low density polyethylene, *Polymer Degradation and Stability*, **97**, 2262-2272.

Jnr A.K.L., Yunana D., Kamsouloum P., Webster M., Wilson D.C., Cheeseman, C., (2018), Recycling waste plastics in developing countries: Use of low-density polyethylene water sachets to form plastic bonded sand blocks, *Waste Management*, **80**, 112-118.

Kirchherr J., Reike D., Hekkert M., (2017), Conceptualizing the circular economy: An analysis of 114 definitions, *Resources, Conservation and Regeneration*, **127**, 221-232.

Loultcheva M.K., Proietto M., Jilov N., La Mantia F.P., (1997), Recycling of high density polyethylene containers, *Polymer Degradation and Stability*, **57**, 77-81.

Luijsterburg B., Goossens H., (2014), Assessment of plastic packaging waste: Material origin, methods, properties *Resources*, *Conservation and Recycling*, **85**, 88-97.

Maris J., Bourdon S., Brossard J. M., Cauret L., Fontaine L., Montembault V., (2018), Mechanical Recycling: Compatibilization of Mixed Thermoplastic Wastes, *Polymer Degradation and Stability*, **147**, 245–266.

MATTM Report, (2018), Circular economy and efficient use of resources. Indicators for measuring the circular economy, (in Italian), , Ministry of the Environment and Territorial Protection, On line at: https://www.minambiente.it/sites/default/files/archivio_immagini/economia_circolare_ed_uso_efficiente_delle_risorse_-_indicatori_per_la_misurazione_della_circolartita_-_bozza_maggio_2018.pdf.

Meran C., Ozturk O., Yuksel M., (2008), Examination of the possibility of recycling and utilizing recycled polyethylene and polypropylene, *Materials and Design,* **29**, 701-705.

MISE, (2018), National Industry 4.0 Plan, (in Italian), Plan, Ministry of Economic Development, On line at: https://www.mise.gov.it/index.php/it/per-i-media/comunicati-stampa/2035187-il-ministro-dello-sviluppo-economico-carlo-calenda-illustra-il-piano-nazionale-industria-4-0.

Mita L., (2019), *Best Practices of cCrcular Economy: from Plastic to Plastic*, (in Italian), 23th Int. Trade Fair of Material & Energy Recovery and Sustainable Development ECOMONDO, Rimini, Italy.

MOLGROUP, (2020), Tipelin 7000F High Density Polyethylene Datasheet, HDPE/7000F/2020, April 2020, On line at: https://www.molgroupchemicals.com/userfiles/products/30/30_tds_en.pdf

Niero M., Hauschild M.Z., (2017), Closing the loop for packaging: finding a framework to operationalize Circular Economy strategies, *Procedia Cirp*, **61**, 685-690.

Nkwachukwu O.I., Chima C.H., Ikenna A.O., Albert L., (2013), Focus on potential environmental issues on plastic world towards a sustainable plastic regeneration in developing countries, *International Journal of Industrial Chemistry*, **4**, 1-13.

Paletta A., Leal Filho W., Balogun A.L., Foschi E., Bonoli A., (2019), Barriers and challenges to plastics valorisation in the context of a circular economy: Case studies from Italy, *Journal of Cleaner Production*, **241**, 118-149.

PE, (2015), Plastics - the facts: An analysis of European plastics production, demand and waste data, Plastic Europe, On line at: https://www.plasticseurope.org/download_file/force/835/181

QAPCO, (2020), Lotrene FD0270 Low Density Polyethylene Datasheet, LDPE/FD0270/2020, May 2020.

Radusin T., Nilsen J., Larsen S., Annfinsen S., Waag C., Eikeland M.S., Fredriksen S.B., (2020), Use of recycled materials as mid layer in three layered structures-new possibility in design for recycling, *Journal of Cleaner Production*, **259**, 120876.

Schut E., Crielaard M., Mesman M., (2016), Circular economy in the Dutch construction sector: A perspective for the market and government, Report, National Institute for Public Health and the Environment Report, No. 197, On line at: http://publicaties.minienm.nl/download-bijlage/80754/circular-economy-in-the-dutch-construction-sector.pdf.

Schiopu A.M., Apostol I., Hodoreanu M., Gavrilescu M, (2007), Solid waste in Romania: management, treatment and pollution prevention practices, *Environmental Engineering & Management Journal*, **6**, 451-465.

Siciliano G., Verdesca D., (2001), *Economic and Environmental Assessment of the Corporate Policies for Regeneration and Reuse of Packaging Waste: Case Study IPT/COOP*, In: *Notebooks of the University of Siena* (in Italian), University of Siena, Siena, Italy, On line at: http://repec.deps.unisi.it/quaderni/339.pdf.

Soto J.M., Blázquez G., Calero M., Quesada L., Godoy V., Martín-Lara M.Á., (2018), A real case study of mechanical recycling as an alternative for managing of polyethylene plastic film presented in mixed municipal solid waste, *Journal of Cleaner Production*, **203**, 777-787.

Sulyman M., Haponiuk J., Formela K., (2016), Utilization of recycled polyethylene terephthalate (PET) in engineering materials: a review, *International Journal of Environmental Science and Development*, **7**, 100-108.

UN, (2019), World Population Prospects 2019: Highlights, Report, United Nations - Department of Economic and Social Affairs, Population Division, ST/ESA/SER.A/423, On line at: https://population.un.org/wpp/Publications/Files/WPP2019_Highlights.pdf.

Van Eygen E., Laner D., Fellner J., (2018), Circular economy of plastic packaging: Current practice and perspectives in Austria, *Waste Management*, **72**, 55-64.

Environmental Engineering and Management Journal October 2020, Vol.19, No. 10, 1807-1811
http://www.eemj.icpm.tuiasi.ro/; hiip://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

HOW TO DEAL WITH ORGANIC MUNICIPAL SOLID WASTE OVER-SIEVE FRACTION

Short communication

Ivana Moscato[1*], David Callejo Munoz[1], Sergio D. González[2]

1B1Shop Srl, c/o POINT Polo Innovazione Tecnologia Dalmine BG-Italy
2University of Alcala, Centre for Applied Chemistry and Biotechnology

Abstract

The steady increase in separate waste collection has highlighted the urgent need to adequately deal not only with urban waste (differentiated and undifferentiated) but also with special waste produced by separate waste collection and recycling processes.
Source collected municipal solid waste produces different waste streams. One of this is the organic fraction of municipal solid waste (OFMSW). This fraction is central for circular economy, since it can be further transformed in order to recover valuable products such as compost and fertilizers, both through biogas fermentation and composting.
OFMSW, however, contains up to 10-20% of non-organic residues, such as plastic and bioplastic bags, coupled materials, textile and cellulose. This fraction is normally mechanically separated from the organic part as an over-sieve, that is in some cases washed, squeezed and dried, and then disposed as special waste.
One of the emerging issues is where to dispose it or even better, if there is a way to recover it. Disposal costs are increasing, since the over-sieve fraction competes for final destination, such as incinerators and cementer production sites, with other more energetic valuable residues. A very new and valuable solution to solve the problem is to recover it through a thermo-chemical transformation into a bioliquid (Reach qualified), with different market destinations, both second-generation fuel and chemical commodity for regenerable plastic production.
The thermo-chemical transformation is energetically self-sustaining and provides thermal energy as an output, that can be valorised in the organic waste transformation process. The present paper shows the technology main features and gives insight to economic aspects.

Keywords: bioliquid, material recovery, municipal waste, over-sieve residues, special waste

Received: February, 2020; Revised final: June, 2020; Accepted: July, 2020; Published in final edited form: October, 2020

1. Introduction

Waste recycling is a worldwide issue that impacts on sustainability and climate change; it is particularly strategic not only to reduce resources exploitation, but also to deal properly with waste disposal. Landfilling is not considered viable for biodegradable waste, because of environmental impacts, such as green gas emissions. The 2018 European Union (EU) *Commission Report on the implementation of EU waste legislation for re-use/recycling target on municipal waste* focuses on the following issues:

1. Introduce measures (incl. taxes) to phase out landfilling and other forms of residual waste treatment (e.g. Mechanical Biological Treatment, and incineration) to provide economic incentives to support the waste hierarchy.

2. Introduce mandatory requirements to sort bio-waste and ensure that planned or existing

*Author to whom all correspondence should be addressed: e-mail: i.moscato@b1shop.it

treatment infrastructure matches the collection systems.

The revised Directive requires Member States to reduce the landfilling of municipal waste to a maximum of 10 % by 2035, and it introduces a ban on the landfilling of separately collected waste, including biodegradable waste.

According to European Circular Economy Action Plan, waste should be considered as raw materials (EU Directive 851, 2018). This new approach is promoting major changes at legislation level, boosting the use of secondary raw materials (SRMs) as one of the objectives of the circular economy action plan. Also, the revised EU Directive on packaging and packaging waste (EU Directive 852, 2018) introduces more ambitious overall recycling targets for packaging (65 % in 2025 and 70 % in 2030), and higher material-specific targets (such as 55 % in 2030 for plastic).

The present paper focuses on a technical solution to deal with OFMSW over-sieve, which allows to recover it as SRM providing an End-of-waste solution with high added value.

Material Recovery of the over-sieve fraction involves its transformation into three different outputs: liquid, solid and gas (Gandidi et al., 2018; Sipra et al., 2018). The liquid phase is an oil, valuable both as second-generation biofuel and as basic material for chemical plants and refineries (Al-Salem et al., 2017). This type of oil has a low carbon footprint and can reduce oil importation with positive impacts on environment and geopolitics. It is also suitable to achieve the recycling targets for plastics. The solid phase is a char, that can have different applications, such as second-generation fuel for furnaces, road foundations and brick production, or, depending on its quality, even as soil amendment (Islam et al., 1970; Taherymoosavi et al., 2017).

The gas is a syngas, with high calorific value, that is used for process purposes and that allows to recover extra-heat for external needs, too (He et al., 2010; Jun et al., 2017).

2. Issues

Dealing with OFMSW, one of the major problems is the presence of an over-sieve fraction, which is not biodegradable. Plastic and bioplastic bags, coupled materials, textile and cellulose are part of the collected waste and contribute to 10-20% of the total amount. Disposal costs are increasing, since the over-sieve fraction competes for final destination with other more energetic valuable residues.

The presence of packaging in the organic fraction is a changing issue over time. Few years ago, the plastics for organic fraction collection were polyolefins. These are non-biodegradable plastics of fossil origin and lasting over time. At present, the organic waste collection boxes are made of treated paper-cardboard or bioplastics. Paper and cardboard are treated with some wax or other vegetable fibres to increase resistance.

With regards to plastic bags in the OFMSW, it can be emphasized that its composition depends on the country. In countries like Italy most of these plastics are derived from starch and the principal polymer derives from polylactic acid. In countries that are implementing the separate collection of organic matter, there is a mixture of polyolefins with other biodegradable plastics. Similar to Italy, these countries will increase the use of bioplastics.

It should be noted that in the coming years the market for garbage bag plastics for organic matter will be dominated by bioplastics. In general, it can be seen that bioplastics are going to be present in many products, and therefore, in the waste according to the data established in the European Green Deal (EU Communication, 2020).

Considering energy, this conversion from polyolefin bags to bioplastics complicates, to a certain extent, their use and recovery. Polyolefins have a composition with carbon and hydrogen with high energy, so they are hydrocarbons. The calorific value of polyolefins is 44-46 MJ/kg. The calorific value of bioplastics is 23-25 MJ/kg. This calorific value is similar to plastics in the family of polyesters such as PET (Polyethylene Terephthalate). The variation is explained by the chemical composition of bioplastics that have molecules formed by hydrogen carbon and many oxygenated groups. Calorific values of different materials in the OFMSW are shown in Table 1.

When analysing the thermochemical transformation of bioplastics, these provide hydrocarbon compounds in which there is a mixture of oxygenated products. It is also important to note that since bioplastics are of biological origin, liquids and solids derived from them are considered as biofuels and biochar.

Table 1. Calorific value of different materials (Fraunhofer Institute for Environmental, Safety, and Energy Technology)

Type of material	*Calorific value (MJ/kg)*
Polyethylene, polypropylene	46
Polystyrene	41
Polyester	24
Wood	19
Newspaper	18
Municipal waste (dry)	16
Gardening waste	7
Food waste	6

Also, the OFMSW usually has a certain content of textile materials. The composition of textile materials usually contains biological part and fossil part. The biological part is due to natural fibres such as cotton, linen, or viscose or rayon, which is a cellulose derivative. Also, in this fraction are those derived from natural fibres of animal origin such as wool (Grishanov, 2011). Textile materials derived from natural products produce liquid compounds with oxygenated products and some nitrogen products. Synthetic fibres are usually derived from polyolefins or polyesters that degrade very easily under thermochemical processing conditions. Within the circular economy measures, the separate collection of textile waste is foreseen. As this separative collection is implanted, the presence of textile waste in the organic fraction will decrease.

3. Thermochemical transformation

Contrary to pyrolysis, that occurs in the absence of oxygen, materials that are processed at high temperatures in the presence of oxygen generate combustion or gasification processes. These processes convert materials into solid products and gases derived from combustion. Combustion processes present technological, environmental problems and do not allow the recovery of materials (Bhattacharya et al., 2009; Lange, 2007).

Processing organic materials at high temperatures and in absence of oxygen, it undergoes transformations producing other molecules. Thermochemical processes in the absence of oxygen are called pyrolysis. Thermochemical transformation in pyrolysis conditions of the material present in the organic fraction will give the typical products of these processes: a gas fraction, a solid fraction and eventually a liquid fraction.

The gas fraction, consisting of a mixture of non-condensable hydrocarbon gases, under normal conditions, contains H_2, CO, CO_2, water vapor. This gas is called synthesis gas or syngas. The most abundant hydrocarbon is usually methane, followed by ethane, propane, butane in iso- and n-configurations. The composition of the syngas depends on the process conditions and the raw material processed (Yaman, 2004).

This syngas can be used for chemical processes, as fuel for electricity generation, for a cogeneration system, or as fuel for the pyrolysis process itself. The use as fuel in the pyrolysis process itself provides high energy efficiency and a low carbon footprint (Rosales et al., 2017).

The solid fraction formed by carbon materials contains inorganic salts and fibres present in the raw material and carbonaceous materials, which are concentrated. This fraction is called char or biochar depending on the raw material processed. In the case of the municipal waste organic fraction MWOF, it can be considered biochar if the organic fraction is collected separately (Taherymoosavi et al., 2017). This biochar must meet the physical and chemical parameters established at European legislation level.

The liquid fraction is formed by a mixture of aqueous and organic products (Demirbas, 2009). The aqueous fraction is principally composed of oxygenated compounds derived from cellulose and hemicellulose cracking. There is a mixture of hydrocarbons that is useful as a fuel or as raw material for new plastics production.

Depending on the thermochemical technology, this liquid fraction can be generated as a single fraction or as two fractions. On an industrial stage, the technology that generates the liquid fraction represents an important advance in waste industrialization.

The thermochemical transformation of products derived from paper and vegetable fibres is similar, in a way, to that generated by lignocellulosic biomass. The transformation of food waste organic fractions is similar to biomass. Food residues are combinations of cellulose, hemicellulose, other sugar-derived polymers mixed with protein and lipid-type polymers. Proteins degraded under pyrolysis conditions produce simpler molecules with oxygenated compounds. Lipids easily develop cracking to highly valuable hydrocarbons. These hydrocarbons are advanced biofuels (Goyal et al., 2008; Lange, 2007; Lian et al., 2012).

After analysing the chemical composition of the major components present in the MWOF, it is observed that all are processable by thermochemical technology. The more complex carbonaceous materials will produce solid products like biochar. The biochar has a high structural component that is derived from the biological structure from which it proceeds (Table 1)(Bolan et al., 2012; Enders et al., 2012; Jafri et al., 2018).

Due to the presence of diverse materials and different composition, it is mandatory that industrial technology is designed for the processing of urban waste complex matrix, as it actuallyis (Hobohm et al., 2018; Satchatippavarn et al., 2016). Therefore, the industrialization of these technologies must be able to treat fractions derived from different urban waste treatment centres. In other words, technology must be able to treat the raw material flows that currently occur in treatment plants.

Industrial plants must perform the following requirements:

A.- Specific design for multi-material waste

Waste materials are of variable, changing composition and are characterized by different mixtures of materials. It is important that the technology is designed for multi-material mixtures waste.

B.- Produce valuable products

Pyrolysis technology must produce liquids and solids that can be further applied for productive processes. The technology must allow production of liquids that can be used for Materials Recycling of or Advanced Biofuels.

C.- Compliance with legislation

Compliance with legislation regarding environmental impact, emissions, treatment and waste recovery.

For pyrolysis, it is necessary to ensure that the thermochemical treatment is suitable, that the pyrolysis gas or syngas has a perfect combustion and with temperature control. Good combustion control of the synthesis gas ensures that atmospheric emissions are satisfactory. The gas treatment through different stages allows controlled combustion and high performances with very low emissions.

D.- High impact on Circular Economy

It is important that the technology has a high efficiency rate and allows obtaining materials that can be used like raw materials in other production processes. In the case of pyrolysis, the main characteristics related to the circular economy are sustainability compliance, carbon footprint reduction and Material Recovery from waste.

4. Case study with mass balance

The study presents the data for pyrolysis transformation of OFMSW over-sieve as a typical feedstock applying Neoliquid technology. Typical values as well as a range of the mass balance provided by Neoliquid are presented, including the technical characteristic and limitations for the feedstock material (Tables 3-4).

5. Basic Business Plan

The business plan for this kind of project strongly depends on the cost of dumping the waste material in traditional landfills or incinerators. In our particular case, we will use an average value of 170 €/Ton (15.000 Ton/year), as a typical value for North-Italy, including transportation cost.

The bioliquid (3.000 Ton/year for our case study) is very valuable depending on the quality, and final market application up to 570-850 €/Ton. If we take into account the sustainability certification and material valorisation as advanced biofuel, the price will be in the highest portion of the interval.

Including all operational costs (labour is the major cost), electricity, raw materials, maintenance, quality control the yearly expenses are approximately 1 M€/year. Considering disposal costs saving and bioliquid and biochar valorisation, the investment cost, including the financial costs, will be fully paid in less than 36 months; even less in case two or more plant are operated on the same site, thanks to labour cost optimization.

Table 2. Typical MWOF over sieve quality

FEEDSTOCK MWOF over-sieve	
PCI (kcal/kg)	3.700-4.000
Humidity	<15%
Particle size (cm)	3-5
Chlorine	<0,5 %
Sulphur	<0,3%
Density (kg/m^3)	>70
Biomass (paper, wood …)	>70%
Plastics	<30%

Table 3. Typical mass balance with pyrolysis transformation

OUTPUT	***% Feedstock***
Crude Oil	15-30%
Char	20-30%
Water	15-30%
Non-Condensable Gas	20-30%

Table 4. Industrial plant operating data

n. PLANTS	1
FEEDSTOCK INLET	
Yearly quantity (t/y)	15.000
Daily quantity (t/d)	55.6
Hourly quantity (t/h)	2.3
OUTPUTS	
Bioliquid yearly production (t/y)	3.000
Char yearly production (t/y)	4.200
Working hours	
Yearly working hours (h)	6.500
Yearly working days (d)	270
Daily working hours (h)	24

6. Conclusions

Due to heterogeneous and variable composition, the over-sieve fraction of municipal solid waste (OFMSW) is actually disposed in landfills or incinerated. Nonliquid technology allows to recover the over-sieve fraction as secondary raw material (SRM) instead of being disposed in landfills or thermally recovered into incinerators. The technology is based on thermo chemical transformation and produces end-of-waste products with high added value; it is the only one operating at industrial level in the market that is able to work on this kind of feedstock.

This technology presents a step forward to circular economy solving the waste recovery problem of the municipal waste organic fraction.

References

Al-Salem S.M., Antelava A., Constantinou A., Manos G., Dutta A., (2017), A review on thermal and catalytic pyrolysis of plastic solid waste (PSW), *Journal of Environmental Management,* **197**, 177-198.

Bhattacharya P., Steele P.H., Hassan E.B.M., Mitchell B., Ingram L., Pittman C.U., (2009), Wood/plastic copyrolysis in an auger reactor: Chemical and physical analysis of the products, *Fuel*, **88**, 1251-1260.

Bolan N.S., Kunhikrishnan A., Choppala G.K., Thangarajan R., Chung J.W., (2012), Stabilization of carbon in composts and biochars in relation to carbon sequestration and soil fertility, *Science of the Total Environment*, **424**, 264-270.

Demirbas A., (2009), *Thermochemical Conversion Processes*, In: *Biofuels. Green Energy and Technology*. Springer, London., 261-304.

Enders A., Hanley K., Whitman T., Joseph S., Lehmann J., (2012), Characterization of biochars to evaluate recalcitrance and agronomic performance, Bioresource Technology, **114**, 644-653.

EU Communication, (2020), COM (2020) Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Sustainable Europe Investment Plan European Green Deal Investment Plan, Brussels, Factsheet 14.1.2020.

EU Directive 851, (2018), Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste, OJ L 150, 14.6.2018, 109-140.

EU Directive 852, (2018), Directive (EU) 2018/852 of the European Parliament and of the Council of 30 May 2018 amending Directive 94/62/EC on packaging and packaging waste PE/12/2018/REV/2, GU L 150 del 14.6.2018, 141-154.

Gandidi I.M., Susila M.D., Mustofa A., Pambudi N.A., (2018), Thermal-Catalytic cracking of real MSW into Bio-Crude Oil, *Journal of the Energy Institute*, **91**, 304-310.

Goyal H.B., Seal D., Saxena R.C.Ã., (2008), Bio-fuels from thermochemical conversion of renewable resources : A review, *Renewable and Sustainable Energy Reviews*, **12**, 504-517.

Grishanov S., (2011), Structure and properties of textile materials, *Handbook of Textile and Industrial Dyeing*, **1**, 28-63.

He M., Xiao B., Liu S., Hu Z., Guo X., Luo S., Yang F., (2010), Syngas production from pyrolysis of municipal solid waste (MSW) with dolomite as downstream catalysts, *Journal of Analytical and Applied Pyrolysis,* **87**, 181-187.

Hobohm J., Auf der Maur A., Dambeck H., Kemmlez A., Koziel S., Kreidelmeyer S., Piégsa A., Wendring P., (2018), Status and perspectives of liquid energy sources in the energy transition, *Prognos AG, Final Report*, 66-83.

Islam M.S., Miah M.Y., Ismail M., Jamal M.S., Banik S.K., Saha M., (1970), Production of bio-oil from municipal solid waste by pyrolysis, *Bangladesh Journal of Scientific and Industrial Research*, **45**, 91-94.

Jafri N., Wong W.Y., Doshi V., Yoon L.W., Cheah K.H., (2018), A review on production and characterization of biochars for application in direct carbon fuel cells, *Process Safety and Environmental Protection*, **118**, 152-166.

Jun Z., Shuzhong W., Zhiqiang W., Haiyu M., Lin C., (2017), Hydrogen-rich syngas produced from the co-pyrolysis of municipal solid waste and wheat straw, *International Journal of Hydrogen Energy*, **42**, 19701-19708.

Lian J., Garcia-Perez M., Coates R., Wu H., Chen S., (2012), Yeast fermentation of carboxylic acids obtained from pyrolytic aqueous phases for lipid production, *Bioresource Technology*, **118**, 177-186.

Rosales E., Meijide J., Pazos M., Sanromán M.A., (2017), Challenges and recent advances in biochar as low-cost biosorbent: From batch assays to continuous-flow systems, *Bioresource Technology*, **246**, 176-192.

Satchatippavarn S., Martinez-Hernandez E., Leung Pah Hang M.Y., Leach M., Yang A., (2016), Urban biorefinery for waste processing, *Chemical Engineering Research and Design*, **107**, 81-90.

Sipra A.T., Gao N., Sarwar H., (2018), Municipal solid waste (MSW) pyrolysis for bio-fuel production: A review of effects of MSW components and catalysts, *Fuel Processing Technology*, **175**, 131-147.

Taherymoosavi S., Verheyen V., Munroe P., Joseph S., Reynolds A., (2017), Characterization of organic compounds in biochars derived from municipal solid waste, *Waste Management*, **67**, 131-142.

Yaman S., (2004), Pyrolysis of biomass to produce fuels and chemical feedstocks, *Energy Conversion and Management*, **45**, 651-671.

Environmental Engineering and Management Journal
October 2020, Vol. 19, No. 10, 1813-1822
http://www.eemj.icpm.tuiasi.ro/; hiip://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

DEVELOPMENT AND IMPLEMENTATION OF A WATER SAFETY PLAN FOR THE DRINKING WATER SUPPLY SYSTEM OF FLORENCE, ITALY

Roberta Muoio[1], Leonardo Rossi[2], Daniela Santianni[2], Cecilia Caretti[1]*, Claudio Lubello[1], Emanuele Ferretti[3]

[1]*Department of Civil and Environmental Engineering, University of Florence, Via di Santa Marta 3, Florence, Italy*
[2]*Publiacqua SpA, Via Villamagna 39, Florence, Italy*
[3]*Department of Environment and Health, National Institute of Health, Viale Regina Elena 299, Rome, Italy*

Abstract

The adoption of the Water Safety Plan (WSP) approach, as recommended by the World Health Organization, represents the most effective means to guarantee public health protection and improve drinking water safety. WSP is a risk assessment and management approach applied to all phases of the water supply chain. This study presents the development and implementation of the WSP for the municipality of Florence. The Florence drinking water supply system (DWSS) has two drinking water treatment plants and supplies a population of about 380 000 inhabitants. The main water resource is the River Arno, characterised by high seasonal and daily variations of water quality and quantity and by extensive anthropogenic contamination. The results of our case-study allowed the identification of more than 70 hazardous events including source water contamination, treatment failures, sedimentation in storage tanks, biofilm erosion in the network. The phases with the highest percentage of hazardous events are the catchment and the treatment steps. According to the risk analysis results, the main corrective actions identified are the installation of an early warning station in order to forecast the changes in the source water quality, the analysis of the main contaminants of emerging concern in the source and treated water, the installation of turbidity probes in the pipes with the lowest flow velocity. The implemented WSP enabled an assessment of the DWSS performance. Moreover, it represents a useful tool for the water manager to improve system management and control, to increase consumer confidence and to reduce the risk of water contamination.

Key words: drinking water, risk assessment, risk management, water safety plan, water treatment plant

Received: February, 2020; Revised final: June, 2020; Accepted: July, 2020; Published in final edited form: October, 2020

1. Introduction

The provision of safe drinking water represents a significant target in order to ensure public health protection in high-income as well as developing countries.

The traditional approach of end-product testing alone, which consists of monitoring the drinking water quality at the delivery point, is not sufficient to constantly ensure the safety of water. Waterborne diseases and outbreaks still occur, even in developed countries (Cann et al., 2013; Hrudey and Hrudey, 2007; Laine et al., 2010; Moreira and Bondelind, 2016). The adoption of risk assessment and management approaches, such as a Water Safety Plan (WSP), has become necessary to reduce the incidence of waterborne diseases. A WSP is a systematic, preventive risk management approach that includes all the phases of the water supply chain, from catchment to consumer (WHO, 2009). WSPs, introduced in 2004 by the World Health Organization (WHO), represent "the most effective means of constantly ensuring the safety of a drinking-water supply" (WHO, 2017a). The principles of a WSP are based on different

* Author to whom all correspondence should be addressed: e-mail: cecilia@dicea.unifi.it; Phone: +39 347 197 7359

systematic management approaches such as the multi-barrier principle and the hazard analysis and critical control points principle (HACCP) (WHO, 2017a). Since their introduction in 2004, WSPs have been implemented at least in 93 countries, covering each region of the world, both in pilot form and on a large scale (WHO and IWA, 2017). Countries and regions for which WSP experiences are reported in literature include: Uganda (Howard et al., 2005); Australia (Jayaratne, 2008); Germany (Mälzer et al., 2010); South Africa (Viljoen, 2010); the Pacific Islands (Hasan et al., 2011); Jamaica, Brazil, Peru, and Costa Rica (Hubbard et al., 2013; Rinehold et al., 2011); Iceland (Gunnarsdottir et al., 2015); France and Spain (Setty et al., 2017); Italy (Sorlini et al., 2017); Portugal (Roeger and Tavares, 2018; Vieira, 2011); Bangladesh (Shamsuzzoha et al., 2018); Ethiopia (Rickert et al., 2019); Colombia (Pérez-Vidal et al., 2020). WSP are included in the Directive (EU) 1787/2015 (EC Directive, 2015) and in the upcoming Drinking Water Directive (EC Directive, 2018).

Implementation of a WSP can provide improvements in hazard control and water quality, and benefits in asset management and public health outcomes (Baum et al., 2015; Gunnarsdottir et al., 2012; Mahmud et al., 2007; Setty et al., 2018; Tsitsifli and Tsoukalas, 2019). The main phases of a WSP can be summarized as follows (Lucentini et al., 2014): 1) drinking water supply system (DWSS) description and analysis; 2) identification of all possible hazards and hazardous events; 3) risk evaluation and definition of an upgrade plan; 4) revision of the WSP on a regular basis.

This paper presents the case-study analysis of the WSP implementation for the municipality of Florence (Italy). The WSP has been implemented following the national and international guidelines (Lucentini et al., 2014; WHO, 2009a). It is the first Italian WSP applied to a large-scale DWSS supplied by a surface water body (River Arno).

2. Material and methods

2.1. The Florence drinking water supply system

The DWSS of Florence treats surface water coming from the River Arno by means of two drinking water treatment plants (DWTPs), Plants A and B, and supplies 380 000 inhabitants. The catchment area upstream from the treatment plants (4 200 km^2 and about 500 000 inhabitants) is characterised by a high density of industrial and agricultural activities, wastewater treatment plant discharges and human activities.

This causes significant and heterogeneous anthropogenic pressure on the system. During the summer period, because of the low river water levels, the flow rate is integrated with water from the Bilancino basin: an artificial lake, located about 10 km north of the city of Florence. For this reason, in summer, about half of the flow rate treated by the two plants comes from Lake Bilancino.

The total production of the DWTPs (85 Mm^3/year) is supplied to the municipality of Florence (55 Mm^3/year) as well as to other surrounding areas (30 Mm^3/year). Plant A is the main DWTP in the system, with an average treated flow rate of 2 200 L/s and a nominal flow rate of 3 100 L/s. The treatment train is reported in

Fig. 1. The water entering the plant is pre-oxidized with ClO_2 after being screened. Then, a clari-flocculation process takes place, followed by rapid sand filtration (two lines) for the removal of turbidity. Clari-flocculation is crucial for the removal of turbidity, sedimentable and colloidal solids. The coagulant (Polyaluminium chloride) dosage ranges on average between 60-70 ppm depending on the source water characteristics (suspended solids, temperature, etc.). Before the sand filtration, intermediate disinfection is carried out with ClO_2 (less frequently with NaClO). Subsequently, the water is treated with Granular Activated Carbon (GAC) for the adsorption of a wide range of organic molecules (natural organic matter, pesticides etc.) and for the reduction of taste and odour.

A final disinfection is carried out with ClO_2 in order to ensure a free chlorine residual concentration of 0.3 mg/L. Plant A treats about 70 Mm^3 each year. Plant B has an average treated flow rate of 350 L/s and a nominal flow rate of 750 L/s. The treatment train is almost equal to that of Plant A (

Fig. 1): clari-flocculation, rapid sand filtration, GAC adsorption, and three disinfection steps (initial, intermediate and final disinfection). Moreover, in addition to the surface water resource, Plant B also treats groundwater (20% of the overall treated volume). The groundwater is only oxidized with ClO_2, together with the surface water, before being distributed.

Plant B treats about 15 Mm^3 each year. The two plants are monitored through different probes (UV_{254}, turbidity, Redox, pH, temperature, ammonia, residual chlorine) located at each treatment steps which allow the real-time control and supervision of all the treatment processes. Laboratory analysis are carried out in order to check and record the quality of the treated and distributed water according to the National regulation limits (Italy Decree, 2001).

The treated water leaving the DWTPs is pumped directly into the distribution network which is about 900 km long. The main pipe materials are cast iron (50%) and spheroidal cast iron (42%). Within the distribution system there are also 20 storage tanks supplying the hilly areas around the city of Florence.

2.2. Water safety plan implementation

The implemented WSP includes the following steps (Lucentini et al., 2014):

1) Formation of a multidisciplinary team (more than 40 experts), in March 2018, supervised by the National Institute of Health (ISS).

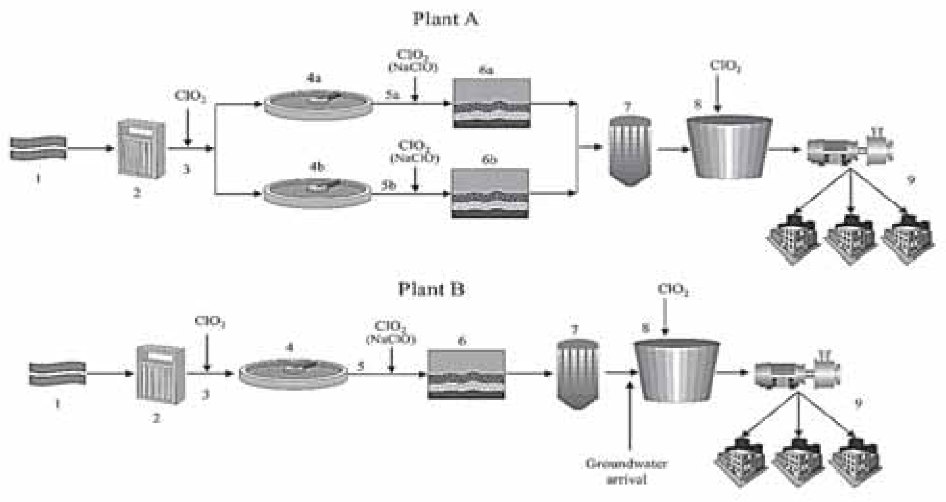


Fig. 1. Plant A - 1: Raw surface water; 2: Screen; 3: Pre-disinfection; 4a: Clari-flocculation line 1; 4b: Clari-flocculation line 2; 5a: Intermediate disinfection line 1; 5b: Intermediate disinfection line 2; 6a: Rapid sand filtration line 1; 6b: Rapid sand filtration line 2; 7: GAC adsorption; 8: Final disinfection; 9: Pumping and distribution. Plant B - 1: Raw surface water; 2: Screen; 3: Pre-disinfection; 4: Clari-flocculation; 5: Intermediate disinfection; 6: Rapid sand filtration; 7: GAC Adsorption; 8: Final disinfection; 9: Pumping and distribution

Each member was chosen in order to cover all the necessary expertise: 1) the DWSS water company (responsible for the WSP implementation); 2) regional environmental and health protection agencies (because of their role in monitoring and controlling the status of the environment and the quality of the drinking water distributed); 3) University of Florence (for the scientific supervision of the study); 4) Tuscany Region and Northern Apennines River Basin District Authority (because of their focusing on water resources conservation, assessment and mapping of flood and geological risks); 5) Tuscany Water Authority (responsible for the planning, organization and control over the management of the integrated water service). The team leader which coordinated the WSP was a DWSS manager, chosen for his extensive experience and knowledge of the system. The team actively participated in all of the project phases bringing expertise, know-how and data and approving the WSP output. This was crucial for the definition of the risk matrix and the subsequent corrective action assessment;

2) Description of the DWSS which includes on-site inspections, historical data analysis, examination of the DWSS management data and characteristics (water treatment processes, storage tank volumes, pipe materials and diameters etc.);
3) Identification of hazardous events, definition of the subsequent hazards, and evaluation of the risks using a semi-quantitative risk matrix approach;
4) Identification of the existing control measures, validation of their effectiveness and second risk evaluation;
5) Development, implementation and maintenance of an improvement/upgrade plan;
6) Verification of the effectiveness of the WSP and periodical revision of the plan.

Since the main purpose of the WSPs is to ensure public health and safety, the consumers play an important role and were therefore involved in and informed of the process steps. For each element of the DWSS, on-site inspections were made and checklists were completed in order to highlight any possible hazardous event or system deficiency. Laboratory data from three years (2015-2017) were analysed for each system infrastructure (catchments, WTPs outlet, storage tanks) and the distribution network (about 70 monitoring points covering the full service area). The sampling frequency varied according to the type of the monitoring point: a weekly sample for the catchments; a daily sample for the WTPs outlet and about 40 samples per month for the network. Approximately 250 parameters were considered (*i.e.*, IPA, VOC, pesticides, microbiological parameters, disinfection by-products, metals, etc.), and more than 150 000 pieces of data were analysed.

The treatment plants efficiency was defined by evaluating the degree of removal of the chemical and microbiological contaminants. Moreover, for the same time period (years 2016-2017), consumer complaints were considered in order to evaluate the population's degree of satisfaction and to highlight the DWSS areas characterised by a higher concentration of complaints. The complaints were analysed per class: odour (which is predominantly related to the chlorine residual concentration in the water), taste (which is mainly related to turbidity and chlorine residual), and aesthetic impact (which is generally linked to the colour of the water). A hydraulic model of the distribution network was activated in order to assess the water age, that is, the time spent by a parcel of water in the network, along the aqueduct. This is a non-specific measure of the overall water quality within the distribution pipes. Since the distribution network is supplied by two different DWTPs, the hydraulic model was also used to assess the area of influence of each plant and, consequently, the extension of possible water contamination.

Subsequently, typical hazards were identified for each hazardous event, such as chemical, microbiological and physical contamination, failures and water scarcity. According to the WHO guidelines, the semi-quantitative risk matrix approach was used to estimate the risk as the product of the likelihood (P) and the severity of the consequences (G) (WHO, 2009). The two factors, P and G, were classified as reported in Table 1 and the risk was evaluated as in

Table 2. **Semi-quantitative matrix approach**
(adapted from WHO, 2009)

		Severity				
		1	*2*	*3*	*4*	*5*
Likelihood/ frequency	**5**	5	10	15	20	25
	4	4	8	12	16	20
	3	3	6	9	12	15
	2	2	4	6	8	10
	1	1	2	3	4	5
Risk score		< 6	6 – 9	10 – 15	> 15	
Risk rating		Low	Medium	High	Very High	

Then, the multidisciplinary team was involved in order to share and validate the matrix results. A two-stage risk assessment was carried out in order to determine the effectiveness of the existing risk reduction control measures. Corrective actions to be implemented were proposed by the DWSS manager when the residual risk was more than six, and the most suitable solutions were identified within the team.

3. Results and discussion

3.1. Data analysis results

The three-year data analysis highlighted the high treatment efficiency of the two DWTPs. Table 3 shows the average values of the main monitored data from the Florence DWSS. The raw water is characterised by a large degree of seasonal and daily variability. One of the most important parameters for the DWTP management is inflow turbidity. High turbidity levels can reduce the efficiency of the disinfection by generating a chlorine demand whose removal is a well-known indicator of the effectiveness of clari-flocculation and filtration processes (AWWA, 1999; 2006, WHO, 2017b). The average turbidity value in the raw water is 21 NTU (standard deviation 46 NTU) while in the treated water it is 0.12 NTU for Plant A and 0.24 for Plant B. The high turbidity removal efficiency and the effectiveness of the multiple-step disinfection system ensure adequate microbiological safety of the treated water. A recent study revealed that a complete treatment train with multiple disinfection steps can reduce the microbiological risk associated with the River Arno water turbidity by more than 600 times (Muoio et al., 2020).

. The risk levels were divided into very high (> 15), high (10 - 15), medium (6 - 9) and low (< 6). Each hazardous event was analysed for all the different phases (catchment, treatment, storage and distribution), where it could be present. The P and G scores are case specific. For example, the presence of pesticides in the source water was classified with P = 5 (almost certain) and G = 5 (catastrophic public health impact), while the same hazardous event in the treated water was classified with P = 1 (rare) and G = 5 (catastrophic public health impact). Moreover, the presence of turbidity in the treated water was classified with P = 1 (rare) and G = 3 (moderate aesthetic impact), while the same hazardous event in the storage tanks was classified with P = 2 (unlikely) and G = 3 (moderate aesthetic impact). The DWSS managers, under the supervision of the ISS and the University of Florence, implemented a first semi-quantitative risk matrix draft with the identification of the hazardous events, the assignment of the P and G scores and the identification of the existing control measures.

Table 1. Identification of the likelihood (P) and severity (G) factors

Likelihood	*Severity*
1. Rare: once every 5 years	1. Insignificant or no impact
2. Unlikely: once a year	2. Minor compliance impact
3. Moderate: once a month	3. Moderate aesthetic impact
4. Likely: once a week	4. Major regulatory impact
5. Almost certain: once a day	5. Catastrophic public health impact

Table 2. Semi-quantitative matrix approach
(adapted from WHO, 2009)

		Severity				
		1	*2*	*3*	*4*	*5*
Likelihood/ frequency	**5**	5	10	15	20	25
	4	4	8	12	16	20
	3	3	6	9	12	15
	2	2	4	6	8	10
	1	1	2	3	4	5
Risk score		< 6	6 – 9	10 – 15	> 15	
Risk rating		Low	Medium	High	Very High	

Then, the multidisciplinary team was involved in order to share and validate the matrix results. A two-stage risk assessment was carried out in order to determine the effectiveness of the existing

risk reduction control measures. Corrective actions to be implemented were proposed by the DWSS manager when the residual risk was more than six, and the most suitable solutions were identified within the team.

3. Results and discussion

3.1. Data analysis results

The three-year data analysis highlighted the high treatment efficiency of the two DWTPs. Table 3 shows the average values of the main monitored data from the Florence DWSS. The raw water is characterised by a large degree of seasonal and daily variability. One of the most important parameters for the DWTP management is inflow turbidity. High turbidity levels can reduce the efficiency of the disinfection by generating a chlorine demand whose removal is a well-known indicator of the effectiveness of clari-flocculation and filtration processes (AWWA, 1999; 2006, WHO, 2017b). The average turbidity value in the raw water is 21 NTU (standard deviation 46 NTU) while in the treated water it is 0.12 NTU for Plant A and 0.24 for Plant B. The high turbidity removal efficiency and the effectiveness of the multiple-step disinfection system ensure adequate microbiological safety of the treated water. A recent study revealed that a complete treatment train with multiple disinfection steps can reduce the microbiological risk associated with the River Arno water turbidity by more than 600 times (Muoio et al., 2020).

The main anthropogenic chemical contaminants in the River Arno are pesticides (especially glyphosate and AMPA). AMPA concentrations exceeded the 0.5 μg/L national regulatory limit for human consumption (Italy Decree, 2001) in the 100% of the raw water samples, while glyphosate resulted always below the limit. However, this does not represent a risk for the consumers since both Plants A and B led to almost complete removal efficiency and hence a concentration in the treated water of less than 0.03 μg/L in 100% of the samples for both plants. In the distribution network, the most concerning parameters are the disinfection by-products (trihalomethanes, chlorite and chlorate) which form during disinfection and propagate in the distribution system in the presence of naturally occurring organic compounds (AWWA, 1999). The Italian legislation suggests a 0.2 mg/L concentration of the free chlorine residual in the distribution network, making it necessary to use chlorine disinfectants, and sets the limit values for disinfection by-products (see Table 3). In order to comply with both these obligations, in Plants A and B the disinfection is provided in multiple steps using both ClO_2 and NaClO, with the disinfectant dosage automatically calculated considering the current chlorine demand. Thanks to this process, the 2015-2017 data showed low concentrations of disinfection by-products in Plants A and B as well as in the distribution network. An appropriate water filtration and disinfection is crucial to ensure the microbiological safety of the water distributed, particularly for WTPs which treat water coming from surface waterbodies in urban areas, as the River Arno. The main indicator organisms in the raw water vary over a wide range (see Table 3), while in the plants outlet and within the distribution network they are almost absent, thus revealing the effectiveness of filtration and disinfection processes and the integrity of the distribution system against possible regrowth and biofilm formation.

Two-years of water quality specific customer complaints were analysed in the full-service area dividing them into classes (odour, taste, aesthetic impact) totalling for about 400 complaints. The main complaints were related to the aesthetic impact (154, 38%), odour (100, 24%) and a combination of the two (aesthetic impact and odour, 133, 33%), while the remaining are related to taste problems (20, 5%). The number of complaints per 1000 consumers resulted equal to 0.7.

We observed a moderate positive correlation (r = 0.44) between the number of complaints and the number of maintenance and/or replacement of water mains, thus highlighting the importance of correct valve operations in order to contain consumer complaints. The water quality complaints will continue to be recorded and analysed after the WSP implementation since they represent a useful evaluation criteria of the WSP effectiveness (Lockhart et al., 2014).

3.2. Risk assessment and proposed control measures

For the risk assessment, more than 70 hazardous events and 110 subsequent hazards were identified (24% during catchment, 43% during treatment, 12% during storage and 20% during distribution). Considering the number of DWSS infrastructures (three abstraction points, two DWTPs, 20 storage tanks, 15 water districts), this led to a risk matrix of about 450 rows.

Table 3. Averages and standard deviations (in brackets) of the main parameters monitored in the Florence DWSS during 2015-2017 years

Parameter	*U.M.*	*Raw surface water*	*Treated water (Plant A outlet)*	*Treated water (Plant B outlet)*	*Distributed water (distribution network)[a]*	*Italian Regulation Limit (Italy Decree, 2001)*
Turbidity	NTU	21 (46)	0.12 (0.09)	0.24 (0.11)	0.30 (0.23)	1[b]

NPOC	mg/L	2.9 (1.4)	1.5 (0.4)	1.7 (0.4)	1.57 (0.51)	
Algae	n/mL	7299 (7895)	32 (51)	66 (213)	-	
Total pesticides	µg/L	0.13 (0.35)	<0.03 (0.0)	<0.03 (0.0)	-	0.5
Glyphosate	µg/L	0.05 (0.03)	<0.02 (0.0)	<0.02 (0.0)	-	
AMPA	µg/L	0.89 (0.33)	<0.02 (0.0)	<0.02 (0.0)	-	
Total coliforms	MPN/100mL	8991 (11067)	0 (0)	0 (0)	0 (1)	0
Escherichia coli	MPN/100mL	954 (3230)	0 (0)	0 (0)	0 (0)	0
Enterococci	MPN/100mL	293 (539)	0 (0)	0 (0)	0 (0)	0
Clostridium perfringens	UFC/100 mL	172 (163)	0 (0)	0 (0)	0 (0)	0
Aluminium	µg/L	236 (217)	95 (34)	82 (38)	81 (63)	200
Iron	µg/L	194 (213)	5 (6)	7 (6)	22 (40)	200
Manganese	µg/L	53 (42)	<2 (1.8)	3 (3)	4 (6)	50
Trihalomethanes	µg/L	-	15 (4)	12 (5)	14 (5)	30
Chlorite	µg/L	-	257 (65)	337 (114)	343 (103)	700
Chlorate	µg/L	-	210 (141)	335 (209)	322 (182)	
Free chlorine residual	mg/L	-	0.30 (0.03)	0.25 (0.05)	0.18 (0.08)	0.2[c]

[a] Mean value of 69 monitoring points within the distribution network and the storage tanks;[b] for surface water resources leaving the DWTPs; [c] Suggested value (Italy Decree, 2001)

The multidisciplinary team met 12 times in two years (2018-2019) and the risk matrix was revised twice before all the experts approved it. Since the WSP is an iterative approach, the team will revise the matrix each time a significant modification of the system or a treatment failure will occur, or a new contaminant will be detected etc. The main hazardous events assessed were contamination events, treatment failures, disinfectant overdosing, insufficient disinfectant dosage, insufficient flocculant dosage, vandalism, sedimentation in storage tanks, biofilm erosion in the distribution network and microbial contamination during pipe maintenance.

The water data analysis together with the on-site inspections highlighted that approximately 90% of the risks are mitigated thanks to the existing control measures. These include water treatment processes (chemical and physical barriers), alarms and remote controls, routine inspections, maintenance programmes, management procedures etc. In order to reduce the remaining 10% of the risks, appropriate control measures were assessed and have already been or will be implemented according to a timeline set by the WSP team (short, medium- and long-term actions). The upgrade plan with the identification of responsibilities and deadlines for the control measures is one of the main pieces of output of the WSP.

Some of these measures have been already implemented, such as the renovation and cleaning of the main storage tanks of the city (total volume 33000 m^3), the installation of an early warning station at the catchment of Plant A, the integration and the revision of all the procedures about operational monitoring and management of the treatment plants, the analysis of specific chemical and microbiological contaminants in the source and treated water. Others, such as the turbidity probes installation in the network and the implementation of video surveillance systems in storage tanks when necessary, will be soon implemented. The most relevant risks and the suitable control measures identified during the implementation of the plan are described below.

Water contamination due to industrial and agriculture activities

Given the great exposure of the system to pollution and contamination events, even though the DWTP treatment is already efficient (Table 3), a preventive approach was implemented against water contamination events using early-warning systems in the DWTP inlet and outlet. The newly installed UV and NPOC (not purgeable organic carbon) probes together with the turbidity, Redox and pH probes already in place, allow changes in water quality to be forecast and perform proactive actions to avoid the consequences of such variations. As far as the probes are concerned, calibration guidelines, frequency of data collection, alarm threshold definition have been assessed.

Chemical water contamination due to emerging contaminants

The occurrence of contaminants of emerging concern (CECs) in water resources, even at trace level, has been detected in different parts of the world, increasing public concern over their presence (López-Pacheco et al., 2019; Pal et al., 2010). CECs originate from various anthropogenic activities and include personal care products (PCPs), pharmaceuticals, pesticides, drugs, per- and polyfluoroalkyl substances (PFASs) etc. The conventional water treatment processes (clari-flocculation, filtration and chlorination) do not seem to provide for sufficient CEC removal, while GAC adsorption and advanced oxidation processes are more suitable for this end (Rossner et al., 2009; Snyder et al., 2007; Yang et al., 2017).

In this study, in order to evaluate the presence of CECs and their removal during the treatment steps, 35 CECs (*i.e.*, pharmaceuticals, drugs, PFASs and endocrine disruptors (EDs)) were analysed in both the raw and treated water. The concentrations were below the quantification limit (LOQ) in all of the samples. A sporadic occurrence of PFASs was detected in the raw water samples, while no PFASs were found in the treated water, thus confirming that GAC adsorption represents an effective barrier for the levels currently found in the source water at the time of study. A CEC monitoring plan was defined and will be applied on a regular basis. Since only PFASs were detected,

Table **4** refers to these and not to all of the CECs that were monitored.

Microbial contamination by waterborne pathogens

Several waterborne pathogens (bacteria, virus and protozoa) were analysed, in the raw and in the treated water, in order to evaluate the DWTPs' removal efficiency. The detection of traditional indicator organisms alone, such as Total Coliforms and *E.Coli*, provides an insufficient safeguard to public health because their absence in treated water does not indicate freedom from all viruses and protozoa. As a matter of fact, viruses and protozoa are more resistant to conventional treatment technologies, including filtration and disinfection by chlorine (WHO, 2017a).

For this reason, in this case-study, the detection of more resistant indicators, such as somatic coliphages, was considered. **Error! Reference source not found.** and

Table **6** show the results of the microbiological analysis. The data highlighted the presence of viruses (*Norovirus GI*, *Norovirus GII*, *Adenovirus*) in the raw water, while bacteria (*Campylobacter spp.*, *Campylobacter jejuni*) were not detected. Free-living amoebae were detected in the raw water and in only one sample from the Plant A outlet, regarding which further investigations are ongoing. Somatic coliphages were detected in the raw water but not in the treated water.

Sedimentation in storage tanks, microbial growth and accumulation of biofilm in pipes

The main hazardous events in the distribution network include biofilm growth and erosion because of the high-water age and loss of residual chlorine. The current maintenance and cleaning programmes, together with the free chlorine residual concentration measures along the aqueduct, led to adequate protection against bacterial growth. In addition, the planned installation of turbidity probes in pipes with a low flow velocity will be a useful tool to determine when the flushing of dead-end zones is necessary.

Error! Reference source not found.-8 shows the risk matrix of selected hazardous events for the Florence DWSS.

Table 4. PFAS analysis results – Plant A

		Raw water (Plant A)	***Treated water (Plant A)***	***Limit value[1]***
	UM	28/10/2019	28/10/2019	
Perfluorobutanoic acid (PFBA)	ng/L	12	<10	100
Perfluoro-n-pentanoic acid (PFPeA)	ng/L	<10	<10	100
Perfluorobutane sulfonic acid (PFBS)	ng/L	<10	<10	100
Perfluorohexanoic acid (PFHxA)	ng/L	<10	<10	100
Perfluoroheptanoic acid (PFHpA)	ng/L	<10	<10	100
Perfluorononanoic acid (PFNA)	ng/L	<10	<10	100
Perfluorodecanoic acid (PFDA)	ng/L	<10	<10	100
Perfluoroundecanoic acid (PFUnA)	ng/L	<10	<10	100
Perfluorododecanoic acid (PFDoA)	ng/L	<10	<10	100
Perfluorohexane sulfonic acid (PFHxS)	ng/L	<10	<10	100
Perfluorooctane sulfonic acid (PFOS)	ng/L	<1	<1	100
Perfluorooctanoic acid (PFOA)	ng/L	6.8	7.5	100
Total PFASs	ng/L	19	<10	500

[1]*European Commission, 2018*

Table 5. Virological analysis results

	Sampling date	*Filtered volume (L)*	*Enterovirus*	*Norovirus GI (n°)*	*Norovirus GII (n°)*	*Adenovirus (n°)*
Raw surface water	08/04/2019	5500	0	344	344	177
Groundwater (Plant B)	09/04/2019	10220	0	0	0	0
Treated water (Plant A)	05/06/2019	7150	0	0	0	0
Treated water (Plant B)	09/04/2019	5980.5	0	0	0	0

Table 6. Microbiological analysis results

	Sampling date	*Campylobacter spp.*	*Campylobacter jejuni*	*Free-living amoebae*	*Somatic coliphages*
Raw surface water (Plant A)	05/06/2019	Absent/2L	Absent/2L	Present/100 mL	8 UFP/10mL
Raw surface water (Plant B)	08/04/2019	Absent/1L	Absent/1L	Present/100 mL	40 UFP/10mL
Groundwater (Plant B)	08/04/2019	Absent/1L	Absent/1L	-	0 UFP/10220L
Treated water (Plant A)	05/06/2019	Absent/1L	Absent/1L	Present/10L	0 UFP/7150L
	18/11/2019	-	-	Absent/10L	-
Treated water (Plant B)	08/04/2019	Absent/1L	Absent/1L	Absent/10L	0 UFP/5980.5L

Table 7. Example of risk assessment and definition of corrective actions (continue…)

Process step	*Hazardous event*	*Hazard type*	*P*	*G*	*R1 score*	*R1 class*
Catchment	Water contamination due to industrial and agriculture activities, urban runoff, etc.	Chemical Physical Microbial	4 4 4	5 3 5	20 12 20	Very High High High
Treatment plant outlet	Presence of contaminants of emerging concern (CECs) and/or waterborne pathogens (viruses, protozoa etc.)	Chemical Microbial	3 3	5 5	15 15	High High
Storage tanks	Sedimentation and microbial growth	Microbial	2	5	10	High
Distribution network	Microbial growth and accumulation of biofilm	Microbial	3	5	15	High

Note: P = likelihood; G = severity; R1 = risk before considering the current control measures; V = validation; R2 = risk after considering the current control measures; PE = partially effective; E = effective.

Table 8. Example of risk assessment and definition of corrective actions

Process step	*Hazardous event*	*Current control measures*	*V*	*P*	*G*	*R2 score*	*R2 class*	*Proposed corrective actions*
Catchment	Water contamination due to industrial and agriculture activities, urban runoff etc.	Treatment with clari-flocculation, sand and GAC filtration, multiple disinfection steps	E E E	1 1 1	5 3 5	5 3 5	Low Low Low	Early warning system
Treatment plant outlet	Presence of contaminants of emerging concern (CECs) and/or waterborne pathogens (viruses, protozoa, etc.)	Treatment with GAC adsorption and multiple oxidation steps	PE E	2 1	5 5	10 5	High Low	Definition of the CEC monitoring plan
Storage tanks	Sedimentation and microbial growth	1. Tank cleaning programme 2. Routine inspections 3. Laboratory analysis	E	1	5	5	Low	Documentation and constant review
Distribution network	Microbial growth and accumulation of biofilm	1. Water main cleaning programme 2. Residual disinfectant 3. Laboratory analysis	E	1	5	10	Low	Installation of turbidity probes in pipes with low flow velocities where sedimentation can occur

Note: P = likelihood; G = severity; R1 = risk before considering the current control measures; V = validation; R2 = risk after considering the current control measures; PE = partially effective; E = effective.

4. Conclusions

This paper presents the results of a WSP case-study successfully implemented in a large-scale DWSS supplied by a surface water body. The plan, applied in the municipality of Florence, was carried out, since March 2018, by the water utility manager with a multidisciplinary team of more than 40 experts, which promoted coordinated work between the stakeholders.

The approach was strictly team-based: all data, expertise and decisions were shared among the experts; the risk matrix and the subsequent corrective measures were discussed and proposed within the team. The implemented WSP allowed the utility manager to assess the current DWSS performance, to define all the possible risks associated with drinking water consumption and to outline new control measures in order to improve the water safety while reducing public health risks and increasing consumer confidence.

The major difficulties faced during the WSP implementation were the assessment of the correct P and G values for the risk evaluation and the identification of the cost-effective solutions among the measures proposed by the team. The DWSS steps characterised by the highest percentage of hazardous events were the catchment and the treatment. Most of the identified risks (90%) are already sufficiently reduced by the current control measures; appropriate control measures were identified in order to reduce the remaining 10%. An upgrade plan was assessed, which established responsibilities and deadlines.

The main actions identified are: the installation of an early warning station at the catchment in order to forecast the changes in the source water quality and to perform proactive actions; the definition of a monitoring plan for the analysis of the CECs which represent a worldwide concern and which are commonly present in the surface waters; the installation of turbidity probes in the pipes with low flow velocity where biofilm growth may occur.

Most of the corrective actions have already been implemented, while others will be applied according to the upgrade plan schedule. All the measures will be applied by 2022. The WSP will be revised by the team on a regular basis and the effectiveness of the implemented measures will be assessed over time. Since the correct implementation of a WSP is time-consuming and cost-intensive, it is important to create a detailed procedure in order to extend more easily the already implemented plan to other supplied water systems.

References

AWWA, (2006), *Waterborne Pathogens: Manuals of Water Supply Practices*, 2nd Edition, American Water Works Association, 1-324.

AWWA, (1999), *Water Quality and Treatment: A Handbook of Community Water Supplies*, 5th Edition, Water Resources in the Built Environment: Management Issues and Solutions, New York.

Baum R., Amjad U., Luh J., Bartram J., (2015), An examination of the potential added value of water safety plans to the United States national drinking water legislation, *International Journal of Hygiene and Environmental Health*, **218**, 677-685.

Cann K.F., Thomas D.R., Salmon R.L., Wyn-Jones A.P., Kay D., (2013), Extreme water-related weather events and waterborne disease, *Epidemiology and Infection*, **141**, 671-686.

EC Directive, (2018), Proposal for a Directive on the quality of water intended for human consumption, On line at: Http://Ec.Europa.Eu/Environment/Water/Water-Drink/Review_En.HtmL.

EC Directive, (2015), Directive 2015/1787 of the European Parliament of 6 October 2015 amending Annexes II and III to Council Directive 98/83/EC on the quality of water intended for human consumption, *Official Journal of the European Union*, **L260**/6.

Gunnarsdottir M.J., Gardarsson S.M., Bartram J., (2015), Developing a national framework for safe drinking water-Case study from Iceland, *International Journal of Hygiene and Environmental Health*, **218**, 196-202.

Gunnarsdottir M.J., Gardarsson S.M., Elliott M., Sigmundsdottir G., Bartram J., (2012), Benefits of water safety plans: Microbiology, compliance, and public health, *Environmental Science and Technology*, **46**, 7782-7789.

Hasan T.J., Hicking A., David J., (2011), Empowering rural communities: Simple Water Safety Plans, *Water Science and Technology: Water Supply*, **11**, 309–317.

Howard G., Godfrey S., Tibatemwa S., Niwagaba C., (2005), Water safety plans for piped urban supplies in developing countries: a case study from Kampala, Uganda, *Urban Water Journal*, **2**, 161-170.

Hrudey S.E., Hrudey E.J., (2007), Published case studies of waterborne disease outbreaks-evidence of a recurrent threat, *Water Environment Research*, **79**, 233-245.

Hubbard B., Gelting R., Portillo M. del C., Williams T., Torres R., (2013), Awareness, adoption and implementation of the water safety plan methodology: Insights from five Latin American and Caribbean experiences, *Journal of Water Sanitation and Hygiene for Development*, **3**, 541-548.

Italy Decree, (2001), Legislative Decree no 31 of 2 February 2001, implementing Directive 98/83/EC on the quality of water intended for human consumption, *Gazzetta Ufficiale,* On line at: www.comune.jesi.an.it

Jayaratne A., (2008), Application of a risk management system to improve drinking water safety, *Journal of Water and Health*, **6**, 547-557.

Laine J., Huovinen E., Virtanen M.J., Snellman M., Lumio J., Ruutu P., Kujansuu E., Vuento R., Pitkänen T., Miettinen I., Herrala J., Lepistö O., Antonen J., Helenius J., Hänninen M.L., Maunula L., Mustonen J., Kuusi M., Collin P., Korpela M., Kuusela A.L., Mustajoki S., Oksa H., Räsänen S., Uotila T., Katto T., (2010), An extensive gastroenteritis outbreak after drinking-water contamination by sewage effluent, Finland, *Epidemiology and Infection*, **139**, 1105-1113.

Lockhart G., Oswald W.E., Hubbard B., Medlin E., Gelting R.J., (2014), Development of indicators for measuring outcomes of water safety plans, *Journal of Water Sanitation and Hygiene for Development*, **4**, 171-181.

López-Pacheco I.Y., Silva-Núñez A., Salinas-Salazar C., Arévalo-Gallegos A., Lizarazo-Holguin L.A., Barceló D., Iqbal H.M.N., Parra-Saldívar R., (2019), Anthropogenic contaminants of high concern: Existence in water resources and their adverse effects, *Science of the Total Environment*, **690**, 1068-1088.

Lucentini L., Achene L., Fuscoletti V., Nigro Di Gregorio F., Pettine P., (2014), Guideline for risk assessment and management within the drinking water chain according to Water Safety Plans., On line at: https://www.britishecologicalsociety.org/applied-ecology-resources/document/20153070836/.

Mahmud S.G., Shamsuddin S.A.J., Feroze Ahmed M., Davison A., Deere D., Howard G., (2007), Development and implementation of water safety plans for small water supplies in Bangladesh: benefits and lessons learned, *Journal of Water and Health*, **5**, 585–597.

Mälzer H.J., Staben N., Hein A., Merkel W., (2010), Identification, assessment, and control of hazards in water supply: Experiences from water safety plan implementations in Germany, *Water Science and Technology*, **61**, 1307-1315.

Moreira N.A., Bondelind M., (2016), Safe drinking water and waterborne outbreaks, *Journal of Water and Health*, **15**, 83-96.

Muoio R., Caretti C., Rossi L., Santianni D., Lubello C., (2020), Water safety plans and risk assessment: A novel procedure applied to treated water turbidity and gastrointestinal diseases, *International Journal of Hygiene and Environmental Health*, **223**, 281-288.

Pal A., Gin K.Y.H., Lin A.Y.C., Reinhard M., (2010), Impacts of emerging organic contaminants on freshwater resources: Review of recent occurrences, sources, fate and effects, *Science of the Total Environment*, **408**, 6062-6069.

Pérez-Vidal A., Escobar-Rivera J.C., Torres-Lozada P., (2020), Development and implementation of a water-safety plan for drinking-water supply system of Cali, Colombia, *International Journal of Hygiene and Environmental Health*, **224**, 1-14.

Rickert B., van den Berg H., Bekure K., Girma S., de Roda Husman A.M., (2019), Including aspects of climate change into water safety planning: Literature review of global experience and case studies from Ethiopian urban supplies, *International Journal of Hygiene and Environmental Health*, **222**, 744-755.

Rinehold A., Corrales L., Medlin E., Gelting R.J., (2011), Water safety plan demonstration projects in latin america and the Caribbean: Lessons from the field, *Water Science and Technology: Water Supply*, **11**, 297-308.

Roeger A., Tavares A.F., (2018), Water safety plans by utilities: A review of research on implementation. *Utilities Policy*, **53**, 15-24.

Rossner A., Snyder S.A., Knappe D.R.U., (2009), Removal of emerging contaminants of concern by alternative adsorbents, *Water Research*, **43**, 3787-3796.

Setty K., O'Flaherty G., Enault J., Lapouge S., Loret J.F., Bartram J., (2018), Assessing operational performance benefits of a Water Safety Plan implemented in Southwestern France, *Perspectives in Public Health*, **138**, 270-278.

Setty K.E., Kayser G.L., Bowling M., Enault J., Loret J.F., Serra C.P., Alonso J.M., Mateu A.P., Bartram J., (2017), Water quality, compliance, and health outcomes among utilities implementing Water Safety Plans in France and Spain. *International Journal of Hygiene and Environmental Health*, **220**, 513-530.

Shamsuzzoha M., Kormoker T., Ghosh R.C., (2018), Implementation of water safety plan considering climatic disaster risk reduction in Bangladesh: A study on Patuakhali Pourashava water supply system. *Procedia Engineering*, **212**, 583-590.

Snyder S.A., Adham S., Redding A.M., Cannon F.S., DeCarolis J., Oppenheimer J., Wert E.C., Yoon Y., (2007), Role of membranes and activated carbon in the removal of endocrine disruptors and pharmaceuticals. *Desalination*, **202**, 156-181.

Sorlini S., Biasibetti M., Abbà A., Collivignarelli M.C., Damiani S., (2017), Water Safety Plan for drinking water risk management: the case study of Mortara (Pavia, Italy), *Ambiente e Agua - An Interdisciplinary Journal of Applied Science*, **12**, 513-526.

Tsitsifli S., Tsoukalas D.S., (2019), Water Safety Plans and HACCP implementation in water utilities around the world: benefits, drawbacks and critical success factors, *Environmental Science and Pollution Research*, doi:10.1007/s11356-019-07312-2.

Vieira J.M.P., (2011), A strategic approach for Water Safety Plans implementation in Portugal, *Journal of Water and Health*, **9**, 107-116.

Viljoen F.C., (2010), The World Health Organization's water safety plan is much more than just an integrated drinking water quality management plan, *Water Science and Technology*, **61**, 173-179.

WHO, (2009), Water Safety Plan Manual: Step-by-step risk management for drinking-water suppliers, WHO Library, On line at: https://iwa-network.org/wp-content/uploads/2019/03/Water-Safety-Plan-Manual_eng.pdf.

WHO, (2017a), Guidelines for drinking-water quality: fourth edition incorporating the first addendum, IV. ed, WHO Library Cataloguing-in-Publication Data. Geneva, On line at: https://www.who.int/publications/i/item/9789241549950.

WHO (2017b), Water quality and health - review of turbidity: Information for regulators and water suppliers, WHO/FWC/WSH/17.01, On line at: https://apps.who.int/iris/handle/10665/254631.

WHO and IWA, (2017), Global status report on water safety plans: A review of proactive risk assessment and risk management practices to ensure the safety of drinking-water, On line at: https://www.who.int/water_sanitation_health/publications/global-status-report-on-water-safety-plans/en/.

Yang Y., Ok Y.S., Kim K.H., Kwon E.E., Tsang Y.F., (2017), Occurrences and removal of pharmaceuticals and personal care products (PPCPs) in drinking water and water/sewage treatment plants: A review, *Science of the Total Environment*, **596**, 303-320.

Environmental Engineering and Management Journal October 2020, Vol.19, No. 10, 1823-1829
http://www.eemj.icpm.tuiasi.ro/; hiip://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

PVCUPCYCLING - CIRCULAR ECONOMY AND ZERO WASTE: "UPCYCLING" WASTE FROM ELECTRICAL SYSTEMS

Consuelo Nava

ABITAlab, Department Architecture and Territory, Mediterranea University of Reggio Cal. (IT)
E-mail address: cnava@unirc.it; Phone: +039 (0)965 1697244

Abstract

A circular economy system will allow company to directly operate an effective re-cycling policy. Establishing a new "zero waste" impact scheme, in order to recover by-products from the production process, thus leading to an increased market price in comparison to their economic value, and by doing so with full respect of the blue and circular economy standards applied to the product. The main objective of the PVC upcycling project is to facilitate the transition of R.ED.EL.'s current production chain, from an economically linear model to a circular type. This is achieved through actions that aim to recycle PVC (polyvinyl chloride materials) from electrical cables ("de-manufacturing") to upcycling the same PVC into new products with a low environmental impact ("re-manufacturing"). While working from the de-manufacturing phase to the re-manufacturing phase, activating circular models with new PVC-MPS supply chains, and implementing experiments in specifically illustrated scenarios, it has also been possible to build a collaborative platform to exchange information. This process intercepts the eco-design phase thus realizing the possibility of intervention in the production of PVCupcycling prototypes.
The project won the regional competition of Calabria (EU funds-POR Calabria 14-20 axis I-action 1.2.2) and has received European funding for the "Promotion of Research and Innovation" thanks to the proposal of the following team: R.ED.EL., a media manufacturing company, in collaboration with ENEA, an Italian energy specialist research organization, UNICAL, a chemistry specialist organ-isation based at the University of Calabria, PMopenlab, an innovative eco-design and additive manufacturing start-up. C.Nava is the technical-scientific team man-ager, a sustainability and design innovation research specialist.

Key words: circular economy, eco-design, smart manufacturing, upcycling, zero waste

Received: February, 2020; Revised final: June, 2020; Accepted: July, 2020; Published in final edited form: October, 2020

1. Introduction

With this project R.ED.EL. aim to reach new possibilities, such as advantageous technical solutions to reuse the so-called waste material and place it into the manufacturing chain. They should also expect to gain leadership in an accelerating market, and so pursuing a real innovation strategy based on three dimensions of sustainability: environmental, economic and social. In the first experience the strategy will trigger "the transition from a linear to a circular economic model", increasing the performance level of new products and services, and enhancing skills for the operators who are involved in the process. By implementing a new design, we change the organization and function of the current model, which is centralised and therefore the project's methods are easy to apply. Thanks to this new design the company is able to control the quality of service in their "end of life cycle".

In favourable terms, the following scenarios are implemented for the company: investments in technology with a higher performance rating; significant improvements to the consequential processes of a recycling chain; integration of present machinery and the "additive" digital printing technologies necessary for prototyping a typical eco-design. New procedure and application protocols will be introduced ultimately contributing to a larger employee capacity with both scientific and consultancy partners. The proposal for the PVC upcycling project calls for an innovative circular chain inserted into an energetic and chemically dynamic environment, from which there is a feed of raw material which consequently has new resources. The company is placed directly into the innovative life cycle of technology contributing to endorsers being labelled as "innovators" (. Such early adopters are identifiable as those who embrace new technologies, and whose radical inventions are characterized by originality and design complexity.

Objectives: The project's specific innovative objectives adhere to experimental developments and industrial research, to which a circular production chain is complimentary. In detail the project addresses:

1) *Procurement of raw materials:* this is the first step of the circular model, with the specific objective of "rethinking" which raw materials are usable in the production process. In the proposed project while recording the characteristics of RAEE, PVC, and other such plastics coming from electrical cables, it will manifest itself that they have historically been single-use materials. Their history as scrap waste is based on the material consistency of the components during their time of use in the first life cycle.

2) *Design:* this second step of the circular model presents a specific objective for directing the products life cycle towards a reliable performance. The project will be realized through the eco-design model ideal "Cradle to Cradle", which will be separated into two different levels. We can define the first level as "capacity building". Dedicated "design driven innovation" laboratories have been founded in order to create relational assets and employ the following four activities: I. Strategies, II. Development and Renewal, III. Interpretation of the Research Advancements, whereby a workshop system enables improvements of methods and equipment so that products can be developed into a prototype concept; IV. Design of the Graft Discours, this increases the company's reputation and begins attracting new competitors and stabilizing our market. The second level concerns itself with "smart manufacturing" which requires a prototyping identification phase for the product's components and its smart solutions, making use of unconventional technology and its high productivity.

3) *Production:* is the third step in the circular model and has the specific objective of reconstructing the production chain towards a zero-waste system, labelled "recovery and recycling". This phase will perform the following strategies: - Strengthen the activities related to an "end of life" process in current systems and the relative disposal of electrical cables, leading to the increment and recovery of recyclable and reusable materials for other uses. (Fig.1) - Innovating the operation, the equipment and the platforms which are available to the company. - Modernization of sustainability models for experiments with advanced technology and increased momentum on the company's own consolidated strategy, which seeks to provide exemplary processes to reduce their impact on the environment.

4) *Distribution:* in this fourth step, of the circular model, the specific objective is to modify the core business strategy. Services will be available while supplying the products, emphasizing that the customer's sustainability objectives have been met: an efficient environmentally-energetic performance, a low environmental impact, and a circular qualification of services.

5) *Consumption:* in the fifth step of the strategic circular model the specific objective is to contribute to a new pattern, that ultimately aims to minimize the impact on the environment by reducing the amount of waste that is sent to landfill. This fits in well with R.ED.EL.'s particular production structure, which manages the end of life cycle system and can accordingly move towards expanding the supply chain to recycle all the electrical cable components, thus centralizing operations and allowing a stronger flow of resources in a renewed supply chain model.

6) *Collection-Recovery and Recycling:* the sixth and seventh steps in the circular model phase are connected by the same objective, which is to instruct the organizational and production of a model that is capable of changing the business' paradigm. There will be modifications to the company's operational internal economics, as well as research and developments becoming externally more competitive. In R.ED.EL.'s case these changes will be achieved by preserving quality, especially in the processes and products coming from its own production chain, thus intensifying innovative designing for new higher level products, namely, upcycling. Taking note of the logistical reserve return on the original prototype in comparison to the outgoing return on the new products that use electrical cables for the construction of plants during their first life cycle. These steps involve designing new levels of management for "zero waste", with a supply chain that reconfigures the existing activities with new products in order to maximize the effectiveness of knowledge systems. Thus, understanding the movements between matter and incorporated energy, while analysing each new phase of the production cycle: resources, paths, values and direction of innovation (LCA and LCC and Design Driven Innovation Model).

2. Case studies

2.1. Strategy: the innovation process and the product's transformation

The "zero waste" strategy in PVCupcycling is applied to the entire production chain; innovation feeds to the generation of new technical-scientific know-how, increases competitiveness in all the operational-technical phases of design, use, maintenance, reusing, regeneration and recycling. This addition also interfaces with those of the "circular" supply chain to business on the value chain; the company goes through the phases of procurement, manufacturing, marketing and sales, product use, product disposal, and as well as, the development of a new product. (Fig.2)

a

b

Fig. 1. Waste and scrap materials from electrical cables (PMopenlab communication, 2018):
(a) The storage of disused cables from renewed electrical systems;
(b) the section of an electric cable with all component materials in plastic and aluminum and copper

R.ED.EL. is inspired by "a vision of enterprise on the possible disruptive meanings of the new product and process languages typical of technology-push" as Nava (2019) demonstrated, and thanks to this project the dream is attainable. Achieving new possibilities and advantageous technical solutions for reusing the so-called "waste" material and reworking it into its own work cycle, as well as gaining leadership in a fast-growing market, thus pursuing a real innovation strategy. Therefore, the PVCupcycling project involves both the "process" and the "product's chain" that has already been produced by R.ED.EL.

The proposed project activity is divided into actions related both to "industrial research" (IR) and to "experimental development" (ED), as defined in the six following WP's:

- WP1 (IR) is dedicated to assessing the sustainability of the activities developed on industrial waste, and whether they are in accordance with the criteria of the circular economy and whether these industrial activities lead towards a zero waste outcome.

- WP2 (IR), addresses the issue of a "Life Recycle Assessment". The production chain is defined by assimilating the instruments that are already available in the company with the newly acquired supplementary equipment in the current project. This type of integration is achieved by MIMPRENDO's actions in the start-up project. Particularly the essential knowledge that will be shared among partners, especially that which is obtained from the second raw material while improving the use of PVC.

- WP3 (IR) is mainly dedicated to identifying the possible application fields for experimentation with the reuse of PVC, which constitutes the second raw material for the project. After an exhaustive characterization both from a chemical and physical point of view of the second raw material (PVC), potential smart solutions for hybridization with other materials will be investigated in the laboratory. In-depth feasibility studies will be developed in labs which will then be the subject of further study in subsequent calls.

- WP4 (ED), has as its purpose in the development of PVC application prototypes, in which characterization tests will be carried out according to the technical standards in force.

- WP5 (ED), defines the LCC (life Cycle Cost) of the defined experimental prototype and the actions for the positioning of the company in the Circular Economy Network.

- WP6 (ED), contains the dissemination and exploitation activities of the results.

2.2. Re-manufacturing and ecodesign for additive manufacturing

The reused PVC from electric cables waste will be applied in the first commercial facing tiles pre-prototypes - categorized as experimental development - and in composites based on cement mortars, which is classified as industrial research. These groups are potentially applicable for the same company in laboratory and warehouse building works, referring to the management of electricity networks and related civil works. Other highly specialist hybrid scenarios are assembled with the use of additive technologies with a digital control process, in which the eco-design is innovated towards the production of sustainable scenarios (such as, a green parking scenario).

In addition to the above objectives we will investigate the physical, mechanical and environmental stress resistance characteristics of the composite materials obtained. As well as environmental testing we seek to define a performance profile of the products, with reference to the technical characteristics, summarized in a "sustainability toolbox".

The main phases of the re-manufacturing process can therefore be characterized by achieving the intended objectives, each of which is described in a process component, as listed below:

- traceable components: selection, characterization and definition of waste materials used as MPS (mapping and physical/chemical and morphological analysis);

- high performance components: energy-environmental profile, CO_2 expenditure, and recovery for the manufacturing of products from the recycling processes;

- "Cradle to Cradle" recycle components: industrial eco-design, operations, and prototype methods of additive manufacturing (3D printing);

- high performance components: references and collections of information and techniques for LCA (Life Cycle Assessment) and LCC (Life Cycle Cost) components;

- trademark products: protocol and technical description for Environmental Product Declaration (EPD pre-qualification);

- commercial products: qualifications for products and possible suppliers for all operations within the production chain (possible route marking on commercial prototype components and patents).

All the prototypes are made with scenarios in the R.ED.EL. and PMopenlab srls laboratory environment, and have in-situ applications and/or different alternatives, in order to test installation and in-use responses. This activity refers to the following definition: an eco-design based on a "Innovation Driven Design" process; tests to be performed on material and system components; hybridization capacity with other aggregating materials and system compatibility for stratified or mixed components; preparation of technical data sheets relating to the scenarios; the matrix on PVC waste value in various contexts; a feasibility study in additional states for the associated design, as well as those tested in the construction site-laboratory.

Scenario no. 3 in the R.ED.EL. construction site-laboratory uses hybrid PVC components, such as MPS, in different consistencies, for example loose powder or powder printed on more than one format. The aim is to account for the quantity of recycled PVC on a functional unit and also define an environmental-energy profile for the CO_2 reduction that corresponds to the realized system.

For that reason it is a question of pursuing two other objectives for the pre-prototype phase: to assess which pre-commercial product can be found when triggering an available sector of the industrial chain, discovering which technologies are already available in the company (results based upon realized scenarios), and the effects of a circular economy at zero waste on the business model and innovative recycling-recovery chain; to evaluate which competitive markets can accommodate higher quality products and which technologies should be activated when widening the technical and economic scale of the company (scenarios to be realized soon). Employing not only a circular model with centralized logistics, but also a "product as a service" model working externally, thus triggering other supply chains and other business space opportunities. Three scenarios have been enabled concerning the field of sustainable building, featuring the PVCupcycling experiments from the site's workshop, the in-situ testing activities with R.ED.EL. and PMopenlab (Fig. 3), and environmental tests on the by-products in ENEA and UNICAL laboratories. (Fig. 4)

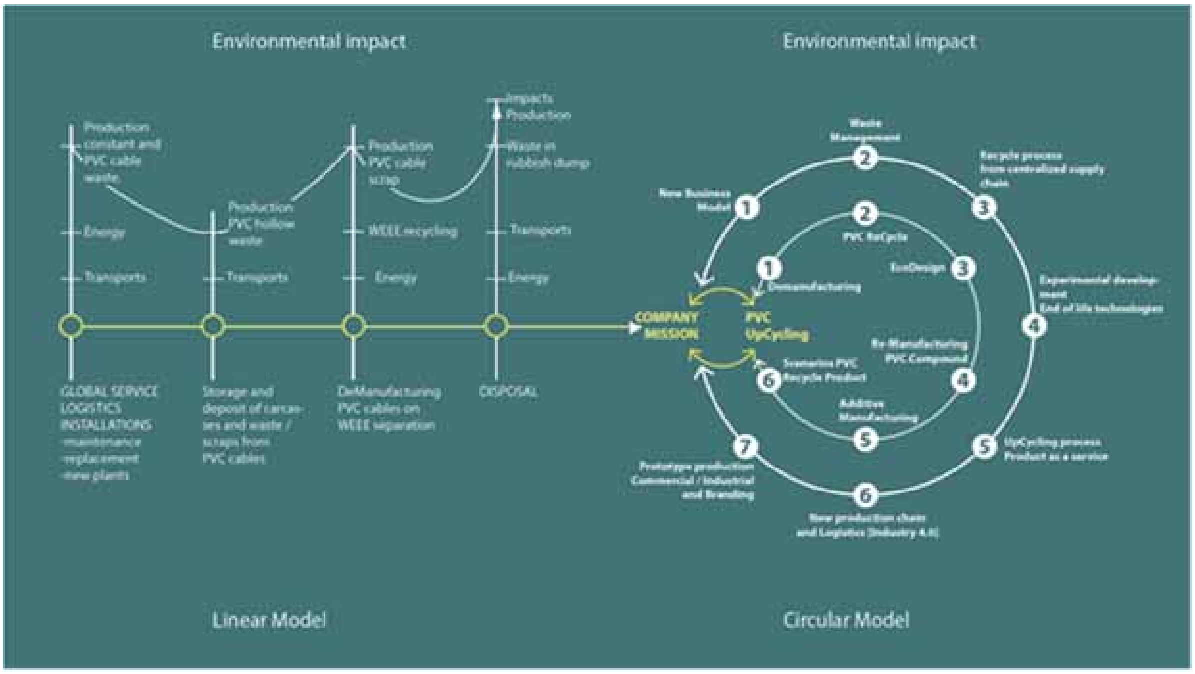


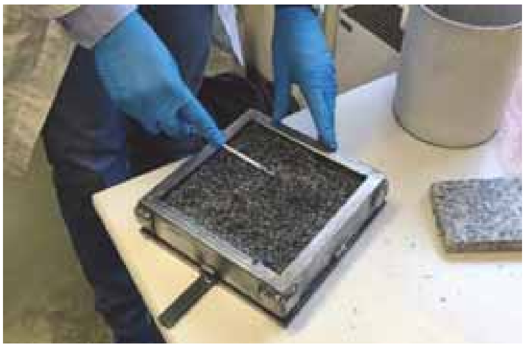
Fig. 2. From the Linear Management of PVC Cable Waste to the Circular Model of Multiple PVCupcycling Chains (Nava and Lucanto, 2020)

(a)

(b)

Fig. 3. Laboratory of Eco-Design and Additive Manufacturing (PMopenlab; Reggio Cal., Italy):
(a) represent the model form manufacturing design phase
(b) represent the verification of compatibility between components to be integrated into the scenario system

(a)



(b)

Fig. 4. Testing in ENEA and UNICAL Diatic Laboratory (Lucanto and Procopio, 2019)
(a) represent the samples of the virgin separated from the metallic matrices
(b) represent the first test of forming the in the mold for the press and the realization of the thickness block for the green parking

3. Results and discussion

3.1. Scenarios and area-testing

In the PVC upcycling experimentation, the manufacturing phase, which includes the supply chain and the services required for the logistical storage of cables, c/o R.ED.EL. company, is 90% covered in terms of energy consumption from the presence of photovoltaic system that has been installed in their industrial buildings. In this sense, for the integration of this energy production technology, the supply chain can be said to be more efficient and sustainable, even in the subsequent phases.

But it is clear that the de-manufacturing and re-manufacturing phase must consciously absorb what is consumed in the middle phase and move towards the afore mentioned sectors by applying sustainability principles and eco-labeling certification models that guarantee the product is coming from the recycling chain. Other production manufacturing processes do not require such an impactful method thus allowing a secondary raw material, such as the PVC compound, to be recycled as a primary, or inert, component for other hybrid systems. This may then be reintroduced into new models of use. Throughout the re-manufacturing phase it is important that the circular economy model triggers processes for ‘industrial symbiosis’ in sectors that are preferably able to take charge of other phases of the sustainable production chain. These may include but are not subject to; sustainable construction, green products, recycled products, etc. **In any case it is estimated that for every kg of recycled cable it is possible to obtain a 2kg saving of CO2 which is not emitted into the atmosphere. (VinylPlus, 2013).** Three scenarios have been enabled concerning the field of sustainable building, featuring the PVCupcycling experiments from the site’s workshop, the in-situ testing activities with R.ED.EL. and PMopenlab, and environmental tests on the by-products in ENEA and UNICAL laboratories (Nava and Lucanto, 2020).

Scenario 1: Coating for outdoor flooring - type A: recycled PVC tiles on existing reinforced screed. Experimenting on the laboratory site involves setting up the scenario on an existing resistant screed that forms the base of the external steel staircase of the R.ED.EL. offices. A tile mat is constructed almost entirely of virgin WEEE PVC and has a surface area of 120x55cm and dimensions 5x7x0.5cm. Two-component polyurethane sealants are used for fastening at the base of the existing screed and adhesive-putty hybridized with PVC powder is used for filling joints between briquettes (Fig.5).

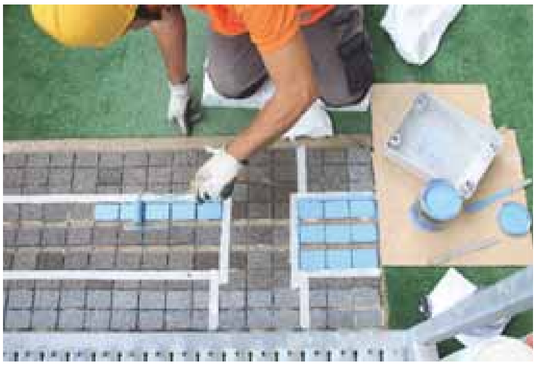
COMPONENTS: Two-component polyurethane sealants, two-component epoxy adhesive putty, recycled PVC powder, pre-painting water-based primer + fast-drying water-based enamel. IMPACTS: kg of PVC per square meter of each scenario: 3.5kg PVC; kg of CO_2 saved per square meter of each scenario: 7kg CO_2; Hours of work necessary for installation: 6h

Scenario 2_ Construction of a driveway for vehicles for handling small loads - using virgin PVC powder hybridized in cement mortar. A pedestrian area is built in front of an entrance of the company's building, with a resistant screed featuring an electro-welded mesh. Using a hybrid mixture of 75% recycled materials, with one-part concrete, one-part recycled PVC powder and one-part wielding aggregates from the company's decommissioned activities and recyclables. (Fig.6)

COMPONENTS: 25kg concrete, 24kg PVC powder, 50kg aggregates (on a functional unit of 1sqm/18cm of thickness), 10x10 welded mesh. IMPACTS: kg of PVC per square meter of scenario put in place: 24kg PVC; kg of CO_2 saved per square meter of each scenario: 50kg of CO_2; Hours required for installation: 16h for 5sqm.

Scenario 3_ Green Parking consists of a road section with draining asphalt and thick blocks made of recycled PVC - the system is hybridized with additive technologies - 3D printing of components and MPS PVC blocks. The experiment carries out what is foreseen in the project in terms of additive manufacturing and scenario realization for the hybrid components which come from eco-design processes. We seek to create a functioning, highly resilient green parking unit measuring 280x450cm. This construction will be with an integrated water absorption system in order to create a permeable and semi-permeable plant and gravel surface, with the completion screed already tested (as in scenario 1) and with a printed and modular system for the disposal of rainwater, which acts as a channel and a joint. The loading surface is reinforced by an alveolar mesh in printed PLA (polylactic acid – bioplastic), this houses the thick blocks of recycled PVC, and the permeable and semi-permeable filling, thus allowing the connection of the component-modules to the water disposal system. The latter, sized and built in the functional unit, responds in a short time to an overloaded capacity from rain washout (water bombs), with a system capacity of about 1.61 cubic meters.

The conveyed water can be recovered and reused to soak the same permeable surface, or for maintenance and waterproofing. Furthermore, 3D printing can be used to form the component prototypes; a mold for production with other performing materials, and one that is in line with industrialized processes. The use of additive technologies has triggered a process of eco-design and engineering of the components which are described in this report's annex in all its phases (WP5.2). (Fig.7)


(a)


(b)_

Fig. 5. Area Testing Scenario 1 (R.ed.el Lab., 2018, Reggio Cal., Italy) (a) represent the coloring of the coating for outdoor flooring (b) represent the test of the joint thicknesses between tiles with recycled PVC powder


(a)


(b)

Fig. 6. Area Testing Scenario 2 (R.ed.el Lab., 2018, Reggio Cal., Italy) (a) represent the preparation of the components for the mixture of the mortar (b) the realization of the 2nd scenario in the testing area

(a) (b)

Fig. 7. Area Testing Scenario 3 (PMopenlab, R.ed.el Lab., 2018, Reggio Cal., Italy) (a) represent the implementation of recycled and printed components, (b) the final construction already in function of the green parking unit.

COMPONENTS: 58 thick blocks in recycled PVC (16.30x17.31x5.00cm); 58 lodgings for recycled PVC blocks (16.60x15.60x3.40cm), 33 alveolar modules (18 for grass, 15 for gravel) of the size 16.60x15.50x5cm; 4 structural joints in PLA printed in 3D, 52 elements for the water storage system in PLA printed in 3D. IMPACTS: Kg of PVC per square meter of scenario put in place: 24kg PVC; kg of CO_2 saved per square meter of each scenario: 50kg of CO_2.

4. Conclusions

A "recovery and recycling" business model shifts the company's interest towards "value", not only in the quality of service and goods, but also the waste materials' phases of life in which its energy can flow efficiently through production logistics.

In this first phase of centralized logistics, the "product as service" customer is the company itself, which acts on its own waste, aiming for a low-impact "zero waste" management model, recovering and re-using its waste.

In particular, with only centralized production for its own supply chain, the company, at its maximum, produces around 960 tons per year of incoming cable scrap; half of this quantity is not sent to landfill but put back on the market and produces a gain of approx. 800,000€ for copper and for aluminium 250,000€. According to the objectives of this proposal by recycling and adding value to PVC waste, i.e. changing it from a compound to a second raw material, we will be able to attain the other 50% of scrap as a unit of cable material, saving about 140,000€ on the cost of plastic disposal, thus rendering it useful for the reinstatement of re-manufacturing into the economy. It is a question of activating an economical valuable chain with “direct” economic benefits for the company and with obvious savings for the costs of transfer to landfill and which translate into revenues for recycling activities. Other benefits are "indirect", from the management for zero waste, which reduces the environmental impact and the disposal chain for an "end of life" cycle (waste, transport, emissions, receiving systems etc. ...).

Acknowledgements

R.ED.EL s.r.l., U. Barreca (Company manager and technical manager) - Prof.ssa Arch. C. Nava (Professor Assistant UniRC/ Scientific Project Manager) | Partners: ENEA, Ing. C. Sposato (Project Contact), Ing. P. De Fazio (Manager DTE-SAEN), Ing. A. Feo (Researcher), Per. Ind. M. B. Alba (Technical Assistant), Ing. Arch. T. Cardinale (Researcher junior) - UNICAL-Dipartimento DIATIC, Prof. Ing. M. Migliori (Project Contact), Prof. G. Giordano (Full Professor of Environmental Chemistry, Dott. A. Marino (PhD student - SIACE Unical) Remanufacturing/Smart solutions - Dissemination and Branding: PMopenlab S.r.l.s whit Arch. A. Procopio, Arch. G. Mangano, Arch. A. R. Palermiti, Arch. D. Emo and Arch. D. Lucanto, Arch. G. Arena, Arch. F. Autelitano (Assistants) – Patents: Ing.Pasquale Cuzzocrea (Certifier)

References

Lucanto D., Procopio A., (2019), *Ecodesign and Manufacturing in Waste Enhancement Processes for PVCupcycling*, Proc. of Green and Circular Economy: Research, Innovation and New Opportunities, Maggioli, Rimini, 107-113.

Nava C., (2019), *Hypersustainability and Enabling Technologies. Theory, Method and Design*, Aracne, Roma, Italy.

Nava C., Lucanto D., (2020), *Eco-Innovative Scenarios for Smart Materials. The PVCupcycling Project – Circular Economy and Zero Waste*, Int. Symp.: New Metropolitan Perspectives, vol. 178, 1458-1467.

Vinylplus, (2013), *The recycling of PVC cables,* PVC Forum Italia, Dossier, On line at: https://vinylplus.eu/index.php?mact=CommunicationProjects,m81d23,default,1&m81d23published_on=2013&m81d23pager_limit=8&m81d23pager_size=5&m81d23pager_page=2&m81d23returnid=77&page=77.

Environmental Engineering and Management Journal October 2020, Vol. 19, No. 10, 1831-1833
http://www.eemj.icpm.tuiasi.ro/; hiip://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

SUSTAINABLE BIOMETHANE: METHANE SLIP REMOVAL APPLYING REGENERATIVE CATALYTIC OXIDATION (RCO) POST COMBUSTION TECHNOLOGY

Short communication

Ivana Moscato[1], David Callejo Munoz[1], Pietro Italiano[2*]

[1]*B1Shop Srl, c/o Kilometro Rosso Innovation District Bergamo Italy*
[2]*Costech Analytical Technologies Inc., Santa Clarita California USA*

Abstract

Biomethane is incentivized in Italy and in many other European countries as a substitute fuel for transport, in order to reduce fossil fuel and cut CO_2 emissions. In Italy, Certificato di Immissione in Consumo (CIC) is actually sustaining biomethane production, charging petrochemical companies who need to cover their obligation quotes. Actually, biomethane production has to fulfil sustainability requirements in order to be entitled to get CIC. Sustainability principles are, among others, the type of feeding, total biogas capture during the fermentation process and last but not least, a very low methane loss associated to the off-gas of the upgrading unit, actually set at < 1 % CH_4 in Italy and most probably further reduced in the short. The upgrading unit off-gas, therefore, has to respect the limit, or as an alternative, it has to be treated in a post-combustion unit. There are technical upgrading solutions on the market that can achieve methane loss < 1% CH_4, but incremental energy, operating and investment cost have to be considered in a cost-benefit evaluation. Post-combustion on the other hand can be a serious issue, since the flow to be burnt does not contain oxygen at all, just traces of methane (normally 2-3%) and CO_2 (97-98%), changing dramatically operating conditions of traditional post-combustor units applied to cogeneration engines off-gas. For the biomethane off-gas combustion, a sustainable cost-effective solution is the Regenerative Catalytic Oxidation (RCO), operating at lower temperature than Thermal Oxidation (TO), therefore reducing energy costs and improving environmental footprint. The purpose of this article is to compare the Regenerative Thermal Oxidizer (RTO) with the Regenerative Catalytic Oxidizer (RCO).

Key words: biomethane, methane-slip, off-gas, sustainable biomethane

Received: February, 2020; Revised final: June, 2020; Accepted: July, 2020; Published in final edited form: October, 2020

1. Introduction

Upgrading of biogas to biomethane can cause GHG emissions (Westerkamp et al., 2014). Every technology for separating methane from biogas leaves a percentage of methane in the off gas. National regulations define the amount of methane to be released to the atmosphere, RED II directive gives specific targets in order to consider biomethane production sustainable and therefore gaining access to incentives.

To satisfy sustainability principles, some requirements must be met, both in terms of feeding of the biogas plant, technical construction aspects and methane loss associated to off-gas (Liebetrau et al., 2017).

In case of biomethane from waste, the target is set to 65% of GHG saving (2021) and will get higher

* Author to whom all correspondence should be addressed: e-mail: i.moscato@b1shop.it

for the next future. One of the major aspects affecting negatively GHG saving in biomethane production is the methane loss in the upgrading unit.

Depending on upgrading technology, technical aspects, type of media applied for separation, different percentages of methane slip are achievable, the range is 0.5-2%. (3) UNI 11567 actually under review, is putting a target of 1% maximum of methane slip in the off-gas, in order to consider biomethane production sustainable, or to install a post-combustion system.

There are technical up-grading solutions on the market that can achieve methane loss < 1% CH_4, but incremental energy, operating and investment cost have to be considered in a cost-benefit evaluation (Petersson and Wellinger, 2009). In case of a proper post-treatment of the off gas, the amount of methane emitted can be reduced to negligible values.

During biogas upgrading, the raw biogas is split into two gas streams: the CH4-rich biomethane stream and the CO_2-rich off-gas stream. Since separation technology doesn't achieve 100% efficiency, the CO_2 off-gas stream still contains methane traces, often in higher concentration than allowed. At the moment, in the newest plants, the upgrading plant off-gas does not contain a methane concentration high enough to maintain a flame without the addition of natural gas or biogas. One way of limiting the methane slip is to mix the off-gas with air that is used for combustion. Alternatively, the methane can be oxidized by thermal or catalytic oxidation (Petersson and Wellinger, 2009).

The significant challenge for the thermal oxidation of this off-gas is the fact that it contains mostly no oxygen and principally carbon dioxide. Among the leading principal solutions to be applied to the off-gas combustion there are:

1. Thermal oxidizer;
2. Catalytic oxidizer;
3. Regenerative thermal oxidizer;
4. Regenerative catalytic oxidizer.

Among them, the most valuable technologies are the regenerative ones, principally because these allow to recover energy. A percentage of the produced heat is recovered by passing alternatively hot exhaust gas and more cooling inlet gas through different heat exchanger chambers made of ceramic walls to absorb and release heat.

The purpose of this article is to compare the regenerative thermal oxidizer (RTO) with the regenerative catalytic oxidizer (RCO).

2. Short overview

Classic thermal oxidizers are not designed to operate under this condition. The major challenge of biomethane off-gas thermal oxidation is the complete lack of oxygen associated with a very little methane concentration (Penteado et al., 2018). Regenerative Thermal Oxidizer (RTO) pre-heat the gas flow up to the temperature that ensures complete oxidation reaction in the combustion chamber by means of heat recovery chambers. Hence, in order to oxidize methane, the most stable hydrocarbon molecule (Kundu et al., 2016), operating temperature is very high and energy consumption is increased also due to the increased flow to be treated (vent gas + air).

Regenerative Catalytic Oxidation (RCO) allows to operate at high yields at almost half the temperature required by thermal combustion, thanks to the catalytical action, hence reducing by half energy costs.

Regenerative Thermal Oxydizer (RTO)

Some of these RTO devices consist of a heat transfer made of ceramic media. When the off-gas flows through the ceramic media, it is heated up to a temperature hot enough for methane oxidation to form water vapor and carbon dioxide (Petersson and Wellinger, 2009).

Other commercially available thermal oxidation devices use step-like oxidation without the presence of a real flame. In the first step, the oxidation chamber is heated burning natural gas (or biogas). Once the target temperature is reached, the off-gas is indirectly preheated by the exhaust gas. The residual heat demand can be delivered by the off-gas during oxidation. The surplus heat can be recovered (Petersson and Wellinger, 2009). Another type of RTO system is made of a series of heat regenerators employed for drain exhaust air treatment in the industries which use solvents (VOCs) in their process. Ceramic heat regenerators are employed to recover more than 95% of heat energy alternating flow directions of hot clean air and cold exhaust air.

Regenerative Catalytic Oxydizer (RCO)

RCO achieves emission annihilation through the process of thermal and catalytic oxidation, transforming the contaminants into carbon dioxide and water vapor. At the same time, thermal energy can be recovered. Re-CAT RCO by Resilco S.r.l. is particularly suited for the treatment of large streams with low concentrations of VOC (0,8-4 mg/Nm3). It can be applied to the combustion of all kind of organic compounds, even in the presence of traces of halogenated compounds.

With reference to biomethane production, off-gas flows are normally in the range of 200-1000 Nm^3/h, approximately the same range of biomethane production size, which is low compared to other industrial air streams where RCO is applied.

As a matter of fact, a possible solution in order to reduce investment costs and to provide a smarter solution also suitable for small plants, is to apply RCO with the following scheme (Fig. 1) with thermal recovery on a heat exchanger instead of heat exchange over ceramic media. Thermal recovery will be slightly reduced, 5% less than the regenerative solution, thus simplifying the treatment scheme, reducing the plant footprint and avoiding transitory emissions that occur during flow inversion.

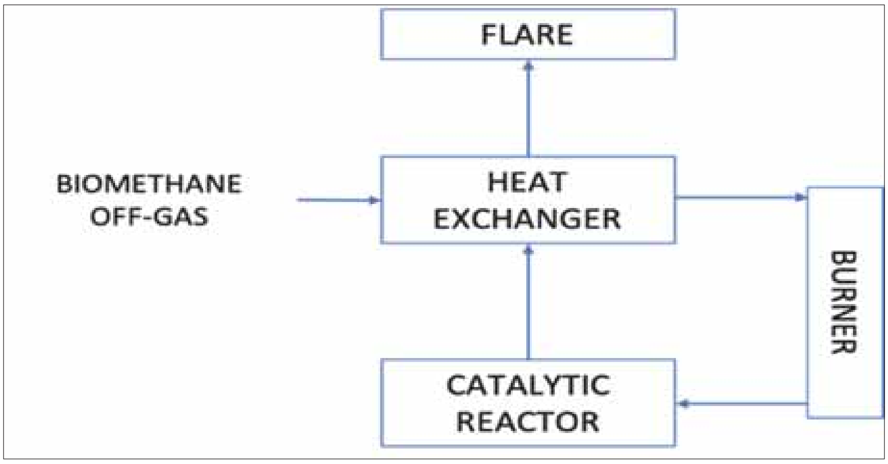


Fig. 1. Process diagram of RCO applied to biomethane off-gas combustion

The off-gas passes through the combustion chamber, where it is heated at maximum 350-400°C and then to the catalytic bed, where methane and the VOC traces are completely oxidised. Hence the hot combustion fumes cross the heat exchanger to preheat the inlet off-gas flow. Compared to high-temperature combustion systems, the Re-cat system is characterized by high efficiency and lower operating temperature. Low-temperature combustion means that NOx is not produced as by-products of conversion, which is usually the major drawback in the thermal conversion at high temperature.

3. Results and discussion

The analysed technologies differ mainly for their emission impact, since RTO operates at higher temperature where NOx is formed, and for energy consumption, since the flow (off-gas + combustion air) have to be heated up much lower temperature applying RCO, the main differences are summarized in Table 1.

4. Conclusions

Post combustion for sustainable biomethane production is necessary, unless very narrow methane-slip is achieved with upgrading systems. In this case, a cost-effective evaluation should be done in terms of major investment and operating costs of the upgrading unit to meet the target.

Among post combustion technologies, the most valuable are the regenerative ones: RTO and RCO, that allow energy reduction. RCO moreover is more environmental-friendly and allows further energy savings.

Table 1. Comparison between different analyzed technologies

	Regenerative thermal oxidizer RTO	***Regenerative catalytic oxidizer RCO (*)***
Operating temperature	800-1000°C	350-450°C
Energy consumption	High	Low
VOC abatement	>95%	>95%
CO abatement	>90%	>95%
NO_x abatement	0% (actual NOx production)	>10% (no NOx production)
Dust abatement	0%	>80%
Plant size	Large	Small

(*) data by Resilco Srl

References

Kundu S., Zanganeh J., Moghtaderi B., (2016), A review on understanding explosions from methane air mixture, *Elsevier Journal of Loss Prevention in the Process Industries*, **40**, 507-523.

Liebetrau J., Reinelt T., Agostini A., Linke B., (2017), Methane emissions from biogas plants: Methods for measurement, results and effect on greenhouse gas balance of electricity produced, IEA Bioenergy Task 37, On line at: https://www.ieabioenergy.com/wp-content/uploads/2018/01/Methane-Emission_web_end_small.pdf

Penteado A.T., Kim M., Godini H.R., Esche E., Repke J.-U., (2018), Techno-economic evaluation of a biogas-based oxidative coupling of methane process for ethylene production, *Frontiers of Chemical Science and Engineering*, **12**, 598-618.

Petersson A., Wellinger A., (2009), Biogas upgrading technologies–developments and innovations, *IEA Bioenergy*, **20**, 1-19.

Westerkamp T., Reinelt, T., Oehmichen, K., Ponit- Ka, J., Naumann, K., (2014), Biomethane Effects on Climate, *DBFZ*, **20**, 2197-4632.

Environmental Engineering and Management Journal

October 2020, Vol. 19, No. 10, 1835-1846
http://www.eemj.icpm.tuiasi.ro/; hiip://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

NATURE-BASED SOLUTIONS FOR FLOOD MANAGEMENT: A STUDY CONDUCTED IN LABARO - PRIMA PORTA DISTRICT, ROME, ITALY

Giulia Pandolfi[1]*, Jessica Pettinari[2]

[1]*Architecture Department - Urban studies, University of Roma Tre, Largo Giovanni Battista Marzi, N10 – 00154, Roma*
[2]*Architecture Department - Landscape, University of Rome Sapienza, Piazza Borghese, N9 - 00186 Roma*

Abstract

'Labaro-Prima Porta' is a district in the outskirts of Rome, increasingly afflicted by recurrent floods. In order to reduce the local runoff volume, this paper defines a resilience and twofold strategy. At first, the use of a hydrologic software, called Storm Water Management Model (SWMM), along the research makes possible the evaluation of which Nature-based Solutions (NbS) are more effective in terms of runoff management. The results demonstrate short-term positive effects, with an immediate reduction of the local discharge of about 8%. The second phase of the study explores the possibility of designing a resilient 'Labaro-Prima Porta' district. A master plan, structured in two overlapping scales, is proposed. One large-scale, improving the ecological network of the Veio Park and the rivers close to the urban settlements; in the second layer a green blue infrastructure at the district scale is defined, including a 3.3 km greenway as an urban and ecological corridor. The overall objective of this study is to provide theoretical support for the "sponge city" theory.

Key words: hydro-ecological infrastructure, landscape design, SWMM, nature-based solutions, sponge city, urban water management

Received: February, 2020; Revised final: June, 2020; Accepted: July, 2020; Published in final edited form: October, 2020

1. Introduction

The growing flood risk is a major challenge today for land and urban planning: there has never been a stronger incentive to re-think our approach to environment and to use differently land, water and space in our towns and cities. One of the urbanization direct effects is the continuous growth of the impervious areas, which interferes with the natural flow of the water cycle, and increases the urban runoff. In recent years, many storm events have haunted the cities, where in most cases the urban sewerage is no longer correctly dimensioned due to recent extreme rain events. The tendency in water management of the current policies is to favor fast and expensive solutions when the damage is already done. Italian authorities, in particular, have often shown little interest in environmental issues, harming the territorial and landscape structure, besides not considering the social aspects at all. On the contrary, this work highlights the importance of working following environmentally sustainable lines joining together the simulation with SMWW of the urban runoff (Rossman, 2010) and the importance of urban and landscape design. The design of city roads should be adjusted timely, since it is a very important part of urban development. It would be crucial to create ecological grass ditches, sunken lawn areas, rain gardens and permeable pavement. Zhang et al. (2009) used SWMM to simulate the surface runoff of a residential area in Nanjing which was reconstructed with sunken lawn areas and permeable pavement (Zhen-ci and Yuongchen, 2017) studied the relationship between rainfall and runoff in the area under four different underlying surfaces conditions, where, thanks to the distributed water stability model, the work achieves some possible suggestions to how

* Author to whom all correspondence should be addressed: e-mail: giuliapandolfi@hotmail.com

to contribute scientific to the creation of an ecological city. Other studies analyzed the effect of different kinds of Nature-based Solutions (NbS) on the control of surface runoff, such as the beneficial hydraulic effects of green roofs (Bliss et al., 2009; Gregoire and Clausen, 2011; Lamera et al., 2014), rainwater storage tanks (Abbott et al., 2007) and draining parking lots (Collins et al., 2008).

In these latter 10 years the most interesting research steps that kept together modeling approach, case study and landscape where carried out on chinese territory since the Chinese government launched the sponge city pilot construction in 2015. There is a long list of case study investigated, but here we mention: Beijing, Liupanshui and Qunli National Wetland Park in Harbin, which define how rain-runoff control effects and landscape security pattern are essential for sponge city theory construction (Kongjian et al., 2015; Xia et al. 2017). A more recent paper describes four aspects that a sponge city construction must have: 1) should consider and be in line with local conditions; 2) in order to play a better role it should take into account the concept of an ecological city and a smart city; 3) should requires the active participation of more citizens; 4) "*… requires intensive interdisciplinary cooperation and cross-scale research. Due to the complexity of the construction of sponge cities, multidisciplinary cooperation is required. The multi-professionals are integrated with each other to solve problems from different scales and maximize environmental, economic, and social benefits"* (Liang and Hou, 2018).

The paper focuses on Labaro-Prima Porta District, located in the north of Rome, as a case study area to assess other content to be added to Sponge City theory. In particular, regarding the four points mentioned above, particular attention was given to point 1, 2 and 4.

2. Case study

The study focuses on Labaro-Prima Porta, a district in the outskirts of Rome (Italy), increasingly afflicted by recurrent floods, even if the drainage system has been recently improved (Fig.1). The negative impacts of rainwater in Labaro-Prima Porta is the result of different aspects: 1) the neighborhood was built during the first decades of the second postwar period, mostly out of planning, without taking into account adequate urbanization criteria, not only from an environmental point of view, but even from a urban one; 2) greater waterproofing of soils due to asphalt and other similar materials does not allow the natural water cycle; 3) recent effects of climate change magnified these structural problems in Rome (Filpa and Ombuen, 2014) specially in some neighborhoods like Labaro-Prima Porta (Benelli and Camerata, 2014).

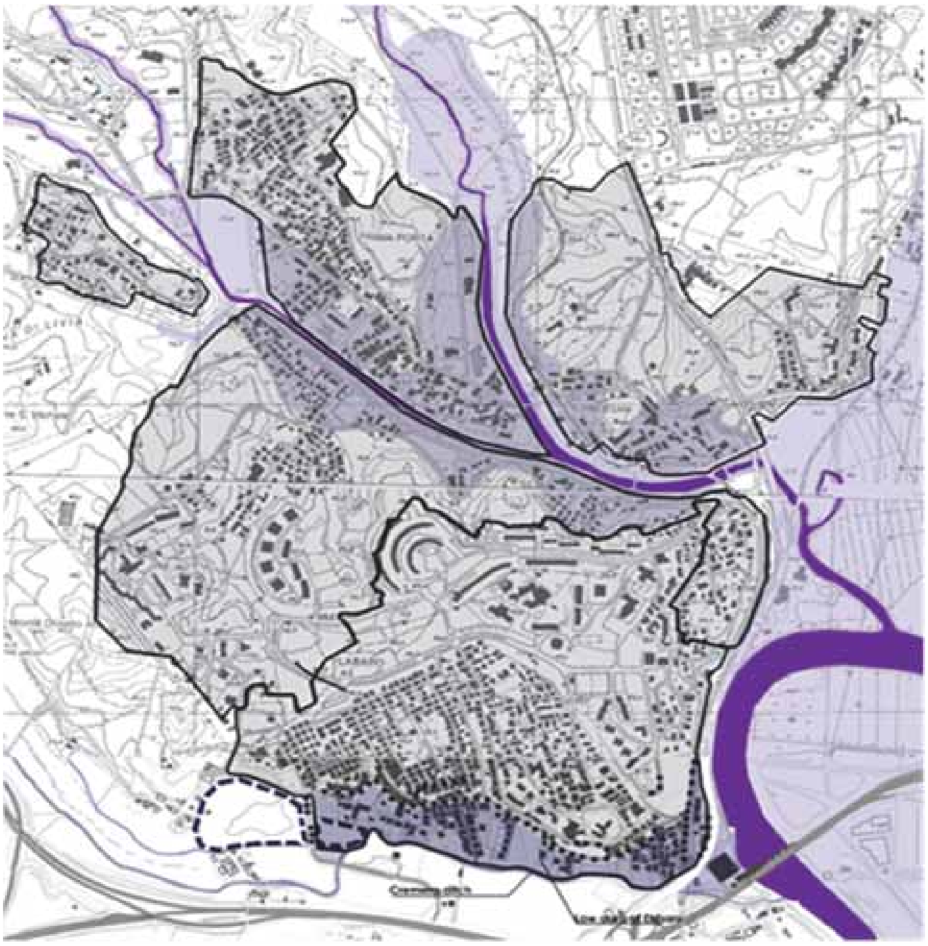


Fig. 1. Labaro-Prima Porta, simulation of the flooded areas on the event 31 January 2014

To this end, the study describes a twofold strategy where, thanks to the use of an open-source hydrologic software, called SWMM it is possible to start an analysis about which devices, depending on the amount of water stored, have greater effectiveness in the context of the project. The research explores three different operational steps and investigates also a possible master plan design. The study is divided into two chapters and final results.

The first chapter describes how the 'Urban Hydrologic Model' was built. In order to study the potential of SWMM and to elaborate a new 'Urban Hydrologic Model' stackable with the existing Sewer Model created by the Department of Hydraulic Engineering of Roma Tre University (Calenda and Mancini, 2009; Calenda et al., 2009; DE, 2005; DSIMU, 2015), it was necessary to improve the detail on the 'Land Area Layer', defining more accurately: urban density, property status, type of coverage (flat or pitched) and soil permeability. To this end it was necessary to use different mapping software DEM, GIS and CAD (Jiang et al., 2010) that could provide the geometric and quantitative characteristics in a form compatible (layers) with the previous Sewer Model.

The second chapter shows a possible design application on the local context. The project intends to exploit the critical aspects as a potential, utilizing the hydro-morphology of the terrain to create a sustainable water drainage system, in order to slow down the water descent into the hilly area. The project is articulated in two different strategies: 1) improvement of the ecological network of the adjoining Veio's park to increase the urban resilience 2) create a connected green and blue infrastructure in the urban settlement.

Finally, 'Results and discussion' consists in the evaluation on the 'Urban Hydrologic Model', at first on public buildings and then on private ones too, of urban runoff reduction (about 8%). Basically, it focuses on the positive effects of NbS, quantitatively evaluating them through the constant application of SWMM and specifically green roofs, draining parking lots and water tanks, which have immediate effects (Qing-yun et al., 2014). These are known interventions that are finding increasing application, although they are not always accompanied by quantitative assessments on an urban and territorial scale.

2.1. Data and urban hydrologic model

Data of the current study is obtained from different agencies: the Digital Elevation Model map – DEM (elevation of 5 m in this model) is produced by th European Environment Agency (EEA, 2015); rainfall data regarding the last 20 years was procured from ISPRA (Higher Institute for the Environmental Protection and Research and Conte et al., 2015), while data for recent rainfall events was taken from Castel Giubileo weather station. Moreover, the drainage network transport layer, built with SWMM, is collected from the Department of Hydraulic Engineering of Roma Tre University, since the Department in 2005 started working on the identification of the causes of flooding in Labaro-Prima Porta district, in collaboration with Rome Municipality and the Civil Protection Agency, for which the adaptation works to the system were then made starting from 2015 until 2018. Finally, the analysis regarding the main statistics of the distribution of channel lengths and hill-slope for the transport layer were carried out by (Volpi et al., 2012), and the urban drainage system replies the method used for Warangal Campus (Rangari et al., 2018), but in general is the procedure suggested in SWMM manual (Gironas et al., 2010).

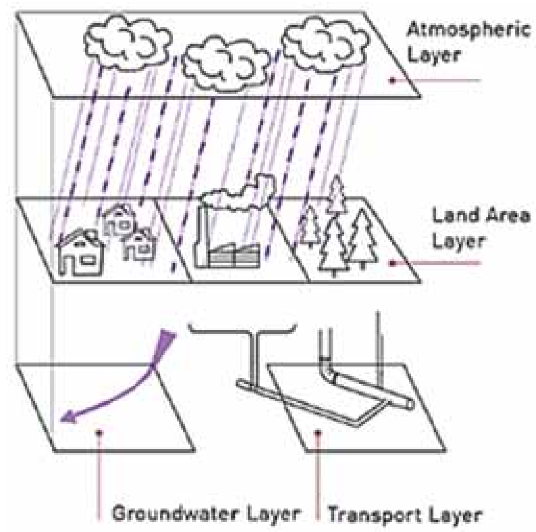


Fig. 2. Simplification of SWMM layers

Basically, SWMM works as shown in the previous figure (Fig. 2) and it consist in 4 main layer: a) Atmospheric layer, where the rain events are inserted, divided mainly into two types: single event with a duration of a few hours or continuous event, respectively days or months. In this study a rectangular single event of about 1 hr was chosen; b) Land area, the territory is divided into sub-basins, which receive the waters from the Atmospheric Layer and the surface runoff from the other portions of the territory. The analysis of this work focuses primarily on the small-scale identification of Land Area Layer, since the study is conducted by architects; C) Groundwater Layer, defines the water infiltrated into the ground where absorption times depend on the type of soil; d) Transport layer, is the sewage network and it is composed by junctions, conduits, channels, manholes, etc. forming a graph consisting of links and nodes. As mentioned above this is the starting point issued by the Department of Hydraulic Engineering on which the work in question overlaps.

For a more detailed analysis, a smaller subarea of 64.5 acres was chosen on the Nord side of the district, in order to study the storm water management as an example of the neighborhood (Fig. 3). This area was chosen because: 1) it has a separated sewage system ending at the point defined as Outfall, 2) the transport layer was made by the Department of Hydraulic Engineering of Roma Tre University and 3) being a hilly and heavily urbanized area features that acts as a demonstration example of the whole area. To apply the methods described below, the project site must first be divided into sub-watersheds areas, that are defined based on topography (water lines, roads, property etc.) and drainage patterns (manholes, drains systems, pipe union etc.).

These watershed areas require physiographic information such as configuration of the channel network, location of drainage systems, channel length and slope, and sub catchment geometric properties. The drainage networks consist of about 137 nodes and one final Outfall, situated at the end of the study area (South-East). All the sub-catchments dividing lines are based on the 'Land area collection', they are plotted along roads, streets, and territorial elements. Finally, the sub-catchments are linked to the nearby manholes according to the topography and to the sewer network. Fig. 3 reflects the structure of the drainage system and the sub-catchment delineation results. Each sub-catchment was classified in different parameters following the map shown in Fig. 4 and Table 1, which include:

1. Infiltration parameters

- In order to simulate the correct imperviousness and infiltration in the context area it was necessary to understand what kind of soil and substrate characterizes this sector. As shown in Fig. 4 there are some sub-catchments that are completely saturated with water since they are classified as alluvial soil (light blu in Fig. 4). Since in this case the soil is already at its full capacity of water-absorption, the sub-catchments that captain in these areas are treated as if they had 95% impervious. Differently, all other Sub-catchments will have 5% as initial parameter of imperviousness and then in the remaining 95% features of each type of soil is introduced as follows (DRCG, 1969):

- Horton coefficients: The parameters for this model include, a) *Maximum infiltration rate* is the initial infiltration rate at the start of a storm; b) *Minimum infiltration rate* is the limiting infiltration rate that the soil attains when fully saturated. The latter has a wide range of values depending on soil type from 3 cm/hr for clays up to 12 cm/hr for sand; c) *Decay coefficient:* this parameter determines how quickly the infiltration rate "decays" from the initial maximum value down to the minimum value. Typical values range between 2 to 7 hr^{-1}.

- Roughness coefficient, has separate values for the impervious and pervious areas of a sub-catchment, for example 0.6 for dense wooded areas versus 0.012 for smooth asphalt.

- Depression Storage (Engman, 1986) this parameter is divided in two sections: the 'Impervious Area' that is usually around 0.3 mm and the 'Pervious Area' from 0.3 mm - 10 mm, depending on the amount of present vegetation. For example, the deep wood determines the maximum parameter (10 mm), and all of this is directly added in the software. Depression storage represents all the elements and areas that could have surface ponding, such as the water that can be collected by flat roofs and vegetation, and surface wetting.

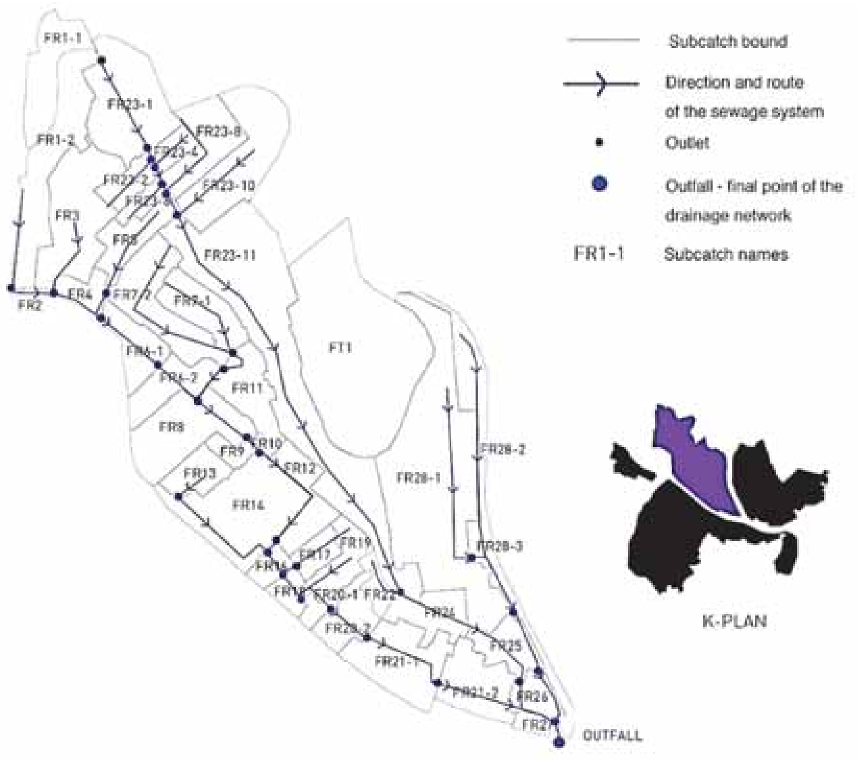


Fig. 3. Sewage system of the Nord-Est part of Labaro-Prima Porta

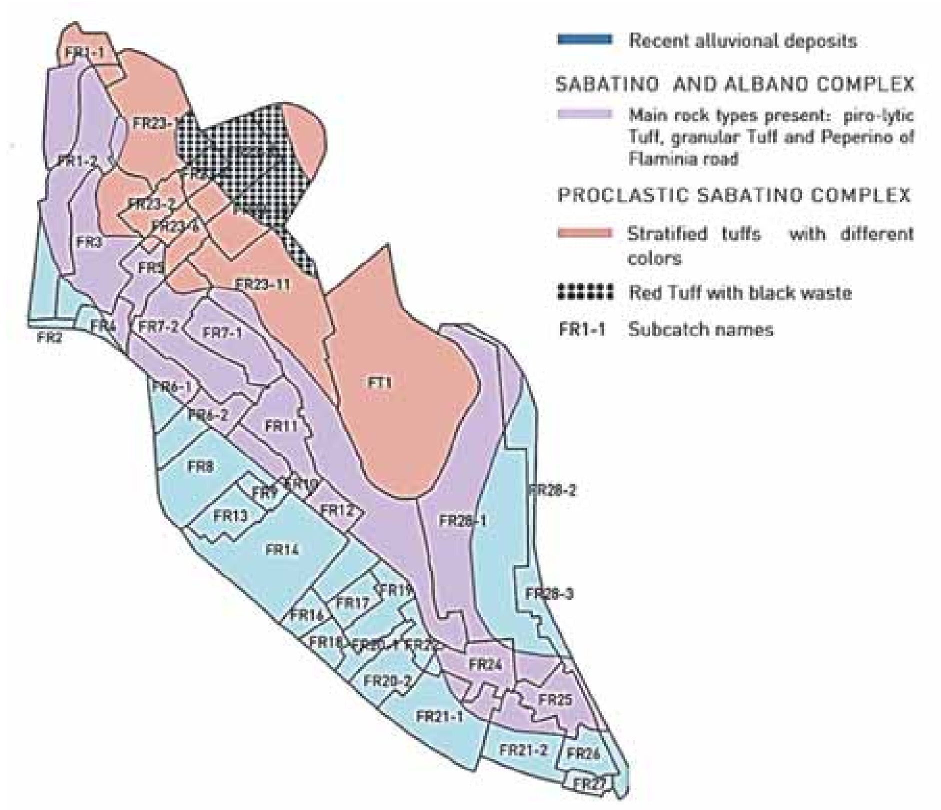


Fig. 4. Geological map. Study of the type of soil in the study area

In the study case the empirical values are specifically, for Clay Areas: Horton coefficients: *Maximum infiltration rate:* 75 mm/h, *Minimum infiltration rate:* 3 mm/h, *Decay Constant:* 2 h^{-1} , Roughness coefficient: *Impervious Area:* 0.024 mm, *Pervious Area:* 0.4 mm. Depression Storage: *Impervious Area:* 0.3 mm, *Pervious Area:* 6 mm. Tuff Areas: Horton coefficients: *Maximum infiltration rate:* 125 mm/h, *Minimum infiltration rate:* 6.50 mm/h, *Decay Constant:* 4 h^{-1} ; Roughness coefficient: *Impervious Area:* 0.024 mm, *Pervious Area:* 0.6 mm; Depression Storage: *Impervious Area:* 0.3 mm, *Pervious Area:* 8 mm

2. Surface cover parameters

Surface is mainly divided in land-use classes of permeability as you can see in the following figure (Fig. 5). Semi-permeable surface was evaluated from the subtraction from the total area of impermeable and permeable surface, the result split up in equal parts to impermeable and permeable. In this study the amount of impervious areas was established by delimiting the following areas in each watershed: streets, parking lots, buildings divided in flat roof or pitched roof and ½ of Semi-permeable. These areas are estimate with just a 25% of Depression Storage, being mainly asphalted or characterized by construction materials. Unless special circumstances are known to exist, a percent imperviousness area without depression storage of 25% is recommended. Lastly, permeable surface is defined as: woods, grass and ½ of Semi-permeable.

3. Geometrical and territorial parameters

There are some other parameters imputed within the software, Table 1 shows and example of it, such as: Name, is the name of each Sub-catchment used in the SWMM Software; Outlet, is the sewer ending point, positioned at the lowest altimetrically spot; Area is the total area, expressed in acres; Width, can be defined as the sub-catchment's subdivisions, obtained by the length of the longest overland flow path that water can travel; Slope, is the average slope within the Sub-catchment.

Total district of the east side of Labaro-Prima Porta has a total surface of 64,5 acres, where, based on the described parameters, the percentage average is 49.2 % impermeable and 50.6% permeable, respectively 317,330 sq m and 326,267 sq m. This percentage is anomalous for the urban context of Rome, that usually has a higher percentage of impervious areas.

But in this case, we are working on a neighborhood being on the edge of the city in close contact with countryside and with some nearby natural systems, like Tiber River and the Veio's Park, so these parameters reflect this urban context. These surface data and all the other layer's data are introduced into the software for the simulation. The graph shown in Fig. 6 is made at the end node (J59 node) of the sewage system, just before the final Outfall. In the Urban Model the outflow observed a volume (CMS - cubic meters per second) of the total flow equal to 3.94 cms/hr.

Fig. 5. Example of the investigation process of permeability that was made for each sub-catchment

Table 1. Example of input parameters for each sub-catchment

NAME	*TOT*	*IMPER.*		*PERME.*		*FLAT*	*PITCH.*	*PARK*	*STREET*	*WOOD*	*GRASS*	*SEMI-PERME.*
	MQ	MQ	%	MQ	%	MQ	MQ	MQ	MQ	MQ	MQ	MQ
FR1-1	14,865	6,696	*45*	8,169	*55*	122	1,627	1,252	1850	4,175	2,150	3,688

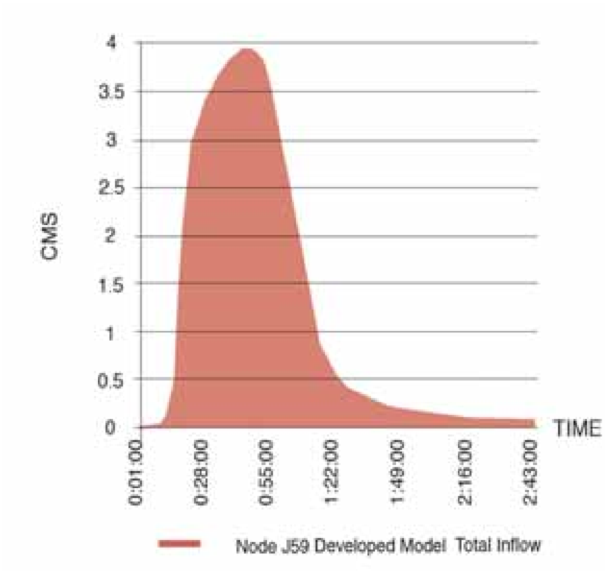


Fig. 6. Graph of the Urban developed runoff, the total flow volume is 3.94 (CMS/hr). Y-axis describes the surface runoff in cubic meters per second, while the X-axis describes the amount of time of the event, in this case is around 1 hr

Having developed this integrated model, it was possible to proceed with the analysis of the margins of action within which to propose possible interventions aimed at reducing and reusing surface water, otherwise destined to the sewage network. In particular, they were outlined three NbS: 1) green roofs, whose beneficial hydraulic effects are now consolidated nationally and internationally; 2) rainwater storage tanks and 3) draining parking lots. Finally, the introduced devices are divided into different scenarios according to the degree of local private support to the project.

2.2. Labaro-Prima Porta's landscape design

The project intends to exploit the critical aspects of flooding and urban runoff, as a potential, utilizing the hydro-morphology of the terrain to create a system of floodable micro-parks and drainage systems, in order to slow down the water descent into the hilly areas. Territorial and landscape interventions will resume connections from the city to the open spaces, on the whole, the project significantly changes the profile of the district.

The design takes in consideration the urban space afflicted by recurrent floods, between the rivers system (Tiber river, Prima Porta's and Cremera's ditches) and Veio's park, an important green ecological corridor where natural beauty blends perfectly with local history and culture. In order to define an intervention strategy the whole neighborhood was divided into types of flooding, such as: *pluvial flooding,* due to heavy rainfall and malfunction of the sewer system; *river flooding*, along the valleys of main rivers and *groundwater flooding* caused by intense rainfall and/or by the rising of the hydrometric level of the local stream network, which, in turn, determine a rising of the water table, not compensated by draining pumps. For the development of the sustainable water drainage system two different scales of approach are established:

1) The territorial scale intervention aims to restores the connectivity of urban settlement with the natural local system, where the realization of a system of floodable river-parks can concurrently slow down the water and re-enforce the local ecosystem. The rapid expansion of impervious urban surfaces and the construction of major road infrastructure has destroyed the ecological networks, therefore is important to establish physical, visual and ecological

connectivity between built-up areas of the city and the surrounding natural areas. The action performed are: increase biodiversity with the elimination of alien species (*Robinia pseudoacacia* and *Ailanthus altissima*); promote urban foresty, planting native riparian vegetation (*Populus spp., Salix spp.)*; use an enviromental engineering approach with partial elimination of weeds (comunity of *Arundo donax, Phragmites australis, Rubus ulmifolius*) for the safety of waterways and realize new linear corridors that pass through the agricoltural system, with mixed tree-lined (*Ulmus minor, Quercus pubescens, Quercus cerris, Acer campestre*, *Morus alba)* and mixed border hedges (*Crataegus monogyna, Spartium junceum, Pyracantha coccinea, Rosa canica, Rosa sempervirens)* wich also provides shelter and food for animals.

2) The urban scale main objective is to intercept the largest amount of rainwater in order to reduce runoff and flooding and to restore the natural hydrological cycle. For this purpose, a green and blue water management infrastructure was designed in the district, (DEP, 2012) improving the connection and the multifunctionality of new urban spaces, with further benefits: economic (increase economic value), environmental (more biodiversity, decrease of impermeable surface) and social (more welfare, public awareness, education on sustainability issues). The multi-stage realization of a main Greenway and secondary Greenstreet as a linear system in the center of the district solves the neighborhood water drainage system. (Fig. 7) Specifically the devices applied are: rain garden, bioswales, permeable pavements, wetlands, green and blue roofs. In particular, bioswales are highly recommended for their functionality, in terms of quantity of water intercepted and runoff management PURVIS (2018). Usually, in the urban context stormwater runs off roofs, sidewalks and roads and it takes many pollutants directly into gutters and storm drains, otherwise with the application of multiple bioswales (DEPOGI, 2017) water flow is diverted into them where, with the use of native plants, different benefits are made (Fig. 8). In particular, urban runoff slows down, new habitat for wildlife is created and water is purified through these processes: phytovolatilization in which plants uptake contaminants and release them into the atmosphere as they transpire, the phyto-stabilization with the sequestration of contaminants in the soil through absorption or accumulation around the root zone, the phytodegradation a metabolic process that breaks down or degrades contaminants into simpler molecules or elements. Finally, detained water also filters through the soil helping to recharge the groundwater.

Through this linear system developed on the greenway, water was collected, phyto-purified and infiltrated into the soil for a total of 3.30 Km and 1655 sq meters of capturing surface, partially restoring water natural cycle. Taking into consideration an area of 2000 sq meters of the greenway, permeable surfaces are 1440 sq meters of total area, against 560 sq meters of impermeable surface, with an increment of 80% (Fig. 9).

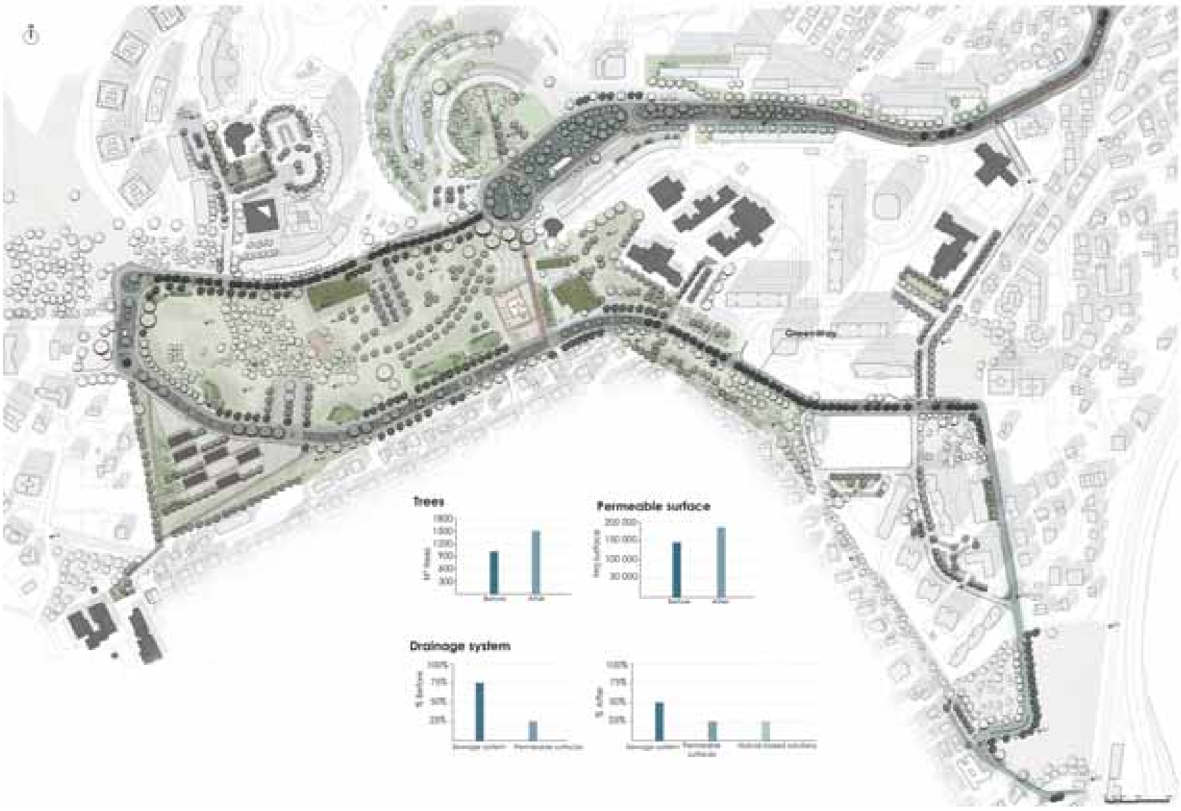


Fig. 7. Urban scale master-plan. The Greenway system connects the main parks and areas of the neighborhood as an ecological and urban connection corridor

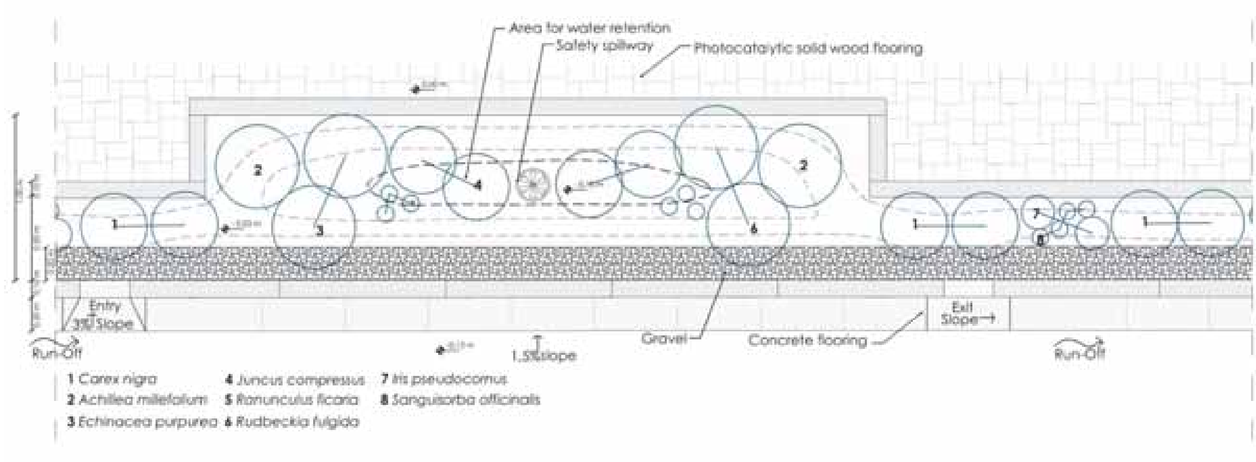


Fig. 8. Bioswales detail. Phyto-depuration plant and system operation for the collection of rainwater

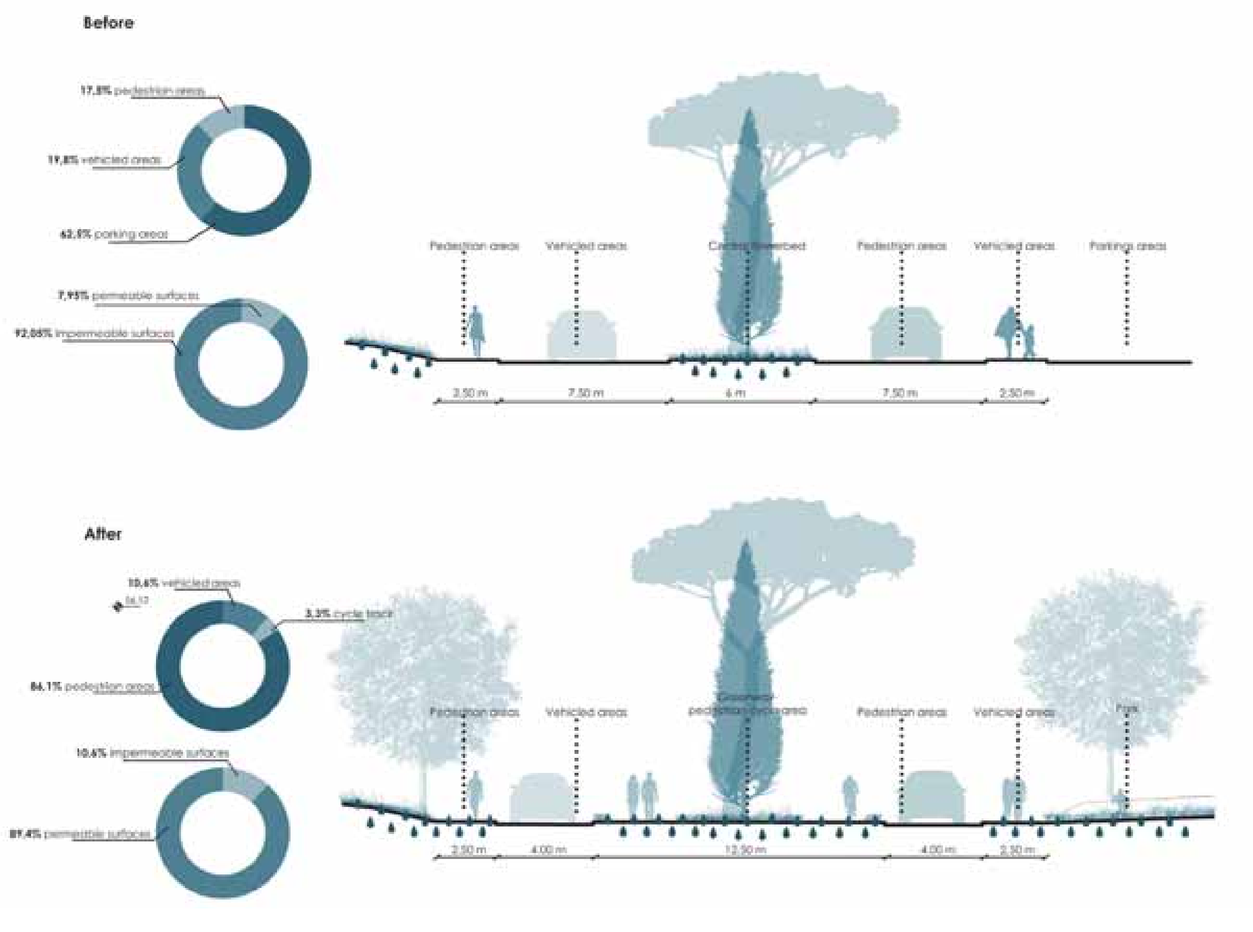


Fig. 9. Section of permeable surface before and after the project and comparison of the difference in permeability. In this case with the project there is an 80% increase of permeable surface.

Also, in this case planting is promoted. The existing boulevards are mostly made by *Pinus pinea* and *Cupressus sempervirens*, species widely used in Rome for their iconography and also for their fast growth. In particular, *Pinus pinea* is not a recommended plant to be used on streets, mainly for two reasons: 1) his big roots have the tendency to branch out the surface cracking the asphalt; 2) the alteration of the growth condition due to urban soil compaction, elevated pH, altered temperature and moisture patterns and the presence of contaminants, can be a risk in the urban settlement. Differently, the new species proposed in the project *Acer campestre* and *Acer monspessulanum* are characterized by being native species with small size and less problematic roots system.

Finally, the Greenway, in addition to performing the function of water collector, constitutes the center of an urban reactivation, where open spaces are an incentive for urban regeneration and social integration. Different devices have been hypothesized: for pedestrian some sustainable modal-split travel is designed; for bicycle repairer different paths are defined, creating a new circuit that joins the existing one along Tiber river; for school children it's possible to walk in safety through the Greenway, which connects schools, libraries, sports centers, markets and parks.

3. Results and discussion

The study here presented shows a possible guideline for the realization of a sponge city in the Italian territory, which can be defined by a set of actions:

1) Analysis of natural conditions, which differ from one territory to another. In particular it is important to review the local conditions in terms of climate (change) and flood vulnerability. The reference study for this section is Filpa and Ombuen, 2014;

2) The use of stormwater models such as, ILLUDAS, MIKE-SWMM, MIKE-URBAN, MOUSE, SWMM, STORM, TRRL and UCURM which could develop a map of the hydrogeological context with identification of the flows of the existing sewage system (hydraulic basins, underground channels, plant drains, etc.). In this case, the work regarding the sewage model was made by the Department of Hydraulic Engineering of Roma Tre University, but a good method to follow for SWMM is made by Rangari et al. (2018);

3) Identification of the devices, depending on the urban section under examination, is suitable for solving the water problem (green roofs, tanks, draining parking lots, etc.). Nature-base Solution used to evaluate their effectiveness, whether taken individually or combined with each other, with the possibility of identifying the fewest number of interventions with the maximum effectiveness in terms of costs/benefits. This operation also includes a recognition of the territory and what the context can make available in terms of open spaces for landscape design. Final result in terms of quantity of water stored with Nature-base Solution are defined in the area represented in Fig. 10, but it could be interesting to impute also the urban design in SWMM and quantify the beneficial effects it exercises.

3.1. Nature-based solutions

In the Urban developed model, the outflow observed a volume (CMS - cubic meters per second) of the total flow equal to 3.94 cms/hr. The graph in Fig. 11 shows how the sum of the three NbS (80% private - 100% public) produce a decrease of the rain peak equal to 8.6% of the total, respectively of 3.60 cms/hr. This result is composed of draining parking lots, of which a single 100% adhesion scenario is envisaged for a 70% draining surface (Table 2). In the project area there are 13,998 sq meters of parking lots, of which about 10,000 are transformed into draining areas. The impact on the rainwater cycle was assessed based on the final flow rate at the last pipeline Node J59 (m^3/second). In particular, the flood waves estimated for the return time RT = 10 years and rain durations d = 1 hour with the combination of the Nature-based Solutions, are shown associated together in Fig. 11 and in different combination in Fig. 12.

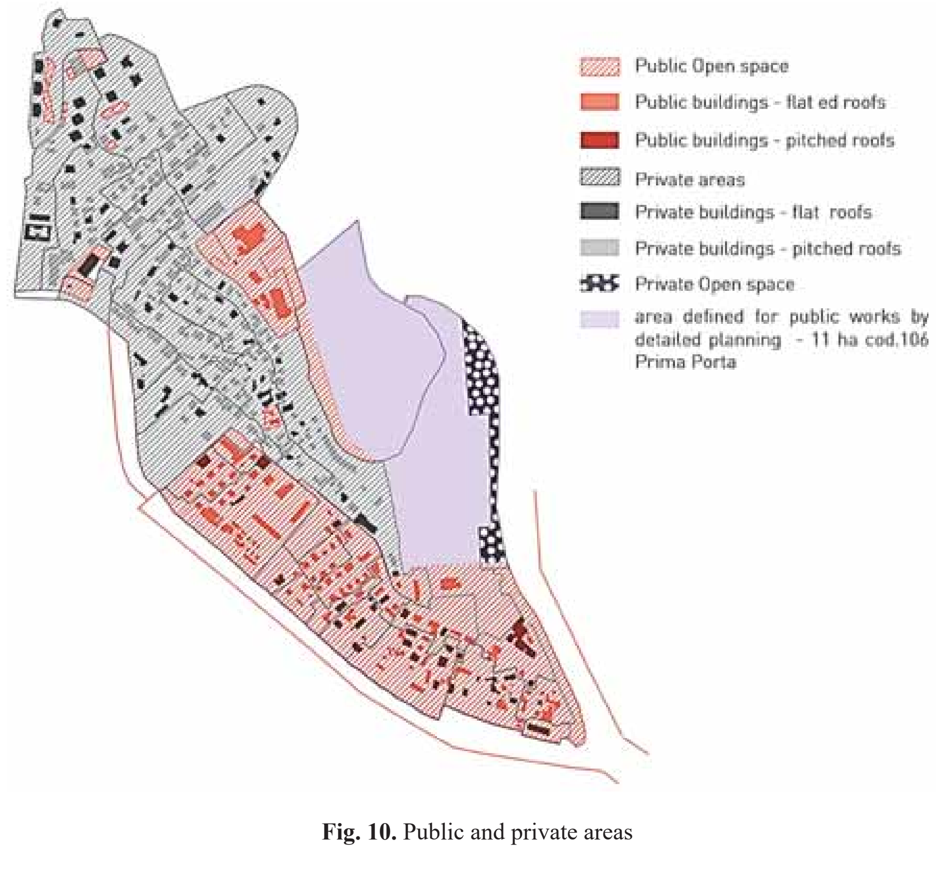


Fig. 10. Public and private areas

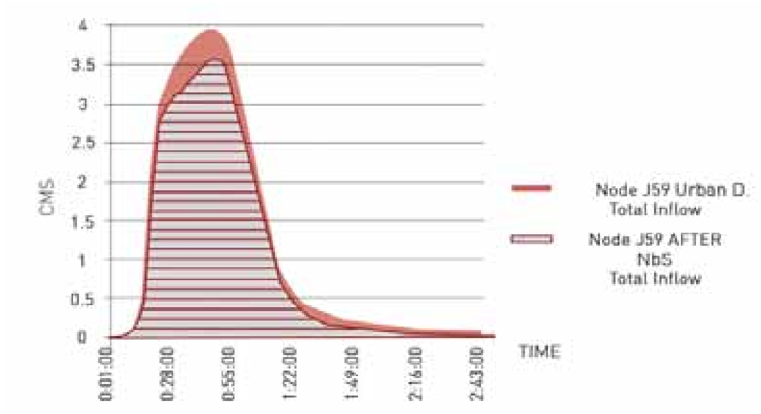


Fig. 11. NbS associated together vs Urban developed. Y-axis describes the surface runoff in cubic meters per second, while the X-axis describes the amount of time of the event, in this case is about 1 hr

Table 2. Results Green roofs vs. Water tanks

Green roofs							
Private	***Small buildings***		***M buildings***		***Big buildings***		***Transformed areas***
SCENARIO	N	Transformed surface	N	Transformed surface	N	Transformed surface	75 %
HIGH	54	3.884 m^2	79	11.493	8	4.530	19.906 m^2
Public	***Small buildings***		***M buildings***		***Big buildings***		***Transformed Areas***
SCENARIO	N	Transformed surface	N	Transformed surface	N	Transformed surface	75 %
ALL	25	1.887 m^2	67	12. 943	9	7.109	21.939 m^2
TOT							**41.846 m^2 ≈ 6.5% of tot. area**

Water tanks								
Private	***Small buildings (flat and pitched) 1 tank per building***		***M buildings (pitched) 2 tanks per building***		***Big buildings (pitched) at least 3 tanks per building***		***Total***	
SCENARIO	N	Cubic m stored	N	Cubic m stored	N	Cubic m stored	N	Cubic m stored
HIGH	60	240	116	928	10	184	360	1.241
Public Flat roof	***Small Buildings 2 tanks per building***		***M buildings 4 tanks per building***		***Big buildings At least 3 tanks***		***Total***	
SCENARIO	N	Cubic m stored	N	Cubic m stored	N	Cubic m stored	N	Cubic m stored
ALL	25	100	67	536	9	270	101	906
Public Pitched Roof	***Small Buildings 2 tanks per building***		***M buildings 4 tanks per building***		***Big buildings At least 3 tanks***		***Total***	
SCENARIO	N	Cubic m stored	N	Cubic m stored	N	Cubic m stored	N	Cubic m stored
ALL	15	60	45	360	5	150	65	570
TOT								**2,670**

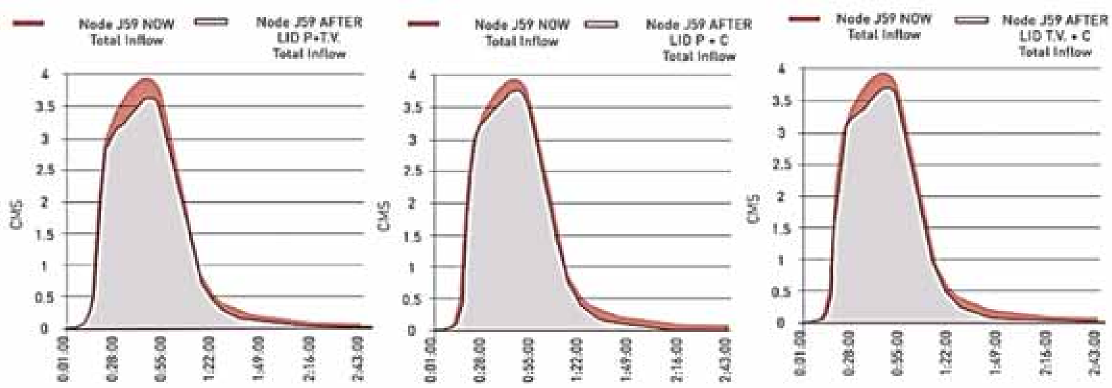


Fig. 12. First graphic: combination of Draining parking lots and Green roofs - reduction of surface runoff to 3.63 cubic meters per second / hr (- 7.9%); Second graphic: combination of Draining parking and Water tanks - reduction of surface runoff to 3.75 cubic meters per second / hr (- 4.9%); Third graphic: combination of Green roofs and Water tanks- reduction of surface runoff to 3.68 cubic meters per second / hr (- 6.8%).

Analyzing the temporal development of the flood waves of the curves associated with the three different scenarios, we can distinguish the effects of the interventions in:

1) you can quantify the amount of water stored depending on which device is used, but the storage interventions could reduce but not eliminate urban flood (engineering-oriented approach);

2) it is interesting to observe how it is not certain that the total sum of the interventions hypothesized is actually the best solution in terms of management and reduction of the surface runoff and in terms of economic and social costs/benefits. As shown in Fig. 11 and Fig. 12 carrying out the interweaving of all the interventions together does not always reach a satisfactory increasing value. As seen in the figures shown, the curve varies slightly, we pass by the decrease of 8.6% in the case of the sum of the three interventions to a decrease of 7.9% with the match of Draining parking lots (P) and Green roofs (T.V.). Therefore, we can establish that in this case study the best combination of intervention, in terms of amount of water held and costs/benefits, is the combination of P and T.V. In particular, is newsworthy that the percentages of the decrease in outflow for individual interventions should not be added together because the final effect is not equal to the sum, but is a different effect linked to the associations of interventions and the reference context. Although in this final evaluation (point 2) the best cost / benefit ratio is taken into consideration, it is necessary to emphasize the importance of starting to promote the collection (water tanks) and the phyto-depuration of rainwater in our territory. In Rome, for example, there is no law prohibiting the use of drinking water to water private or public gardens, small plots or large plots. It is therefore necessary to point out that drinking water resources are drastically decreasing and that increasingly difficult times are ahead in terms of the amount of drinking water available for everyone. Furthermore, as we have recently seen, long periods of drought are much more frequent in our country, which risk ruining local crops and productions, in addition to our landscapes known all over the world.

3) Nature-based Solution play a key role in terms of water storage, but is absolutely necessary to combine them with other hydrological processes, such as: wetlands and lakes, evapotranspiration, phyto-purification and infiltration (landscape approach); and in general the study outlines that, to define an integrated waterlogging strategy, it is necessary to work with integrated disciplines, where a larger point of view is absolutely needed (urban planning/decision makers).

In conclusion, the results show how, in the present case, a careful choice and combination of technologies could be able to mitigate the urban runoff, and how a well thought out strategy could contribute to increase the ability to adapt and modify the environmental quality of a urban district.

4. Conclusions

Flooded squares and streets, urban forests, urban devices, wet parks, increase of absorbent surfaces, etc. these are just some of the elements that could merge into a new image of an ecological and sponge city. The need is to trace a general rethinking on how a sponge city should appear, in terms of design of the relationship between landscape, environment and social systems, where ecology can become creativity and where water, redetermining its founding nature, can become a first useful agent for a new urban design. Usability gradually promote new values and protective behaviors, of which, going back from the citizen to the top decision-making, landscape architecture aspires to make everyone aware of what world we could live in.

Practical solutions for water flood adaptation must be combined with a unitary design of the urban space, which takes into account the territorial and landscape context, but also the local urban structure. In order for the adaptation strategy to work on all defined elements, this dual nature should be kept together: a unitary project through the definition of aesthetic characteristics relevant to the old and new landscape and the necessary contemporary emergency techniques.

Therefore, the overall objective of this study is to provide theoretical support for the “sponge city” theory, where the general benefits can be listed as follows: • reduction of surface runoff • improved water quality • preservation of urban biodiversity • mitigation of climate change • reduction of air pollution • stimulation of green economy • preservation of the natural and cultural heritage • stimulation of social innovation • improvement of environmental quality • landscape design.

References

Abbott S., Caughley B., Douwes J., (2007), *The Microbiological Quality of Roof-Collected Rainwater of Private Dwellings in New Zealand*, In: *Rainwater and Urban Design*, Barton A.C.T. (Ed.), 13th Int. Rainwater Catchment Systems,Engineers Australia, 9-16, On line at: https://www.ctahr.hawaii.edu/hawaiirain/Library/papers/Abbots,%20Leder,%20Heyworth%20papers/Abbott1.pdf

Benelli F., Camerata F., (2014), Labaro-Prima Porta: an in-depth case, *Urbanistica Tre*, **5**, 85-93.

Bliss D.J., Neufeld R.D., Ries R.J., (2009) Storm water runoff mitigation using greenroof, *Environmental Engineering Science*, **26**, 407-418.

Calenda G., Mancini C.P., (2009), Sustainable water resources management in the Tiber River basin (central Italy), *Italian Journal of Engineering Geology and Environment*, **1**, 41-51.

Calenda G., Mancini C.P., Volpi E., (2009), Selection of the probabilistic model of extreme floods: the case of the River Tiber in Rome, *Journal of Hydrology*, **371**, 1-11.

Collins K.A., Hunt W.F., Hathaway J.M., (2008), Hydrologic comparison of fourtypes of permeable pavement and standard asphalt in Eastern North carolina, *Journal of Hydrologic Engineering*, **13**, 1146-1157.

Conte G., Del Bon A., Gafà R.M., La Vigna F., Martarelli L., (2015), Thermo-pluviometric and hydrometric data of the last 20 years in Rome, the technical report, On line at: https://www.comune.roma.it/resources/cms/documents/DelBon.pdf.

DE, (2005), Department of Engineering Roma Tre University, Study for the identification of the causes of flooding and flooding of the town of Prima Porta and the preliminary definition of the interventions for the prevention of future calamitous events, Rome 2005, On line at: https://www.ording.roma.it/application/files/2514/7825/5963/13785-seminariorischioidraulicomancini.pdf.

DEP, (2012), Guidelines for the Design and Construction of Stormwater Management Systems, Guidelines, New York CityDepartment of Environmental Protection, New York City Department of Buildings, On line at: https://www1.nyc.gov/assets/dep/downloads/pdf/water/stormwater/stormwater-design-construction-guidelines-2012-final.pdf.

DEPOGI, (2017), Standard designs and guidelines for green infrastructure practices, Manual design , New York City Department of environmental protection office of green infrastructure, On line at: https://www1.nyc.gov/assets/dep/downloads/pdf/water/stormwater/green-infrastructure/green-infrastructure-standard-designs.pdf.

DRCG, (1969), Denver Regional Council of Governments, Urban storm drainage criteria manual - volume 1, On line at: https://www.mhfd.org/wp-content/uploads/uploads/vol1%20criteria%20manual/00_front%20docs%20and%20Preface_V1.pdf.

DSIMU, (2015), Study for the hydraulic rehabilitation of the basins relating to the drainage systems of the Airports of Roma Company located east of the airport (Piana del Sole and West Quadrant of Fiumicino) and of the urbanized areas of Prima Porta (Fossi Torraccia, Monte Oliviero, Pietra Petrusa, Giustiniana and Marrana di Prima Porta) and identification of interventions for the mitigation of hydraulic risk in the areas under study, On line at: https://www.comune.roma.it/web-resources/cms/documents/Fasc2_All.2_PrimaPorta_2020.pdf.

EEA, (2015), European Environment Agency Digital Elevation Model over Europe (EU-DEM), On line at: https://www.eea.europa.eu/data-and-maps/data/eu-dem.

engman e.t., (1986) roughness coefficients for routing surface runoff, *Journal of Irrigation and Drainage Engineering*, **112**, 39-53.

Filpa A., Ombuen S., (2014), The climate vulnerability map of Rome 1.0, *Urbanistica Tre*, **5**, 47-58.

Gironas J.L., Roesner A., Rossman L.A., Davis J., (2010) A new applications manual for the Storm Water Management Model (SWMM), *Environmental Modelling and Software*, **25**, 813-814.

Gregoire B.G., Clausen J.C., (2011) Effect of a modular extensive green roof on stormwater runoff and water quality, *Ecological Engineering*, **37**, 963-969.

Jiang X.Y.; Ji Y.; Zhang J.Q.; Tong Z.J.; Bao Y.L.; Chen P.; Jiang L.P., (2010), *The Simulation on Hazard of Urban Waterlogging Disaster Based on GIS*, In: *Chinese Perspective on Risk Analysis and Crisis Response*; Huang, C.F., Zhang, J.Q., Zhou, Z.F., (Eds.) Atlantis Press, Paris, France, **13**, 280.

Kongjian Y., Li Dihua, Yuan Hong, Fu Wei, Qiao Qing, Wang Sisi, (2015), Sponge City: theory and practice, *China Academic Journal - City Planning Review*, **39**, 26-36.

Lamera C., Becciu G., Rulli M.C., Rosso R., (2014), Green roofs effects on the urban water cycle components, *Procedía Engineering*, **70**, 988-997.

Liang W., Hou L., (2018), A Review of research on Sponge Cities, *Journal of Landscape Reserch*, **10**, 19-24.

Qing-yun L., Lei L., Cun-dong X., Zhong-pei L., Corresponding author Yan-wei S., (2014), Hydrological simulation approaches for BMPs and LID practices in highly urbanized area and development of hydrological performance indicator system, *Water Science and Engineering*, **7**, 143-154.

Rangari V.A., Prashanth S.S., Umamahesh N.V., Patel A. K., (2018), Simulation of Urban Drainage System Using a Storm Water Management Model (SWMM), *Asian Journal of Engineering and Applied Technology*, **7S1**, 7-10.

Rossman L.A., (2010) Storm Water Management Model User's Manual, Version 5.0, In: National Risk Management Research Laboratory, Cincinnati, On line at: https://www.owp.csus.edu/LIDTool/Content/PDF/SWMM5Manual.pdf.

Volpi E., Di Lazzaro M., Fiori A., (2012), A simplified framework for assessing the impact of rainfall spatial variability on the hydrologic response, *Advances in Water Resources*, **46**, 1-10.

Xia J., Zhang Y. Young X., Li H., He S., Wang L. Feng Y. Zhong B., (2017), Opportunities and challenges of the Sponge City construction related to urban water issues in China, *Science China Earth Sciences*, **60**, 652-658.

Zhang D., Zhao D., Chen J., (2009), Review and application of urban storm runoff control technology, *Water Wastewater Engineering*, **35**, 25-29.

Zhen-ci X., Yongchen G., (2017), Simulation test of runoff on different underlying surfaces in urban area, *South North Water Transfers Water Science and Technology*, **10**, 64-66.

Environmental Engineering and Management Journal

October 2020, Vol. 19, No. 10, 1847-1855
http://www.eemj.icpm.tuiasi.ro/; hiip://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

CIRCULAR ECONOMY MODEL OF RECYCLED AGGREGATES FOR THE CONSTRUCTION SECTOR OF SARDINIA ISLAND

Luisa Pani*, James Rombi, Lorena Francesconi, Anania Mereu

University of Cagliari, Italy, Department of Civil Environmental Engineering and Architecture, Marengo Street, 09123 Cagliari, Italy

Abstract

This study analysed the recycling of debris derived from the partial and selective demolition of concrete structures of Sant'Elia Stadium in Cagliari (Sardinia, Italy). This recycling was carried out to obtain coarse recycled aggregates for the production of recycled concrete.
The experimental investigations demonstrated the possibility of using these recycled concrete aggregates in structural concrete and in precast concrete element, with unchanged production processes and suitable mechanical properties. Additionally, the required quantity of recycled aggregates for new construction works and the refurbishment of buildings in three towns of Sardinia South West coast was determined. The applied research provides a significant contribution to the management plan of construction and demolition waste in Sardinia Island. In this context, the circular economy model is the best to achieve the sustainable development of the construction sector.

Keywords: circular economy, precast concrete industry, recycled aggregate, recycled concrete, urban planning

Received: February, 2020; Revised final: June, 2020; Accepted: July, 2020; Published in final edited form: October, 2020

1. Introduction

The construction sector annually consumes a huge amount of aggregates which contribute to environmental problems. The recycling of construction and demolition waste (C&DW), as recycled aggregates in structural concrete, reduces the exploitation of natural resources and the extension of landfills. Maximising the quantity of recycled materials, used in concrete members, is an effective approach towards sustainable construction (Kovler and Roussel, 2011; Meyer, 2009; Rao et al., 2007). Available experimental data on concrete produced with recycled concrete aggregate (RA) are highly varied and inconsistent. Some researchers (Kou and Poon, 2015; Padmini et al., 2009) confirmed that the quality of RA depends on the quality of the parent concrete. Other researchers (Ajdukiewicz and Kliszczewicz, 2002; Etxeberria et al., 2007; Francesconi et al., 2016; González-Fonteboa and Martínez-Abella, 2008; Kou and Poon, 2015; Rahal, 2007; Stochino et al., 2017; Tabsh and Abdelfatah, 2009) found that recycled concrete (RC) having medium compressive strength can be produced, regardless of the parent concrete quality. Contradictory conclusions have been drawn by different researchers owing to different reasons. First, the RC was mainly compared to control concrete, using natural aggregates. However, the quality of natural aggregates significantly influenced the conclusions because the same recycled aggregate can have different effects if the natural aggregate possesses excellent or poor mechanical properties. Second, different approaches were adopted for comparing the RC using different substitution ratios: the same total water-cement ratio, the same effective water-cement ratio, or the same workability, which yielded different effective water-cement ratios.

*Author to whom all correspondence should be addressed: e-mail: lpani@unica.it; Phone: +396755400; Fax: +396755418

Finally, the conclusions depended on the characteristics of the recycled aggregates used, such as form, size, and mechanical properties (Le and Bui, 2020). The significant variations in the properties of available resources and recycled aggregates need to be investigated to gain the required confidence in using the recycled concretes.

In literature, the performance of recycled aggregates, recycled concretes, precast recycled concrete element and waste management have been separately analyzed. In this paper, starting from the case study of reinforced concrete large structure demolition (football Sant'Elia stadium in Cagliari) all stages have been analyzed and connected (characterization of parent concrete, recycled aggregates, concrete aggregates, precast recycled concrete elements and waste management). Based on the urban and coastal area planning of three towns on Sardinia South West coast, the required quantity of recycled aggregates for new construction works and the refurbishment of buildings was determined.

This study demonstrates that it is possible to produce structural concrete C30/37 using coarse RA from crushed structural concrete, including concrete with low compressive strength. In this study, the RA was derived from partially demolished concrete structures (foundations and cantilever beams) of the old Sant'Elia football stadium, built in 1968.

Before demolishing these concrete structures, tests were performed to evaluate their mechanical performance. The foundations and cantilever beams were demolished and crushed separately to obtain two types of coarse RA, with both types having 4/16 mm aggregate sizes. RC mixtures were obtained by mass using three replacement percentages (30%, 50%, and 80%) of RA to replace coarse natural aggregate (NA). An additional mixture of normal concrete (NC), containing only NA, was manufactured for target properties control.

Furthermore, the production of concrete blocks with these recycled aggregates was analysed. Concrete block properties showed insignificant differences even when the percentage of RA substitution reached 100%. Generally, the production process remained unchanged, even when the RA was used.

Contributing to the proper management of waste (9000 m^3), obtained from demolition of Sant'Elia football stadium, in compliance with the current European Union legislation on demolition waste recycling, a virtuous circular economy model is proposed. This model can be replicated in other contexts, and the planning of needed actions shows the specific innovative contribute of this work.

2. Experimental investigation

2.1. Quality of parent concrete

During the first phase of this study, the integrity and the mechanical behavior of concrete structures of the football stadium (Fig. 1) were analyzed. The stadium will be demolished shortly, and a new stadium will be constructed. The concrete structural elements selected for the preliminary analysis were cantilever beams and foundation blocks. A total of 12 cored specimens were collected from both the foundation and cantilever beams, named respectively: 'C. Fond.' and 'C. Be'. A preliminary visual inspection performed on the cored specimens did not indicate any defects. In Table 1, the average values of carbonation depth (C_D), density (D), compressive strength (R_c), modulus of elasticity (E_c), and splitting tensile strength (f_{ct}), are listed.

A polarizing microscope was used to assess the conditions of concrete for both foundations and cantilever beams. The samples were characterised by the presence of different aggregates incorporated in the cement matrix.

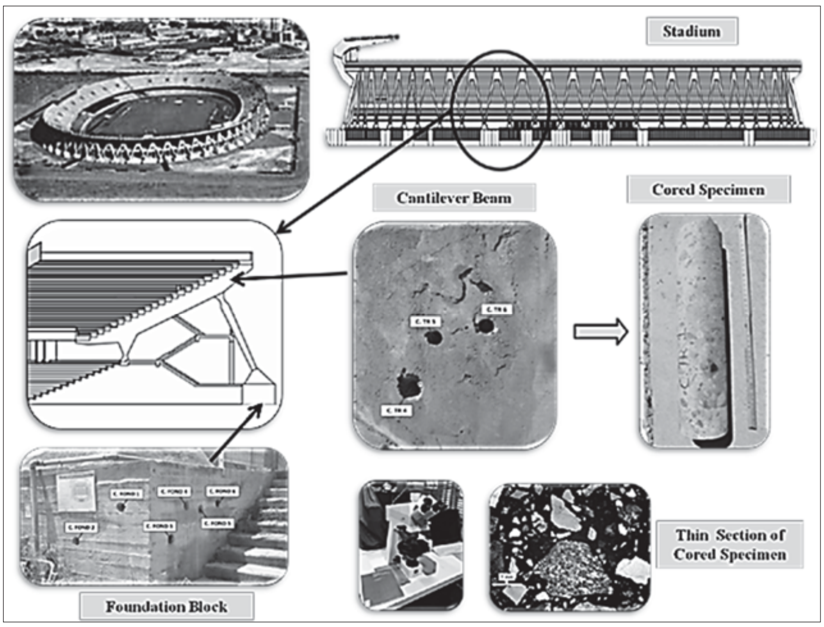


Fig. 1. Concrete structures of Cagliari football stadium

The investigation performed on the C. Be samples showed that in the cement matrix, the coarse fraction consisted of limestone fragments, and the fine fraction of granite, metamorphic rock fragments, quartz crystals, and feldspar. The C. Fond samples had a homogeneous composition, with the coarse fraction composed of granite rock fragments and metamorphic rocks, whereas the fine fraction included quartz, feldspar, and biotite.

2.2. RA characterization

Two types of RA were produced, which were recycled aggregates obtained by crushing the foundations (RA_F) and the beams (RA_B) (Fig. 2). Each type of RA was tested according to UNI EN 12620 (2008) and UNI 8520-1 (2015) specifications (Table 2, Fig. 3). The cement mortar, which adhered to the RA, significantly influenced the physical properties, workability, mechanical performance, and durability of the RC (Bahrami et al., 2020; Bidabadi et al., 2020; Otsuki et al., 2003; Pani et al., 2011, 2013a, 2013b; Sánchez de Juan and Alaejos Gutiérrez, 2009). Previous studies attributed the decrease in compressive strength (Tavakoli and Soroushian, 1996) and modulus of elasticity (Salem and Burdette, 1998) of RC, compared to NC, to the presence of adhered old cement mortar. The determination of residual mortar content (RMC) is necessary for evaluating the properties of concrete produced with RA. However, a standard method for determining the RMC has not been universally accepted, and the method used in this study was proposed by Abbas et al. (2008). Representative samples of the RA have daily undergone freezing and thawing cycles in a solution of sodium sulphate. The RMCs derived from RA_F and RA_B were classified into two particle size fractions, i.e. particles retained on sieves 4 and 10 mm (Table 3).

2.3. RC experimental programme

CEM II/A-LL 42.5 R was used in the concrete mixtures. Both coarse NA and RA were used. The NA comprised crushed limestone and river gravel and represented the typical NA used in the Sardinia concrete. Table 4 lists the aggregate size (d_g), bulk density (ρ_a), saturated surface-dried density (ρ_{ssd}), water absorption (WA), and resistance to fragmentation (LA) values of NA.

Table 1. Characterisation of parent concrete

Identification	*C_D (mm)*	*D (kg/m³)*	*R_c (MPa)*	*E_c (MPa)*	*f_{ct} (MPa)*
C. Fond.	10	2314	27.9	25335.3	2.04
C. Be.	31	2270	21.0	18041.6	1.49

Table 2. Results of recycled aggregate characterisation tests

Property	*RA_F*	*RA_B*
RA size	4/16	4/16
Category grading	G_C = 90/15; G_T = 17.5	G_C = 90/15; G_T = 17.5
Flakiness index	4	4
Shape index	59	34
Saturated surface-dried density	2.39 Mg/m³	2.38 Mg/m³
Bulk density	ρ_b = 1.23 Mg/m³; v% = 45	ρ_b = 1.14 Mg/m³; v% = 49
Percentage of fines	0.15%	0.59%
Percentage of shells	Absent	Absent
Resistance to fragmentation	39%	39%
Constituents of coarse recycled aggregate	X = 0; R_c = 74%; R_u = 27%; R_b = R_a = R_g = 0	X = 0; R_c = 78%; R_u = 22%; R_b = R_a = R_g = 0
Hydro-soluble chloride content	0.005%	0.005%
Acid soluble chloride-salt content	0.325%	0.325%
Acid soluble sulphate content	0.43%	0.26%
Sulphate determination	S < 0.1%	S < 0.1%
Hydro-soluble sulphate content	SS = 0.148%	SS = 0.068%
Lightweight contaminants	Absent	Absent
Water absorption	WA_{24} = 7.0%	WA_{24} = 6.7%
Resistance to freezing and thawing	41%	42%
Resistance to magnesium sulphate	2.56%	0%
Presence of humus	Absent	Absent

Table 3. Residual mortar contents of recycled aggregates

RMC (%)	*RA_F (%)*	*RA_B (%)*
Retained at sieve 4 mm	55.81	49.67
Retained at sieve 10 mm	45.82	45.65

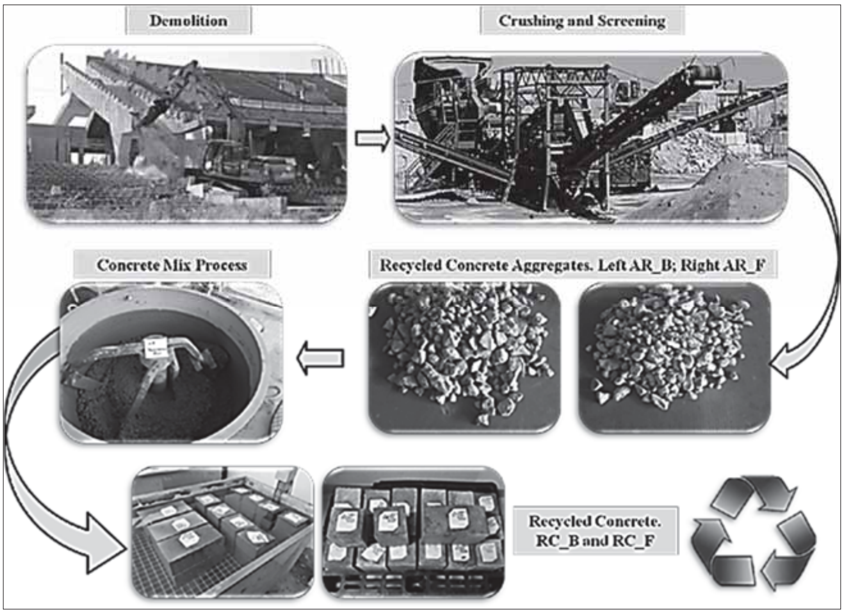


Fig. 2. Demolition of Sant'Elia Stadium concrete structures, RA and RC obtained

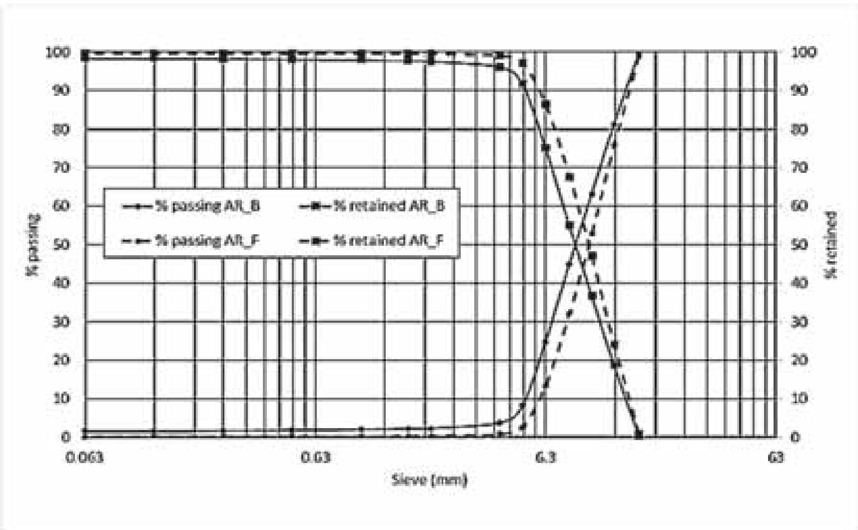


Fig. 3. Particle size distributions of recycled aggregates

Two types of coarse RA (RA_F and RA_B) were used as replacement of coarse NA, natural sand was utilised as fine aggregate in the concrete mixtures. The natural and recycled aggregates were used in saturated surface-dried conditions to obtain well-controlled concrete mixtures. A polycarboxylate-based superplasticiser was added to all the mixtures. The quantities of superplasticiser added to the mixtures were adjusted to maintain the same casting condition and to obtain a slump of approximately 200 mm.

RC mixes were produced using different replacement percentages (30%, 50%, and 80%) by mass of the RA to replace the coarse NA. A total of six RC mixes were produced using both types of coarse RA separately. An additional mix NC, containing only NA, was produced as control mix. Cubic and prismatic specimens were cast to determine compressive strength, splitting tensile strength and modulus of elasticity. All specimens were cast in steel moulds, vibrated and cured in a standard controlled atmosphere of 20 ± 5 °C and 97 ± 2% humidity. The concrete mixtures and specimens were manufactured in a Calcestruzzi–HeidelbergCement Group (Quartu Sant'Elena, Cagliari, Italy) ready-mix concrete plant through quality control processes. Table 5 lists the proportions of each mix by mass. The workability of fresh concrete was determined through the standard slump test. Tests were performed immediately after the mixing process and subsequently measured after 30 min. The obtained slump values of the RC and NC mixtures were very close (Table 6). Compressive strength (R_c), splitting tensile strength (f_{ct}), and secant modulus of elasticity in compression (E_c) tests were performed according to UNI EN 12390-3 (2019), UNI EN 12390-6 (2010), and UNI EN 12390-13 (2013) standards. The compressive strength for each mixture was determined at 14 and 28 days, whereas the splitting tensile strength and the modulus of elasticity were determined at 28 days. Table 7 lists the average mechanical properties of the concrete specimens (three specimens for each test).

2.4. Precast recycled concrete elements

Concrete blocks are classic precast products used for different purposes in the construction sector. Concrete blocks are characterised by low strength and simple production processes. The production of concrete blocks with recycled aggregates will help to protect the environment and reduce production costs due to the lower price of recycled aggregates compared to natural aggregates.

Four RC mixtures containing different replacement percentages (20%, 50%, 70%, and 100%) of RA (RA_F type) were produced (Table 8). An additional mixture, NC containing only NA, was also produced as control mix. CEM II/A-LL 32.5 R was used in all the concrete mixtures. The concrete blocks were cast in a precast concrete element plant (Farris Roberto Siliqua, Cagliari, Italy).

Natural and recycled aggregates were arranged outdoors in separate piles under awnings sheets in a non-sunny condition. The aggregates were collected from the piles, weighed, and introduced into the production plant. Water was added to obtain the suitable workability for the production process. Table 9 lists the average values of the density (D), compressive strength (f_c), and absorption (A) of the concrete blocks.

2.5. RA and urban planning

Case studies were carried out in three towns (Carloforte, Calasetta, and Portoscuso) on Sardinia South West coast (Fig. 4) to explore the possibility of using RA based on the urban and coastal area planning. This planning included the construction of cycle tracks, pedestrian paths, new buildings, and the maintenance of existing buildings.

.

Table 4. NA properties

d_g (mm)	ρ_a (Kg/m^3)	ρ_{ssd} (Kg/m^3)	WA (%)	LA (%)
0-4	2707	2630	2.0	21
4-16	2691	2600	1.4	

Table 5. Concrete mixes by mass (1 m^3)

Mix (kg)	*w/c*	*Cement*	*Water*	*NA*	*NA*	*RA_F*	*RA_B*	*Superplasticiser*
				Fine	*Coarse*			
NC	0.463	400	185	847.49	880.06	-	-	2.91
RC_B30%	0.463	400	185	821.80	616.04	-	263.69	3.31
RC_F30%	0.463	400	185	821.80	616.04	263.69	-	3.31
RC_B50%	0.463	400	185	802.97	440.03	-	440.27	3.31
RC_F50%	0.463	400	185	802.97	440.03	440.27	-	4.00
RC_B80%	0.463	400	185	778.15	176.01	-	703.96	4.00
RC_F80%	0.463	400	185	778.15	176.01	703.96	-	4.00

Table 6. Slump values

Mix	*Slump (mm)*	
	t = 0 min	*t = 30 min*
NC	210	180
RC_B30%	210	155
RC_F30%	210	180
RC_B50%	210	190
RC_F50%	200	130
RC_B80%	220	200
RC_F80%	195	180

Table 7. Mechanical properties of RC

Specimen	$R_{c,14d}$ (MPa)	$R_{c,28d}$ (MPa)	f_{ct} (MPa)	E_c (MPa)
NC	39	42	3.66	26037
RC_B30%	42	45	3.78	23512
RC_F30%	41	44	3.89	24902
RC_B50%	44	44	3.90	23011
RC_F50%	44	47	3.40	25509
RC_B80%	43	47	3.85	23486
RC_F80%	40	44	3.69	24043

Table 8. Concrete block mixes by mass (1 m^3)

Mix (kg)	*Cement*	*Water*	*Fine NA*	*Coarse NA*	*Coarse RA_F*
NC	140	40	200	900	-
20% RA	140	41	200	720	180
50% RA	140	46	200	503	503
70% RA	140	46	200	270	630
100% RA	140	47	200	-	900

Table 9. Properties of recycled concrete blocks

Specimen	*D (kg/m^3)*	*f_c (MPa)*	*A (g/(m$^2 \cdot$ s$^{0.5}$)*
NC	2069	3.77	108.9
20% RA	2009	3.58	103.9
50% RA	2087	3.58	93.3
70% RA	2039	2.85	126.3
100% RA	1954	3.40	111.1

The aim of the case study was to define a methodological approach for developing short-, medium-, and long-term approaches to RA use in urban planning.

Fig.4. Geographical position of Carloforte, Calasetta and Portoscuso

The following points were developed:

• The logical context of environmental impact assessment, municipal urban plan, coastal plan, and management plan of Nature 2000 network.

• A methodology for determining the RA demand based on municipal urban plan previsions.

The planned actions in the three towns, according to the municipal urban plan, coastal plan, and management plan of Nature 2000 network, are as follows:

• The construction of new tourist complexes in Carloforte (area: 51 km^2; population: 6100; located in sub-area F2 of a spontaneous tourist village).

• The construction of cycle tracks and pedestrian paths to connect the town centre with the coastal areas in Calasetta (area: 31 km^2; population: 2857).

• The construction of cycle tracks and pedestrian paths in Portoscuso (area: 39 km^2; population: 5034).

The analysis of the planning systems indicated that the RA could be used in different locations, including coastal areas. The required quantity of the RA was determined considering municipal urban plan for new constructions (buildings and road foundation layers for cycle tracks and pedestrian paths) and refurbishment of buildings. Both the existing and planned volumes, as well as the territorial indices for each area, were considered.

The estimated quantities of aggregate required for new buildings, refurbishment, and cycle tracks and pedestrian paths were approximately 2, 0.1, and 0.5 t/m^2, respectively.

The hypothetical zone subjected to maintenance work was equal to 12% of the total existing building area in Zones A, B, and C (Zone A: historical settlements; Zone B: consolidated urban areas; Zone C: urban expansions). The urban space for cycle tracks and pedestrian paths was equal to 10% of the non-built areas in Zones B, C, G, and F (Zone G: general services; Zone F: tourist expansions). It was estimated that the coarse aggregate mass was approximately 30% of the total mass of concrete (Table 10).

The recycling procedures were as follows: a percent yield of 50% was determined to produce coarse RA from concrete C&DW, e.g. 2 t of C&DW should be used to obtain 1 t of coarse RA.

In this context, the evaluation suggested that up to 800000 t of concrete C&DW could be recycled.

3. Results and discussion

Experimental data for the parent concrete quality showed that the beams and foundations were made of two types of concrete and had different mechanical properties, carbonation state, and composition. The mechanical properties and carbonation depth of the foundation concrete were better than those of the beam concrete. Furthermore, the differences between the two types of materials were confirmed through petrographic analysis of the thin section. The results showed that the RA types had very similar characteristics, even when obtained by crushing different concretes. Only four parameters (shape index, fines percentage, acid-soluble sulphate content, and water-soluble sulphate content) were slightly different (Table 2). The RMC values obtained from RA_F and RA_B were similar (Table 3). Overall, the results indicated that although the parent concrete types were different, the RA_F and RA_B were similar.

These findings support the simplification of the recycling processes of secondary raw materials for commercial RA production. Hence, the separate procedures of preliminary characterisation and parent concrete storage may be unnecessary. Furthermore, according to the specifications of UNI EN 12620 (2008), UNI 8520-1 (2015), and UNI 8520-2 (2016), RAs are suitable to be used as aggregate in structural concrete.

The average compressive strength at 14 and 28 days, $R_{c,14d}$ and $R_{c,28d}$, showed optimal performance even when the percentage of coarse RA reached 80% (Table 7). The compressive strength of RC did not appear to be influenced by the parent concrete. Furthermore, in some cases, the compressive strength values of the RC were higher than those of the NC, and the splitting tensile strength values, f_{ct}, for all the RC specimens were higher than or equal to those of the NC. These results were expected (Bahrami et al, 2020) and could be attributed to the significant roughness of the RA, which increased the tensile strength of concrete.

The secant modulus of elasticity values in compression, E_c, were slightly lower (with a maximum decrease of 11%) for the RC compared to the NC (Table 7). This observation was expected and attributed to the adhered mortar content (Salem and Burdette, 1998). The obtained results confirmed the optimal performance of the RC, even when the replacement percentage reached 80%. Following UNI EN 771-3 (2015) standards, concrete block properties showed insignificant differences even when the percentage of RA substitution reached 100% (Table 9). Generally, the production process (Fig. 5) remained unchanged, even when the RA was used.

The experimental results for the natural and recycled aggregates showed significant differences in absorption and resistance to fragmentation. The water absorption of the RA was five times higher than that of the NA, and the resistance to fragmentation of the RA was approximately two times greater than that of the NA (Table 2, Table 4).

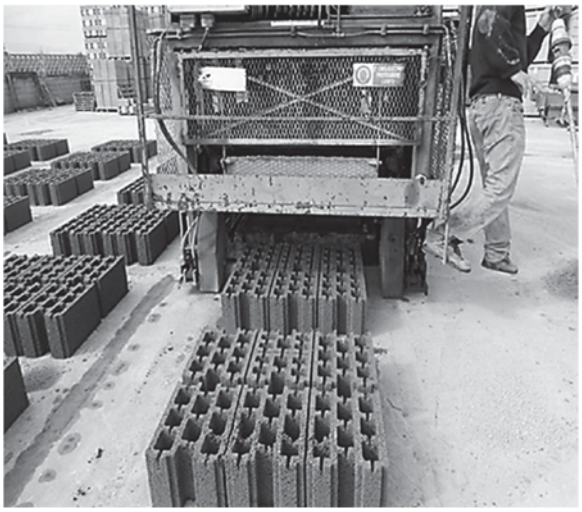


Fig. 5. Production of recycled concrete blocks

The reduced performance of the RA compared to the NA was not significant for the concrete block properties (density, water absorption, and compressive strength). The average values of density, water absorption, and compressive strength of the recycled concrete blocks, containing replacement percentages up to 50%, were unaffected by the RA content. These parameters were practically close to the values for concrete blocks made of NA. When the replacement percentage was 70%-100%, a slight increase in the water absorption (16%) and a decrease in the compressive strength (24%) of the recycled concrete blocks were observed. However, the density almost remained constant (6% decrease).

This study demonstrates that RA can be used to manufacture precast concrete blocks without additional costs for precast companies.

The analysis of the three case studies, conducted on the South West coast of Sardinia, to explore the possibility of using RAs in new construction and the refurbishment of buildings, suggested that there were no drawbacks in using RAs. The total quantity of RA was approximately 400000 t (Table 9).

Table 10. Estimated quantities of RA and recyclable C&DW

Town	***Calasetta***		***Carloforte***		***Portoscuso***	
RA	30%	80%	30%	80%	30%	80%
RA for new building (t)	8673	23127	15336	40897	18753	50008
RA for refurbishment (t)	152	404	342	911	486	1296
Town	***Calasetta***		***Carloforte***		***Portoscuso***	
RA	100%		100%		100%	
RA for road layers (t)	34198		167872		66989	
Town	***Calasetta***		***Carloforte***		***Portoscuso***	
RA total (t)	43022	57729	183550	209675	86228	118794
C&DW of concrete (t)	86044	115458	367100	419359	172456	236587

4. Circular economy in the construction sector

C&DW has a high reuse potential but it is usually disposed of in landfills with severe environmental consequences. In Italy, C&DW recycling for RA is generally limited as filling materials and road foundation layers. In other European countries, they are reused in a more extensive way, e.g. for structural concrete.

C&DW recycling also has economic benefits: the price of RA is approximately half of the one of NA. The benefits of C&DW recycling should be communicated to contractors, public administrators, technical experts, and the general public, to promote sustainability through waste recycling and reuse.

Generally, undifferentiated streams of debris are produced during the demolition of structures. Selective demolition facilitates the waste management plan and recycled aggregate production suitable for structural concrete.

The University of Cagliari Research Group, trade associations, and the public administration work together in partnership. A significant development for Sardinia was when in 2019, for the first time, RA was included in the regional price list. This inclusion demonstrates a critical need for its practical use in the construction industry, which still presents an enormous challenge.

5. Conclusions

The conclusions of this study, according to circular economy model of recycled aggregates, are summarised as follows:

- The results showed that the coarse RAs had similar mechanical, chemical, and physical properties, even though they were derived from different structural concrete members. This knowledge will be useful in simplifying their storage and the marketing organisation in the recycling of secondary raw materials. The RC produced with coarse RA had similar mechanical properties of the NC, even when the NA replacement percentage reached 80%. The RC performance was not related to the mechanical properties of the parent concrete.
- Concrete blocks can be produced with RA without modifying the production process. The performance of recycled concrete blocks made using replacement percentages up to 50% was unaffected by the replacement of NA with RA. For replacement percentages exceeding 70%, slightly lower properties were observed.
- The analysis for three case studies conducted on Sardinia South West coast to explore the possibility of using RA in new construction projects (buildings and road layers for cycle tracks and pedestrian paths) and the renovation of buildings indicated that there were no drawbacks in using RAs. The use of the estimated quantity of recycled C&DW will significantly contribute to environmental protection.
- Waste mapping and selective demolition should be promoted and enforced whenever possible. These measures are required to obtain good-quality RAs for structural concrete applications and are effective practices for environmental sustainability.
- The synergy between trade associations, research groups, and public administrations is necessary for carrying out pilot projects that demonstrate the feasibility of RA usage in structural concrete. This practice can be replicated in other international contexts.
- The obtained experimental results support the use of recycled concrete aggregates in the production of structural concrete. However, more extensive experimental investigations that allow for statistical analyses should be conducted.

Acknowledgements

Authors would like to acknowledge Sardegna Ricerche for the financial support (POR FESR 2014/2020, Axis 1 "Scientific Research, Technological Development and Innovation").

References

Abbas A., Fathifazl G., Isgor O.B., Razaqpur A.G., Fournier B., Foo S., (2008), Proposed method for determining the residual mortar content of recycled concrete aggregates, *Journal of ASTM International*, **5**, 1-12.

Ajdukiewicz A., Kliszczewicz A., (2002), Influence of recycled aggregates on mechanical properties of HS/HPC, *Cement and Concrete Composites*, **24**, 269-279.

Bahrami N., Zohrabi M., Mahmoudy S.A., Akbari M., (2020), Optimum recycled concrete aggregate and micro-silica content in self-compacting concrete: Rheological, mechanical and microstructural properties, *Journal of Building Engineering*, **31**, 101361.

Bidabadi M.S., Akbari M., Panahi O., (2020), Optimum mix design of recycled concrete based on the fresh and hardened properties of concrete, *Journal of Building Engineering*, **32**, 101483.

Etxeberria M., Vázquez E., Marí A., Barra M., (2007), Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete, *Cement and Concrete Research*, **37**, 735-742.

Francesconi L., Pani L., Stochino F., (2016), Punching shear strength of reinforced recycled concrete slabs, *Construction and Building Materials*, **127**, 248-263.

González-Fonteboa B., Martínez-Abella F., (2008), Concretes with aggregates from demolition waste and silica fume. Material and mechanical properties, *Building and Environment*, **43**, 429-437.

Kou S., Poon C., (2015), Effect of the quality of parent concrete on the properties of high performance recycled aggregate concrete, *Construction and Building Materials*, **77**, 501-508.

Kovler K., Roussel N., (2011), Properties of fresh and hardened concrete, *Cement and Concrete Research*, **41**, 775-792.

Le H.B., Bui Q.B., (2020), Recycled aggregate concretes. A state of the art from the microstructure to the structural performance, *Construction and Building Materials*, **257**, 1-15.

Meyer C., (2009), The greening of the concrete industry, *Cement and Concrete Composites*, **31**, 601-605.

Otsuki N., Miyazato S.S., Yodsudjai W., (2003), Influence of recycled aggregate on interfacial transition zone, strength, chloride penetration and carbonation of concrete, *Journal Materials in Civil Engineering*, **15**, 443-55.

Padmini K., Ramamurthy K., Mathews M.S., (2009), Influence of parent concrete on the properties of recycled aggregate concrete, *Construction and Building Materials*, **23**, 829-836.

Pani L., Balletto G., Naitza S., Francesconi L., Trulli N., Mei G., Furcas C, (2013a), *Evaluation of Mechanical, Physical and Chemical Properties of Recycled Aggregates for Structural Concrete*, Proc. Int. Sardinia Symp. Waste Management and Landfill, S. Margherita di Pula, Italy, 30 September, 4 October, 482-483.

Pani L., Francesconi L., Concu G., (2013b), *Relation between Static and Dynamic Modulus of Elasticity for Recycled Aggregate Concrete*, Proc. First Int. Conference on Concrete Sustainability, Tokyo, 27-29 May, 676-681.

Pani L., Francesconi L., Concu G., (2011), *Influence of Replacement Percentage of Recycled Aggregates on Recycled Aggregate Concrete Properties*, Proc. Int. Fib Symp. Prague 2011, on Concrete Engineering for Excellence and Efficiency, Prague, 1249-1252.

Rahal K., (2007), Mechanical properties of concrete with recycled coarse aggregate, *Building and Environment*, **42**, 407-415.

Rao A., Jha K.N., Misra S., (2007), Use of aggregates from recycled construction and demolition waste in concrete, *Resources, Conservation and Recycling*, **50**, 71-81.

Salem R.M., Burdette E.G., (1998), Role of chemical and mineral admixtures on physical properties and frost-resistance of recycled aggregate concrete, *ACI Materials Journal*, **95**, 558-563.

Sánchez de Juan M., Alaejos Gutiérrez P., (2009), Study on the influence of attached mortar content on the properties of recycled concrete aggregate, *Construction and Building Materials*, **23**, 872-877.

Stochino F., Pani L., Francesconi L., Mistretta F., (2017), Cracking of reinforced recycled concrete slabs, *International Journal of Structural Glass and Advanced Materials Research*, **1**, 3-9.

Tabsh S.W., Abdelfatah A.S., (2009), Influence of recycled concrete aggregates on strength properties of concrete, *Construction and Building Materials*, **23**, 1163-1167.

Tavakoli M., Soroushian P., (1996), Strength of recycled aggregate concrete made using field-demolished concrete as aggregate, *ACI Materials Journal*, **93**, 182-190.

UNI 8520-1, (2015), Italian National Unification Standard on Aggregates for concrete. Additional provisions for the application of EN 12620 Part 1: Designation and conformity criteria, Italian Autority Standardization, On line at: http://store.uni.com/catalogo/uni-8520-1-2015.

UNI 8520-2, (2016), Italian National Unification Standard on Aggregates for concrete. Additional provisions for the application of EN 12620 Part 1: Requirements. Italian Autority Standardization, On line at: http://store.uni.com/catalogo/uni-8520-2-2016.

UNI EN 771-3, (2015), European Standard on Specification for masonry “Specification for masonry units – Part 3: Aggregate concrete masonry units (Dense and lightweight aggregates), European Committee for Standardization, On line at: http://store.uni.com/catalogo/uni-en-771-3-2015.

UNI EN 12390-3, (2019), European Standard on Testing hardened concrete – Part 3: Compressive strength of test specimens, European Committee for Standardization, On line at: http://store.uni.com/catalogo/uni-en-12390-3-2019.

UNI EN 12390-6, (2010), European Standard on Testing hardened concrete – Part 6: Tensile splitting strength of the specimens, European Committee for Standardization, On line at: http://store.uni.com/catalogo/uni-en-12390-6-2010.

UNI EN 12390-13, (2013), European Standard on Testing hardened concrete – Part 13: Determination of secant modulus of elasticity in compression, European Committee for Standardization, On line at: http://store.uni.com/catalogo/uni-en-12390-13-2013.

UNI EN 12620, (2008), European Standard on Aggregates for concrete, European Committee for Standardization, On line at: http://store.uni.com/catalogo/uni-en-12620-2008.

Environmental Engineering and Management Journal

October 2020, Vol. 19, No. 10, 1857-1868
http://www.eemj.icpm.tuiasi.ro/; hiip://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

LAND CONSUMPTION IN ITALIAN COASTAL AREA

Nicola Riitano[1*], Pasquale Dichicco[2], Paolo De Fioravante[3], Alice Cavalli[3], Valentina Falanga[1], Chiara Giuliani[1], Lorella Mariani[2], Andrea Strollo[1], Michele Munafò[1]

[1]Italian Institute for Environmental Protection and Research (ISPRA), Roma, Italy
[2]University of Pavia, Center for Astronomical and Remote-sensing Observations (ICARO), Pavia, Italy
[3]University of Tuscia, Department of Innovation in Biology, Agri-food and Forest systems (DIBAF), Viterbo, Italy

Abstract

Italian coastal urban development is a problem which requires measures to contain land consumption and a continuous monitoring action on the phenomenon, especially in those areas where the tendency to consume land is high. Two of the major limitation in achieving full awareness of the phenomenon are the lack of common European policies and land consumption definition issues
In this study the aim is to analyse the evolution of land consumption occurred in the Italian coastline on a diachronic basis (2012-2018). We used the National Land Consumption Map, produced by ISPRA yearly covering all the Italian territory, adopting a proper definition of what is meant to be consumed. Moreover, the phenomenon is assessed showing its relation to the distance from the coastline, morphological typologies, administrative boundaries and protected areas, in order to identify consumption patterns and highlight particular areas most frequently affected by land consumption. This study finds consumed land is increasingly distributed within 100 meters from the coastline, with different peaks and trends. At the same time new changes increase proportionally to the distancing from the coast. This is partially argued with the saturation, already built, of the territory between 0 and 200 meters, that constitutes a major spatial constraint. The relationship between the phenomenon and the distance from the coastline, connotes a characteristic feature at regional level Through a set of finalised indicators, distinctive pattern of the evolution occurred have been analytically highlighted, showing that density of changes is more intense between 300 and 500 meters, in the first unrestricted portion of land. The level of detail allows to provide a useful database as an effective support for territorial policies and planning, with the aim of preserving the coastal landscape and increasing awareness of the finiteness of the soil resource, a true challenge, that in a medium-long term, with required organized and coordinated interregional policies can be tackled in its various issues.

Key words: coastal area, land consumption, monitoring, soil sealing.

Received: February, 2020; Revised final: June, 2020; Accepted: July, 2020; Published in final edited form: October, 2020

1. Introduction

Coastal landscapes represent an extraordinary distinctive element of the Italian territory and generally a natural heritage subject to vulnerability issues due to land cover change. In particular, land consumption in coastal areas is a global level concern, especially in those areas where population growth and urban developments are incomparable with the dynamic nature of the coastal system (Congedo et al., 2017; Dada et al, 2019). Generally, the land consumption has been expressed more frequently, not only in coastal areas, but also in the plains and valleys, where, in general soils are less available (Marchetti et al., 2012), given their characteristics of high fertility and accessibility increasing their demand. Biodiversity of Italian littorals and their cultural heritage make these areas important resources to be protected against threats. Climate change and touristic exploitation are the two main factors that put pressure on these areas, which are known to be highly sensitive to environmental risks. Nevertheless, socioeconomic

* Author to whom all correspondence should be addressed: e-mail: nicola.riitano@isprambiente.it; Phone: +393289458477

pressures continue undeterred, with a land consumption rate that can sharpen the vulnerability of the coast, already made critical from the seaside by the phenomena of advance and retreat of the coastline (Bird, 1985), For this reason, it becomes necessary to monitor the phenomenon to quantify the loss of a non-renewable resource (Munafò, 2019) and its impact on essential ecosystem services (Hasan et al., 2020, Ye et al., 2018, Tang et al., 2014) such as carbon sequestration (Fu et al. 2018). The demographic growth, the economic development and the competition for the soils have produced the current landscape structure of the Italian coasts. The process of land consumption is still in progress in these areas going to affect even more on areas already distorted by urban transformations on which pressures of real estate markets and the tourism industry converge. Coastal areas can be considered as the transition zones between terrestrial and marine ecosystem composed by dunes, shores, cliffs, interdunal fresh water areas and dry areas near the coast, which are not influenced by salt spray (APAT, 2004). These are the zones where both natural and socio-economic forces have their most intense combination. (Felsenstein and Lichter, 2014a; 2014b). Coastal territories are complex environments, related to many different systems, both physical (hydrological, geomorphological) and human (socio-economic, institutional and cultural) (Casazza et al., 2002). This zone distinctive dynamism and complexity makes its spatial boundaries laborious to be defined (Runko Luttenberger et al., 2018). The coastline and its hinterland among the Italian territories occupy a foreground position for the richness and variety, among the Italian territories. The current spatial configuration is the product of secular interactions between the effects of anthropic actions and those resulting from natural origins due to physical and geomorphological processes (Romano et al, 2017). The intensification of urban transformations, closest to the entire Mediterranean coastline has compromised, with greater magnitude over the last 50 years, the natural ability of the coast to adapt to climate changes enhancing the potential exposure to coastal hazards (Small and Nicholls, 2003). Considering the Italian coastline, it can be divided into two main categories: high and rocky shores covering 59% of the total and low, and sandy shores covering the remaining 41%; the latter has undergone major transformations under the pressure of the tourism industry. Also, coastal dunes and wide lowlands behind the dunes, where wetlands are most frequently present, despite being one of the most vulnerable ecosystems, have suffered severe changes, not only at national but also at global level. In particular, the dunes contain a large reserve of sand useful for feeding the shore, but they are also important barrier against coastal instability and marine surges. In coastal areas processes of urban densification occur more frequently than previously undeveloped natural areas, for several factors. Available land for urban expansion is determined by the sea on one side and coastal mountain range, on the other. Restricting the space in which the city expands can facilitate urban densification, one of the major components of land recycling (Louwagie, 2016).

In order to provide a detailed picture of the current state of the transformations that took place at the expense of the land on the coastal strip some definitions are necessary, defining framework and what we are investigating. First, we need to define Land Consumption, which is the conversion of a non-artificial land cover to an artificial one. Land consumption is distinguished between a permanent land consumption component (due to permanent artificial cover) and another mutually exclusive part defined as reversible land consumption. The distinction of the latter allows to include in the count of the areas consumed also those subjected to "consuming" effects such as excavation and compaction (eg. dumps and quarries) (Munafò et al., 2015) which occur less than soil sealing but with equally harmful effects (Jones et al., 2012). Soil sealing, however, can be considered as the most intense and the major component of land consumption (EC, 2011) which contains in Munafò et al. (2015) definition other processes besides the sealing, as mentioned before. It differs from the definition provided by the European Environment Agency (EEA, 2013) which define Land take, whereas take or uptake are often used as a synonym of consumption, as the “Change of the amount of agriculture, forest and other semi-natural and natural land taken by urban and other artificial land development”. It represents a limit for those studies that need a dichotomous distinction between natural and artificial soil, that’s why the notion of soil sealing seems to be more objective (Decoville and Schneider, 2016) which however, from our perspective, needs to be integrated with other components of consumption.

Despite the impact of the phenomenon being evident and universally recognized, there is no a Community policy. To fill the gap in the lack of environmental legislation, in 2002 the approach of the European community to the theme of the soil was presented through a communication entitled "Towards a thematic Strategy on Soil Protection” published later in 2006 (Ludlow, 2006). The Soil Thematic Strategy (EC, 2006) promoted the inclusion of soil protection measures in different policy areas. This strategy, emphasized prevention of further land degradation and maintenance of its functions, underlining the need to implement good practices suggesting guidelines (EC, 2012) to reduce the negative effects of land use and, in particular, its most obvious and irreversible form: soil sealing (Munafò, 2019). With the Seventh Environment Action Programme and Resource Efficiency Roadmap, the European Commission recognizes soil sealing as a major threat (EC, 2013), setting targets with both communications of no net land take by 2050, even if a soil sealing limit at Regional and local level has not yet been set (EC, 2016). However, as in the rest of Europe, there is a lack of a soil framework directive; in Italy, the Parliament has not yet approved a law that aims to protect the soil from its progressive artificial cover. Currently a law to limit land consumption is under discussion in the Parliament, in which EC Directive (2007) has presented the definition proposal mentioned before. Commission had already considered it useful to indicate the priorities for action and the guidelines to be followed in order to achieve no net land take by 2050 by publishing guidelines for limiting, mitigating and compensating the soil sealing (EC, 2012).

This work aims to illustrate the land consumption evolution along the Italian coast since 2012. It provides analysis on a diachronic basis in the intervals between 2012 and 2018, in order to evaluate the ratio of land consumption on coastal municipalities. Moreover, it is calculated on particular areas (protected areas, urban areas, etc.) considering different distances from shoreline, for highlighting where land consumption is more intense. Finally, land consumption status at 2018 is provided and the main reasons, which caused the phenomenon, are explained. We have used distinct indicators to understand quantitative and qualitative features of the phenomenon highlighting regional and national scale differences.

Although drivers of soil consumption act similarly in various regional contexts, regional peculiarities do exist as different planning restrictions and are strongly influenced by the configuration of transport infrastructure networks (Lai and Lombardini, 2016).

2. Area of study

The Italian coastal area extends with almost 8300 km in the centre of the Mediterranean Sea, in which Greece has the longest length with over 13 000 km.

It is composed for 2827 km by high coast, low coast is 5720 km long most common in the Adriatic coast, which consists of long shores and lagoons. All these different types of coastal areas are washed by local seas (Ligurian, Tyrrhenian, Ionanian, Adriatic and the Sardinian and Sicilian seas). These different typologies of coastal areas well represent the variety that can be found in the Mediterranean basin as well as the various hydrological characteristics of local seas (Casazza et al., 2002).

The study area involves 15 regions; land-locked regions are excluded. In 3 cases it was necessary to split spatial analysis for the presence of two coasts dataset referring to different seas. On the Italian coastline there are 663 Municipalities, with a total area of 44.071 $km^{2.}$ Coastal zones in Italy are the most populated areas with 17.098.640 inhabitants (28,4% of the population) and a density of 397 inhabitants/km^2. Campania, Lazio and Liguria are the most populated Regions with a population density of 1.233, 1.041, 948 inhabitants/km^2 respectively: Lower values are present also in Friuli-Venezia Giulia and Abruzzo with a density of 703 and 692 inhabitants/km^2. In line with the national demographical evolution, population has decreased since 2014 while the overall balance has been positive since 2012.

3. Material and methods

The main research goal is to observe the land consumption in relation to the distance from the coast in Italy. In order to achieve this result, land consumption maps (LCM) and the coastline shapefile produced in accordance with the methodology proposed by Barbano et al. (2006) have been used. Land consumption map produced by ISPRA (Munafò, 2019), last updated in 2019 (referring to 2018 state of the soil in Italy) is currently the best available spatial information capturing the artificial land cover. It delivers a national geographic coverage and high temporal resolution (yearly updated since 2015 and available for the year 2012 potentially upgradeable for previous years), high spatial resolution of 10 meters. It was produced through photointerpretation of very high resolution images and semiautomatic classification of high resolution remote sensing images (Strollo et al., 2020). It is provided with the distinction between reversible and permanent processes of land consumption, although this information has not been used in this work. It was chosen to reclassify the LCM in a binary classification system that allows to distinguish the consumed land from the rest of the territory.

The production of the coastline was performed by ISPRA and Planetek, Orthophotos acquired during IT2000 flight, and cartography made by the Italian Military Geographical Institute (IGM) in scale 1: 25000 were the source used for the digitalization of the Italian coastline. Using GIS techniques, starting from the coastline up to 10 km, a raster has been built assigning each cell its euclidean distance. Raster spatial resolution is 10 meters and its grid is aligned to the land consumption map with the aim of speeding up and improving the processing. Combining the Distance Raster, reclassified in 10m zones, starting from the coast (value = 0) with the LCM, it was produced a new raster providing in a unique attribute both of the above-mentioned information's. Results are then aggregated into buffer zones shown in Fig. 1.

Permanent water bodies and wetlands were excluded from the spatial analysis because administrative boundaries used as spatial reference for the LCM (ISTAT, 2018) include, in some regions, water bodies that are located outside the coastline, see for instance Fig. 2, showing the municipality of Venice and its lagoon. Later, other spatial information's, such as coastal morphology and administrative, regional (NUTS1) boundaries, were integrated in order to provide aggregate results on several factors. All the calculations were made on two different land consumption map releases, referred to 2012 and 2018 (Munafò, 2019).

Indicators calculations and comparison were implemented in a spreadsheet and performed for the regions in the area of study. Within the extent of 10 km, the analysis considered the distribution of variables in five distance ranges (100m, 300m, 500m, 1 km, 10 km) and in the three coastal typologies: high, low and other. The latter class includes, in aggregated form, typologies referring to artificial coastal manufacts (ports, docks, riverbanks, piers, connections, etc.). In order to separate the state of soil (consumed land) from its variation (land consumption) we introduced the following indicators, which are later discussed in the following paragraphs.

Consumed land – CL (2012) and (2018), is the amount of land, usually expressed in square km or hectares occupied by an artificial land cover (as defined by ISPRA in Munafò (2019). Land Consumption - LC (12-18) is the amount of land converted to an artificial land cover during the observation period, derived as difference between Consumed Land in the two years of observation (Eq. 1):

$$LC(12\_18) = LC(2018) - LC(2012) \quad (1)$$

In the first 300 meters, the cumulated Land consumption (CLC) and cumulated Consumed land (CCL) was calculated starting from the values for 30 bands 10 meters wide and normalized with respect to the total (Eqs. 2-3):

$$CLC_n = \frac{\sum_{i=0}^{n} LC_i}{LC_{29}} \quad (2)$$

where: n= 0, …, 29 is the n-th distance band starting from the coastline.

$$CCL_n = \frac{\sum_{i=0}^{n} CL_i}{CL_{29}} \quad (3)$$

Finally, the demographic variation was investigated in the study area, using ISTAT databases for the municipal level aligned with the reference period, aggregating the variations at national level, in order to correlate land use and demographic variation.

Only the municipalities with coastline access were considered in this calculation and the inhabitants residing in them without regard of their extension towards the inland.

Fig. 1. Example of buffer zones originated from the coastline

Fig. 2. Aerial views of Venice Lagoon, Italy. Background source: General Agency for Agricultural Subsidies Orthophotos

4. Results

Results of the analysis are illustrated in this section: they refer to the land consumption between 2012 and 2018 and the consumed land (2018) in relation to the distance from the coastline and to the different types of coast. Both national and regional level have been analyzed. In general, in the italian coastal area included within 300 meters from the coastline, about 76 ha of land per year were consumed in the reference period, for a total of almost 458 ha. Comparing the results with that of similar calculation experiences for Mediterranean areas, two French case studies have been analyzed. Enault et al. (2020) evaluated the status of coastal areas in two areas in the Southeastern France, in the Var department: Toulon Provence Méditerranée and Saint-Tropez Gulf. The first area is largely covered by urban areas (40% in 2011) and it has been characterized by urban sprawl at a rate of 64 ha/year between 2003 and 2011 (total +512.6 ha). Most of the urban sprawl was located in agricultural areas (70% of the land consumption between 2003 and 2011). Urban areas in Saint-Tropez Gulf represent the 17% of the territory but between 2003 and 2014 the annual rate of land consumption was higher than the one of Toulon 67 ha/year (total +743 ha); even if in this area natural and agricultural areas are still large, they are threatened by the urbanization. In Fig. 3 percentage of Consumed Land per distance band and its relative variation between 2012-2018 is shown.

The first has its peak close to the coast with a maximum of 30.76% between 100 and 110 meters, and then decreases whilst the second has a remarkable increase after 550 meters away from the coast, where the increase is greater than 1%.

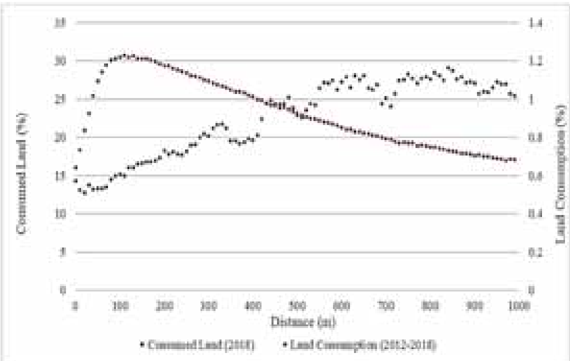


Fig. 3. Comparison between Consumed Land (percentage of the total distance band area) and Land Consumption (percentage of change from the Consumed Land in 2012)

The percentage of consumed land near the coast (Table 1.) is above the national average (7.6%, ISPRA 2019) in all the buffer zones examined and illustrated in Fig. 3. The highest value occurs between 100 and 300 meters from the coastline, with 29.4% of Consumed land and it stay above 20% until the 500 m buffer zone. In order to further explore and provide interpretation on the land consumption pattern, results are aggregated in different distance bands, 23.58% of the land consumption occurring between 2012 and 2018 in Italy falls within the buffer zone of 10 km, which occupies 15.9% of the national surface. Moreover, 19.58% of the total changes are concentrated in the range between 1 km and 10 km. This band is also the most dynamic, in fact, between 2012 and 2018 there were 165.8 m^2 of land consumption per hectare of consumed land in 2012, higher than the national average of 138.66 m^2 / ha (ISPRA 2019). Considering the density of changes (ha of land consumption on the area of each distance band) it is interesting to highlight that it is more intense between 300 and 500 meters, in the first unrestricted by law portion of land with a value of 21.91 m^2 consumed for each ha of territory in that band.

Another significant result, analyzing distribution of typologies within 300 meters from the coastline, (Table 2), is the percentage of 29.27% low coast being consumed, which represents 55.41% of the Italian coastline. The low coast is also the most dynamic, with hectare of land consumption in the studied interval. Moreover, 7.27% of the consumed land falls within the high coast areas; these areas are less affected by the construction of buildings and infrastructures but still show values above the national average. The "other" class contains 33.79% of the consumed land within 300 m and is consumed for 45.07% of its extension.

The analysis' results of coastal typologies on regional scale (Table 3.) are aligned with the national ones, the consumed land is concentrated in the low coast in eleven out of fifteen regions. In Friuli-Venezia Giulia, Liguria and Veneto, the consumed land is above all in the "other" class, while in Sardinia 50.45% of the consumed soil is placed on high coast. Sardinia is also the only region (Table 3) where the high coast is slightly prevalent (50.45% of the total). The consumed land percentage on the total extension (Table 4.) is maximum in the "other" class for 13 of the 15 regions; exceptions are Abruzzo and Molise, where the percentage of consumed land is higher in the low coast (Tables 3-4). Analyzing the changes on a regional scale between 2012 and 2018 (Table 4) are in line with the national trend in four regions (Emilia Romagna, Lazio Molise and Sardinia). In seven of the fifteen regions the most dynamic areas are those with low coast. Considering percentage of change in consumed land, the in particular in Basilicata (0.05%) and Friuli-Venezia Giulia (0.02%).

In 13 of the 15 regions, the percentage of soil consumed (Table 4.) in the buffer zone of 10000 (Fig.6) meters follows the national trend, with a peak between 100 and 300 meters. The maximum value occurs in the Marche region (50.18%). In the first 100 meters, land consumption is higher than 20% in 12 regions out of 15 and with a maximum of 50.04% in Liguria. The consumed land in the first 1000 meters (Fig.5) from the coast is higher than the national average in fourteen regions out of fifteen (except for Basilicata). Table 5. shows that Sicily is the region with the largest area of consumed land in all areas (179.481.67 ha), followed by Puglia (117.157.00) and Calabria (81.040.87). Figs. 4, 5 and 6 point out the CL as a percentage of the municipality's surface, for the buffer distances of 100, 300 and 1000 m.

Peaks for the municipal level can also be observed in regions where the overall CL is not among the largest in Italy (e.g. in Calabria or Friuli Venezia Giulia).

Table 1. Consumed Land (2018) in hectares, percentage on the band surface, and Land Consumption (2012-2018) in hectares, percentage of Change (cha%) and annual land consumption in the observation period

Bands			*Consumed land (2018)*		*Land consumption (2012-2018)*		
Range		*Area*					
m		*ha*	*ha*	*%*	*ha*	*cha %*	*ha/yr*
0	*100*	82 612.3	20 534.9	24.86	112.1	0.55	18.7
100	*300*	137 183.0	40 407.1	29.45	279.2	0.70	46.5
300	*500*	125 494.8	31 868.0	25.39	275.0	0.87	45.8
500	*1000*	287 114.7	56 376.1	19.64	593.3	1.06	98.9
1000	*10000*	4 165 111.6	378 211.8	9.08	6169.0	1.66	1028.2

Table 2. Distribution of land consumption in coastal typologies, Consumed Land (2018) in hectares, percentage on the band surface, and Land Consumption (2012-2018) in hectares

Typology	*% of the Coastline*	*Consumed land within 300 m (2018)*		*Land consumption within 300 m (2012-2018)*
		ha	*%*	*ha*
high	23.58	2081158.0	8.64	27.35
low	55.41	3565524.0	29.27	250.45
other	21.01	447520.0	45.07	113.46

Table 3. Consumed land in the coastal typologies within 300 m, in hectares and percentage of the buffer zone, regional level (2018)

Regions	*Consumed land (2018)*			*Consumed land (2018)*		
	ha			*%*		
	high	*low*	*other*	*high*	*low*	*other*
Abruzzo	3420	321783	100388	13.63	37.53	36.45
Basilicata	48669	101643	37617	8.73	5.96	5.65
Calabria	107051	1789320	317641	14.42	29.75	36.8
Campania	401699	627585	262368	17.45	39.04	58.27
Emilia-Romagna	0	288046	145903	0	41.15	45.14
Friuli-Venezia Giulia	912	276182	318413	14.69	17.53	39.26
Lazio	109591	702062	204055	10.33	32.28	45.14
Liguria	309139	389250	404084	19.36	51.5	68.95
Marche	45248	391397	123584	3.67	46.4	62.38
Molise	0	96241	24567	0	21	18.44
Apulia	378516	1697158	416343	18.52	27.79	52.73
Sardinia	2291977	1629855	621509	4.59	12.96	29.63
Sicily	822326	2708453	724321	8.38	33.54	39
Tuscany	643078	737448	304480	6.18	21.67	53.34
Veneto	0	388872	599752	0	28.98	45.84

Table 4. Distribution of coastal typology land consumption Consumed land in the coastal typologies within 300 m, in hectares and percentage of the buffer zone, regional level (2018)

Regions	*Distribution of coastal typology*			*Land Consumption (12-18)*		
	ha			*%*		
	high	*low*	*other*	*high*	*low*	*other*
Abruzzo	0.8	75.61	23.59	3.0	399.0	195.0
Basilicata	25.9	54.09	20.02	9.0	328.0	10.0
Calabria	4.84	80.82	14.35	202.0	5040.0	1008.0
Campania	31.1	48.59	20.31	156.0	916.0	442.0
Emilia-Romagna	0	66.38	33.62	0.0	224.0	199.0
Friuli-Venezia Giulia	0.15	46.38	53.47	0.0	849.0	1670.0
Lazio	10.79	69.12	20.09	39.0	818.0	341.0

Liguria	28.04	35.31	36.65	241.0	522.0	802.0
Marche	8.08	69.86	22.06	6.0	740.0	199.0
Molise	0	79.66	20.34	0.0	129.0	39.0
Apulia	15.19	68.1	16.71	446.0	4553.0	1918.0
Sardinia	50.45	35.87	13.68	343.0	1050.0	1095.0
Sicily	19.33	63.65	17.02	1333.0	9060.0	2342.0
Tuscany	38.16	43.77	18.07	63.0	358.0	343.0
Veneto	0	39.33	60.67	0.0	1134.0	1028.0

Fig. 4. Consumed land within 300 meters in 2018 (values as percentage of the municipality's surface)

Fig. 5. Consumed land within 1 km. in 2018 (values as percentage of the municipality's surface)

Fig. 6. Consumed land within 10 km in 2018 (values as percentage of the municipality's surface)

Table 5. Percentage of consumed land in the distance bands

			Distance Bands (m)					
			0-100	*100-300*	*300-500*	*500-1000*	*1000-10000*	*0-10000*
Consumed Land (2018)	**%**	*Abruzzo*	25.2	43.5	39.7	28.7	11.0	**13.39**
		Basilicata	5.0	7.5	5.1	5.3	3.8	**4.03**
		Calabria	24.2	33.1	27.1	17.2	5.1	**7.02**
		Campania	34.6	37.2	34.2	28.7	16.3	**18.48**
		Emilia-Romagna	28.9	50.1	44.1	32.9	14.2	**16.95**
		Friuli-Venezia G.	29.2	29.1	25.5	21.8	12.9	**15.22**
		Lazio	30.2	33.8	27.5	20.6	10.7	**12.43**
		Liguria	50.0	48.2	38.3	27.5	8.3	**11.85**
		Marche	39.8	50.2	39.9	26.2	12.0	**14.58**
		Molise	15.9	23.0	21.5	14.7	5.3	**6.63**
		Apulia	29.1	31.4	27.0	20.9	10.2	**11.98**
		Sardinia	9.9	11.7	10.2	8.2	4.5	**5.27**
		Sicily	25.9	31.7	27.8	23.7	10.4	**12.74**
		Tuscany	20.0	22.4	18.7	15.3	8.8	**10.38**
		Veneto	37.0	40.9	37.3	25.8	15.3	**17.88**

Table 6. Consumed land in 2018 in the distance bands

			Distance Bands (m)					
			0-100	*100-300*	*300-500*	*500-1000*	*1000-10000*	*0-10000*
Consumed Land (2018)	**ha**	*Abruzzo*	378	1578	2649	4516	17309	**26430**
		Basilicata	33	124	184	332	2336	**3009**
		Calabria	1869	6647	10452	16384	45688	**81041**
		Campania	1623	4680	7300	12411	51667	**77681**
		Emilia-Romagna	449	1844	3021	5037	19579	**29930**
		Friuli Venezia G.	704	1735	2475	3758	12349	**21022**
		Lazio	1121	3301	4867	7667	33030	**49985**
		Liguria	2107	5389	7804	11873	30874	**58048**
		Marche	795	2597	3988	6229	23358	**36967**
		Molise	68	247	409	676	2386	**3787**
		Apulia	2683	7613	11553	18694	76614	**117157**
		Sardinia	1752	5006	7486	11823	42146	**68214**
		Sicily	3998	12598	19634	33161	110090	**179482**
		Tuscany	1265	3620	5380	8601	29918	**48783**
		Veneto	1609	3876	5524	7938	29966	**48913**
		*Italy**	20454	60855	92726	149100	5273106	**850449**

Land consumption, as expected, increases with distance (Table 7.), in accordance with the national trend in 14 of the 15 regions. Friuli-Venezia Giulia is an exception; here the peak of consumption occurred between 100 and 300 meters (+1.47%), due to some major changes, involving almost 15 ha in the municipalities of Grado and Monfalcone as already mentioned in ISPRA (2019). In Sicily (1687.6 ha) and Apulia (1292.2 ha) there are the greatest number of changes (Table 7.).

Basilicata is the region with the least number of changes but with the greatest number of changes per hectare of land consumed, especially in the first 100 meters (422.58 m^2/ha) and between 500 and 1000 meters (510.79 m^2/ha) (Table 7). This trend denotes a high dynamism of building activity in the region, especially on the Ionian coast (Fig. 7).

In order to highlight regional difference in the land consumption pattern, Fig. 8 provides additional information concerning the distance over which the phenomenon has its diversity from the national trend. Within 300 m from the coastline, normalized values of land consumption illustrate the distance needed in order to reach the cumulated percentages, with Emilia Romagna Marche and Campania showing less "landivorous" attitudes in the first 200 m, on the contrary, Abruzzo Basilicata and Molise concentrate most of their consumption in the first 200m.

In the same graph (Fig.8) the cumulated consumed land emphasizes particular tendency for the regions of Campania, Liguria and Veneto, in which the left facing convexity occurs before 50% of the total. In the study area, there was a population growth of +503.837 inhabitants (+3.08%), in line with the Italian trend (+1.83%). Considering the 6416 ha consumed, in the same area between 2012 and 2018, it can be calculated for comparative purposes, the value of 127 m^2 for each new inhabitant which is surprisingly lower than the same value calculated for the rest of the municipalities of Italy (442 m^2 for each new inhabitant) that consumed 25896 ha for 585929 new inhabitants.

Table 7. Land consumption in hectares between 2012 and 2018 and percentage of change in consumed land in the same period

	Region	***Distance Range m***				
		0-100	***100-300***	***300-500***	***500-1000***	***1000-10000***
Land Consumption (Ha) / Percentage of Change in Consumed Land (%)	*Abruzzo*	2.15 (+0.57%)	3.64 (+0.30%)	3.88 (+0.36%)	8.15 (+0.43%)	215.91 (+1.71%)
	Basilicata	1.34 (+4.22%)	2.03 (+2.27%)	1.35 (+2.32%)	7.22 (+5.1%)	24.14 (+1.21%)
	Calabria	12.16 (+0.65%)	48.03 (+1.01%)	51.87 (+1.38%)	107.82 (+1.85%)	517.51 (+1.79%)
	Campania	3.01 (+0.18%)	11.68 (+0.38%)	6.09 (+0.23%)	19.99 (+0.39%)	466.89 (+1.2%)
	Emilia-Romagna	0.27 (+0.06%)	3.81 (+0.27%)	6.18 (+0.52%)	8.23 (+0.41%)	151.79 (+1.05%)
	Friuli-Venezia G.	9.46 (+1.36%)	14.96 (+1.47%)	9.03 (+1.23%)	10.85 (+0.85%)	236.62 (+2.83%)
	Lazio	4.43 (+0.39%)	7.26 (+0.33%)	9.61 (+0.61%)	29.5 (+1.06%)	494.34 (+1.98%)
	Liguria	3.84 (+0.18%)	11.15 (+0.34%)	18.19 (+0.75%)	34.69 (+0.85%)	144.71 (+0.76%)
	Marche	1.29 (+0.16%)	7.33 (+0.4%)	7.48 (+0.54%)	19.26 (+0.86%)	359.09 (+2.14%)
	Molise	0.74 (+1.1%)	0.85 (+0.47%)	0.73 (+0.45%)	1.62 (+0.61%)	33.48 (+1.99%)
	Apulia	20.21 (+0.75%)	46.48 (+0.95%)	53.96 (+1.38%)	86.94 (+1.23%)	1084.64 (+1.9%)
	Sardinia	8.15 (+0.46%)	15.95 (+0.49%)	13.46 (+0.54%)	45.95 (+1.07%)	524.19 (+1.75%)
	Sicily	35.99 (+0.9%)	86.69 (+1.01%)	62.09 (+0.89%)	131.43 (+0.98%)	1371.36 (+1.81%)
	Tuscany	2.67 (+0.21%)	4.79 (+0.2%)	3.87 (+0.22%)	21.72 (+0.67%)	181.89 (+0.86%)
	Veneto	5.83 (+0.36%)	14.53 (+0.64%)	27.25 (+1.68%)	59.97 (+2.54%)	362.46 (+1.67%)

Fig. 7. Intensity of Land Consumption: the area of change represented is proportional to the hectares consumed between 2012 and 2018

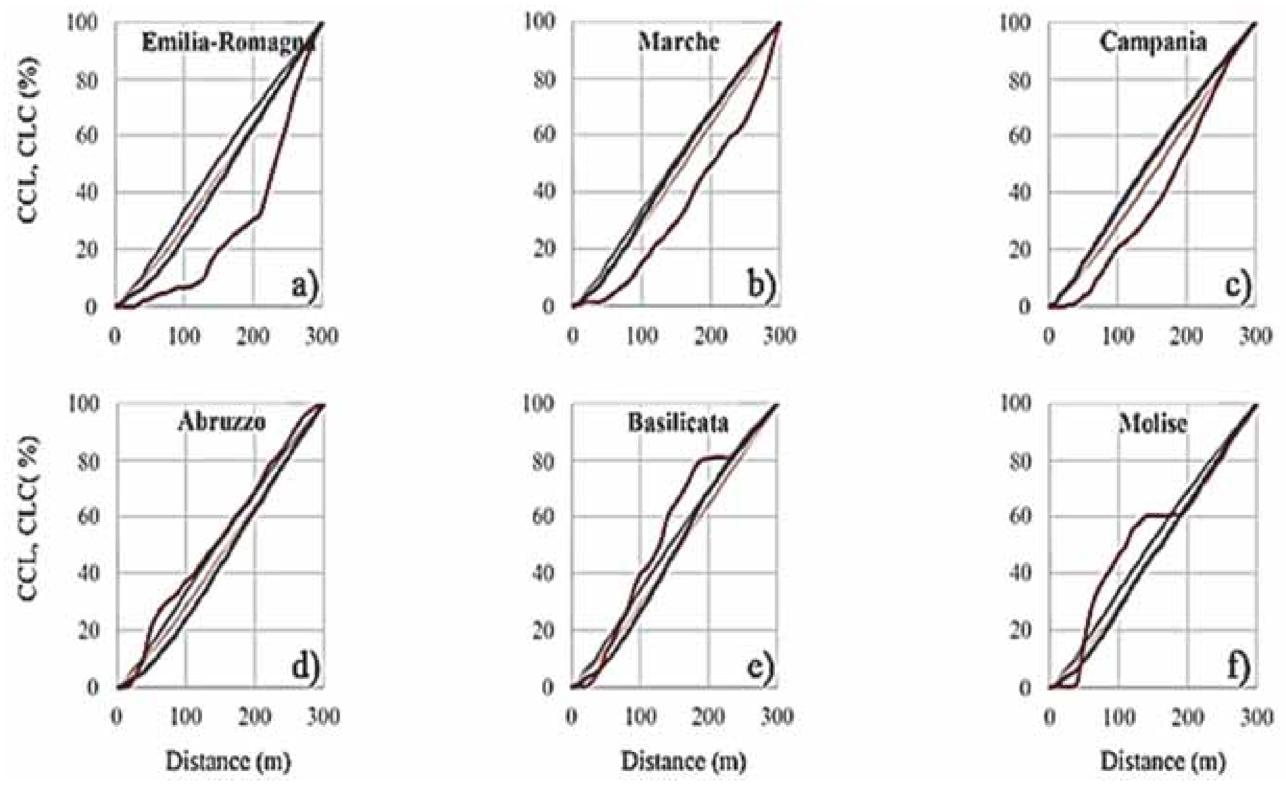


Fig. 8. Cumulated Consumed Land (in red, light red for the national trend) and Cumulated Land Consumption (in black, grey for the national trend): a comparison between normalized values within 300 m from the coastline: (a) Emilia-Romagna, (b) Marche and (c) Campania in the first row are the less impacting regions, whilst d) Abruzzo, e) Basilicata and f) Molise are the regions that consumed more land within 200 meters from the coastline

5. Conclusions

In this paper we described land consumption trend in coastal areas, underlining its evolution since 2012. Findings open up interesting opportunities of thought: for instance, the need for urban expansion containment in these vulnerable areas, and the urge for an effort in locating geographically those ones which are more influenced by the phenomenon.

In 2018 consumed land percentage along the Italian coast was higher than the national average, especially between 100 and 300 m from the coast line, which are restricted by national law (D.lgs. 431/85); even considering the distance band between 1000 and 10000 m, the trend of the phenomenon is still higher than the national level in many Italian regions. Furthermore, both at national and regional level, soil sealing and consumed land concern above all low coasts, which, as seen before, are characterized by the fragile balance of biodiversity and soil erosion and the most prone to seasonal exploitation by tourism. The trend concerns the whole national territory, in-fact there is no clear difference between North, Centre or South. It is however striking, a higher level of variability between the regions. It leads to reflections about the geomorphological conformation but also to distinctions between different social and cultural realities, a wide range of factors that outline different behaviors for which dedicated policy approaches would be necessary.

The extent of the changes, which would lead to results of greater concern, if considering the impacts in terms of ecosystem services on the surrounding area, along with the spatial localization of the consuming processes, (e,g, in restricted areas referred to D.lgs. 431/85, between 0-300 m from the coastline) and the high rate of anthropogenic pressure on low coasts, suggests focusing on the management of the coastal areas as necessary within the urban planning framework, in order to protect vulnerable areas from further exploitation, avoiding already alarming problem such as coastal erosion and loss of biodiversity. Moreover, the analysis of the demographic variation has returned very high values of land consumed per capita, which, focuses on the use of these tools for an effective sustainable management of urban sprawl, related to actual demographic needs rather than those of tourism coastal. However, the value of the rest of the Italian territory shows how the phenomenon is more intense in the inland. Concerning the respect of restrictions, this study highlights the need of monitoring the land consumption. High spatial and temporal resolution images, as orthophotos, allow to define land cover and its changes. A precise characterization of coastal areas through land use and land cover, properly defined, both for their status and changes, can lead to a better comprehension of their dynamics; in this study, along with a clear and unique definition of "land consumption" would help to solve ambiguities of the most common classification methods used in Europe. The lack of a national land use and land cover map, with appropriate spatial and temporal resolution, does not allow to assess the type of soil involved in the consumption, which would be interesting to deepen the understanding of the transitional flows between land cover classes in the coastal area, to highlight landscape transformation patterns for the national scale.

Furthermore, there is not a homogeneous framework of regional land use/land cover maps; they have different spatial, temporal and thematic resolutions, which make these products not comparable to each other. In some cases, there are not any official maps, except of CORINE Land Cover, which is developed at European scale, which makes it not fully exploitable for the local level. The knowledge of the typology of consumed land could be an important tool for planning policies, in order to identify unauthorized constructions and to constitute a base to improve planning tools in force. Territorial policies could be effectively addressed, for example, focusing the monitoring on the low coasts, as demonstrated by this work the most common and the most affected by urban transformations.

References

APAT, (2004), Habitats according to the EUNIS nomenclature: classification manual for the Italian case, Reports 39/2004, On line at: http://www.isprambiente.gov.it/it/pubblicazioni/rapporti/gli-habitat-secondo-la-nomenclatura-eunis-manuale.

Barbano A., Corsini S., Mandrone S., Rotunno M., La Mantia C., Barbieri V., (2006), *Techniques and methods for studying the state of the coasts in a GIS environment*, On line at: https://www.amazon.it/Tecniche-metodi-studio-dello-ambiente/dp/B07RT6QJSX.

Bird E.C.F., (1985), Coastline changes, A global review, Journal of Coastal Research (Online), 2, On line at. https://journals.flvc.org/jcr/article/view/77436/74916.

Casazza G., Silvestri C., Spada E., Melley A., (2002), *Coastal Environment in Italy: Preliminary Approach Using the 'DPSIR scheme' of Indicators*, 6th Int. Symp. Proc. A multi-disciplinary symposium on coastal zone research, vol 2, 541-9.

Congedo L., Marinosci I., Riitano N., Strollo A., De Fioravante P., Munafò M., (2017), Monitoring of land consumption: An analysis of loss of natural and agricultural areas in Italy, *Annali Di Botanica*, **7**, 1-9.

Dada O.A., Agbaje A.O., Adesina R.B., Asiwaju-Bello Y. A., (2019), Effect of coastal land use change on coastline dynamics along the Nigerian Transgressive Mahin mud coast, *Ocean and Coastal Management*, **168**, 251-264.

Decoville A., Schneider M., (2016), Can the 2050 zero land take objective of the EU be reliably monitored? A comparative study, *Journal of Land Use Science*, **11**, 331-349.

EC Directive, (2007), Directive 2007/2/EC of the European Parliament and of the Council of 14 March 2007 establishing an infrastructure for Spatial Information in the European Community (INSPIRE), *Official Journal of the European Union*, L 108.

EC, (2006), Soil Thematic Strategy, Commission of the European Communities, COM (2006) 231, 22.9.2006, Brussels, On line at: http://eur-lex.europa.eu/legal content/EN/TXT/PDF/?uri=CELEX:52006DC0231&from=EN.

EC, (2011), Roadmap to a resource efficient Europe, European Commission, COM (2011), 571, 20.9.2011, Brussels, On line at: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52011DC0571.

EC, (2012), Guidelines on best practice to limit mitigate or compensate soil sealing, European Commission Staff Working Document, Luxembourg, On line at: https://ec.europa.eu/environment/soil/pdf/guidelines/pub/soil_en.pdf.

EC, (2013), The 7th Environment Action Programme (EAP). General Union Environment Action Programme to 2020. Living Well, Within the Limits of Our Planet. *Official Journal of the European Union*, **L 354**.

EC, (2016), Science for Environment Policy, No net land take by 2050?, Future Brief 14, produced for the European Commission DG Environment by the Science Communication Unit, UWE, 04.2016, Bristol, On line at: ec.europa.eu/environment/integration/research/newsalert/pdf/no_net_land_take_by_2050_FB14_en.pdf.

EEA, (2013), Land take, On line at: http://www.eea.europa.eu/data-and-maps/indicators/land-take-2.

Enault L.C., Popoff T., Debolini M., (2020), Vacant lands on French Mediterranean coastlines: Inventory, agricultural opportunities, and prospective scenarios, *Land Use Policy*, **100**, doi: https://doi.org/10.1016/j.landusepol.2020.104914.

Felsenstein D., Lichter M., (2014a), Social and economic vulnerability of coastal communities to sea-level rise and extreme flooding, *Natural hazards*, **71**, 463-491.

Felsenstein D., Lichter M., (2014b), Land use change and management of coastal areas: Retrospect and prospect, *Ocean & Coastal Management*, **101**, 123-125.

Fu D., Bu B., Wu J., Singh R. P., (2018), Investigation on the carbon sequestration capacity of vegetation along a heavy traffic load expressway, *Journal of Environmental Management*, **241**, 549-557.

Hasan S., Shi W., Zhu, X. (2020), Impact of land use land cover changes on ecosystem service value - A case study of Guangdong, Hong Kong, and Macao in South China. *PLoS ONE*, **15**, 1–20. https://doi.org/10.1371/journal.pone.0231259

ISTAT, (2018), Italian statistical yearbook, National Institute of Statistics, On line at: https://www.istat.it/it/files/2018/12/Asi-2018.pdf.

Jones A., Panagos P., Barcelo S., Bouraoui F., Bosco. C., Dewitte O., Jeffery S., (2012), The state of soil in Europe, A Contribution of the JRC to the European Environment Agency's Environment State and Outlook Report – SOER 2010, European Commission: Luxembourg, On line at: https://publications.jrc.ec.europa.eu/repository/bitstream/JRC68418/lbna25186enn.pdf.

Lai S., Lombardini G., (2016), Regional drivers of land take: A comparative analysis in two Italian regions, *Land Use Policy*, **56**, 262-273.

Louwagie G., (2016), Land recycling in Europe-approaches to measuring extent and impacts, EEA Report 31/2016, On line at: http://www.eea.europa.eu/publications/land-recycling-in-europe

Ludlow D., (2006), Urban sprawl in Europe: The ignored challenge, EEA Technical Report 10/2006, Office for Official Publications of the European Communities, Luxembourg, On line at: https://www.eea.europa.eu/publications/eea_report_2006_10/eea_report_10_2006.pdf.

Marchetti M., Bertani R., Corona P., Valentini R., (2012), Changes of forest coverage and land uses as assessed by the inventory of land uses in Italy, *Forest@-Journal of Silviculture and Forest Ecology*, **9**, 170-184.

Munafò M., (2019), Land Consumption, territorial dynamics and ecosystem services, SNPA Report 08/19, On line at: http://www.isprambiente.gov.it/it/evidenza/snpa/no-homepage/consumo-di-suolo-dinamiche-territoriali-e-servizi-ecosistemici.-edizione-2019.

Munafò M., Assennato F., Congedo L., Luti T., Marinosci I., Monti G., Riitano N., Strollo A., Tombolini I., Marchetti, M. (2015), Land Consumption in Italy, ISPRA Reports, 218/15, On line at: https://www.isprambiente.gov.it/it/pubblicazioni/rapporti/il-consumo-di-suolo-in-italia-edizione-2015

OECD, (1993), Coastal Zone Management - Integrated Polices, Organisation for Economic Co-operation and Development, Paris, On line at: http://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=OCDE/GD(97)83&docLanguage=En.

Romano B., Zullo F., Fiorini L., Marucci A., Ciabò S., (2017), Land transformation of Italy due to half a century of urbanization, *Land Use Policy*, **67**, 387–400.

Runko Luttenberger L., Gudelj I., Hršak V., (2018), Natural capital preservation in the coastal area, *Pomorstvo*, **32**, 191-200.

Tang Z., Shi C., Bi K. (2014), Impacts of land cover change and socioeconomic development on ecosystem service values. *Environmental Engineering and Management Journal*, 13(10), 2697–2705.

Small C., Nicholls R., (2003), A Global Analysis of Human Settlement in Coastal Zones, *Journal of Coastal Research*, **19**, 584-599.

Strollo A., Smiraglia D., Bruno R., Assennato F., Congedo L., De Fioravante P., Giuliani C., Marinosci I., Riitano N., Munafò M., (2020), Land consumption in Italy. *Journal of Maps*, **16**, 113–123.

Ye Y., Zhang J., Bryan B. A., Gao L., Qin Z., Chen L., Yang J. (2018), Impacts of rapid urbanization on ecosystem services along urban-rural gradients: a case study of the Guangzhou-Foshan Metropolitan Area, South China. *Ecoscience*, **25**, 235–247.

Environmental Engineering and Management Journal

October 2020, Vol. 19, No. 10, 1869-1889
http://www.eemj.icpm.tuiasi.ro/; hiip://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

CITRUS AS A MULTIFUNCTIONAL CROP TO PROMOTE NEW BIO-PRODUCTS AND VALORIZE THE SUPPLY CHAIN

Paola Sangiorgio*, Alessandra Verardi[1], Anna Spagnoletta[1], Roberto Balducchi[1], Gian Paolo Leone[2], Daniele Pizzichini[2], Stefania Raimondo[3,4], Alice Conigliaro[3,4], Riccardo Alessandro[3,4]

[1]*ENEA, Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Department of Sustainability, Trisaia Research Center, SS Jonica 106, km 419+500, 7026 Rotondella, Italy.*
[2]*ENEA, Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Department of Sustainability, Casaccia Research Center, Via Anguillarese 301, 00123, Rome (RM), Italy.*
[3]*Department of Biomedicine, Neuroscience and Advanced Diagnostics (Bi.N.D.), Section of Biology and Genetics, University of Palermo, Palermo, Italy*
[4]*NAVHETEC s.r.l. Via Enzo ed Elvira Sellerio, 57, Palermo, Italy*

Abstract

Citrus is one of the most important fruit tree crops worldwide, with respect to both total production and economic value. About 80% of the world production is destined to the fresh market, the remaining is processed to obtain various products (juices, jams, etc.). *Citrus* processing residues account for about 50-60% of processed fruits; their huge amounts and peculiar characteristics need a correct management that imply cost for producers and processors. If not well managed, they can represent an environmental issue. On the contrary, *Citrus* residues are a valuable source of bio-based products of interest in several sectors, as well as molecules useful for the chemical industry, cosmetics and human health. In a bioeconomy perspective of full exploitation and valorization of agricultural and processing residues, *Citrus* as a multifunctional crop can therefore generate new economic opportunities and benefits for all stakeholders, promoting at the same time the development of territories. This paper describes the current and promising pathways of valorization of *Citrus* residues by reviewing the most recent scientific literature. Alongside the bioproducts useful in agro-livestock field (feed, fertilizers), energy (biofuels), environmental and industrial sector (bio-sorbents, fibers for papermaking and textiles), a particular emphasis is given to the value added compounds with application in food, pharmaceutical, nutraceutical, cosmetic and chemical industries (polyphenols, carotenoids, essential oils, citric acid, dietary fibers and pectin, single cell proteins, Extracellular Vesicles). To our knowledge this is the first review that considers Extracellular Vesicles as a way to valorize *Citrus* processing residues.

Key words: biofuels, cascading biorefinery, *citrus* processing residues, extracellular vesicles, value added products

Received: February, 2020; Revised final: June, 2020; Accepted: July, 2020; Published in final edited form: October, 2020

1. Introduction

Citrus is one of the most important commodities in the world. *Citrus* global production for 2018/2019 stands at about 100 million Mg (Mg is the SI unit equivalent to tonne), with China leading the ranking of producers (34%), followed by Brazil (19%), European Union (11%), United States and Mexico (7%) (USDA, 2020). Italian *Citrus* production stands at around 3.2 million Mg produced: the highest production relates to oranges (1.9 million Mg), followed by mandarins and lemons (with 816 and 460 thousand Mg, respectively). In particular, production is mainly concentrated in Sicily (for about 55%), a southern region where around 84,000 hectares are devoted to citriculture; most of them are dedicated to

* Author to whom all correspondence should be addressed: e-mail: paola.sangiorgio@enea.it; Phone: +39-0835974717; Fax: +39-0835974724

orange cultivation (around 65%) (ISTAT, 2019). About 80% of the world production is destined to the fresh market, the remaining is processed to obtain various products (juices, jams etc.). In the period 2018-2019, Brazil is the main *Citrus* processor (14 million Mg of total processed citrus), followed by United States (4 million Mg), Argentina and European Union (about 2 million Mg), (USDA, 2020).

Citrus processing residues (CPR) account for about 50-60% of processed fruits, depending on adopted technology and fruit cultivar. CPR is characterized by low pH, high organic matter (95% of total solids) and high-water content (around 80–90%) (Satari and Karimi, 2016). Unfortunately, it is still considered as waste and often disposed in the fields, with related environmental problems. On the contrary, it can find application in different sectors, after proper technological processes, as feed, fertilizers (Zema et al., 2018), bio-sorbents (Timková et al., 2018), biofuels (Taghizadeh-Alisaraei et al., 2017), etc. and is a valuable source of bio-based products, as well as molecules useful for the chemical industry, cosmetics and human health (Negro et al., 2016). It is important to set up a bioeconomic strategy for the exploitation and full utilization of *Citrus* waste, according to a cascading biorefinery concept: this can solve problems related to the management of the large amounts of CPR and meet the needs of agricultural/agro-industrial sectors, that aim to “capture value” from their production residues (Campos et al., 2020).

In view of an effective valorization of *Citrus* by-products, seasonality, transportation and storage issues cannot be overlooked (Raimondo et al., 2018a). Indeed, CPR can be stored for short periods as its high moisture and high levels of residual sugars often support secondary fermentation and/or mold growth, as well as attracting flies and releasing sludge hazardous to the environment. On-site valorization can be a solution, but if this is not technically or economically possible, stabilization treatment can be carried out to allow better storage and improve the handling characteristics for transport to an off-site treatment (Satari and Karimi, 2018; Zema et al., 2018).

Transport costs may affect considerably the economical convenience of a CPR valorization; they mainly depend on CPR mass, distance, roads and accessibility (Calabrò et al., 2017). Moreover, the presence of pesticides (or other unwanted compounds that could be found and concentrate in the final product) can limit its use (Tayengwa and Mapiye, 2018; Wadhwa et al., 2015).

CPR is constituted by about 40-55% peels, 30-35% internal tissues and less than 10% seeds (Sharma et al., 2018). CPR mainly contains soluble and insoluble carbohydrates (cellulose, pectin), sugars (glucose, fructose, sucrose, galactose), acids (mostly citric and malic acids), lipids (oleic, linoleic, linolenic, palmitic, stearic acids, glycerol and phytosterol), limonoids (limonin, isolimonin), essential oils (mainly D-limonene), pigments and carotenoids (carotene, xanthophylls, lutein), polyphenols (flavonoids and phenolic acids) and vitamins (ascorbic acid, complex B vitamins) (Satari and Karimi, 2018; Sharma et al., 2017, 2018; Zema et al., 2018). CPR composition is affected by different factors, such as cultivar, fruit cultivation technique, harvesting time and maturity stage and the different juice extraction methods (Sharma et al., 2017). As shown in Fig. 1, *Citrus* and its processing residues provide a variety of valuable products that can find application in several sectors, such as agricultural, textile and paper sector, environmental remediation, green energy, nutraceutical, pharmaceutical, cosmetic and food industry. In particular, *Citrus* residues deriving from juice processing contains interesting vesicles, on which several studies have focused in recent years (Raimondo et al., 2015).

This work describes the current and promising pathways of CPR valorization, in the light of the most recent scientific literature. Citrus-derived bioproducts are described in a holistic vision - uses/functionalities, production technologies and market size-, and a wide range of CPR applications is examined. Moreover, among the high-added value compounds, this work focuses on Extracellular Vesicles (EVs), that have very powerful and interesting applications in pharmaceutical and nutraceutical sectors: to our knowledge, it is the first time that a paper concerning the CPR valorization takes in consideration these bioactive structures.

2. Valorization of C*itrus* processing residues

2.1. Livestock feed

As conventional feedstuffs are often expensive, the use of CPR as animal feed may be economically worthwhile; indeed, it is still the cheapest and easiest way to manage the large amount of waste produced every day from *Citrus* processing facilities, alongside the biofuel production. However, it is not very profitable (Chavan et al., 2018). Several authors reviewed the use of CPR, as well as cull or excess fruit, as ingredient for ruminant feed: their high levels of structural fiber and bioactive molecules meet ruminant nutrient requirements for maintenance, growth, reproduction and production (Correddu et al., 2020; Vasta et al., 2019; Wadhwa et al., 2015).

Fresh CPR is readily consumed by dairy cattle, but in consideration of the high fermentability of its carbohydrate content, together with its high moisture, dried CPR is a preferred alternative. Alongside sun-drying, the ensiling can be a simple and cheap conservation method of CPR, especially in less-developed countries or at the level of small villages. Alternatively, lime can be added to CPR, after shredding, to release the bound water and facilitate the moisture removal by simply pressing. In this way, the subsequent drying step is less costly. Dried CPR can be included up to 40% in the diets of fattening cattle without altering animal health and can be a cereal substitute for ruminants.

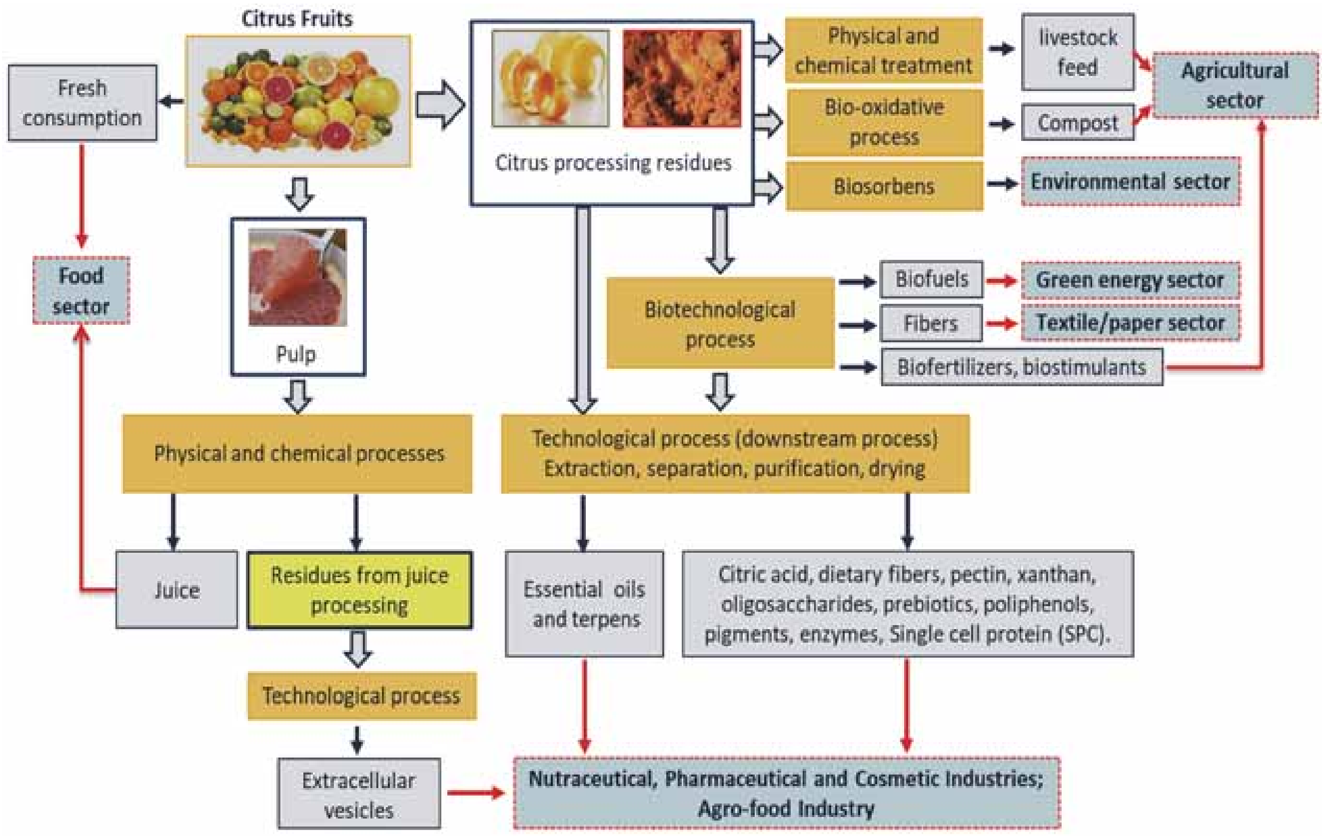


Fig. 1 Pathways of valorization of *Citrus* processing residues

It is a good source of energy, fibers and water soluble sugars, and it is rich in calcium (1-2%) if lime is added in the drying process (Alnaimy et al., 2017). Although its fiber content is too high for non-ruminant species, dried orange pulp has been fed to laying lens to study the antioxidant levels of the resulting egg yolk (Goliomytis et al., 2018): the results showed a significant increase in the egg oxidative stability, although egg quantity and quality decreased. Dried *Citrus* pulp was also added to pig feed: added up to 7.5%, it didn't affect significantly the growth of weanling pigs and gut morphology (Almeida et al., 2017). In order to modify the fibrous materials, enzymatic pretreatment was studied on *Citrus* by-products for feed/food applications. Two pectin methylesterases, two pectinases and a cellulase were used in different conditions; *Citrus* modified residues showed an increase both in swelling and water-holding capacity compared to the untreated material, dependently on temperature and treatment duration (Canela-Xandri et al., 2018).

Another feedstuff deriving from processing is *Citrus* molasses, i.e. the product resulting from the concentration of the press liquor from peels residues. *Citrus* molasses is extremely bitter, but its taste is accepted by cattle, in the same way as sugarcane molasses. *Citrus* residues containing seeds may be toxic to non-ruminants, because of its limonin content (Fuller, 2004). Finally, even if *Citrus* by-products show low nitrogen content, this can be compensated by mixing them with other feedstocks (Tayengwa and Mapiye, 2018).

2.2. Fertilizing products

Agronomic utilization of CPR as soil conditioner or organic fertilizer is a suitable practice to improve soil fertility, but its feasibility depends on many factors, including the mechanization level of distribution operations and the distance between the production and the spreading site. Direct land spreading of citrus waste might have harmful effects: the presence of bioactive molecules and essential oils (EOs) interferes with soil micro-organisms and microbial decomposition of the waste, thus polluting the environment (Mahato et al., 2019). In the past, up to 30-40% of the total CPR produced in Italy has been used as soil conditioner on fallow lands in rotation with durum wheat. Tuttobene et al. (2009) examined the direct and residual effects of increasing doses of industrial dried orange waste on the growth and productivity of durum wheat. Organic fertilization stimulated the growth of crops compared to mineral fertilization, but it seriously prevented settlement, growth rate and production if applied for two consecutive years at the maximum dose. By contrast, other studies reported positive effects on the physical-chemical characteristics of the soil when dried orange wastes were applied for a long time as organic fertilizer in orange orchards (Zema et al., 2018).

An alternative use of *Citrus* residues in agriculture is composting. Bio-transforming organic waste into agricultural products, rich in organic matter and nutrients, is a valuable strategy for recycling waste and improving soil fertility in sustainable agriculture. Moreover, composting transforms organic matter into stable compounds which can be handled, stored, transported and applied to land without adversely affecting the environment.

As for the compost obtained from orange residues, an acceptable degree of maturity, absence of phytotoxicity and low content of simple phenolic compounds are reached after an aerobic bioconversion of 5 months (Gelsomino et al., 2010). In addition, the research results suggested that orange compost can be used for organic fertilization of tomato and zucchini at field scale, while in nurseries it can be mixed with commercial impregnation substrates (such as peat) selected in relation to the sensitivity of the plants. In another study, conducted on melon plants under natural and induced *F. oxysporum f. sp. melonis* pressure, composts from *Citrus* residues mixed with pruning material from *Citrus* trees and ornamental shrubs showed not only nutriactive effects (due to their content of nutrients and hormone-like compounds), but also a biocontrol effect (mainly due to the biotic components). This allows to partially or integrally substitute non-renewable resource (i.e. peat) and reduce agrochemical costs (Bernal-Vicente et al., 2008). Similar results are found in a more recent work on composts and vermicomposts prepared from *Citrus*, maize and fig: *Citrus* residues showed the best performance on the growth of rosemary and lavender (Ryan, 2016).

Another important application of CPR is its use as a biofertilizer (Satari and Karimi, 2018). Biofertilizer is a substance that contains living microorganisms whose activity influences the soil ecosystem and promotes growth by increasing the supply or availability of primary nutrients to the host plant. Several studies have been conducted on the use of agro-industrial residues for the production of bio-fertilizers by using the Solid-State Fermentation process (SSF) on agro-industrial waste. Biofertilizers obtained by this technology from CPR showed to contribute significantly to the increase of the weight of Mustard plants; however, a reduction in the number of leaf growth and a lower length of longest root were observed, probably due to lower pH value than other biofertilizes (Lim and Matu, 2015).

Some authors reported that the digestate obtained by proper mixing of animal manure, maize silage, and *Citrus* waste is an antioxidant-rich compound that can be used as fertilizer in agriculture (Panuccio et al., 2016). Finally, the biostimulant activity of CPR has been studied on organic tomato. Aqueous extracts from lemon processing residues were tested alone or in combination with extracts from other by-products; results demonstrated their biostimulation potential on plant productivity (Abou Chehade et al., 2018).

2.3. Biofuels

The boosting global use of fossil fuels as the main source of energy, including oil, coal and natural gas, results in an increase of worldwide pollution levels and in a progressive depletion of fossil reserves, with a simultaneous rise of the cost of fossil fuels. Additionally, fossil fuels combustion is associated with the extensive release of carbon dioxide (CO_2), the most significant anthropogenic greenhouse gas (GHG) responsible for global warming (Wei et al., 2018). Currently, the CO_2 concentration exceeds 400 ppm by volume; its further growth in concentration potentially increases the greenhouse effect and, consequently, the global surface temperature.

In this scenario, the exploitation of new renewable resources for the production of biofuels is one of the greatest global challenges, necessary to replace the use of fossil fuels and to reduce GHG emissions (Jiang et al., 2018), thus improving air quality and reducing the pollution risks of groundwater (Cucchiella et al., 2019).

CPR is a promising lignocellulosic biomass for the manufacture of biofuels, due to its richness in soluble and insoluble carbohydrates and low lignin content (Taghizadeh-Alisaraei et al., 2017). Several studies have focused on CPR bioprocessing, in order to produce, in particular, bioethanol and biomethane, *via* the pretreated-biomass fermentation by the action of different aerobic and anaerobic microorganisms (Patsalou et al., 2019). Bioethanol is currently considered one of the best renewable liquid fuels from plant biomass for several reason: i) it can be used in current internal combustion engines as an alternative to gasoline, or mixed with gasoline in any ratio, enhancing security of supply (Baeyens et al., 2015); ii) it is easily carried and stored, as it is liquid at room temperature (Kirstine and Galbally, 2012); iii) it may form ethyl tert-butyl ether (ETBE) with isobutylene. ETBE is an oxygenate gasoline additive used as a substitute for methyl-tert-butylether (MTBE), obtained from petrochemical feedstock (Bušić et al., 2018). Biomethane production also offers many possibilities of use. It can be used for all natural gas end-user applications, resulting suitable for vehicle fuel, injection into the gas grid, and for electricity and heat production (Salman et al., 2017).

The current CPR biorefinery strategy aims at producing bioethanol and biomethane via a multi-step process: i) feedstock pretreatment, that generates EOs and pectin, while rendering the pretreated material more readily hydrolyzed by enzymes than untreated biomass (Patsalou et al., 2019); ii) enzyme hydrolysis; iii) fermentation and anaerobic digestion for bioethanol and biomethane production, respectively (Fig. 2). CPR pretreatment includes the removal of EOs and pectin to avoid biosystem inhibition (Indulekha et al., 2017; Ruiz and Flotats, 2016).

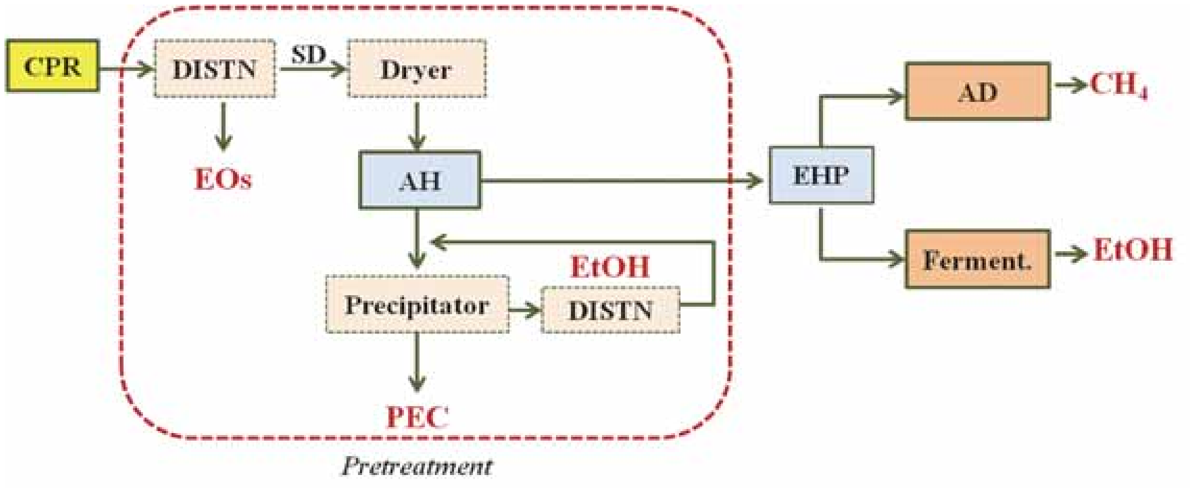


Fig. 2. Biorefinery strategy for CPR valorization. Based on Patsalou et al., 2019. (AD=anaerobic digestion; AH=acid hydrolysis; CH_4 = Methane; DISTN= distillation; EHP= enzymatic hydrolysis procedures; EtOH= ethanol; Ferment=fermentation; PEC=pectins; SD=solid fraction)

Different pretreatment methods for EOs extraction were investigated, such as hydrothermal sterilization (Indulekha et al., 2017), steam explosion (Golmohammadi et al., 2018), drying (Oberoi et al., 2010), popping (Choi et al., 2013), and dilute acid hydrolysis (Patsalou et al., 2019). EOs extraction is obtained via distillation, while the remaining solid residues are dried and subjected to dilute acid hydrolysis, performed under several conditions (Patsalou et al., 2019).

Thus, pectin is extracted from the hydrolysate by a precipitation process with ethanol addition (Kaya et al., 2014;). The hydrolysate is subsequently distilled to recover and recycle the ethanol used for pectin precipitation. The dilute acid hydrolysis of CPR is a fundamental processing step both for the pectin removal, and for breaking down hemicellulose to monosaccharides, making cellulose more susceptible to enzymatic degradation (Zhou et al,. 2014).

The enzyme hydrolysis is usually carried out by highly specific enzymes. The most commonly used enzymes mainly include *cellulases*, proteins able to work together synergistically to accelerate the cellulose degradation. Cellulase are conventionally divided into three major groups: exoglucanases or cellobiohydrolases, which hydrolyse the 1,4glycocidyl linkages to obtain cellobiose; endoglucanases, which attack low crystallinity regions in the cellulose fibers by endoaction, creating free chain-ends; and β-glucosidases, which convert cellulooligosaccharides and disaccharide cellobiose into glucose residues (Verardi et al., 2012).

The CPR hydrolysate, obtained *via* acid and enzyme hydrolysis, is utilized as a fermentation medium for bio-ethanol production (Joshi et al., 2015). The fermentation process can be performed by three techniques: batch, fed-batch, and continuous fermentation (Verardi et al., 2020). Batch culture is a technique of discontinuous fermentation in which growth takes place in a closed-loop system. The substrates and supplementary nutrients are added to the fermenter containing microorganisms at the start of the process. Then, the fermentation proceeds without any addition of new culture medium. After a proper time, the fermenter contents are taken out for processing. This technique is the simplest fermentation mode and it is argued to be more economic than continuous production. However, the batch culture shows several disadvantages, mainly the difficulty to maintain absolute sterility, solvent inhibition and low productivity (Bankar et al., 2014). In the fed-batch fermentation, a technique between batch and continuous fermentation, the substrate is gradually added at proper rate intervals, as it is consumed by the culture. Fed-batch fermentation is therefore applied when high concentration of substrate turns out to be toxic for microbial culture. The fermentation is stopped and products recovered when the volume of the fermentation broth achieves 75% of the fermenter volume (Amelio et al., 2016). In continuous fermentation, the substrate is added to the fermenter continuously at a fixed rate and the fermentation products are taken out constantly. Continuous fermentation determines a higher productivity, but also a relatively lower product concentration than that obtained by batch process. Moreover, the solvent production could be unstable over time and decrease with time (Amelio et al., 2016).

The fermentation process is carried out by microorganisms, including: i) bacteria, such as *Zymomonas mobilis*, *Bacillus macerans*, *Bacillus polymyxa*, *Klebsiella pneumoniae*, *Aeromonas hydrophila*, *Aerobacter sp.*, *Erwinia sp.*, *Leuconostoc sp.*, *Lactobacillus sp.* (Thatoi et al., 2016), and bacterial resources as engineering *E. Coli* (Scrichuwong et al., 2009); ii) yeasts and fungi, such as *Saccharomyces cerevisiae* that contains invertase, an enzyme able to hydrolyze sucrose in glucose and fructose (Baeyens et al., 2015), *Pichia kudriavzevii, Kluyveromyces marxianus* and several fungal species belonging to genera *Fusarium, Rhizopus*, *Monilia*, *Neurospora*, and *Paecilomyces* (Ali et al., 2016).

Several recent studies have tested and compared three major yeasts - *Kluyveromyces marxianus*, *Saccharomyces cerevisiae*, and *Pichia kudriavzevii* - for ethanol production in batch fermentations from pretreated CPR, by acid hydrolysis or a combined acid and enzymatic hydrolysis. In these studies, the highest ethanol concentration was obtained using the thermotolerant strain P. *kudriavzevii* (Patsalou et al., 2019).

CPR biomethanization is mainly obtained following EO extraction in order to both generate an added-value product and to reduce the anaerobic digestion inhibition caused by the antimicrobial properties of the oil (Negro et al., 2018). In some research studies, untreated CPR was directly used in anaerobic digestion of fresh or dried *Citrus* fragments (peel, pulp, and seeds) under mesophilic (Sanjaya et al., 2016) and thermophilic (Koppar and Pullammanappallil 2013) conditions. However, the CPR pretreatment in anaerobic digestion increases production of biomethane compared to the use of untreated CPR (Patsalou et al., 2019).

The anaerobic digestion, using pretreated CPR, is a naturally occurring biological process that can be divided in several steps (Xu et al., 2019): i) the complex organic polymers, decomposed into simpler utilizable corresponding monomers (e.g. amino acids, fatty acids, and sugars) are converted into a mixture of short chain volatile fatty acids (FA) by acidogenic bacteria (acidogenesis); ii) the volatile FAs are converted into acetic acid, CO_2, and H_2 by acetogenic bacteria or acetogens (acetogenesis); iii) finally, the acetate, CO_2, and H_2 are converted to methane and carbon dioxide by methanogens, a diverse group of strictly anaerobic bacteria belonging to the *phylum Euryarchaeota* in five orders that include mesophiles to thermophiles: *Methanobacteriales*, *Methanococcales*, *Methanomicrobiales*, *Methanopyrales*, and *Methanosarcinales* (Qiao et al., 2014). This process, known as methanogenesis, is the final step in anaerobic degradation of carbon and includes distinct pathways. The main pathway, called acetoclastic methanogenesis or acetate fermentation, is carried out by two genera of acetoclastic methanogens, belonging to *Methanosarcinales* order: *Methanosarcina* and *Methanosaeta*, which can split acetate to produce methane (Schlesinger and Bernhardt, 2013). When acetate is not available, a much wider variety of hydrogenotrophic methanogenesis, belonging to all five above mentioned orders, can use H_2 coupled to CO_2 reduction.

2.4. Bio-sorbents

During the 20th century, a wide dissemination of toxic metals in the environment has occurred, deriving from several anthropogenic sources (e.g. alloy production, leather tanning, mining, battery production, etc.). The environmental impact of toxic metals is a growing concern, owing to their persistence and non-degradable nature. Many heavy metals can enter the food chain and cause serious damage (Timková et al., 2018).

Biosorption is a physicochemical process that comprises the phenomena of molecules adsorption and absorption (Chen et al., 2014). It is based on the exploitation of biological sources with bio-adsorbent capacity to remove toxic metals and pollutants from contaminated water bodies. Different biological material types are being used as bio-sorbents - living biomass (microorganisms such as algae, fungi, yeast, mold and bacteria) or nonliving biomass (cellulosic nature materials, lignins and chitosans) - obtaining very promising results (Behnam et al., 2015; Shakoor et al., 2016).

Agro-industrial residues are the most used materials (Alalwan et al., 2020). CPR potential as bio-sorbent has been widely investigated for the uptake of different heavy metals and different activation methods or chemical treatments, useful to improve or change the adsorption, have been reported. The research studies analyze the effect of adsorbent amount, contact time, pH, temperature and competitive ions on the metal sorption and its ability to be regenerated, in order to well characterize the CPR sorption behavior (Satari and Karimi, 2018). Orange peels (activated and/or preloaded and or chemically modified) were used for binding: Pb(II), Zn(II), Cd(II), Cr(III), Cu(II), Fe(III), As(III) and As(V), Sb(III) and Sb(V), U(VI) (Arslan et al., 2017; Bakalár and Pavolová, 2019; Guiza, 2017; Inoue et al., 2017; Šabanović et al., 2019). *Citrus limetta* fruit residues, impregnated with iron, and pomelo peels were studied for the removal of As(III), As(V) and Cu(II), Cd(II), Ni(II), respectively (Chao et al., 2014; Verma et al., 2019). CPR bio-sorbents represent a promising alternative to ineffective and very expensive technologies commonly used for heavy metal removal from the environment, such as chemical precipitation, reverse osmosis, ion-exchange, ultrafiltration and electro-dialysis (Timková et al., 2018).

Studies on the comparison of biosorption capacity of orange native peels, depectinated peels and peel peptic acid confirm the important role of pectin in metal binding by CPR; indeed, the results indicate that pectic acid has the highest binding capacity, while native peels the lowest one (Schiewer and Iqbal, 2010). Pectin binding capacity is due to its large amount of functional groups (hydroxyl, carboxyl, amide and methoxy) that are known to be able to bind various compounds (Atzei et al., 2001; Ferri and Sangiorgio, 1996). Pectin-based bio-sorbents can therefore be usefully prepared from CPR. Removal of Ni(II) from aqueous solutions was achieved using a modified pectin sorbent, treating the extracted pectin from oranges with NaOH as demethylating agent (Kakoui et al., 2018).

Recent studies have also combined pectin and cellulose microfibers extracted from CPR to form composite beads for the removal of multi-metal ions from wastewater, in particular Fe(II), Cd(II) and Cd(II) (Lessa et al., 2020). *Citrus* pectin-based bio-sorbents can also be used for the removal of dyes. Porous carbons derived from *Citrus* pectin reported high adsorption capacity, rapid adsorption rate and good reusability for trapping methylene blue and methyl orange from water (Li et al., 2016; Zhang and Zhou, 2017). Orange pectin resulted a good support, not only to bind methylene blue and indigo carmine, but also to remove turbidity from water (Kebaili et al., 2018).

Finally, activated carbons are advantageously prepared from CPR (orange peels, in particular) as a carbon precursor instead of lignite, wood or synthetic precursors. They have shown an excellent sorption capacity, higher compared to dried orange peel (precursor) for trapping dyes and chlorophenoxyacid herbicides from water (Gutierrez et al., 2018; Pandiarajan et al., 2018). In a recent study, Zheng et al. (2020) have modified pomelo peel by using potassium hydroxide as activating agent and hydrothermal treatment; resulting biosorbents show excellent adsorption behavior for the removal of congo red in wastewater treatment.

Experimental results of the most recent researches on biosorbents derived from CPR for the removal of organic and inorganic contaminants are summarized in Table 1.

2.5. Fibers for paper production and textiles

Considering the shortage of conventional raw materials for papermaking, along with the increasing demand for paper products, it becomes necessary to find new raw materials for pulp production, such as agro-residues. *Citrus* (orange and lemon) peels can be used as supplements for tissue paper manufacture in low proportions (2.5-10%); in this way, a 0.9-4.5% reduction in final paper price could be achieved (Ververis et al., 2007).

Table. 1. Different citrus by-products used as biosorbents for organic and inorganic contaminants removal (Qm= maximum adsorption capacity)

Citrus biomass	***Biosorbent/ Treatment***	***Contaminants***	***Results***	***Ref.***
Lemon peel *(Citrus limon)*	Chemical modification with nitric acid, then sodium hydroxide	U(VI)	Qm=24.39 mg/g	Šabanović et al. (2018)
Orange peel *(Citrus sinensis)*	Drying	Ni(II)	Qm=19.76 mg/g (at Ni(II) 100 mg/L)	Kakoui et al. (2018)
Orange waste *(Citrus sinensis)*	Composite beads formed by extracted pectin and cellulose microfibers	Cd(II), Cu(II), Fe(II)	Adsorption capacities and removal efficiencies: Fe(II) > Cu(II) > Cd(II). Qm for Cu(II), Cd(II) and Fe(II) ions were 192.30, 88.5 and 98.0 mg/g, respectively.	Lessa et al. (2020)
Pomelo peel (*Citrus maxima*)	Degreasing	Cu(II), Cd(II), Ni(II), Pb(II)	Metal removal in a fixed-bed column. Great adsorption capacity.	Chao et al. (2014)
Orange juice residues *(Citrus sinensis)*	Saponification with calcium hydroxide	Pb(II), Cu(II), Cd(II), Zn(II), Mn(II), Fe(III), As(III and V), Sb(III and V)	Selectivity: Pb(II) > Fe(III) > Cu(II) > Cd(II) > Zn(II) > Mn(II). Qm: Fe(III)=1.55 mol/kg; other metal ions= 1.10 mol/kg. Biosorbents preloaded with Fe(III) and Zr(IV), selectively separated As(III and V) and Sb(III and V) from chloride, nitrate, and sulfate.	Inoue et al. (2017)
Waste orange peel *(Citrus sinensis)*	Drying	Cu(II)	Sorption capacity 63mg/g	Guiza (2017)
Orange peel *(Citrus sinensis)*	Drying	Zn(II), Cd(II)	Qm of Zn(II) and Cd(II) were 15.51 and 19.8 mg/g, respectively	Bakalar et al. (2019)
Orange Peel *(Citrus sinensis)*	Activation with Potassium Carbonate	Cr(III)	Qm depends on the initial Cr(III) concentration and increases from 0.579 mg/g (at Co=5 mg/L) to 5.77 mg/g (at Co= 50 mg/L)	Arslan et al. (2017)
Limetta peel and pulp *(Citrus limmeta)*	Two developed biosorbents (PAC-500 and PPAC-500)	As(III), As(V)	Qm for As(III): PAC-500: 714.28 μg/g PPAC-500: 526.31 μg/g, for As(V); 2,000 μg/g for both the biosorbents.	Verma et al. (2019)
Orange waste *(Citrus sinensis)*	Coagulant prepared from extracted pectin. Adsorbent prepared from waste residue of pectin extraction	Methylene blue, indigo carmine, turbidity	Good coagulant to reduce turbidity. Valuable adsorbent for removal of dyes	Kebaili et al. (2018)
Citrus biomass	Carbon microspheres prepared by hydrothermal method without any chemicals.	Methylene blue	Superior adsorption capacity, high adsorption rate, and good reusability	Zhang et al. (2017)
Waste orange peel *(Citrus sinensis)*	Orange peel activated carbon	Chlorophenoxyacetic acid herbicides	Qm= 574.71 mg/g	Pandiarajan et al. (2018)
Pomelo peel (*Citrus maxima*)	Carbonization and activation with KOH	Methyl orange	Qm= 680.2mg/g	Li et al. (2016)
Pomelo peel (*Citrus maxima*)	Carbonization and activation with KOH	Congo red	Qm= 144.93 mg/g at 303 K	Zheng et al. (2020)

The incorporation of CPR in paper and paperboard has been investigated and several products and processes have been patented in this area (Kasaai and Moosavi , 2017; Robinson et al., 2017). Textile fibers production can represent another alternative to recycle the large amounts of discarded *Citrus* fruits or *Citrus* waste; in Italy, a process for producing spinnable cellulose from orange and lemon has been recently developed and patented. The produced fibers don't compete with food crops for land and, compared to cotton ones, require much less water (as cotton irrigation water is about 5 times that of citrus) and pesticides (for 1 kg of yarn, 1,6 g and 127 g of pesticides are used for *Citrus* and cotton, respectively) (Santanocito and Vismara, 2015).

2.6. High value compounds

CPR is a valuable source of soluble sugars, organic acids, fibers, proteins, amino acids, minerals, oils, lipids, vitamins, polyphenols and pigments. Its economic potential is demonstrated by the market size of these high added value products, as shown in Fig. 3, as regards flavonoids, carotenoids, EOs, citric acid and pectin. Different technological processes can be employed to obtain these high value compounds from *Citrus* by-products (Mahato et al., 2019). In this regard, many efforts have been made to develop processes that are not only efficient, cost-effective and sustainable, but also easy to apply. Novel extraction technologies have been recently used for sustainable bioactive and high-added value compounds from *Citrus* fruits, such as microwave-assisted extraction (MAE), ultrasound-assisted extraction (UAE), enzyme-assisted extraction (EAE), high voltage electrical discharges (HVED), pulsed electric fields assisted extraction (PEF), pressurized liquid extraction (PLE), supercritical fluids extraction (SFE), and others, aligned with the "green" concepts and able to provide raw materials on industrial scale with optimal energy and chemicals expenditure. After extraction, the high-added value compounds are separated and purified using different techniques, including chromatographic and membrane separation.

Some of the main bioactive compounds and high value products will be considered in detail in this paper. Their main recovery methods from CPR and their health benefits are summarized in Fig. 4. Experimental results of the most recent researches on bioactive compounds extracted from CPR by some novel extraction technologies are reported in Table 2.

2.6.1. Polyphenols

Citrus fruits are an important source of polyphenols, generally contained in the fruits' outside surface (peels, shells and hulls) and involved in the protection of the *Citrus* fruits' inner tissues from harmful UV and IR sun rays, as well as in the defense from microbial infections (Mahato et al., 2019). Moreover, the content of total polyphenols is higher in peels than in peeled fruits: this confirms the high value of *Citrus* residues and the need for their valorization (Ballistreri et al., 2019). Polyphenols are secondary natural metabolites with high biological health-promoting properties, related to their antioxidant, redox modulating, anti-inflammatory (Castellani et al., 2018; Magrone et al., 2017a) and anti-aging activities (Wu et al., 2020), as well as to their modulatory properties on various signalling pathways influencing the immune system response, neuronal development, survival, regeneration or death (Magrone et al., 2017b, 2017c, 2019a, 2019b; Mansuri et al., 2014).

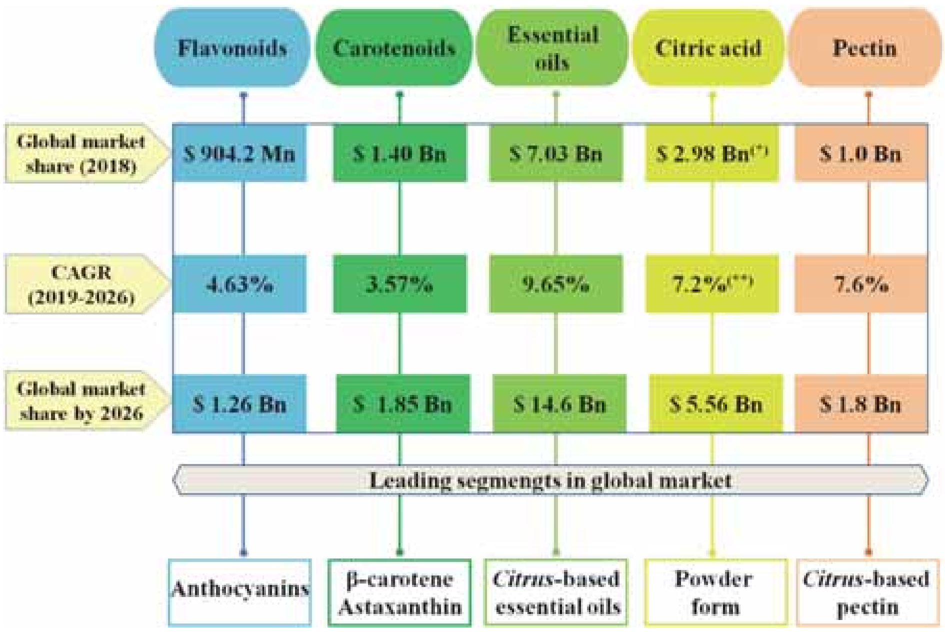


Fig. 3. Global Market of Flavonoids, Carotenoids, EOs and Pectin (Mn=million; Bn=billion). Statistics referring to: 2017 (*) , 2020-2026 (**). Data elaborated from: DBMR, 2019; FBIR, 2019a; 2019b; IndustryARC Report, 2019; Orian Research Report, 2019; Zion Market Research Report, 2018

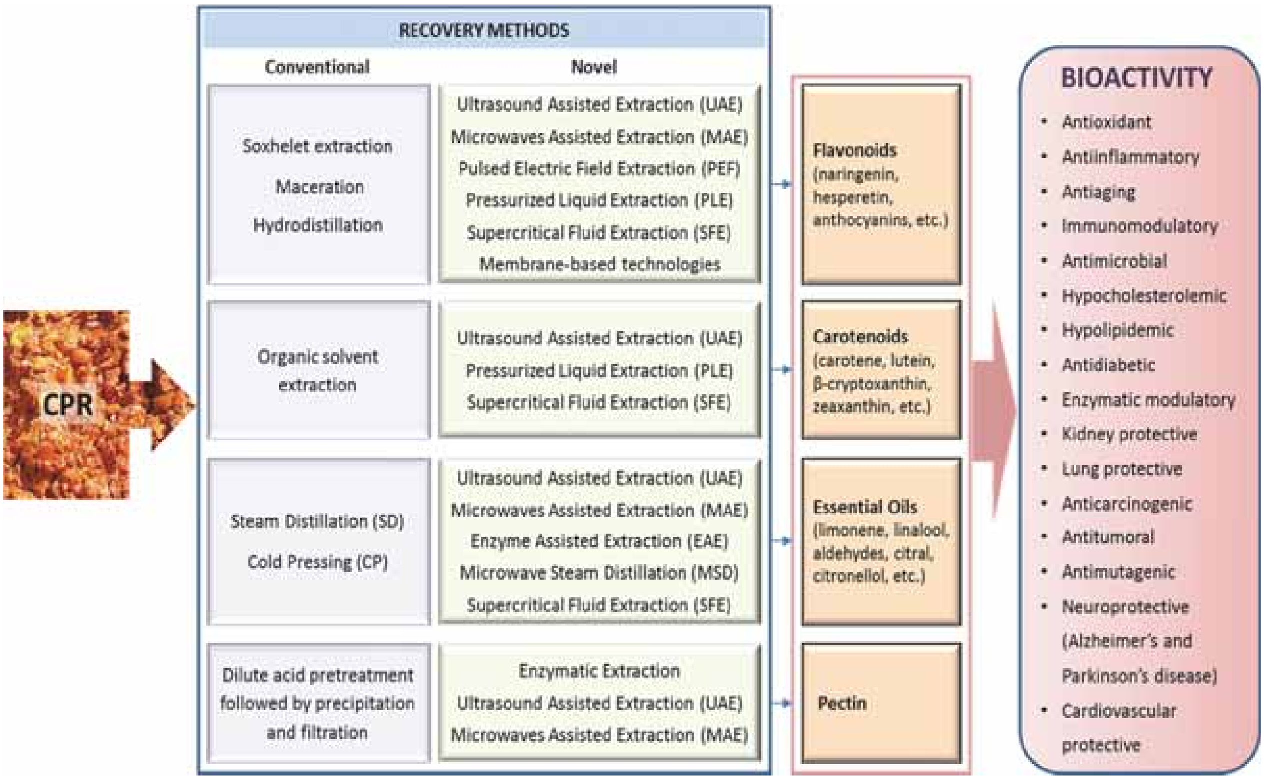


Fig. 4. Recovery methods of *Citrus* bioactive compounds from CPR and their health benefits

Table. 2. Bioactive compounds from CPR by some novel extraction technologies

POLYPHENOLS			
Citrus By-Product	**Technique Employed**	**Results/ Extraction Yield**	**Ref.**
Orange peel *(Citrus sinensis (L.) Osbeck)*	UAE	TPC: 31%; Hesperidin: 42%; Naringin: 38%.	Putnik et al. (2017)
Orange peel *(Citrus spp. N/A)*	UAE	TPC: 105.96 mg GAE/100 g; Hesperidin: 113.03 mg/100 g.	Montero-Calderon et al. (2019)
Orange peel *(Citrus spp. N/A)*	UAE	TPC: 2,140 mg GAE/100g DP; Hesperidin: 794.4 mg/100g DP; Naringin: 80.5 mg/ 100 g DP.	M'hiri et al. (2015)
Orange peel *(Citrus spp. N/A)*	UAE	Global yield: 21.9± 0.5 %; TPC: 580 mg GAE /100 g DP.	Barrales et al. (2018)
Mandarin peel (*Citrus reticulate* Blanco cv. Sainampueng)	UAE	Global yield: 26.52%; TPC: 15,263.32 mg GAE/100 g DP; Hesperidin: 6,435.53 mg/100 g DP.	Nipornram et al. (2017)
Orange peel *(Citrus spp. N/A)*	PLE	Global yield: 34.8 ± 0.3 %; TPC: 1,590 mg GAE/100 g DP; Hesperidin: 5,400 mg/100 g DE; Naringin: 22.6 mg/100 g DE.	Barrales et al. (2018)
Orange peel *(Citrus sinensis (L.) Osbeck)*	MAE	TPC: 1,220 mg GAE/ 100 g DP.	Putnik et al. (2017)
Orange peel (*Citrus sinensis (L.) Osbeck*)	MAE	TPC: 2,688 mg GAE /100 g DP; Hesperidin: 928.9 mg/100g DP; Naringin: 125.6 mg/ 100 g DP.	M'hiri et al. (2015)
CAROTENOIDS			
Citrus By-Product	**Technique Employed**	**Results/ Extraction Yield**	**Ref.**
Orange peel *(Citrus sinensis)*	UAE	TC: 0.63 mg β-carotene/100 g.	Montero-Calderon et al. (2019)
Orange peel *(Citrus spp. N/A)*	UAE	TC: 3.20 mg β-carotene/100 g.	Murador et al. (2019)
Orange peel *(Citrus spp. N/A)*	UAE	TC: 1.13 mg β-carotene/100 mL of extraction.	Boukrofa et al. (2017)
Citrus peel *(Yuzu ichandrin*)	SFE	TC: 1,463 mg/g oil.	Ndayishimiye and Chun (2017)
Mixture of *Citrus* peel and seed *(Yuzu ichandrin*)	SFE	TC: 1,952 mg/g oil.	Ndayishimiye and Chun (2017)
Mandarin peel (*Citrus unshiu*)	SFE	β-carotene: 0.04-0.39 mg/100 g.	Tsitsagi et al. (2018)

ESSENTIAL OILS			
Citrus By-Product	**Technique Employed**	**Results/ Extraction Yield**	**Ref.**
Mandarin, orange, grapefruit and lemon peel (*Citrus spp.* N/A)	UAE	Limonene: 3,010 mg/100 g (mandarin); 1,360 mg/100 g (grapefruit); 1,280 mg/100 g (orange); 140 mg/100 g (lemon).	Omar et al. (2013)
Orange peel (*Citrus spp.* N/A)	MAE	D-limonene yield: 11.1%.	Attard et al. (2014)
Lemon peel (*Citrus lemon*)	SFE	D-limonene yield: 4.5%.	Lopresto et al. (2019)
DIETARY FIBERS: PECTINS			
Citrus By-Product	**Technique Employed**	**Results/ Extraction Yield**	**Ref.**
Orange peel *(Citrus Aurantifolia)*	EAE (Cellulase, Xylanase)	26.50 %	Data adapted from Panwar et al. (2019)
Cedar peels *(Citrus Medica)*	MAE	23.83 %	
Pomelo peel *(Citrus Maxima)*	Bronsted acidic ionic liquid based MAE	29.16 %	
Orange peel *(Citrus Sinensis*)	Surfactant based MAE	28 %	
Orange peel *(Citrus Aurantium)*	UAE	28.07 %	
CITRIC ACID			
Citrus By-Product	**Technique Employed**	**Results/ Extraction Yield**	**Ref.**
Orange peel *(Citrus sinensis)*	SMF	7.4 - 9.2 g/L	Rivas et al. (2008)
Lemon peel *(Citrus limon)*	SMF	84.5 - 94.3 %	Mohammed et al. (2020)
Orange peel *(Citrus sinensis)*	SSF	193 mg/g DP	Torrado et al. (2011)
Orange peel *(Citrus sinensis)*	SSF	With 10% nitrogen supplement: (27.60 - 38.16)%. With 15% carbon supplements: (22 - 32)%. With 3% methanol: (22.56 - 38.88)%.	Babu et al. (2017)
Abbreviations: TPC= total phenolic content; DE = Dry extract; DP= Dry peel; N/A=not available; TC= total carotenoids.			

Polyphenols are primarily classified into two major classes: non flavonoids (benzoic and cinnamic acid derivatives, stilbenes, tannins and lignans) and flavonoids (Singla et al., 2019). Flavonoids are the typical polyphenols of *Citrus* species, constituting 10% of the dry weight of the *Citrus* fruit (Mahato et al., 2019); they represent a very large group of natural compounds sharing the same basic structure: a flavan nucleus, consisting of two benzene rings (ring A and ring B) linked together through a third heterocyclic oxygen-containing pyrane ring (ring C). According to the location of the B-ring to C-ring and to the unsaturation and oxidation degree of the C-ring, flavonoids can be distinct in the following different sub-classes: flavanones, flavonols, flavones, isoflavones, flavanols (catechins and proanthocyanidins), and anthocyanins. Approximately 95% of flavonoids are represented by flavanones, mainly including: naringenin, hesperetin, eriodictyol, isosakuranetin and their respective glycosides. In particular, naringenin, hesperetin and its glycosides are present in high concentrations in *Citrus* fruits: naringenin and its derivatives are mainly found in grapefruit and sour orange; hesperetin and its derivatives are mostly found in sweet orange, tangelo, lemon and lime (Karak, 2019; Khan et al., 2014). Typical Italian pigmented orange cultivars (*Moro, Tarocco* and *Sanguinello*) are rich in anthocyanins, that show a high antioxidant activity acting as scavengers of free radicals (Cebadera-Miranda et al., 2019). Flavonoids are associated with a broad spectrum of health-promoting effects, due to their properties as antioxidants, anti-inflammatories, anti-mutagenic and anti-carcinogenic agents and to their lipid anti-peroxidation activities. They are also able to modulate key cellular enzyme functions and to inhibite several enzymes, such as xanthine oxidase (XO), cyclooxygenase (COX), lipoxygenase and phosphoinositide 3-kinase. Therefore, flavonoids are widely exploited in a variety of nutraceutical, pharmaceutical, medical and cosmetic applications (Panche et al., 2016).

The extraction of polyphenols from *Citrus* fruits is commonly carried out by conventional methods which include Soxhlet extraction, maceration and hydro-distillation, using organic solvents like water, alcohols (methanol, ethanol and/or their blends), acetone, diethyl ether, ethyl acetate, N,N-dimethylformamide (DMF) or their mixtures with different proportions of water (Rajbhar et al., 2015). In conventional methods, *Citrus* residues are treated with solvents for a defined time and then centrifuged; the supernatant is filtered and the obtained aliquot is concentrated by solvent evaporation (Mahato et al., 2019). The yield of the recovered phenolic compounds depends on the type of solvents used and on solvent polarity, as well as on the extraction time and temperature, and the physical-chemical properties of the samples (Rajbhar et al., 2015). However, these extraction techniques are characterized by long extraction times (which make phenolic acids susceptible to degradation), low extraction yields and high consumption of organic solvents. Different solvent residues, considered unsafe for food aims, may also remain in the final products, causing hazardous effects on human health; therefore, additional purification steps are needed, influencing the total process' costs (Mojzer et al., 2016).

Several research studies have focused on improving the polyphenols recovery by using non-conventional methods (green techniques), such as MAE (Putnik et al., 2017), UAE (Montero-calderon et al., 2019), PLE (Barrales et al., 2018), PEF (Luengo et al., 2013), SFE (Tyśkiewicz et al., 2018), and membrane-based technologies (Bassani et al., 2016). Nipornram et al. (2017) investigated the effects of different UAE parameters (temperature, time and power) on the extraction yield, total phenolic content and hesperidin content in mandarin peel: the optimized conditions resulted more efficient than the conventional maceration extraction. M'hiri et al. (2015) optimized the processing conditions for MAE, UAE, and SFE techniques, obtaining the highest total phenol and flavonoid contents from orange peel. These three methods are compared to the conventional extraction method. Membrane-based technologies represent one of the most powerful and widely used method for the recovery of polyphenols in combination with several extraction techniques. They are characterized by high selectivity towards specific compounds *via* a sieving mechanism and offer several other advantages compared to conventional separation methodologies: mild operating conditions in terms of pressure and temperature, preserving the functional properties of phenolic compounds; non-use of chemical agents or solvents and, consequently, product contamination; a reduced number of processing steps and low energy consumption. The scale-up of separation process by membrane-based technologies is therefore relatively easy, also considering the simple equipment required (Cassano et al., 2018; Martín et al., 2017). However, all the above-mentioned alternative extraction technologies are more competitive in comparison with conventional methods, since they allow to shorten the extraction time, reducing energy consumption and preventing the degradation of the phenolic compounds, as well as lowering the solvent amounts used in the extraction (Grosso et al., 2015). This results in a higher yield of polyphenolic compounds compared to conventional methods, as confirmed by different antioxidant assay systems (Mahato et al., 2019).

2.6.2. Carotenoids

Carotenoids are secondary metabolites widely distributed in plants, algae, bacteria, yeasts and molds, in which they play a role in the photosynthetic process or in the protective mechanism against damage by light and oxygen. In plants, carotenoids are essential for life, as they perform photo-protective functions during the photosynthesis process, prevent the photo-oxidative damage, act as precursor for the biosynthesis of the phytohormone abscisic acid (ABA) and promote the attraction of pollinators. Carotenoids are the main organic pigments in *Citrus* fruits, where they are responsible for coloration of the peel and pulp (Lado et al., 2019). About 600 carotenoids have been identified in nature and characterized (Young and Lowe, 2018), and more than 115 of these compounds have been found in *Citrus* fruits, in which they provide a wide range of colors, from yellow to red. As seen for polyphenols, peels are richer in carotenoids than pulp; their abundance in CPR makes them a valuable source of dietary bioactive molecules (Sharma et al., 2017). Indeed, a strong relationship has been observed between the intake of carotenoids and health benefits (Zhou et al., 2016). This correlation is due to their ability to interact with free radicals and singlet oxygen, therefore acting as effective antioxidants (Young and Lowe, 2018). In addition, many oncological and epidemiological investigations evidence as a nutritional regimen rich in carotenoids could reduce the incidence of several degenerative and cancer diseases. Chemically, carotenoids are lipid-soluble C40-tetraterpenoids and their basic structure is made up of eight isoprene units, resulting in a C40 carbon polyene chain that is considered the molecule's backbone. This chain could be terminated by cyclic end-groups (rings) and complemented with oxygen-containing functional groups. According to the structure, carotenoids are usually classified in two main classes: carotenes, that are hydrocarbon carotenoids, including β-carotene and lycopene, and xanthophylls, that are oxygenated carotenoids, including zeaxanthin and lutein (hydroxy), spirilloxanthin (methoxy), echinenone (oxo), and antheraxanthin (epoxy) (Eldahshan and Singab, 2013). Research has largely focused on few carotenoids that are mainly involved in aspects of human health, such as β-carotene, lutein and lycopene. In particular, *Citrus* fruit is generally rich in β-carotene, one of the most effective pro-vitamin A, used as ingredient in many supplements and cosmetic, pharmaceutical products. Currently, 97-98% of the β-carotene on the market is of synthetic origin and only 2-3% derives from bio-resources (Marino et al., 2020). *Citrus* fruits may represent one of the main bioresources from which to obtain this compound.

Conventional extraction of *Citrus* carotenoids, along with polyphenols, is carried out mainly by organic solvent methods (using solvents like isopropanol and petroleum ether, acetone followed by hexane, diethyl ether and methanol), considered environmentally harmful (Shukla et al., 2016). A non-conventional process used for the carotenoids extraction from *Citrus* peels is UAE (Boukroufa et al., 2017; Montero-Calderon et al., 2019; Murador et al., 2019); in this technique ultrasonic devices assist the extraction, so that lower amounts of cleaner solvents can be used. However, UAE needs to be followed by steps of separation and purification in order to remove undesired compounds.

SFE using CO_2 as supercritical fluid (SC-CO_2) is one of the most efficient alternative methods for carotenoids extraction from natural sources, such as plants and microalgae (Di Sanzo et al., 2018;

Mehariya et al., 2019; Molino et al., 2020a; Molino et al., 2020b). CO_2 is advantageously used since it is non-toxic and non-flammable, and its critical conditions (T = 31°C and P = 74 bar) are easily achievable and mild, reducing the degradation of thermo-labile molecules such as carotenoids. Furthermore, the presence of impurities among the extracted molecules is avoided through the total recovery of gaseous CO_2 during the separation between CO_2 and extracted molecules. Positive extraction results can be achieved also by adding co-solvent to increase the extraction efficiency. The extracts obtained by SFE are highly concentrated, as the solvent is separated by process depressurization making the extract free of residues. Although SFE equipment is characterized by high capital investment costs, the operating costs are usually lower compared to those required for conventional extraction. Moreover, the obtained products are characterized by high purity, meeting the market's needs of mild extraction conditions and sustainable production. Several researchers have carried out carotenoids recovery from *Citrus* fruit *via* SC-CO_2 (De Andrade Lima et al., 2019; Ndayishimiye and Chun, 2017; Satari and Karimi, 2018). In recent years, a stepwise extraction method has been carried out to sequentially extract EOs, carotenes, hesperidin and pectin from tangerine peel, by increasing the polarity of the supercritical fluid using different solvents as modifiers of CO_2 (Tsitsagi et al., 2018).

2.6.3. Essential oils

EOs are among the most important bio-products of CPR. EOs are a complex mixture of natural, volatile and aromatic compounds present at different depths in the peel and cuticles of the *Citrus* fruit, released from crushed oil sacs during juice extraction (Mahato et al., 2019). EOs are classified as secondary metabolites, including terpenoids, shikimates, polyketides and alkaloids, produced *via* three main pathways: methyl-erithrytol, mevalonate, and shikimic acid pathways (Dilworth et al., 2017). Among these, a high portion consists of monoterpenes, particularly d-limonene (merely called limonene), the most commonly found optical isomer or enantiomer of limonene and the main component of the EOs. All monoterpenes have antiseptic properties and some of these, such as limonene and α-pinene, show antitumoral properties (Buckle, 2015). Further *Citrus* major components are linalool, aldehydes, citral, and citronellol (Mahato et al., 2019). EOs are widely used in several products such as perfumes, cosmetics, food products, beverages, daily consumables, essences, pesticides and pharmaceuticals, due to its characteristic pleasant aroma, and to its antioxidant, antimicrobial, antibacterial and anti-insect properties. In addition, limonene can be used as clean solvent, instead of the toxic toluene (Dosoky and Setzer, 2018).

EOs are extracted by two main conventional methods: cold pressing (CP) and steam distillation (SD). During CP extraction, the peel and cuticle oils are removed mechanically, in order to obtain a watery emulsion, which is then centrifuged to recover the EOs. During SD process, the *Citrus* peels are exposed to boiling water or steam, so that the oils are released into water; in distillation, EO-vapors are condensed and collected. However, SD turns out to be a relatively simpler and cheaper method for recovering oil components compared to CP: the yield achieved by SD is also better (0.21%) than the CP yield (0.05%) (Mahato et al., 2019).

Modern extraction methods, including UAE, MAE, SFE, show many advantages over traditional methods, such as shorter time, higher extraction rate, energy saving and better products with low cost (Lopresto et al., 2019; Omar et al., 2013; Putnik et al., 2017). In particular, MAE technique enhances d-limonene recovery from *Citrus* peels in a relatively short time (Attard et al., 2014). Compared to conventional SD method, microwave steam distillation (MSD) is more efficient, greatly accelerating the extraction process and allowing EOs recovery without causing any changes in the oil composition. Short extraction time in MSD process is favored by more rapid breakdown of the cell wall under strong microwaves and by release of cell cytoplasm (Mahato et al., 2019). SFE using CO_2 is one of the most suitable methods for the extraction of EOs, thanks to the non-polar characteristic of supercritical CO_2; results showed higher extraction rate and yield than conventional systems. However, moisture content in the matrix decreases remarkably SFE performance, thus a pre-drying step is often required (Yasumoto et al., 2015).

2.6.4. Citric acid

Citrus fruits are rich in soluble organic acids, contained especially in the juice, such as citric (or citrate), malic, ascorbic, lactic, tartaric, benzoic, succinic, oxalic, formic acids. Citric (CA) and malic (MA) acids are the main contributors to *Citrus* juice acidity: CA is the most abundant acid (except for Clementines), followed by MA (Mahato et al., 2019). CA is widely used in several industries like food, beverage, pharmaceutical, chemical, cosmetics etc., as acidulant, chelating agent, emulsifiers, antioxidant, flavor additive, preservatives and plasticizer (Tong et al., 2019). CA is a weak organic six-carbon tricarboxylic acid, produced *via* three main methods: extraction from *Citrus* fruits, chemical synthesis and fermentation (Kanse et al., 2017). More than 90% of the CA produced worldwide is obtained by fermentation; in particular, for CA production from CPR, submerged fermentation (SmF) or Solid-State Fermentation (SSF) are more widely adopted, mainly using *Aspergillus niger* (Babu et al., 2017; Mohammed et al., 2020; Rivas et al., 2008). Other commonly utilized microorganisms are: *Penicillium restrictum*, *Penicillium janthinellum*, *Mucor piriformis*, *Trichoderma viride*, *Ustulina vulgaris*, various species of the genera *Eupenicillium*, *Botrytis*, *Absidia*, *Ascochyta*, *Talaromyces*, and *Acremonium* (Torrado et al., 2011). Among filamentous fungi, *Yarrowia lipolytica* has been recently investigated for

CA production; this species is able to use n-paraffins and fatty acids as carbon sources, thus increasing CA yield (Pandeeti et al., 2019). SmF is the most widely used fermentation method for CA production, but SSF has several advantages: ability to utilize agro-industrial by-products as substrates for bioconversion, lower energy and water requirements, lower operating costs (Show et al., 2015).

2.6.5. Dietary fibers: pectin

CPR contains both simple carbohydrates - reducing (fructose, glucose, and galactose) and non-reducing (sucrose) sugars - and nonstarch polysaccharides, commonly known as dietary fibers (DFs). DFs are complex carbohydrates conventionally classified in two groups: soluble dietary fibers (SDFs), including pectin, gums, pentosans and mucilage, and insoluble dietary fibers (IDFs), including cellulose, hemicelluloses, and lignin (Rivas-Cantu et al., 2013). *Citrus* fibers have higher quality than those from cereals, due to a higher balance between SDFs and IDFs, and higher capacities of water-holding and oil-holding. Moreover, Fibers extracted from *Citrus* exert high health benefits, due to the combined effects of DFs and antioxidants (flavonoids and vitamin C) present in CPR (Medhe et al., 2017). The amount of soluble sugars and DFs, such as pectin, cellulose, hemicelluloses and lignin, contained in CPR, are shown in Fig. 5. Soluble sugars and IDFs can be valuably employed in the production of bioethanol and energy (see section 2.3), SCP (see section 2.6.6) and other value added products, while pectins are widely used in food and cosmetic sectors (as gelling, thickening, and stabilizer agent), as well as in pharmaceutical industries (as bioactive components) and biomedical applications (drug delivery, tissue engineering, and wound healing) (Putnik et al., 2017; Robledo et al., 2019).

Pectins represent the most important compounds among SDFs, and have recently received great interest in the research field, thanks to their multiple positive effects on human health, including lowering lipid, cholesterol, serum glucose and insulin levels (Liu et al., 2016). Pectin has also immune-regulatory, anti-inflammatory, anti-bacterial, antioxidant and anti-tumoral effects, and it is associated with decreased risk of diabetes (Minzanova et al., 2018). In addition, pectin can bind toxic metal ions, thus decreasing their retention in the body and lowering their harmful effects, while enhancing intestinal solubility and absorption of ferric iron. Chemically, pectin is a complex mixture of heteropolysaccharides, containing a backbone referred to as galacturonan and composed by α-1-D-galacturonic (GAL) acid units linked via α-(1→4)-glycosidic bond (Lara-Espinoza et al., 2018).

Currently, 85% of the commercial pectin worldwide is extracted from *Citrus* peels. It is primarily used as a gelling and stabilizing agent. The capacity to form gel is one of the main and most attractive characteristics of pectin, as it is considered as a possible mechanism to improve cholesterol and lipid metabolism, gastric emptying, and glucose metabolism (Mudgil, 2017). Gelling mechanism mainly depends on the degree of methylation and is different for High Methoxyl and Low Methoxyl pectins; it is also affected by several parameters, such as temperature, pH, and the presence of co-solutes (Gawkowska et al., 2018).

Pectin extraction from citrus peel is commonly carried out by a multi-stage physical chemical process that requires a first cell walls treatment step, with hot dilute acid solution (e.g. HCl, HNO_3 and H_2SO_4), followed by a precipitation step, using ethanol or isopropanol, and a final filtration step. In this process, special care should be paid to several process parameters such as temperature, time and pH to prevent polymeric degradation (Satari et al., 2016). Main drawbacks of this acid extraction are the production of hazardous contaminants during treatment and the possible undesirable changes in pectin properties (Panwar et al., 2019).

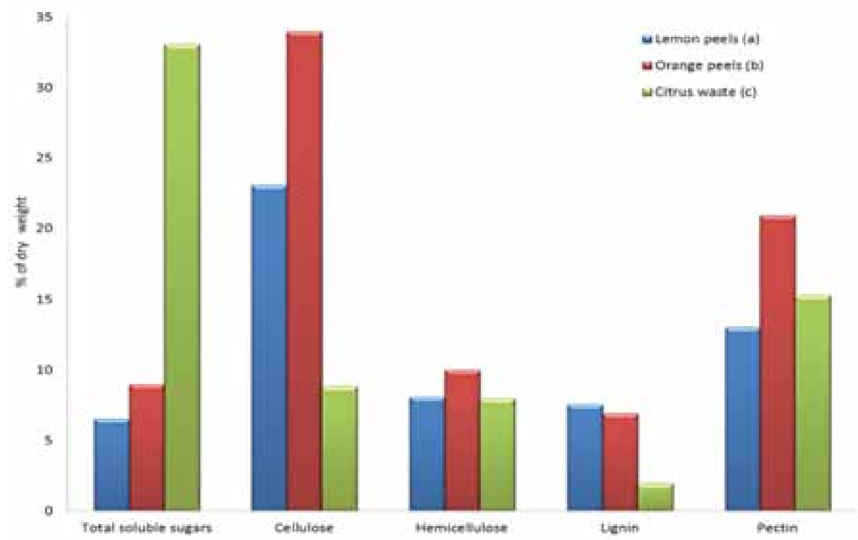


Fig. 5. Approximate chemical composition of some Citrus fruits processing residues, as % of dry weight. Based on: Satari and Karimi, 2018 (a, c); Rivas-Cantu et al., 2013 (b)

Several studies on pectin extraction *via* novel techniques have been extensively reviewed (Adetunji et al., 2017), including: i) enzymatic extraction, carried out by pectinolytic enzymes such as endo-/exo-polygalacturonase, pectinesterase, pectin lyase and pectate lyase, but also using proteases and cellulases; ii) UAE, whose implementation has produced a yield high pectin from grapefruit peel, compared with the conventional heating extraction; iii) MAE, reported as a successful method and used in presence or in absence of a solvent. Extraction by these sustainable technologies resulted in a higher yield of pectin compounds than the conventional method (Adetunji et al., 2017).

2.6.6. Single cell protein (SCP)

Single cell proteins (SCPs), as also called “microbial proteins”, are dead, dry cell of microorganisms such as algae, bacteria, yeasts and fungi, used as a non-conventional protein source in human foods and animal feeds (Raziq et al., 2020). The microalgae of interest for SCP production contain 42-62% protein on a dry weight base (DWB), that can be higher than conventional animal or plant sources (Barka and Blecker, 2016). Protein content in bacterial SCP is 50-80% on DWB and 30-50% on DWB in Yeasts and Fungi grown as SCP (Ritala et al., 2017). CPR contains carbohydrates that are natural substrates for microorganisms; therefore, it can be widely used as the source of carbon and energy for microbial growth by fermentation, promoting biomass development and protein concentrates (Yunus et al., 2015). The main SCP amounts have been provided by the cultivation of yeast and filamentous fungal species on *Citrus* waste materials, such as *Saccharomyces cerevisae, Kluyveromyces marxianus* and *Kefir* (Aggelopoulos et al., 2014), *Aspergillus niger* (Azam et al., 2014), *Candida utilis* and *Candida tropicalis* (Reihani and Khosravi-Darani, 2019). Before fermentation process, CPR needs to be pretreated and hydrolyzed by physical, chemical and enzymatic methods, in order to break down its lignocellulosic structure into cellulose, hemicelluloses and lignin components. These prior steps are fundamental to reduce the cellulose crystallinity and to increase the carbohydrates availability (amorphous cellulose and hemicelluloses) for microorganisms (Reihani and Khosravi-Darani, 2019).

The main fermentation systems employed for SCP production include solid state fermentation (SSF) and submerged fermentation (SmF). In the SSF process, the microorganism’s growth is achieved on predominantly insoluble substrate where there is no free liquid; in the SmF process, the growth of the microorganism occurs in a liquid medium in which various nutrients are dissolved or suspended as particulate solids (Azam et al., 2014; Zhou et al., 2019). The yield and productivity of SCP production are strongly dependent on culture medium composition and environmental conditions, such as pH, temperature, incubation period, dissolved oxygen, aeration rate, and nutritional requirements (carbon and nitrogen sources) (Hezarjaribi et al., 2016).

Currently, at least 25% of the world's population suffers from proteins deficiency, to a condition that may cause various health problems such as kwashiorkor, marasmus, immune system weakness, organ failure etc. (Khan et al., 2017). In this context, CPR bioconversion into SCP is a key to alleviate the worldwide protein scarcity, by obtaining a low-cost and safe product for human and animal consumption (Raziq et al., 2020).

2.6.7. Extracellular vesicles

Citrus cloudy juice can be clarified using different technologies, including centrifugation, depectinization (Uçan et al., 2014), fining agents and membrane technologies (Cassano and Jiao, 2014). Liquid residues, deriving from juice clarification, still contain interesting compounds as EVs. These vesicles are structures delimited by a lipid bilayer, naturally released by cells into the extracellular space (Raposo and Stoorvogel, 2013), differing for cellular origin, composition and size, thus representing a very heterogeneous population. Based on the physical characteristics, EVs are classified in small EVs, with a diameter <100nm, medium EVs, with diameter <200nm, and large EVs, with diameter >200nm (Thery et al., 2018). Interestingly, regardless of the compartment of origin and size, EVs mirror the physiologic or pathologic state of the releasing cells, carrying complex macromolecules including proteins, nucleic acids and lipids that have been selectively packaged inside. Moreover, today the EVs are counted among the cell-cell communication systems within the body; released EVs, in fact, can be internalized by other cells and their content can affect the phenotype of the receiving cell.

Although interest in cellular vesicles has arisen in biomedical research aimed at identifying the role of vesicles in influencing the body's physiology, a growing interest has recently emerged for vesicles introduced daily with our diet, including milk (Matsuda and Patel, 2018; Munagala et al., 2016) and vegetables (Yang et al., 2018). Several aspects make vesicles particularly attractive, not only for their intrinsic properties, depending on the bio-functional compounds naturally loaded in them, but also for their lack of toxicity, together with the possibility to be carried with other compounds for therapeutic applications.

Recent studies have shown that it is possible to isolate EVs of different diameters from various plant species: broccoli (Deng and Rong, 2017), grape (Ju and Mu, 2013), grapefruit (Wang and Zhuang, 2014), ginger (Zhuang and Deng, 2015) and different *Citrus* species, *C. sinensis*, *C. limon*, *C. paradisi* and *C. Aurantium* (Pocsfalvi and Turiak, 2018; Raimondo et al., 2015, Raimondo et al., 2018b). These studies, in addition to reporting the isolation methods and the morphological and biochemical analysis of isolated vesicles, highlighted their significant anti-inflammatory effect on cellular and murine models, as well as their inhibitory effect on tumour cell growth. In particular, studies carried by researchers of the University of Palermo have shown that vesicles isolated from lemon juice reduce the growth of neoplastic cells and induce apoptotic cell death (Raimondo et al., 2015); further studies have also shown that these vesicles negatively regulate colon cancer cell lipid metabolism (Raimondo et al., 2018b).

To date, protocols for EVs isolation (Konoshenko et al., 2018) have been established on matrices of animal origin, in particular on conditioned medium of cell cultures and body fluids. For the improvement of the existing purification techniques, the heterogeneity of the sample and the volumes to be processed have been taken into account. The gold-standard in the isolation of vesicles today is represented by the use of ultracentrifuge coupled with density gradient, in particular for particles of small size. However, contamination by other macromolecules, as well as time-consuming represent limits to its application at industrial level. Other methods include precipitation-based and immunoaffinity-based protocols (Agrahari et al., 2019).

Numerous works have recently highlighted how size-exclusion chromatography (SEC) can represent a valid method of isolation even from a matrix of larger volumes than those processed using the methods described above (Monguio-Tortajada et al., 2019). SEC is based on the separation of particles by their sizes, *via* the use of a porous matrix, usually a resin, packed in a column. The results obtained so far have shown that SEC allows a faster purification of vesicles and that is able to eliminate soluble proteins that often precipitate during the ultracentrifugation process. Some of the isolation methods described above have just been applied to matrices from the plant kingdom, but, considering the necessity to process large volumes of such matrices and the need to lower production costs, the implementation of proper purification technologies for industrial application in the nutraceutical and cosmetic fields is required. Currently, a collaboration between two ENEA's research groups (ENEA is a major research organization in Italy), researchers from the University of Palermo and the Innovative Start-up Navhetec s.r.l. has started the development of a method that allows to purify and concentrate lemon vesicles from liquid residues, deriving from juice clarification (patent pending, ITA n. 102019000005090).

3. Conclusions

In a bioeconomy perspective, the efficient and sustainable use of large amounts of *Citrus* residues can pave the way to several high-added value products (including energy), allowing their environmental-friendly disposal, creating new business opportunities and new revenues. Within the framework of several UE and national projects in the bioeconomy sector, academic and industrial researchers have made great efforts to optimize and upgrade current pathways of CPR valorization or to develop new ones. For these reasons, further research is needed in order to study the required technological processes aimed at obtaining sustainable and cost-effective bio-products from *Citrus* residues; at the same time, it is necessary to develop new production chains based on the multi-functionality of *Citrus* primary products and by-products, and to encourage integrated supply chain approaches on the territories.

In addition, a common vision and common goals should be shared by all the stakeholders involved in the supply chain (farmers, processors, bio-products producers, etc. up to consumers) in order to achieve the expected results and co-innovation. CPR valorization might be a tool to create new business opportunities and add value to the entire chain that, for a long time, has been characterized by market-related concerns and poor remuneration, particularly in the primary production sector.

4. References

Abou Chehade L., Al Chami Z., De Pascali S.A., Cavoski I., Fanizzi F.P., (2018), Biostimulants from food processing by-products: agronomic, quality and metabolic impacts on organic tomato (*Solanum lycopersicum L.*), *Journal of the Science of Food and Agriculture*, **98**, 1426-1436.

Adetunji L.R., Adekunle A., Orsat V., Raghavan V., (2017), Advances in the pectin production process using novel extraction techniques: a review, *Food Hydrocolloids*, **62**, 239-250.

Aggelopoulos T., Katsieris K., Bekatorou A., Pandey A., Banat I.M., Koutinas A.A., (2014), Solid state fermentation of food waste mixtures for single cell protein, aroma volatiles and fat production, *Food Chemistry*, **145**, 710-716.

Agrahari V., Agrahari V., Burnouf P.A., Chew C.H., Burnouf T., (2019), Extracellular Microvesicles as new industrial therapeutic frontiers, *Trends in Biotechnology*, **37**, 707-729.

Alalwan H.A., Kadhom M.A., Alminshid A.H., (2020), Removal of heavy metals from wastewater using agricultural byproducts, *Journal of Water Supply: Research and Technology-Aqua*, **69**, 99-112.

Ali S.S., Nugent B., Mullins E., Doohan F.M., (2016), Fungal-mediated consolidated bioprocessing: the potential of Fusarium oxysporum for the lignocellulosic ethanol industry, *AMB Express*, **6**, 13.

Almeida V.V., Nunez A.J.C., Schinckel A.P., Alvarenga P.V.A., Castelini F.R., Silva-Guillen Y.V., Thomaz M.C., (2017), Interactive effect of dietary protein and dried citrus pulp levels on growth performance, small intestinal morphology, and hindgut fermentation of weanling pigs, *Journal of Animal Science*, **95**, 257-269.

Alnaimy A., Gad A.E., Mustafa M.M., (2017), Using of citrus by-products in farm animals feeding, *Open Access Journal Science*, **1**, 58-67.

Amelio A., Lopresto C.G., Verardi A., Calabrò V., Luis P., Van Der Bruggen B., (2016), *Pervaporation Membrane Reactors: Biomass Conversion into Alcohols*, In: *Membrane Technologies for Biorefining*, Figoli A., Cassano A., Basile A. (Eds.), Elsevier, 331-381.

Arslan Y., Kendüzler E., Kabak B., Demir K., Tomul F., (2017), Determination of adsorption characteristics of orange peel activated with potassium carbonate for Chromium(III) removal, *Journal of the Turkish Chemical Society Section A: Chemistry*, **4**, 51-64.

Attard T.M., Watterson B., Budarin V.L., Clark J.H., Hunt A.J., (2014), Microwave assisted extraction as an important technology for valorising orange waste, *New Journal of Chemistry*, **38**, 2278-2283.

Atzei D., Ferri T., Sadun C., Sangiorgio P., Caminiti R., (2001), Structural characterization of the complexes between iminodiacetate blocked on styrene-divinyl benzene matrix (Chelex-100 resin) and Fe(III), Cr(III), Zn(II) in solid phase by energy dispersive X-ray diffraction, *Journal of the American Chemical Soc*iety, **123**, 2552-2558.

Azam S., Khan Z., Ahmad B., Khan I., Ali J., (2014), Production of single cell protein from orange peels using Aspergillus niger and Saccharomyces cerevisiae, *Global Journal Biotechnology & Biochemistry*, **9**, 14-18.

Babu S.R., Jayaprakash J., Packiam M., Roch V., Ramakrishnan M., Ignacimuthu S., (2017), Eco-friendly utilization of citrus peels for citric acid production by Aspergillus niger, *International Journal of Recent Scientific Research*, **8**, 17882-17885.

Baeyens J., Kang Q., Appels L., Dewil R., Lv Y., Tan T., (2015), Challenges and opportunities in improving the production of bio-ethanol, *Progress in Energy and Combustion Science*, **47**, 60-88.

Bakalár T., Pavolová, H., (2019), Application of organic waste for adsorption of Zn(II) and Cd(II) ions, *Environment Protection Engineering*, **45**, 35-54.

Ballistreri G., Fabroni S., Romeo F.V., Timpanaro N., Amenta M., Rapisarda P., (2019), *Anthocyanins and Other Polyphenols in Citrus Genus: Biosynthesis, Chemical Profile, and Biological Activity*, In: *Polyphenols in Plants: Isolation, Purification and Extract Preparation*, Watson R.R. (Ed.), Elsevier, 91-216.

Bankar S.B., Survase S.A., Shrikant A., Heikki O., Granström T., (2014), Biobutanol: the outlook of an academic and industrialist, *RSC Advances*, **3**, 24734-24757.

Barka A., Blecker C., (2016), Microalgae as a potential source of single-cell proteins. A review, *Biotechnology, Agronomy, Society and Environment*, **20**, 427-436.

Barrales F.M., Silveira P.F., Barbosa P.D., Ruviaro A.R., Paulino B.N., Pastore G.M., Macedo G.A., Martínez J., (2018), Recovery of phenolic compounds from *Citrus* by-products using pressurized liquids - An application to orange peel, *Food and Bioproducts Processing*, **112**, 9-21.

Bassani B., Rossi T., De Stefano D., Pizzichini D., Corradino P., Macrì N., Noonan D.M., Albini A., Bruno A., (2016), Potential chemopreventive activities of a polyphenol rich purified extract from olive mill wastewater on colon cancer cells, *Journal of Functional Foods*, **27**, 236-248.

Behnam S., Zamani A., Karimi K., Mehrabani-Zeinabad A., (2015), Copper removal using different fungal-based adsorbents: a comparative and detailed study, *Journal of Dispersion Science and Technology*, **36**, 866-876.

Bernal-Vicente A., Ros M., Tittarelli F., Intrigliolo F., Pascual J.A., (2008), Citrus compost and its water extract for cultivation of melon plants in greenhouse nurseries, Evaluation of nutritive and biocontrol effects, *Bioresource Technology*, **99**, 8722-8728.

Boukroufa M., Boutekedjiret C., Chemat F., (2017), Development of a green procedure of citrus fruits waste processing to recover carotenoids, *Resource-Efficient Technologies*, **3**, 252-262.

Buckle J., (2015), *Basic Plant Taxonomy*, *Basic Essential Oil Chemistry, Extraction*, *Biosynthesis*, *and Analysis*, In: *Clinical Aromatherapy, Essential Oils in Healthcare*, Livingstone C., (Ed.), Elsevier, 37-72.

Bušić A., Marđetko N., Kundas S., Morzak G., Belskaya H., Ivančić Šantek M., Komes D., Novak S., Šantek B., (2018), Bioethanol Production from Renewable Raw Materials and Its Separation and Purification: A Review, *Food Technology and Biotechnology*, **56**, 289-311.

Calabrò P.S., Folino A., Tamburino V., Zappia G., Zema D.A., Zimbone S.M., (2017), *Valorisation of Citrus Processing Waste: A Review*, Proc. of 16th Intern. Waste Management and Landfill Symposium, Italy.

Campos D.A., Gómez-García R., Vilas-Boas A.A., Madureira A.R., Pintado M.M., (2020), Management of Fruit Industrial By-Products-A Case Study on Circular Economy Approach, *Molecules*, **25**, 320.

Canela-Xandri A., Balcells M., Villorbina G., Cubero M.A., Canela-Garayoa R., (2018), Effect of enzymatic treatments on dietary fruit fiber properties, *Biocatalysis and Biotransformation*, **36**, 172-179.

Cassano A., Conidi C., Ruby-Figuero R., Castro-Muñoz R., (2018), Nanofiltration and tight ultrafiltration membranes for the recovery of polyphenols from agro-food by-products, *International Journal of Molecular Sciences*, **19**, 351, doi:10.3390/ijms19020351.

Cassano A., Jiao B., (2014), *Integrated Membrane Operations in Citrus Processing*, In: *Integrated Membrane Operations in the Food Production*, Cassano A., Drioli E., (Eds.), De Gruyter, 87-112.

Castellani S., Trapani A., Spagnoletta A., di Toma L., Magrone T., Di Gioia, S., Mandracchia D., Trapani G., Jirillo E., Conese M., (2018), Nanoparticle delivery of grape seed-derived proanthocyanidins to airway epithelial cells dampens oxidative stress and inflammation, *Journal of Translational Medicine*, **16**, 140.

Cebadera-Miranda L., Domínguez L., Dias M.I., Barros L., Ferreira I.C.F.R., Igual M., Martínez-Navarrete N., Fernández-Ruiz V., Morales P., Cámara M., (2019), Sanguinello and Tarocco (*Citrus sinensis* [L.] *Osbeck*): Bioactive compounds and colour appearance of blood oranges, *Food Chemistry*, **270**, 395-402.

Chao H.P., Chang C.C., Nieva A., (2014), Biosorption of heavy metals on Citrus maxima peel, passion fruit shell, and sugarcane bagasse in a fixed-bed column, *Journal of Industrial and Engineering Chemistry*, **20**, 3408-3414.

Chavan P., Singh A.K., Sidhu G., (2018), Recent progress in the utilization of industrial waste and by-products of citrus fruits: A review, *Journal of Food Process Engineering*, 12895.

Chen Y.L., Hong X.Q., He H., Luo H.W., Qian T.T., Li R.Z., Jiang H., Yu H.Q., (2014), Biosorption of Cr (VI) by Typha angustifolia: mechanism and responses to heavy metal stress, *Bioresource Technology*, **160**, 89-92.

Choi I.S., Kim J.H., Wi S.G., Kim K.H., Bae H.J., (2013), Bioethanol production from mandarin (*Citrus unshiu*) peel waste using popping treatment, *Applied Energy*, **102**, 204-210.

Correddu F., Lunesu M. F., Buffa G., Atzori A. S., Nudda A., Battacone G., Pulina G., (2020), Can Agro-Industrial By-Products Rich in Polyphenols be Advantageously Used in the Feeding and Nutrition of Dairy Small Ruminants?, *Animals*, **10**, 131.

Cucchiella F., D'Adamo I., Gastaldi M., (2019), Sustainable Italian cities: the added value of biomethane from organic waste, *Applied Sciences*, **9**, 2221.

DBMR, (2019), Global Flavonoids Market - Industry Trends and Forecast to 2026, Report Code: SKU-48060 in: Food & Beverages, Data Bridge Market Research, 1-350.

De Andrade Lima M., Kestekoglou I., Charalampopoulos D., Chatzifragkou A., (2019), Supercritical Fluid Extraction of carotenoids from vegetable waste matrices, *Molecules*, **24**, 466doi:10.3390/molecules24030466.

Deng Z., Rong Y., (2017), Broccoli-derived nanoparticle inhibits mouse colitis by activating dendritic cell AMP-Activated Protein Kinase, *Molecular Therapy*, **25**, 1641-1654.

Di Sanzo G., Mehariya S., Martino M., Larocca V., Casella P., Chianese S., Musmarra D., Balducchi R., Molino A., (2018), Supercritical carbon dioxide extraction of astaxanthin, lutein, and fatty acids from haematococcus pluvialis microalgae, *Marine Drugs*, **16**, 334.

Dilworth L.L., Riley C.K., Stennett D.K., (2017), *Plant Constituents Carbohydrates*, *Oils*, *Resin*s, *Balsams*, *and Plant Hormones*, In: *Pharmacognosy*, Academic Press, 61-80.

Dosoky N., Setzer W., (2018), Biological activities and safety of *Citrus spp*. essential oils. *International Journal of Molecular Sciences*, **19**, 1966.

Eldahshan O.A., Singab A.N.B., (2013), Carotenoids, *Journal of Pharmacognosy and Phytochemistry*, **2**, 225-234.

Ferri T., Sangiorgio P., (1996), Determination of selenium speciation in river waters by adsorption on iron(III)-Chelex-100 resin and differential pulse cathodic stripping voltammetry, *Analytica Chimica Acta*, **321**, 185-193.

FBIR, (2019a), Fortune Business Insights Report, Carotenoids Market Size, Share and Industry Analysis By Type (Beta-Carotene, Lutein, Lycopene, Astaxanthin, Zeaxanthin, Canthaxanthin, and Others), By Application (Animal feed, Foods & Beverages, Dietary Supplements, Personal Care & Cosmetic, and Pharmaceuticals), By Source (Synthetic and Natural), and Regional Forecast 2019-2026, Report ID: FBI100180, in: Market Research Report, Fortune Business Insights (Eds), , On line at: https://www.marketsandmarkets.com/Market-Reports/carotenoid-market-158421566.html.

FBIR, (2019b), Fortune Business Insights Report Essential Oils Market Size and Industry Analysis By Type (Citrus, Eucalyptus, Lavender, Rosemary, Tea Tree, and Others), Application (Food & Beverages, Personal Care & Cosmetics, Pharmaceuticals, and Others) and Regional Forecast 2019-2026, Report ID: FBI101063, On line at: https://www.fortunebusinessinsights.com/industry-reports/essential-oils-market-101063.

Fuller M.F., (2004), *The Encyclopedia of Farm Animal Nutrition*, CABI Publishing Series, United Kingdom.

Gelsomino A., Abenavoli M.R., Princi G., Attina E., Cacco G., Sorgona A., (2010), Compost from fresh orange waste: a suitable substrate for nursery and field crops?, *Compost Science & Utilization*, **18**, 201-210.

Goliomytis M., Kostaki A., Avgoulas G., Lantzouraki D.Z., Siapi E., Zoumpoulakis P., Simitzis P., Deligeorgis S.G., (2018), Dietary supplementation with orange pulp (*Citrus sinensis*) improves egg yolk oxidative stability in laying hens, *Animal Feed Science and Technology*, **244**, 28-35.

Golmohammadi M., Borghei A., Zenouzi A., Ashrafi N., Taherzadeh M.J., (2018), Optimization of essential oil extraction from orange peels using steam explosion, *Heliyon*, **4**, 00893.

Gawkowska D., Cybulska J., Zdunek A., (2018), Structure-Related Gelling of Pectins and Linking with Other Natural Compounds: A Review, *Polymers*, **10**, 762.

Grosso C., Valentão P., Ferreres F., Andrade P.B., (2015), Alternative and efficient extraction methods for marine-derived compounds, *Marine Drugs*, **13**, 3182-3230.

Guiza S., (2017), Biosorption of heavy metal from aqueous solution using cellulosic waste orange peel, *Ecological Engineering*, **99**, 134-140.

Gutierrez I.R., Tovar A.K., Godínez L.A., (2018), *Sustainable Sorbent Materials Obtained from Orange Peel as an Alternative for Water Treatment*, *Wastewater and Water Quality*, In: *Wastewater and Water Quality*, Yonar T. (Ed.), IntechOpen, 201-218.

Hezarjaribi M., Ardestani F., Ghorbani H.R., (2016), Single cell protein production by Saccharomyces cerevisiae using an optimized culture medium composition in a batch submerged bioprocess, *Applied Biochemistry and Biotechnology*, **179**, 1336-45.

Indulekha J., Karuppan M., Appusamy A., (2017), A review on the potential of citrus waste forD-Limonene, pectin, and bioethanol production, *International Journal of Green Energy*, **14**, 599-612.

IndustryARC Report, (2019), Flavonoids Market – Forecast (2020 - 2025), Report Code: FBR 0058, IndustryARC (Ed.), On line at: https://www.industryarc.com/Report/7482/flavonoids-market-analysis.html.

Inoue K., Parajuli D., Ghimire K.N., Biswas B.K., Kawakita H., Oshima T., Ohto K., (2017), Bio-sorbents for removing hazardous metals and metalloids, *Materials*, **10**, 857.

ISTAT, (2019), ISTAT Statistics, On line at: http://dati.istat.it/.

Jiang Y., Ding D., Zhao S., Zhu H., Kenttamma H.I., Abu-Omar M.M., (2018), Renewable thermoset polymers based on lignin and carbohydrate derived monomers, *Green Chemistry*, **20**, 1131-1138.

Joshi S.M., Waghmare J.S., Sonawane K.D., Waghmare S.R., (2015), Bio-ethanol and bio-butanol production from orange peel waste, *Biofuels*, **6**, 55-61.

Ju S., Mu J., (2013), Grape exosome-like nanoparticles induce intestinal stem cells and protect mice from DSS-induced colitis, *Molecular Therapy*, **21**, 1345-1357.

Kakoui N., Nikzad M., Ghoreyshi A.A., Mohammadi M., (2018), Extraction of pectin from sour orange and its application as the adsorbent for removal of nickel from aqueous solution: kinetic and equilibrium study, *Iranian Journal of Chemical Engineering*, **15**, 3-21.

Kanse N.G., Deepali M., Kiran P., Priyanka B., Dhanke P., (2017), A review on citric acid production and its applications, *International Journal of Current Advanced Research*, **6**, 5880-5883.

Karak P., (2019), Biological activities of flavonoids: an overview, *International Journal of Pharmaceutical Science and Research*, **10**, 1567-1574.

Kasaai M.R., Moosavi A., (2017), Treatment of Kraft paper with citrus wastes for food packaging applications: water and oxygen barrier properties improvement, *Food Packaging and Shelf Life*, **12**, 59-65.

Kaya M., Sousa A.G., Crepeau M.J., Sorensen S.O., Ralet M.C., (2014), Characterization of citrus pectin samples extracted under different conditions: Influence of acid

type and pH of extraction, *Annals of Botany*, **114**, 1319-1326.
Kebaili M., Djellali S., Radjai M., Drouiche N., Lounici H., (2018), Valorization of orange industry residues to form a natural coagulant and adsorbent, *Journal of Industrial and Engineering Chemistry*, **64**, 292-299.
Khan A., Khan S., Jan A.A., (2017), Health complication caused by protein deficiency, *Journal Food Science Nutrition*, **1**, 1-2.
Khan M.K., Huma Z.E, Dangles O., (2014), A comprehensive review on flavanones, the major citrus polyphenols, *Journal of Food Composition and Analysis*, **33**, 85-104.
Kirstine W.V., Galbally I.E., (2012), Ethanol in the environment: a critical review of its roles as a natural product, a biofuel, and a potential environmental pollutant, *Critical Reviews in Environmental Science and Technology*, **42**, 1735-1779.
Konoshenko M.Y., Lekchnov E.A., Vlassov A.V., Laktionov P.P., (2018), Isolation of Extracellular Vesicles: general methodologies and latest trends, *BioMed Research International*, **2018**, 8545347.
Koppar A., Pullammanappallil P., (2013), Anaerobic digestion of peel waste and wastewater for on site energy generation in a citrus processing facility, *Energy*, **60**, 62-68.
Lado J., Alós E., Manzi M., Cronje P.J.R., Gómez-Cadenas A., Rodrigo M. J., Zacarías L., (2019), Light regulation of carotenoid biosynthesis in the peel of mandarin and sweet orange fruits, *Frontiers in Plant Science*, **10**, 1-288.
Lara-Espinoza C., Carvajal-Millán E., Balandrán-Quintana R., López-Franco Y., Rascón-Chu A., (2018), Pectin and pectin-based composite materials: beyond food texture, *Molecules*, **23**, 942.
Lessa E.F., Medina A.L., Ribeiro A.S., Fajardo A.R., (2020), Removal of multi-metals from water using reusable pectin/cellulose microfibers composite beads, *Arabian Journal of Chemistry*, **13**, 709-720.
Li H., Sun Z., Zhang L., Tian Y., Cui G., Yan S., (2016), A cost-effective porous carbon derived from pomelo peel for the removal of methyl orange from aqueous solution, *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, **489**, 191-199.
Lim S.F., Matu S.U., (2015), Utilization of agro-wastes to produce biofertilizer, *International Journal of Energy and Environmental Engineering*, **6**, 31-35.
Liu Y., Dong M., Yang Z., Pan S., (2016), Anti-diabetic effect of citrus pectin in diabetic rats and potential mechanism via PI3K/Akt signaling pathway, *International Journal of Biological Macromolecules*, **89**, 484-488.
Lopresto C.G., Meluso, A., Di Sanzo, G., Chakraborty, S., Calabrò V., (2019), Process-intensified waste valorization and environmentally friendly d-limonene extraction, *Euro-Mediterranean Journal for Environmental Integration*, **4**, 31.
Luengo E., Álvarez I., Raso J., (2013), Improving the pressing extraction of polyphenols of orange peel by pulsed electric fields, *Innovative Food Science and Emerging Technologies*, **17**, 79-84.
M'hiri N., Ioannou I., Mihoubi Boudhrioua N., Ghoul M., (2015), Effect of different operating conditions on the extraction of phenolic compounds in orange peel, *Food and Bioproducts Processing*, **96**, 161-170.
Magrone T., Jirillo E., Spagnoletta A., Magrone M., Russo M.A., Fontana S., Laforgia F., Donvito I., Campanella A., Silvestris F., De Pergola G., (2017a), Immune profile of obese people and in vitro effects of red grape polyphenols on peripheral blood mononuclear cells, *Oxidative Medicine and Cellular Longevity*, **2017**, 9210862, doi:10.1155/2017/9210862.
Magrone T., Salvatore R., Spagnoletta A., Magrone M., Russo M.A., Jirillo E., (2017b), In vitro effects of nickel on healthy non-allergic peripheral blood mononuclear cells. The role of red grape polyphenols, *Endocrine, Metabolic & Immune Disorders - Drug Targets*, 1**7**, 166-173.
Magrone T., Romita P., Verni P., Salvatore R., Spagnoletta A., Magrone M., Russo M.A., Jirillo E., Foti C., (2017c), In vitro effects of polyphenols on the peripheral immune responses in nickel-sensitized patients, *Endocrine, Metabolic & Immune Disorders-Drug Targets*, **17**, 324-331.
Magrone T., Spagnoletta A., Bizzoca A., Russo M.A., Jirillo E., Gennarini G., (2019a), Polyphenol effects on splenic cytokine response in post-weaning contactin 1-overexpressing transgenic mice, *Molecules*, **24**, 2205.
Magrone T., Spagnoletta A., Magrone M., Russo M.A., Corriero A., Jirillo E., Passantino L., (2019b), Effects of polyphenol administration to European farmed sea bass (*Dicentrharcus labrax* L.): special focus on hepatopancreas morphology, *Endocrine, Metabolic and Immune Disorders- Drug Targets*, **19**, 526-533.
Mahato N., Sinha M., Sharma K., Koteswararao R., Cho M.H., (2019), Modern extraction and purification techniques for obtaining high purity food-grade bioactive compounds and value-added co-products from Citrus wastes, *Foods*, **8**, 523.
Mansuri M.L., Parihar P., Solanki I., Parihar M.S., (2014), Flavonoids in modulation of cell survival signaling pathways, *Genes & Nutrition*, **9**, 400, doi: 10.1007/s12263-014-0400-z.
Marino T., Casella P., Sangiorgio P., Verardi A., Ferraro A., Hristoforou E., Molino A., Musmarra D., (2020), Natural Beta-carotene: a Microalgae Derivate for Nutraceutical Applications, *Chemical Engineering Transactions*, **79**, 103-108.
Martín J., Díaz Montaña E.J., Asuero A.G., (2017), Recovery of anthocyanins using membrane technologies: a review, *Critical Reviews in Analytical Chemistry*, **48**, 143-175.
Matsuda A., Patel T., (2018), Milk-derived Extracellular Vesicles for therapeutic delivery of small interfering RNAs, *Methods in Molecular Biology*, **1740**, 187-197.
Medhe S., Anand M., Anal A.K., (2017), *Dietary Fibers, Dietary Peptides and Dietary Essential Fatty Acids from Food Processing By-Products*, In: *Food Processing By-Products and Their Utilization*, John Wiley&Sons, 111-136.
Mehariya S., Iovine A., Di Sanzo G., Larocca V., Martino M., Leone G., Casella P., Karatza D., Marino T., Musmarra D., Molino A., (2019), Supercritical fluid extraction of lutein from scenedesmus almeriensis, *Molecules*, **24**, 1324.
Minzanova S.T., Mironov V.F., Arkhipova D.M., Khabibullina A.V., Mironova L.G., Zakirova Y.M., Milyukov V.A., (2018), Biological activity and pharmacological application of pectic polysaccharides: a review, *Polymers*, **10**, 1407.
Mohammed S. S. D., Aliyu A. D., Wartu J. R., Ninyo N. N., (2020), Citric acid produced from lemon peel using Aspergillus Niger isolated from cereal gruel, *Journal of Microbial Cell and Biotechnology*, **1**, 15-20.
Mojzer E.B., Hrncic M.K., Škerget M., Knez Ž., Bren U., (2016), Polyphenols: extraction methods, antioxidative action, bioavailability and anticarcinogenic effects, *Molecules,* **21**, 901.

Molino A., Iovine A., Leone G.P., Di Sanzo G., Palazzo S., Martino M., Sangiorgio P., Marino T., Musmarra D., (2020a), Microalgae as Alternative Source, *Chemical Engineering Transactions*, **79**, 277-282.

Molino A., Mehariya S., Di Sanzo G., Larocca V., Martino M., Leone G.P., Marino T., Chianese S., Balducchi R., Musmarra D., (2020b), Recent developments in supercritical fluid extraction of bioactive compounds from microalgae: role of key parameters, technological achievements and challenges, *Journal of CO_2 Utilization*, **36**, 196-209.

Monguio-Tortajada M., Gàlvez-Monton C., Bayes-Genis A., Roura S., Borras F.E., (2019), Extracellular Vesicle isolation methods: rising impact of size-exclusion chromatography, *Cellular and Molecular Life Science*, **76**, 2369-2382.

Montero-Calderon A., Cortes C., Zulueta A., Frigola A., Esteve M.J., (2019), Green solvents and Ultrasound-Assisted extraction of bioactive orange (*Citrus sinensis*) peel compounds, *Scientific Reports*, **9**, 16120, doi:10.1038/s41598-019-52717-1.

Mudgil D., (2017), *The Interaction Between Insoluble and Soluble Fiber*, In: *Dietary Fiber for the Prevention of Cardiovascular Disease*, R.A. Samaan (Ed.), Elsevier: Amsterdam, The Netherlands, 35-59.

Munagala R., Aqil F., Jeyabalan J., Gupta R.C., (2016), Bovine milk-derived exosomes for drug delivery, *Cancer Letters*, **371**, 48-61.

Murador D.C., Braga A.R.C., Martins P.L., Mercadante A.Z., de Rosso V.V., (2019), Ionic liquid associated with ultrasonic-assisted extraction: A new approach to obtain carotenoids from orange peel, *Food Research International*, **126**, 108653.

Ndayishimiye J., Chun B.S., (2017), Optimization of carotenoids and antioxidant activity of oils obtained from a co-extraction of citrus (Yuzu ichandrin) by-products using supercritical carbon dioxide, *Biomass and Bioenergy*, **106**, 1-7.

Negro V., Mancini G., Ruggeri B., Fino D., (2016), Citrus waste as feedstock for bio-based products recovery: Review on limonene case study and energy valorization, *Bioresource Technology*, **214**, 806-815.

Negro V., Ruggeri B., Fino D., (2018), Recovery of energy from orange peels through anaerobic digestion and pyrolysis processes after D-limonene extraction, *Waste and Biomass Valorization*, **9**, 1331–1337.

Nipornram S., Tochampa W., Rattanatraiwong P., Singanusong R., (2017), Optimization of low power ultrasound-assisted extraction of phenolic compounds from mandarin (*Citrus Reticulata Blanco* cv. Sainampueng) peel, *Food Chemistry*, **241**, 338-345.

Oberoi H.S., Vadlani P.V., Madl R.L., Saida L., Abeykoon J.P., (2010), Ethanol production from orange peels: two-stage hydrolysis and fermentation studies using optimized parameters through experimental design, *Journal of Agricultural and Food Chemistry*, **58**, 3422–3429.

Omar J., Alonso I., Garaikoetxea A., Etxebarria N., (2013), Optimization of focused ultrasound extraction (FUSE) and supercritical fluid extraction (SFE) of citrus peel volatile oils and antioxidants, *Food Analytical Methods*, **6**, 1244-1252.

Orian Research Report, (2019), Citric Acid –Global Market Outlook (2017-2026), Report ID: 956027, Stratistics Market Research Consulting, On line at: https://www.marketresearch.com/Stratistics-Market-Research-Consulting-v4058/Citric-Acid-Global-Outlook-12385389/

Panche A.N., Diwan A.D., Chandra S.R., (2016), Flavonoids: an overview, *Journal of Nutritional Science*, **5**, 47.

Pandeeti E.V.P., Veeraiah S., Routhu G.D., (2019), *Emerging Trends in the Industrial Production of Chemical Products by Microorganisms*, In: *Recent Developments in Applied Microbiology and Biochemistry*, Viswanath B. (Ed.), Elsevier, 107-125.

Pandiarajan A., Kamaraj R., Vasudevan S., Vasudevan S., (2018), OPAC (orange peel activated carbon) derived from waste orange peel for the adsorption of chlorophenoxyacetic acid herbicides from water: adsorption isotherm, kinetic modelling and thermodynamic studies, *Bioresource Technology*, **261**, 329-341.

Panuccio M.R., Attinà E., Basile C., Mallamaci C., Muscolo A., (2016), Use of recalcitrant agriculture wastes to produce biogas and feasible biofertilizer, *Waste Biomass Valorization*, **7**, 267-280.

Panwar D., Panesar P.P., Chopra H.K., (2019), Recent trends on the valorization strategies for the management of citrus by-products, *Food Reviews International*, doi: 10.1080/87559129.2019.1695834.

Patsalou M., Samanides C.G., Protopapa E., Stavrinou S., Vyrides I., Koutinas M., (2019), A *Citrus* peel waste biorefinery for ethanol and methane production, *Molecules*, **24**, 2451, doi:10.3390/molecules24132451.

Pocsfalvi G., Turiak L., (2018), Protein biocargo of citrus fruit-derived vesicles reveals heterogeneous transport and extracellular vesicle populations, *Journal of Plant Physiology*, **229**, 111-121.

Putnik P., Kovaˇcevi´c D.B., Režek Jambrak A., Barba F.J., Cravotto G., Binello A., Lorenzo J.M., Shpigelman A., (2017), Innovative "Green" and novel strategies for the extraction of bioactive added value compounds from citrus wastes-a review, *Molecules*, **22**, 680.

Qiao J., Tan Z., Wang M., (2014), Potential and existing mechanisms of enteric methane production in ruminants, *Scientia Agricola*, **71**, 345-355.

Raimondo M., Caracciolo F., Cembalo L., Chinnici G., Pecorino B., D'Amico M., (2018a), Making virtue out of necessity: managing the citrus, waste supply chain for bioeconomy applications, *Sustainability*, **10**, 4821, doi:10.3390/su10124821.

Raimondo S., Saieva L., Cristaldi M., Monteleone F., Fontana S., Alessandro R., (2018b), Label-free quantitative proteomic profiling of colon cancer cells identifies acetyl-CoA carboxylase alpha as antitumor target of Citrus limon-derived nanovesicles, *Journal of Proteomics*, **173**, 1-11.

Raimondo S., Naselli F., Fontana S., Monteleone F., Lo Dico A., Saieva L., Zito G., Flugy A., Manno M., Di Bella M.A., De Leo G., Alessandro R., (2015), Citrus limon-derived nanovesicles inhibit cancer cell proliferation and suppress CML xenograft growth by inducing TRAIL-mediated cell death, *Oncotarget*, **6**, 19514-19527.

Rajbhar K., Dawda H., Mukundan U., (2015), Polyphenols: methods of extraction, *Scientific Reviews and Chemical Communication*, **5**, 1-6.

Raposo G., Stoorvogel W., (2013), Extracellular vesicles: exosomes, microvesicles, and friends, *Journal of Cell Biology*, **200**, 373-383.

Raziq A., Lateef M., Ullah H., Khan M., (2020), Single cell protein (SCP) production and potential substrates: A comprehensive review, *Pure and Applied Biology*, **9**, 1743-1754.

Reihani S.F.S., Khosravi-Darani K., (2019), Influencing factors on single-cell protein production by submerged fermentation: a review, *Electronic Journal of Biotechnology*, **37**, 34-40.

Ritala A., Häkkinen S.T., Toivari M., Wiebe M.G., (2017), Single cell protein-state-of-the-art, industrial landscape and patents 2001-2016, *Frontiers of Microbiology*, **8,** 2009.

Rivas B., Torrado A., Torre P., Converti A., Domínguez J.M., (2008), Submerged citric acid fermentation on orange peel autohydrolysate, *Journal of Agricultural and Food Chemistry*, **56**, 2380-2387.

Rivas-Cantu R.C., Jones K. D., Mills P.L., (2013), A citrus waste-based biorefinery as a source of renewable energy: technical advances and analysis of engineering challenges, *Waste Management and Research*, **31**, 413-420.

Robledo V.R., Castro Vázquez L.I., (2020), Pectin - Extraction, Purification, Characterization and Applications, in: *Pectins*, Masuelli M. (Eds.), IntechOpen, 1-20.

Ruiz B., Flotats X., (2016), Citrus essential oils and their influence on the anaerobic digestion process: An overview, *Waste Management and Research*, **34**, 2063-2079.

Ryan M.D., (2016), *Revaluing residues: effects of composts and vermicomposts from corn, fig and citrus residues on the development of Rosmarinus officinalis L. and Lavandula angustifolia L*, MSc Thesis, Norwegian university of life sciences, Ås, Norway.

Robinson K.W., Moffitt R., Moss P.R., Gainey S., (2017), System and methods for reducing edge wicking of a paperboard comprising fruit fiber, WO 2017106646A9, On line at: https://patents.google.com/patent/WO2017106646A9/en.

Šabanović E., Muhić-Šarac T., Nuhanović M., Memić M., (2019), Biosorption of uranium(VI) from aqueous solution by *Citrus limon* peels: kinetics, equilibrium and batch studies, *Journal of Radioanalytical and Nuclear Chemistry*, **319**, 425-435.

Salman C.A., Naqvi M., Thorin E., Yan J., (2017), Impact of retrofitting existing combined heat and power plant with polygeneration of biomethane: a comparative techno-economic analysis of integrating different gasifiers, *Energy Conversion and Management*, **152**, 250-265.

Sanjaya A.P., Cahyanto M.N., Millati R., (2016), Mesophilic batch anaerobic digestion from fruit fragments, *Renewable Energy*, **98**, 135-141.

Santanocito A.M., Vismara E., (2015), Production of textile from citrus fruit, WO *2015018711* Patent, On line at: https://patents.google.com/patent/WO2015018711A1/en.

Satari B., Karimi K., (2018), Citrus processing wastes: environmental impacts, recent advances, and future perspectives in total valorization, *Resources, Conservation & Recycling*, **129**, 153-167.

Satari B., Karimi K., Taherzadeh M., Zamani A., (2016), Co-production of fungal biomass derived constituents and ethanol from citrus wastes free sugars without auxiliary nutrients in airlift bioreactor, *International Journal of Molecular Science*, **17**, 302, doi:10.3390/ijms17030302.

Schiewer S., Iqbal M., (2010), The role of pectin in Cd binding by orange peel bio-sorbents: a comparison of peels, depectinated peels and pectic acid, *Journal of Hazardous Materials*, **177**, 899-907.

Schlesinger W.H., Bernhardt E.S., (2013), *Wetland Ecosystems*, In: *Biogeochemistry, An Analysis of Global Change*, Elsevier /Academic Press, New York, USA, 233-274.

Scrichuwong S., Fujiwara M., Wang X., Seyama T., Shiroma R., Arakane M., Mukojima N., Tokuyasu K., (2009), Simultaneous saccharification and fermentation (SSF) of very high gravity (VHG) potato mash for the production of ethanol, *Biomass and Bioenergy*, **33**, 890-898.

Shakoor M.B., Niazi N.K., Bibi I., Murtaza G., Kunhikrishnan A., Seshadri B., (2016), Remediation of arsenic-contaminated water using agricultural wastes as bio-sorbents, *Critical Reviews in Environmental Science and Technology*, **46**, 467-499.

Sharma K., Mahato N., Cho M.H., Lee Y.R., (2017), Converting citrus wastes into value-added products: economic and environmently friendly approaches, *Nutrition*, **34**, 29-46.

Sharma K., Mahato N., Lee Y.R., (2018), Extraction, characterization and biological activity of citrus flavonoids, *Reviews in Chemical Engineering*, **35**, 265-284.

Show P.L., Oladele K.O., Siew Q.Y., AzizZakry F.A., Lan J.C., Ling T.C., (2015), Overview of citric acid production from *Aspergillus niger*, *Frontiers in Life Science*, **8**, 271-283.

Shukla P., Gawande S., Thorat A., (2016), Extraction, identification and utilization of pigments extracted from citrus wastes, *International Journal of Science and Research*, **5**, 840-847.

Singla R.K., Dubey A.K., Garg A., Sharma R.K., Fiorino M., Ameen S.M., Haddad M.A., Al-Hiary M., (2019), Natural polyphenols: chemical classification, definition of classes, subcategories, and structures, *Journal of AOAC International*, **102**, 1397-1400.

Taghizadeh-Alisaraei A., Hosseini S.H., Ghobadian B., Motevali A., (2017), Biofuel production from citrus wastes: a feasibility study in Iran, *Renewable and Sustainable Energy Reviews*, **69**, 1100-1112.

Tayengwa T., Mapiye C., (2018), Citrus and winery wastes: promising dietary supplements for sustainable ruminant animal nutrition, health, production, and meat quality, *Sustainability*, **10**, 3718, doi:10.3390/su10103718.

Thatoi H., Dash P.K., Mohapatra S., Swain M.R., (2016), Bioethanol production from tuber crops using fermentation technology: a review, *International Journal of Sustainable Energy*, **35**, 443-468.

Thery C., Witwer K.W., Aikawa E., Alcaraz M.J., Anderson J.D., Andriantsitohaina R., Antoniou A., Arab T., Archer F., Atkin-Smith G.K., (2018), Minimal information for studies of extracellular vesicles 2018 (MISEV2018): a position statement of the International Society for Extracellular Vesicles and update of the MISEV2014 guidelines, *Journal of Extracellular Vesicles*, **7**, 1535750, http://doi.org/10.1080/20013078.2018.1535750.

Timková I., Sedláková-Kaduková J., Pristaš P., (2018), Biosorption and bioaccumulation abilities of actinomycetes/streptomycetes isolated from metal contaminated sites, *Separations*, **5**, 54, http://doi.org/10.3390/separations5040054.

Tong Z., Zheng X., Tong Y., (2019), Systems metabolic engineering for citric acid production by *Aspergillus niger* in the post-genomic era, *Microbial Cell Factories*, **18**, 28, http://doi.org/10.1186/s12934-019-1064-6.

Torrado A.M., Cortés S., Salgado J.M., Max B., Rodríguez N., Bibbins B.P., Converti A., Domínguez J.M., (2011), Citric acid production from orange peel wastes by

Solid-State Fermentation, *Brazilian Journal of Microbiology*, **42**, 394-409.
Tsitsagi M., Ebralidze K., Chkhaidze M., Rubashvili I., Tsitsishvili V., (2018), Sequential extraction of bioactive compounds from tangerine (*Citrus Unshiu*) peel, *Annals of Agrarian Science*, **16**, 236-241.
Tuttobene R., Avola G., Gresta F., Abbate V., (2009), Industrial orange waste as organic fertilizer in durum wheat, *Agronomy for Sustainable Development*, **29**, 557-563.
Tyśkiewicz K., Konkol M., Rój E., (2018), The application of supercritical fluid extraction in phenolic compounds isolation from natural plant materials, *Molecules,* **23**, 2625.
Uçan F., Akyildiz A., Ağçam E., (2014), Effects of different enzymes and concentrations in the production of clarified lemon juice, *Journal of Food Processing*, **2014**, 215854, doi:10.1155/2014/215854.
USDA, (2020), Citrus: World Markets and Trade, On line at: https://apps.fas.usda.gov/psdonline/app/index.html#/app/downloads.
Vasta V., Daghio M., Cappucci A., Buccioni A., Serra A., Viti C., Mele M., (2019), Invited review: Plant polyphenols and rumen microbiota responsible for fatty acid biohydrogenation, fiber digestion, and methane emission: Experimental evidence and methodological approaches, *Journal of Dairy Science*, **102**, 3781-3804.
Verardi A., De Bari I., Ricca E., Calabrò V., (2012), *Hydrolysis of Lignocellulosic Biomass: Current Status of Processes and Technologies and Future Perspectives*, In: *Bioethanol*, Publisher IntechOpen, Pinheiro Lima M.A. (Ed.), 95-122.
Verardi A., Lopresto C.G., Blasi A., Chakraborty S., Calabrò V., (2020), *Bioconversion of Lignocellulosic Biomass to Bioethanol and Biobutanol*, In: *Lignocellulosic Biomass to Liquid Biofuels*, Yousuf A., Pirozzi D., Sannino F. (Eds.), Academic Press, 67-125.
Verma L., Siddique M.A., Singh J., Bharagava R.N., (2019), As(III) and As(V) removal by using iron impregnated bio-sorbents derived from waste biomass of Citrus limmeta (peel and pulp) from the aqueous solution and ground water, *Journal of Environmental Management,* **250**, 109452, http://doi.org/10.1016/j.jenvman.2019.109452.
Ververis C., Georghiou K., Danielidis D., Hatzinikolaou D., Santas P., Santas R., Corleti V., (2007), Cellulose, hemicelluloses, lignin and ash content of some organic materials and their suitability for use as paper pulp supplements, *Bioresource Technology*, **98**, 296–301.
Wadhwa M., Bakshi Mohinder P.S., Makkar Harinder P.S., (2015), Wastes to worth: Fruit wastes and by-products as animal feed. *CAB Reviews*, **10**, 043, http://doi.org/10.1079/PAVSNNR201510043.
Wang B., Zhuang X., (2014), Targeted drug delivery to intestinal macrophages by bioactive nanovesicles released from grapefruit, *Molecular Therapy*, **22**, 522-534.
Wei P.S., Hsieh Y.C., Chiu H.H., Yen D.L., Lee C., Tsai Y.C., Ting T.C., (2018), Absorption coefficient of carbon dioxide across atmospheric troposphere layer, *Heliyon*, **4**, 00785, http://doi.org/10.1016/j.heliyon.2018.e00785.
Wu M., Luo Q., Nie R., Yang X., Tang Z., Chen H., (2020), Potential implications of polyphenols on aging considering oxidative stress, inflammation, autophagy, and gut microbiota, *Critical Reviews in Food Science and Nutrition*, http://doi.org/10.1080/10408398.2020.1773390
Xu N., Liu S., Xin F., Zhou J., Jia H., Xu J., Jiang M., Dong W., (2019), Biomethane production from lignocellulose: biomass recalcitrance and its impacts on anaerobic digestion, *Frontiers in Bioengineering and Biotechnology*, **7**, 191, http://doi.org/10.3389/fbioe.2019.00191.
Yang C., Zhang M., Merlin D., (2018), Advances in plant-derived edible nanoparticle-based lipid nano-drug delivery systems as therapeutic nanomedicines, *Journal of Materials Chemistry B: Royal Society of Chemistry*, **6**, 1312-1321.
Yasumoto S., Quitain A.T., Sasaki M., Iwai H., Tanaka M., Hoshino M., (2015), Supercritical CO_2-mediated countercurrent separation of essential oil and seed oil, *The Journal of Supercritical Fluids*, **104**, 104–111.
Young A.J, Lowe G.L., (2018), Carotenoids-Antioxidant Properties, *Antioxidants*, **7**, 28, http://doi.org/10.3390/antiox7020028.
Yunus F., Nadeem M., Rashid F., (2015), Single-cell protein production through microbial conversion of lignocellulosic residue (wheat bran) for animal feed, *Journal of The Institute of Brewing*, **121**, 553-557.
Zema D.A., Calabrò P.S., Folino A., Tamburino V., Zappia G., Zimbone S.M., (2018), Valorisation of citrus processing waste: a review, *Waste Management*, **80**, 252-73.
Zhang W., Zhou Z., (2017), Citrus pectin-derived carbon microspheres with superior adsorption ability for methylene blue, *Nanomaterials*, **7**, 161, https://doi.org/10.3390/nano7070161.
Zheng H., Sun Q., Li Y., Du Q., (2020), Biosorbents prepared from pomelo peel by hydrothermal technique and its adsorption properties for congo red, *Materials Research Express*, **7**, 045505, http://doi.org/10.1088/2053-1591/ab8a83.
Zhou M., Chen P., Guo S., Shen Y., Yan P., Yang X., (2019), Recycling of orange waste for single cell protein production and the synergistic and antagonistic effects on production quality, *Journal of Cleaner Production*, **213**, 384-392.
Zhou Z., Wanpeng X., Yan H., Chao N., Zhou Z., (2016), Antioxidant activity of Citrus fruits, *Food Chemistry*, **196**, 885-896.
Zhou X., Ma J., Ji Z., Zhang X., Ramaswamy S., Xu F., Sun R.C., (2014), Dilute acid pretreatment differentially affects the compositional and architectural features of Pinus bungeana Zucc. compression and opposite wood tracheid walls, *Industrial Crops and Products,* **62**, 196–203.
Zhuang X., Deng Z.B., (2015), Ginger-derived nanoparticles protect against alcohol-induced liver damage, *Journal of Extracellular Vesicles*, **4**, 28713, http://doi.org/10.3402/jev.v4.28713.
Zion Market Research Report, (2018), Flavonoids Market (Anthocyanins, Flavones, Anthoxanthins, Flavanones, Isoflavonens and Chalcones) for Pharmaceutical, Food and Beverages, Nutraceuticals and Animal Feed: Global Industry Perspective, Comprehensive Analysis, Size, Share, Growth, Segment, Trends and Forecast, 2016 – 2026, Zion Market Research, Report Code: ZMR-536, 1-110, On line at: https://www.zionmarketresearch.com/report/flavonoids-market

Environmental Engineering and Management Journal October 2020, Vol.19, No. 10, 1891-1903
http://www.eemj.icpm.tuiasi.ro/; hiip://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

EVALUATION OF REMEDIATION TECHNOLOGIES FOR CONTAMINATED MARINE SEDIMENTS THROUGH MULTI CRITERIA DECISION ANALYSIS

Claudia Labianca, Sabino De Gisi, Francesco Todaro*, Michele Notarnicola

Department of Civil, Environmental, Land, Building Engineering and Chemistry (DICATECh), Polytechnic University of Bari, Via E. Orabona n.4, 70125 Bari (BA), ITALY

Abstract

Remediation of contaminated marine sediments present a difficult challenge for environmental decision-makers. In socially relevant situations, as in the Mar Piccolo of Taranto case study (Southern Italy), the decision-maker needs to explain to the citizens why some remediation technologies are adopted compared to others. Multi criteria decision analysis (MCDA) is a scientifically sound decision tool for management of contaminated sites, not only to denote effective or technologically and economically feasible remediation alternatives, but also to point out the most sustainable remediation alternatives. The aim of this study was to develop and apply a MCDA approach allowing the identification of the best remediation technologies for the decontamination of contaminated marine sediments of the Mar Piccolo of Taranto, one of most polluted areas in Europe. The main methodological steps were: (i) preliminary screening of technologies potentially applicable, (ii) detailed analysis of the technologies according to several evaluation criteria, and (iii) identification of the optimum technologies by means of the construction of a composite indicator. The 13 criteria, identified based on a literature study, have been used for the assessment of the technologies; these were classified in applicability aspects ones (e.g., type of sediments and contaminants) and technological ones (e.g., residuals produced and development status). The results of the MCDA showed how the most performing technologies were (i) *in situ* remediation with amendments, (ii) vitrification and (iii) stabilization/solidification. These solutions were then validated based on the full-scale remediation technologies generally applied. The adopted approach has proved to be an excellent tool to support the decision-maker. Transparency is its strength and suggests its application in contexts similar to that of the case study.

Keywords: contaminated marine sediments, decision support system, multi criteria decision analysis, remediation technologies

Received: February, 2020; Revised final: June, 2020; Accepted: July, 2020; Published in final edited form: October, 2020

1. Introduction

Nowadays, industrial activities and human impacts are responsible for the accumulation of high concentrations of contaminants in river sediments, ports, and coastal marine zones. In all the aquatic systems, sediments have a high storage capacity for contaminants (Salomons, 1998). Contaminated sediments pose a serious risk to human health and to the environment in general; as a result, the definition of the remediation strategies of contaminated sediments has given rise to great scientific and public concern throughout the world (Lofrano et al., 2017).

In the remediation projects of contaminated marine sediments, there is a wide range of potentially available remediation technologies. The alternatives can involve physical, chemical or biological treatment technologies to reduce contaminant concentrations within the sediments in order to reach the environmental remediation goals. Remediation includes two types of approaches: *in situ*, if the treatment takes place on the site to be restored, and *ex situ*, if contaminated sediments are dredged and then, treated and stabilized on a different place. In general,

*Author to whom all correspondence should be addressed: e-mail: francesco.todaro@poliba.it

in situ technologies are feasible and less expensive but also less effective; instead, the most practical ex situ approaches tend to be high in cost and complexity (Careghini et al., 2010).

A suitable remediation alternative typically needs to fulfil several objectives, sometimes of a conflicting nature (e.g. sustainability, economy, and public acceptance).

In general, the most promising remediation technologies are analysed based on site-specific data related to, for example, site investigations, stakeholder views and financial analyses. The definition of a remediation project is strictly related to the area to be decontaminated. It requires a deepening of the study area in reference to the site-specific parameters about hydro-geomorphology and chemical characterization (US EPA, 2004), but also performance duration and total costs. However, many more aspects are often neglected in the remediation decision process such as calling for more wide-ranging decision-making approaches.

In this context, for the selection of the most promising remediation alternatives the use of Multi-Criteria Decision Analysis (MCDA) is highly recommended in order to structure the diverse and sometimes uncertain information (e.g. site investigations, stakeholder views and financial analyses).

Moreover, MCDA can provide a framework that helps the decision makers to understand and interpret better the stakeholders' preferences and be explicit about the trade-offs among different elements of value (JRCEC, 2008).

Extensive research about MCDA has developed practical methods for applying scientific decision theoretical approaches to multi-criteria problems (Linkov et al., 2006). Some of the most theoretically and empirically sound MCDA methods in literature are: Analytical Hierarchy Process (AHP) (Saaty, 1990), Elimination et Choix Traduisant la Realite (ELECTRE) (Figueira et al., 2010), technique for order preference by similarity to an ideal solution (TOPSIS) (Tzeng and Huang, 2011), utilities additives (UTA) (Jacquet-Lagreze and Siskos, 1982), DEcision Support sYstem for the REqualification of contaminated sites (DESYRE) (Carlon et al., 2004; Critto et al., 2006), and preference ranking organization method for enrichment evaluation (PROMETHEE) (Brans and Vincke, 1985). The above-mentioned decision technologies are widely used in several fields such as economics, engineering, public administration, ecological and environmental management (Gorsevski et al., 2012; Hsu et al., 2015). For instance, Li et al. (2018) modified the criteria framework (US EPA, 1988) by using AHP-PROMETHEE to determine the priority ranking of the remedial alternatives and the solute transport simulation.

Tony et al. (2011) adopted MCDA for health technology assessment; Carlon et al. (2004) and Critto et al. (2006) applied DESYRE for remedial purpose in Venice, Italy. Additionally, the UK Environment Agency (UKEA) developed a Cost–Benefit analysis for remediation of land contamination, as tool to shortlist potential remediation techniques through MCDA and cost–benefit analysis (UKEA, 1999). MCDA-based approaches for the management and remediation of contaminated sediments have been successfully applied in the US by the US Army Corps of Engineers (2006) and the US Environmental Protection Agency (USEPA) (Zheng et al., 2019). Other available resources in the remediation decision process are represented by searchable databases such as the clean-up technologies screening matrix of US Federal Remediation Technologies Roundtable (FRTR, 2002) and the US Environmental Protection Agency (US EPA, 2005).

This study was aimed at identifying the most suitable remediation technologies for complex marine sites–using the MCDA analysis. A literature review allowed us to identify 50 remediation technologies potentially applicable to soil and sediments contaminated by different categories of pollutants. We used the MCDA tool to determine the best alternative for contaminated marine sediments from the Mar Piccolo (South of Italy). For the scope, three scenarios characterized by different contamination (i.e., by inorganic pollutants alone, mixed organic-inorganic contamination etc.) have been considered, all referred to the case study.

The main methodological steps are described below.

2. Material and methods

2.1. Background information

Mar Piccolo is a semi-enclosed basin in Taranto area, Southern Italy (Fig. 1). It has a surface area of about 21 km^2 divided in two inlets, called First Seno and Second Seno, with a maximum depth of 13 m and 9 m, respectively (Labianca et al., 2020). With a reduced water circulation, it is strongly influenced by human activities. In fact, from several decades this area has been subjected to chemical pollution deriving from the factories in the surroundings, the most important of which were the steel plant ILVA, the concrete producer Cementir, the oil refinery station Eni and the Military Arsenal (Lisco et al., 2016) (Fig. 1). The city of Taranto was declared as "at high risk of environmental crisis" by the national government (Italian Law n. 349 of 1986). Different chemical characterizations of the basin over the years have revealed the strong presence and distribution of organic pollutants (i.e., polycyclic aromatic hydrocarbons, PAHs, and polychlorinated biphenyls, PCBs) and metals (i.e., Arsenic, Cobalt, Chrome, Copper, Nickel, Lead, Vanadium, and Zinc) in the sediments from the Mar Piccolo. However, despite the serious contamination, this basin is one of the most productive areas in Italy for mussel farming with ca. 30,000 tons year^{-1} of mussels (Petronio et al., 2012).

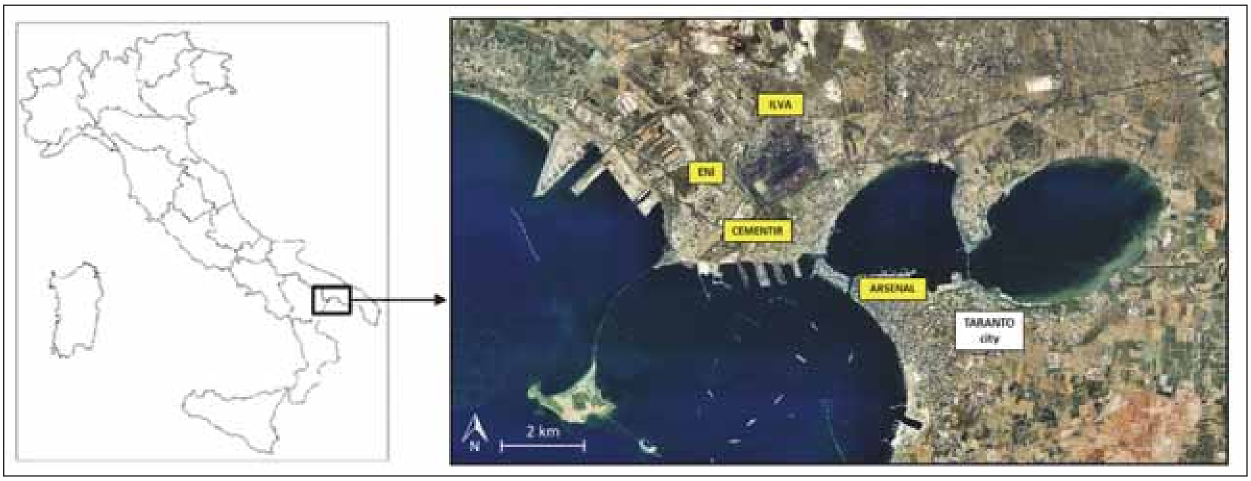


Fig. 1. Mar Piccolo localisation map

2.2. Framework of the experimentation

Methodologically, this study involves the development of an approach based on MCDA with the goal of helping the decision-maker to select the most sustainable technology for the remediation of contaminated marine sediments.

The decision-making process is based on the following phases:

1. identification of alternative treatments and preliminary screening;
2. definition of evaluation criteria to assess and compare environmental, social and economic aspects of the technologies;
3. definition of the weights to be attributed to the evaluation criteria, based on local knowledge of experts and stakeholders;
4. construction and normalization of the decision matrix made of all the criteria and alternatives to investigate;
5. construction of the composite indicator (I_p) used as parameter for choosing the best alternatives through weighting evaluation criteria;
6. selection of the best solution based on the final ranking of the compared treatment schemes.

A decision is the choice to undertake an action among different possible alternatives by a single or a group of decision-makers (Linkov et al., 2006).

2.3. Identification of alternative treatments and preliminary screening

A literature review allowed us to identify 50 remediation technologies, classified according to: (i) treatment site (*ex situ* and *in situ*) and (ii) treatment nature (biological, chemo-physical, thermal), potentially applicable to soil and sediments contaminated by different categories of pollutants. In order to identify the best technologies suitable for the case-study (sediments), a preliminary screening of remediation alternatives was carried out by a Technical Working Group (TWG).

2.4. Definition of evaluation criteria and analysis of the technologies

The applicability of the selected remediation technologies is evaluated in function of a series of parameters related to (i) the contaminant nature (i.e. concentration, spatial distribution), (ii) the area characteristics (i.e. soil extension to remediate, chemo-physical features), (iii) the operational conditions of the treatment plants, (iv) the total costs of the intervention and (v) the environment and sanitary-related regulations. In detail, the selected technologies were evaluated through 13 criteria, identified by means of a critical analysis of published sources by the TWG (Table 1). In particular, to evaluate the effect of remediation efforts, the contaminant removal was defined as the removal ratio of pollutants in pilot or full-scale applications (FRTR, 2002).

A practical overview was drawn up for each remediation technology, based on several technical and scientific reports (FRTR, 2002; Hasegawa et al., 2016; Reible, 2016; SMOCS, 2012; UNIDO, 2007; US ACE, 2014), with a qualitative criteria evaluation. Table 1 shows the qualitative scores assigned to each criterion, according to all different technologies.

These selection factors represent therefore the relevant criteria to estimate the most suitable treatment technology for full-scale applications in a remediation project, within a risk-based framework (Manap and Voulvoulis, 2014; Ren et al., 2017; Rosén et al., 2015; Zheng et al., 2019).

2.5. Definition of weights for the evaluation criteria

Based on previous chemical characterizations of Mar Piccolo sediments, three different site-specific scenarios of contamination were considered as follows:

- Scenario 1 (SC1), with metals, PAHs and PCBs simultaneously present in the same concentration;

• Scenario 2 (SC2), with concentration of metals is higher than the one of PAHs and PCBs;

• Scenario 3 (SC3), with concentration of PAHs and PCBs is higher than the one of metals.

Each evaluation *criterion* (C_i) was given a *weight* (w_i), according to the relation among all other criteria. The corresponding *vector of weights* (W) was defined by the TWG according to their technical preferences, shown in Table 2 as criteria priorities. The *Paired Comparison Technique (PCT)* (Goletsis et al., 2003) was used for a pairwise confrontation among different criteria.

The PCT matrix is constructed by using scores that represent experts' judgments when comparing the importance of each indicator in relation to all the other indicators. All criteria were evaluated using three numerical judgments: 1 means 'more important than'; 0.5 means 'equal importance to'; 0 means 'less important than'. The weight of each criterion is calculated by means of the following formula (Eq. 1):

$$w_i = \sum_{j=1}^{13} S_j \tag{1}$$

where: S_j represents the scores of experts' judgments. For instance, the weights of evaluation criteria adopted in SC1 are reported in Table 3.

The weight vectors for the three scenarios are visible in Table 4.

2.6. Construction and normalization of the Alternatives Matrix

The Matrix of Alternatives (MOA) consists of the technologies to be compared in the rows and the evaluation criteria in the columns.

Since most of criteria were on a qualitative base as visible from Table 1, the transformation from qualitative to quantitative judgment was carried out according to the rules set out below.

Table 1. Evaluation criteria considered in MCDA

Criterion	*Description*	*Score* [(a)]	*Evaluation*
PAHs	It is referred to the contaminant removal	+	High removal ratio, able to guarantee concentrations below the regulatory threshold
		■	Medium removal ratio strictly connected to initial concentrations
		-	Low removal efficiency
		*	The technology does not allow contaminant removal or there are not enough data
PCBs	It is referred to the contaminant removal	+	High ratio able to guarantee concentrations below the regulatory threshold
		■	Medium ratio strictly connected to initial concentrations
		-	Low removal efficiency
		*	The technology does not allow contaminant removal or there are not enough data
Heavy Metals	It is referred to the contaminant removal	+	High ratio able to guarantee concentrations below the regulatory threshold
		■	Medium ratio, strictly connected to initial concentrations
		-	Low removal efficiency
		*	The technology does not allow contaminant removal or there are enough data to estimate the remediation duration
Time	It is referred to the time necessary for remediation to be concluded	+	*Ex situ*: < 6 months *In situ*: < 1 year
		■	*Ex situ*: 6 months – 1 year *In situ*: 1 year – 3 years
		-	*Ex situ*: > 1 year *In situ*: > 3 years
		*	There are not enough data to estimate the remediation duration
Residue	It is referred to by-products or residue production, including sediment resuspension during the activity	+	There is not residue production
		■	The expected residue production does not affect the environmental status
		-	Hazardous and toxic residue production
		*	The residue hazard is not adequately estimated
Costs	It includes costs of design, construction and maintenance	+	< 100 Euro/1000 kg
		■	100 - 300 Euro/1000 kg
		-	> 300 Euro/1000 kg
		*	Costs are relatively estimable
Safety	It is referred to public and environmental safety	+	Low safety requirements

	measures	■	Medium safety requirements (attention to short and medium term)
		-	High uncertainty level with necessity for long term monitoring
		*	Information available in literature are not enough to adequately evaluate the technology
Development	It is referred to the development of the technological level in terms of diffusion and use	+	Full-scale applications
		■	Pilot-scale applications
		-	Lab-scale applications
		*	Application only as research
Efficacy and Monitoring	It considers how remediation technologies restore the situation *quo ante* also through monitoring programs	+	Risk to humans and environment is not significant
		■	Remediation target achievement needs to be verified over time
		-	Exposure scenarios need to be often monitored post-remediation
		*	There are not enough data to estimate the technology
Reliability and Maintenance	It is referred to the complexity level of the technology or system, and to its maintenance ease	+	High reliability and low maintenance
		■	Reliability and medium maintenance
		-	Low reliability and high maintenance
		*	Maintenance level is not estimable from literature data
Preliminary Investigations	It is referred to the need to deepen investigations for site characterization, even though pilot-studies	+	Investigations do not strongly influence remediation costs and duration
		■	Strong efforts are required for the site characterization
		-	Investigations strongly influence remediation costs and duration
		*	It is not possible to determine the investigation influence
Auto-sustainability	It establishes the role of other technologies compared to the chosen one with the aim to reach the predetermined objectives	+	There is no need to adopt other technologies
		■	Necessity to adopt other technologies in function to the contaminated site characteristics
		-	There is the need to adopt other technologies
		*	The auto-sustainability level is not defined
Acceptability	It is referred to the acceptability level of the community in reference to the social involvement	+	The community opposition is minimum
		■	Social involvement is required but the technology is usually accepted
		-	An important social involvement is required
		*	An important social involvement is required, and the final result is highly uncertain

[a] Legend

Score	**Symbol**	**Evaluation**
High	+	Efficacy demonstrated in pilot test or in real-scale applications.
Medium	■	Limitated efficacy demonstrated in pilot test or in real-scale applications.
Low	-	Not demonstrated efficacy in pilot test nor in real-scale applications.
Not applicable	*	Efficacy level strictly dependent on site-specific conditions or not sufficiently investigated yet.

Table 2. Scenarios assumed about different types of contamination and criteria priorities

Scenario	***Description***	***Criteria priorities***
SC1	Contamination is indistinctly associable to metals, PAHs and PCBs	Metals, PAHs, PCBs > Time, Cost, Residue, Reliability and Maintenance > Safety, Development, Efficacy and Monitoring > Preliminary Investigations, Auto-sustainability > Acceptability
SC2	Metal contamination is higher than PAH and PCB concentration	Metals > PAHs, PCBs > Time, Cost, Residue, Reliability and Maintenance > Safety, Development, Efficacy and Monitoring > Preliminary Investigations, Auto-sustainability > Acceptability
SC3	PAH and PCB contamination is higher than metal concentration	Metals, PAHs, PCBs > Time, Cost, Residue, Reliability and Maintenance > Safety, Development, Efficacy and Monitoring > Preliminary Investigations, Auto-sustainability > Acceptability

Table 3. Evaluation criteria weights adopted in MCDA for SC1

	PAHs	*PCBs*	*Heavy Metals*	*Time*	*Residue*	*Costs*	*Safety*	*Development*	*Efficacy and Monitoring*	*Reliability and Maintenance*	*Preliminary Investigations*	*Auto-sustainability*	*Acceptability*	*Fictious Criterion*	*Weights*
PAHs		0.5	0.5	1	1	1	1	1	1	1	1	1	1	1	**12.0**
PCBs	0.5		0.5	1	1	1	1	1	1	1	1	1	1	1	**12.0**
Heavy Metals	0.5	0.5		1	1	1	1	1	1	1	1	1	1	1	**12.0**
Time	0	0	0		0.5	0.5	1	1	1	0.5	1	1	1	1	**8.5**
Residue	0	0	0	0.5		0.5	1	1	1	0.5	1	1	1	1	**8.5**
Costs	0	0	0	0.5	1		1	1	1	0.5	1	1	1	1	**8.5**
Safety	0	0	0	0	0	0		0.5	0.5	0	1	1	1	1	**5.0**
Development	0	0	0	0	0	0	0.5		0.5	0	1	1	1	1	**5.0**
Efficacy and Monitoring	0	0	0	0	0	0	0.5	0.5		0	1	1	1	1	**5.0**
Reliability and Maintenance	0	0	0	0.5	0.5	0.5	1	1	1		1	1	1	1	**8.5**
Preliminary Investigations	0	0	0	0	0	0	0	0	0	0		0.5	1	1	**2.5**
Auto-sustainability	0	0	0	0	0	0	0	0	0	0	0.5		1	1	**2.5**
Acceptability	0	0	0	0	0	0	0	0	0	0	0	0		1	**1.0**
Fictious Criterion	0	0	0	0	0	0	0	0	0	0	0	0	0		**0.0**

Table 4. The weight vectors for the investigated scenarios

	PAHs	*PCBs*	*Heavy Metals*	*Time*	*Residue*	*Costs*	*Safety*	*Development*	*Efficacy and Monitoring*	*Reliability and Maintenance*	*Preliminary Investigations*	*Auto-sustainability*	*Acceptability*
Weights SC1	12.0	12.0	12.0	8.5	8.5	8.5	5.0	5.0	5.0	8.5	2.5	2.5	1.0
Weights SC2	11.5	11.5	13.0	8.5	8.5	8.5	5.0	5.0	5.0	8.5	2.5	2.5	1.0
Weights SC3	12.5	12.5	11	8.5	8.5	8.5	5.0	5.0	5.0	8.5	2.5	2.5	1.0

First, four different scores were considered: *high, medium, low,* and *scarce/not defined*. In accordance with the precautionary approach, the *not defined* indicator was given the lowest weight. Hence: *Scarce/not defined* = 0.125; *Low* = 0.375; *Medium* = 0.625; *High* = 0.875. The normalization of the MOA was carried out in accordance to the max/min method, reported in Eqs. (2-3):

$$x_{ij}^{-} = x_{ij}/Max(x_j) \tag{2}$$

$$x_{ij}^{-} = Min(x_j)/x_{ij} \tag{3}$$

where: x_{ij} was the performance of the alternative i-th (each remediation technology) with respect to the j-th indicator (each evaluation criterion), w_j the weight of each indicator, x_{ii}^{-} the normalized value of x_{ij} calculated with Eqs. (2) and (3) if the criterion was to be maximised or to be minimised, respectively. As result, all the values of the normalized matrix were in the range [0, 1]. The TWG chose all the criteria to be maximized (Eq. 2).

2.7. Normalized alternatives matrix resolution

The resolution of the MOA was carried out using the *Simple Additive Weighting (SAW)* method (Afshari et al., 2010), which multiplies each element of the matrix with the weight of the corresponding column.

The PI index of the single alternative was calculated with Eq. (4):

$$PI_i = \sum_{j=1}^{m} x_{ij}^{-} \cdot w_j \tag{4}$$

where: w_j is the weight for each evaluation criteria.

The best technogical alternative was identified with the highest I_p. The best solution was identified according to the three different scenarios considered and, subsequently, distinguished between *in situ* and *ex situ* approach.

3. Results and discussion

3.1. Identification of alternative treatments and preliminary screening

The 50 remediation technologies identified in this study are reported in Fig. 2. Based on an expert opinion validation, the pre-screening process allowed reducing the total number of remediation technologies from 50 to 38 (see technologies crossed out in the Fig. 2). For instance, some remediation alternatives could be hardly applicable to contaminated marine sediments or emerging technologies have no historical reliable data. Soil Vapor Extraction (SVE) was excluded because it normally works in the vadose zone (Barnes, 2003), while our case study is related to the remediation of marine sediments.

Some of the alternatives were removed due to their emerging nature and lack of data about performances and costs (electrical resistance heating, steam injection and extraction, conductive heating, radio frequency heating, *in situ* vitrification, gas-phase chemical reduction, anaerobic thermal processes).

Fracturing-based remediation was also excluded because it is designed for low permeability soils or rocks, working similarly to SVE. In fact, it is based on injecting pressurized air beneath the surface to develop cracks in low permeability and over-consolidated sediments, creating new passageways that increase the effectiveness of other *in situ* processes (FRTR, 2002).
Since not applicable to sediments, the last two technologies not considered in the MCDA approach were open burn/open detonation, conducted to destroy obsolete or unserviceable munitions and energetic materials, and hot gas decontamination, applied to waste or metallic structures (FRTR, 2002).

3.2. Matrix resolution and best alternative identification

Fig. 3 shows how MOA was solved according to each scenario of contamination considered. In all the three scenarios investigated, the best technology identified is *Amendments*. In the worst case scenario (SC1) where contamination is given by metals, PAHs and PCBs simultaneously, the preference index highlights the priority of also using an *ex situ* solution (*Vitrification*); instead, in the other two scenarios, where metal concentration was assumed higher than PAH and PCB value, and viceversa, I_p moves towards an *in situ* solution (*Assisted Natural Attenuation*).

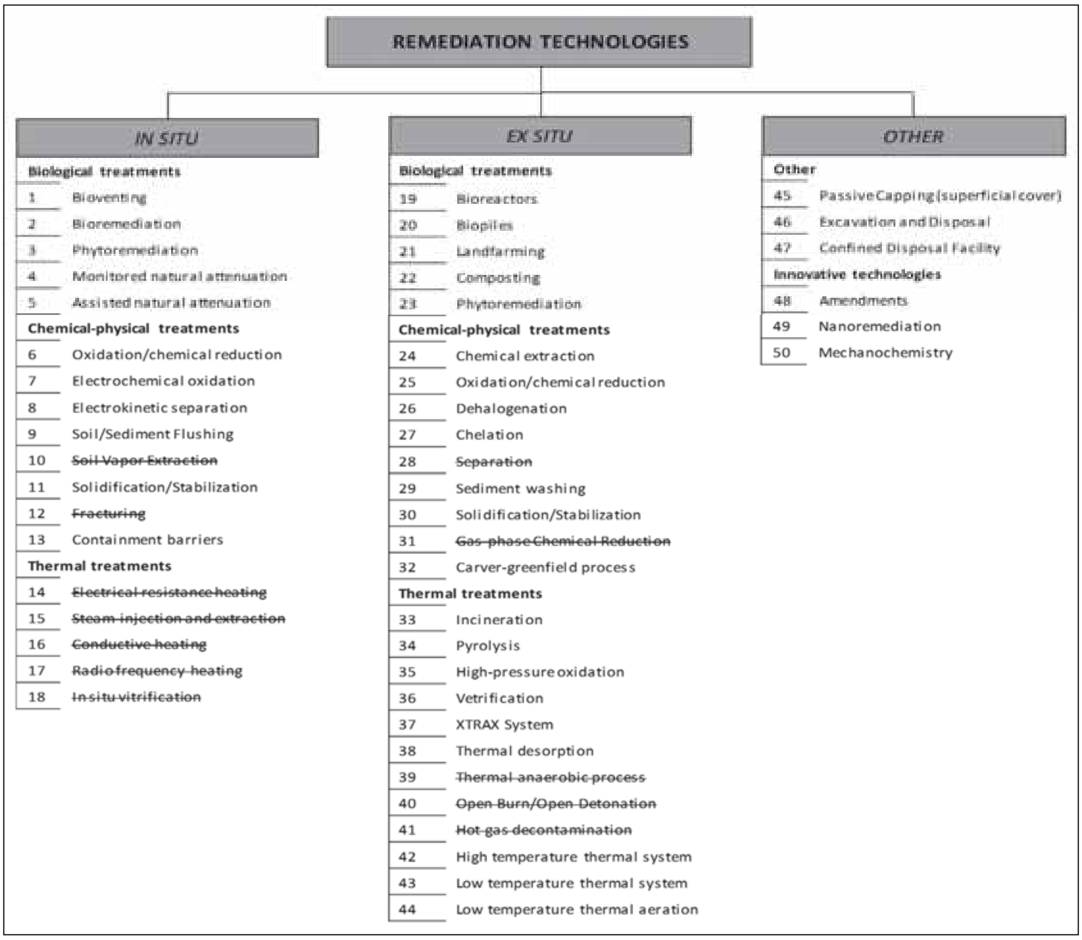


Fig. 2. Remediation technologies identified for in situ, ex situ and other types of technologies

In detail, considering the *in situ* approach, Table 5 shows the first ten remediation alternatives for each specific scenario considered. The best ten *ex situ* technologies identified are shown in Table 6. For the *in situ* approach and in all the three scenarios investigated, the first five positions are covered by the same technologies: (1) Amendments, (2) Assisted Natural Attenuation, (3) Monitored Natural Attenuation, (4) Containment barriers, (5) Passive capping. It is interesting to underline the MNA option, with the monitoring of natural reduction of contamination by means of microorganisms and the general auto-depurative capacity of the system.

In case of metal pollution, bioremediation and solidification/stabilization cover the sixth and seventh position for SC1 and SC2, respectively. Instead, sediment flushing results more appropriate to solve a multifactorial contamination (SC1), the electrochemical oxidation for a contamination by metals prevalently, and bioventing in case of PAH and PCB presence (SC3). For the case of *ex situ* technologies, vitrification was found to be the most promising alternative. Solvent extraction and desorption appeared to depend on the scenario (second or third position), while mechanochemistry and confined disposal facility fall on the fourth and fifth position, respectively, in all the scenarios considered, showing to be indipendent from the type of contaminants. Another interesting aspect to highlight is that incineration appears only in scenarios 1 and 2. It is noteworthy to underline that the disposal option represents the last choice to undertake, as the application of nanoremediation technologies. For the latter, although some positive results were found in literature (Comba et al., 2011; Karn et al., 2009) this type of treatment needs a strong preliminary study to investigate the feasibility of the remediation action (Lofrano et al., 2017).

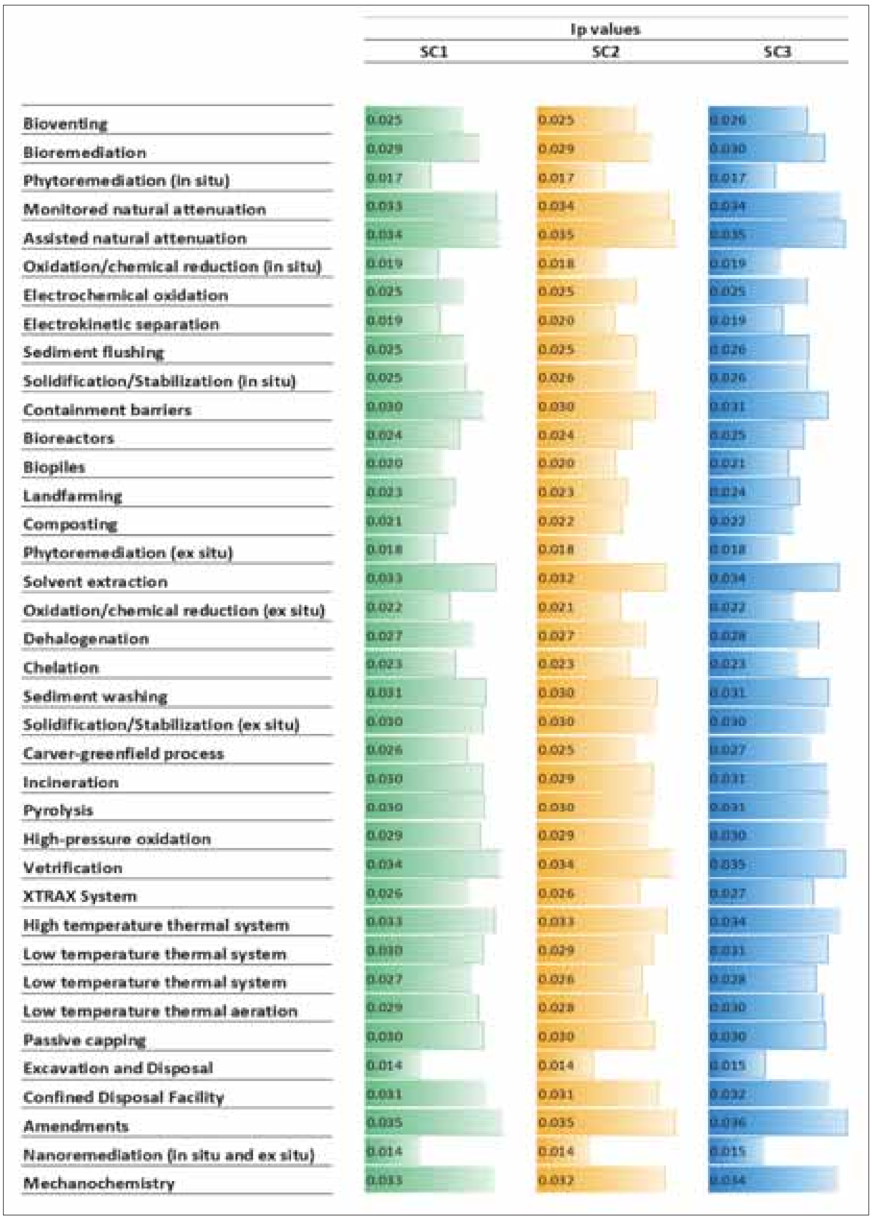


Fig. 3. I_p values for (a) SC1, (b) SC2 and (c) SC3

Table 5. Prioriotized in situ technologies through MCDA

IN SITU technologies		
SC1	**SC2**	**SC3**
Amendments	Amendments	Amendments
Assisted Natural Attenuation	Assisted Natural Attenuation	Assisted Natural Attenuation
Monitored Natural Attenuation	Monitored Natural Attenuation	Monitored Natural Attenuation
Containment barriers	Containment barriers	Containment barriers
Passive Capping	Passive Capping	Passive Capping
Bioremediation	Bioremediation	Sediment flushing
Solidification/Stabilization	Solidification/Stabilization	Bioremediation
Sediment flushing	Ossidazione elettrochimica	Bioventing
Electrochemical oxidation	Sediment flushing	Solidification/Stabilization
Bioventing	Bioventing	Electrochemical Oxidation

Table 6. Prioriotized ex situ technologies through MCDA

EX SITU technologies		
SC1	**SC2**	**SC3**
Vitrification	Vitrification	Vitrification
Solvent extraction	Desorption	Desorption
Desorption	Solvent extraction	Solvent extraction
Mechanochemistry	Mechanochemistry	Mechanochemistry
Confined Disposal Facility	Confined Disposal Facility	Confined Disposal Facility
Sediment Washing	Sediment Washing	Pyrolysis
Pyrolysis	Solidification/Stabilization	Sediment Washing
High temperature thermal system	Pyrolysis	High temperature thermal system
Incineration	High temperature thermal system	Solidification/Stabilization
Solidification/Stabilization	Incineration	High pressure oxidation

3.3. Discussion

As by MCDA results, the best *in situ* technology was based on the use of innovative amendments. Amendments tend to increase contaminant binding and stability by modifing sediment geochemistry.

In a first application, they are used in capping technology for containing and treating contaminated sediments on site (Fig. 4). Reactive materials can provide degradation and/or adsorption of contaminants while allowing upward groundwater flow. The use of reactive materials can greatly reduce the thickness required for cap compared to conventional sand caps (Wessels Perelo, 2010). The most common sorptive materials applied in pilot and real-scale experiments include: apatites (Reible et al., 2016; Zhang et al., 2016) and zeolites (Kang and Park, 2015) which adsorb and complex different metals; organophilic clay (Olsta, 2010; Erten et al., 2012; Todaro et al., 2016), biochar or activated carbon (Janssen and Beckingham, 2013; Todaro et al., 2020) which effectively adsorb organic compounds; zero-valent iron (ZVI) for treating nitroaromatics, chromium, lead, DDT, and related compounds (De Gisi et al., 2017b; Sayles et al., 1997). Among all, AC, organoclay, and apatite were identified as particularly promising sorptive amendments for *in situ* remediation (US EPA, 2013).

An innovative technology consists in using the amendments encapsulated in a non-woven core matrix bound between two geotextiles. This is called Reactive Core Mat (RCM) and represents an effective method to deliver difficult-to-place, high-value, and sorptive media into thin-layer caps (De Gisi et al., 2017c). Reible et al. (2006) monitored the long-term fate and transport of polycyclic aromatic hydrocarbons (PAHs) in a field demonstration of capping contaminated sediments at the Anacostia River in Washington DC. They successfully demonstrated the ability to place the capping materials AquaBlok^{TM} (for permeability control), apatite, (for enhanced metal sorption and control), and coke (for enhanced organic sorption and control) and their ability to reduce contamination. Several experiments have modeled the contaminants' fate and transport in the long-term in a single or multilayered reactive cap for a large range of sediment contaminants (Bortone et al., 2020; Viana et al., 2008).

In a second application, amendments are mixed *in situ* by means of a rotating tool equipped with propellers and/or mixing blades, which ensure the disintegration of the sediment and its remixing with the binder injected by means of special nozzles. An example of full scale application is the STAMIX Stabilization System by Allu Stamix Oy (Finland), of which some images are visible in Fig. 5 (Allu Stamix, 2020).

The interest in applying monitored or assisted natural attenuation as a remediation treatment arose after extensive studies on reductive dechlorination of PCBs in numerous sites, such as the Hudson River (NY, USA), Silver Lake (MA, USA), Sheboygan River (WI, USA), Waukegan Harbor (IL, USA), New Bedford Harbor (MA, USA), and Acushnet Estuary (MA, USA) (Kaštánek et al., 1999; Pakdeesusuk et al., 2003). However, this approach requires the realization of analytical or numerical simulations of the natural recovery which requires a highly detailed conceptual model of the site (De Gisi et al., 2017a).

Vitrification is an emerging technology that uses plasma reactor to destroy organic compounds and immobilize inorganic contaminants on sediments (Wu, 2008). Vitrification has many full scale applications in the United States to remediate soils contaminated with heavy metals mixed with radioactive metals. The vitrified product, enclosing metals, is more leach resistant and chemically stable for longer periods of time (Dermont et al., 2008). However, the technology requires extensive pre-processing of the dredged material. Salts must be removed from the sediment before the vitrification, since some of them volatilized during the melting process, providing problems of corrosion to the system.Furthermore, the pretreatment process includes dewatering of the sediments to remove water prior to injection into the melting chamber (Todaro et al., 2016). Solidification and stabilization (S/S), instead, is a widely-used treatment process for the management and disposal of a broad range of waste materials, even those classified as hazardous (Shi and Fernández, 2006; Todaro et al., 2020).

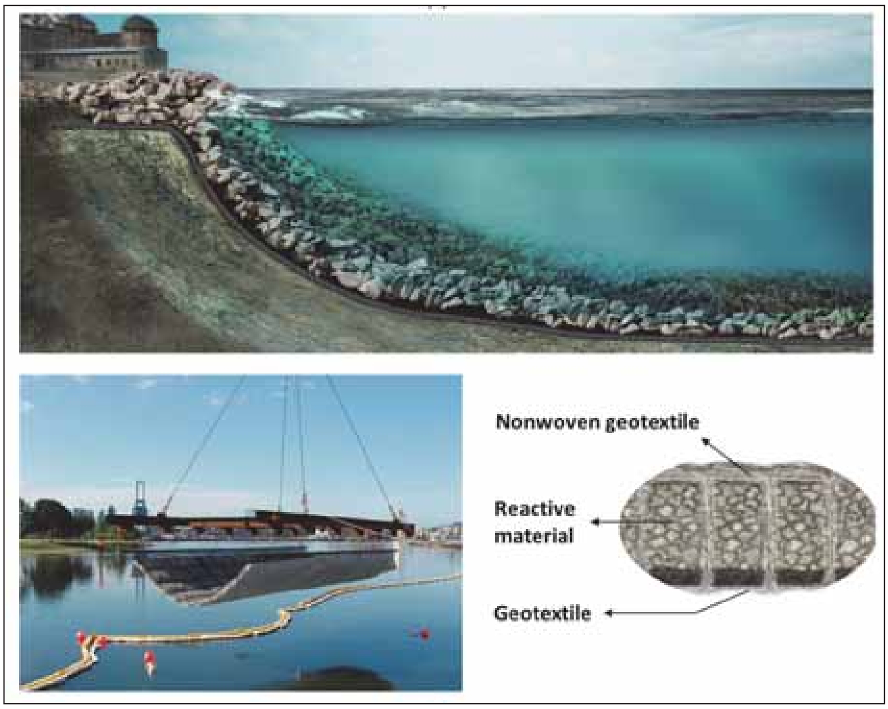


Fig. 4. Examples of full-scale amendments capping applications and schematic of reactive core mat (Huesker, 2020; Mineralstech, 2020)

Fig. 5. Examples of full-scale in situ mixed amendments applications: STAMIX by Allu Stamix Oy (Allu Stamix, 2020)

The last technology present in the first three positions of the MCDA output is thermal desorption. Many plants based on thermal desorption treatment are in operation at full scale in several countries (e.g. Italy, Belgium, The Netherlands, Germany, Japan etc.) (Manni et al., 2004; Sato et al., 2010). However, S/S can be paired to thermal desorption so as to isolate with inertization inorganic pollutants (i.e. by granulation) and with thermal desorption the organic component. Careghini et al. (2010) studied a system for the remediation and reuse of mercury-contaminated sediments based on a cement-based granulation step (S/S), followed by a thermal process under vacuum during which volatile and semi-volatile compounds were removed.

It is evident that extensive research has been conducted on chemical remediation treatment. The solvent extraction technology, in fact, is widely present in literature. Experiments at bench and semi-pilot scale with binary solvent mixture of alkanes and alcohols reached 90% extraction efficiencies for PCB (Nam et al., 2001).

However, this extraction needs to be coupled to chemical dehalogenation or radiolytic degradation (γ-ray irradiation). Solvent extraction has also proven to be successful in a full-scale case in Kobe, Japan, where an illegal dumping was discovered, with about 68 m^3 (92 t) of soil contaminated and approximately 6.6 kg of PCB (Takigami et al., 2008). They used isopropyl alcohol reaching a removal efficiency of 98.6%. The above review has shown that the technologies identified with MCDA have different practical applications.

4. Conclusions

A MCDA-based decision support tool for the assessment of remediation technologies for contaminated marine sediments based on technical, environmental, financial and social criteria was developed and applied to the case study of the Mar Piccolo in Taranto. For the *in situ* technologies, in all the three scenarios investigated, the first five positions are covered by amendments, assisted natural attenuation, monitored natural attenuation, containment barriers and passive capping. For the case of *ex situ* technologies, vitrification was found to be the most promising alternative. Solvent extraction and desorption appear to depend on the pollution scenario. Stabilization/solidification has confirmed its position as a well-established technology.

The proposed framework based on an expert opinion validation, and a comparative procedure appears transparent and interdisciplinary. Moreover, the results showed that the developed tool is a reliable way of selecting the best remediation alternative as well as quantifying the impacts of different criteria in the selection.

This work ensures that decision makers understand how results are produced and therefore secures their participation and the acceptance of the results. Finally, the integration of guidelines shared by the international scientific community gives solidity to the entire decision process.

The framework and weights of the screening criteria can be easily modified and improved to fit the development of new remedial techniques and last regulations, helping the decision makers to efficiently select the best remedial alternative.

References

Afshari A., Mojahed M., Yusuff R.M., (2010), Simple additive weighting approach to personnel selection problem, *International Journal of Innovation, Management and Technology*, **1**, 511-515.

Allu Stamix, (2020), Soil Improvement System Treating Contaminated Sludge, On line at: https://www.allu.net/en/Applications?ProductId=91.

Barnes D.L., (2003), Estimation of operation time for soil vapor extraction systems, *Journal of Environmental Engineering*, **129**, 873-878.

Bortone I., Labianca C., Todaro F., De Gisi S., Coulon F., Notarnicola M., (2020), Experimental investigations and numerical modelling of in-situ reactive caps for PAH contaminated marine sediments, *Journal of Hazardous Materials*, **387**, 121724.

Brans J.P., Vincke P., (1985), A preference ranking organization method, *Management science*, **31**, 647-56.

Careghini A., Dastoli S., Ferrari G., Saponaro S., Bonomo L., De Propris L., Gabellini M., (2010), Sequential solidification/stabilization and thermal process under vacuum for the treatment of mercury in sediments, *Journal of Soils and Sediments*, **10**, 1646-1656.

Carlon C., Giove S., Agostini P., Critto A., Marcomini A., (2004), *The role of Multi-Criteria Decision Analysis in a DEcision Support sYstem for REhabilitation of contaminated sites (the DESYRE software)*, Proc. 2th Int. Symp. on Environmental Modelling and Software, vol. 1, Osnabrück, 55.

Comba S., Di Molfetta A., Sethi R., (2011), A comparison between field applications of nano-, micro-, and millimetric zero-valent iron for the remediation of contaminated aquifers, *Water, Air, and Soil Pollution*, **215**, 595-607.

Critto A., Cantarella L., Carlon C., Giove S., Petruzzelli G., Marcomini A., (2006), Decision support-oriented selection of remediation technologies to rehabilitate contaminated sites, *Integrated Environmental Assessment and Management*, **2**, 273-285.

De Gisi S., Minetto D., Todaro F., Lanzolla A.M.L., Notarnicola M., (2017a), *Monitored Natural Recovery of Contaminated Marine Sediments. Proposal of a Monitoring Plan for in situ Continuous Testing and Sensing*, Proc. 2017 IEEE International Instrumentation and Measurement Technology Conference (I2MTC), 1-6.

De Gisi S., Minetto D., Lofrano G., Libralato G., Conte B., Todaro F., Notarnicola M., (2017b), Nano-scale Zero Valent Iron (nZVI) treatment of marine sediments slightly polluted by heavy metals, *Chemical Engineering Transactions*, **60**, 139-144.

De Gisi S., Todaro F., Notarnicola M., (2017c), Effect of reactive mats on in-situ remediation of contaminated marine sediment, *Procedia Environmental Science, Engineering and Management*, **4**, 17-22.

Dermont G., Bergeron M., Mercier G., Richer-Laflèche M., (2008), Metal-Contaminated soils: Remediation practices and treatment technologies, *Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management*, **12**, 188-209.

Erten M., Reible D., Gilbert R., El Mohtar C., (2012), *The Performance of Organophilic Clay on Nonaqueous Phase Liquid Contaminated Sediments Under Anisotropic Consolidation*, In: *Contaminated Sediments: Restoration of Aquatic Environment*, Mulligan C., Li S. (Eds.), ASTM International, West Conshohocken, 32-44.

Figueira J.R., Greco S., Roy B., Słowiński R., (2010), *ELECTRE Methods: Main Features and Recent Developments*, Springer, Berlin-Heidelberg, 51-89.

FRTR, (2002), Remediation technologies screening matrix and reference guide, Federal Remediation Technology Roundtable, On line at: https://frtr.gov/matrix2/top_page.html.

Goletsis Y., Psarras J., Samouilidis J.E., (2003), *Project Ranking in the Armenian Energy Sector Using a Multicriteria Method for Groups*, In: *Annals of Operations Research*, Boros E. (Eds.), Springer, 135-157.

Gorsevski P.V., Donevska K.R., Mitrovski C.D., Frizado J.P., (2012), Integrating multi-criteria evaluation techniques with geographic information systems for landfill site selection: A case study using ordered weighted average, *Waste Management*, **32**, 287-296.

Hasegawa H., Rahman I.M., Rahman M.A., (2016), *Environmental Remediation Technologies for Metal-Contaminated Soils*, Springer, Japan.

Hsu J.C., Hsieh C.Y., Yang Y.H., Lu C.Y., (2015), Net clinical benefit of oral anticoagulants: A multiple criteria decision analysis', *PLoS One*, **10**, e0124806.

Huesker, (2020), Active Capping, On line at: https://www.huesker.co.uk/applications/environmental-eng/remediation/active-capping.html.

Jacquet-Lagreze E., Siskos J., (1982), Assessing a set of additive utility functions for multicriteria decision-making, the UTA method, *European Journal of Operational Research*, **10**, 151-164.

Janssen E.M., Beckingham B.A., (2013), Biological Responses to Activated Carbon Amendments in Sediment Remediation, *Environmental Science and Technology*, **47**, 7595-7607.

JRCEC, (2008), Joint Research Centre-European Commission Handbook on constructing composite indicators: methodology and user guide, OECD publishing, On line at: https://www.oecd.org/els/soc/handbookonconstructingcompositeindicatorsmethodologyanduserguide.htm

Kang K., Park S.J., (2015), Application of Limestone, Zeolite, and Crushed Concrete as Capping Material for Interrupting Heavy Metal Release from Marine Sediments and Reducing Sediment Oxygen Demand, *Journal of The Korean Society of Agricultural Engineers*, **57**, 31-38.

Karn B., Kuiken T., Otto M., (2009), Nanotechnology and in situ remediation: A review of the benefits and potential risks, *Environmental Health Perspectives*, 1823-1831.

Kaštánek F., Demnerova K., Pazlarova J., Burkhard J., Maleterova Y., (1999), Biodegradation of polychlorinated biphenyls and volatile chlorinated hydrocarbons in contaminated soils and ground water in field condition, *International Biodeterioration and Biodegradation*, **44**, 39-47.

Li W., Zhang M., Wang M., Han Z., Liu J., Chen Z., Liu B., Yan Y., Liu Z., (2018), Screening of groundwater remedial alternatives for brownfield sites: a comprehensive method integrated MCDA with numerical simulation, *Environmental Science and Pollution Research*. Springer Verlag, **25**, 15844-15861.

Linkov I., Varghese A., Jamil S., Seager T.P., Kiker G., Bridges T., (2006), *Multi-Criteria Decision Analysis: A Framework for Structuring Remedial Decisions at Contaminated Sites*, In: *Comparative Risk Assessment and Environmental Decision Making*, Linkov I., Ramadan A.B. (Eds.), Kluwer Academic Publishers, 15-54.

Lisco S., Corselli C., De Giosa F., Mastronuzzi G., Moretti M., Siniscalchi A., Tursi A., (2016), Geology of Mar Piccolo, Taranto (southern Italy): the physical basis for remediation of a polluted marine area, *Journal of Maps*, **12**, 173-180.

Lofrano G., Libralato G., Minetto D., De Gisi S., Todaro F., Conte B., Calabrò D. Quatraro L., Notarnicola M., (2017), In situ remediation of contaminated marinesediment: an overview, *Environmental Science and Pollution Research*, **24**, 5189-5206.

Manap N., Voulvoulis N., (2014), Risk-based decision-making framework for the selection of sediment dredging option, *Science of the total environment*, **496**, 607-623.

Manni A., Massacci P., Piga L., Serranti S., (2004), Screening and thermal desorption for remediation of a sediment polluted by the mercury of a chlor-alkaly plant, *Soil and Sediment Contamination*, **13**, 391-404.

Mineralstech, (2020), Sediment Capping Technologies. Solutions for in-situ capping of contaminated sediments, On line at: https://www.mineralstech.com/business-segments/performance-materials/cetco/environmental-products/products/.

Nam P., Kapila S., Liu Q., Tumiatti W., Porciani A., Flanigan V., (2001), Solvent extraction and tandem dechlorination for decontamination of soil, *Chemosphere*, **43**, 485-491.

Olsta J., (2010), *In-situ Capping of Contaminated Sediments with Organophilic Clay*, Proc. 12th Triannual International Conference Ports, 1, 603-610.

Pakdeesusuk U., Freedman D., Lee C.M., Coates J.T., (2003), Reductive dechlorination of polychlorinated biphenyls in sediment from the Twelve Mile Creek arm of Lake Hartwell, South Carolina, USA, *Environmental Toxicology and Chemistry*, **22**, 1214-1220.

Petronio B.M., Cardellicchio N., Calace N., Pietroletti M., Pietrantonio M., Caliandro L., (2012), Spatial and temporal heavy metal concentration (Cu, Pb, Zn, Hg, Fe, Mn, Hg) in sediments of the Mar Piccolo in Taranto (Ionian Sea, Italy), *Water, Air, and Soil Pollution*, **223**, 863-875.

Reible D., Lampert D., Constant D., Mutch R.D., Zhu Y., (2006), Active capping demonstration in the Anacostia river, Washington, *Remediation Journal*, **17**, 39-53.

Reible D., (2016), *Processes, Assessment and Remediation of Contaminated Sediments*, Springer Science, New York.

Ren L., He L., Lu H., Li J., (2017), Rough-interval-based multicriteria decision analysis for remediation of 1, 1-dichloroethane contaminated groundwater, *Chemosphere*, **168**, 244-253.

Rosén L., Back P.E., Söderqvist T., Norrman J., Brinkhoff P., Norberg T., Döberl G., (2015), SCORE: a novel multi-criteria decision analysis approach to assessing the sustainability of contaminated land remediation, *Science of the Total Environment*, **511**, 621-638.

Saaty T., (1990), *Multicriteria Decision Making: The Analytic Hierarchy Process: Planning, Priority Setting*

Resource Allocation, RWS Publications, Pittsburgh.

Salomons W., (1998), Biogeodynamics of contaminated sediments and soils: Perspectives for future research, *Journal of Geochemical Exploration*, **62**, 37-40.

Sato T., Todoroki T., Shimoda K., Terada A., Hosomi M., (2010), Behavior of PCDDs/PCDFs in remediation of PCBs-contaminated sediments by thermal desorption, *Chemosphere*, **80**, 184-189.

Sayles G.D., You G., Wang M., Kupferle M.J., (1997), DDT, DDD, and DDE dechlorination by zero-valent iron, *Environmental Science and Technology*, **31**, 3448-3454.

Shi C., Fernández-Jiménez A., (2006), Stabilization/ solidification of hazardous and radioactive wastes with alkali-activated cements, *Journal of Hazardous Materials*, **137**, 1656-1663.

SMOCS, (2012), Technologies and Solutions for Handling of Contaminated Sediments. State of the art review, Baltic Sea Region Programme Project n. 39, Sustainable Management of Contaminated Sediments, On line at: https://keep.eu/projects/15625/.

Takigami H., Etoh T., Nishio T., Sakai S.I., (2008), Chemical and bioassay monitoring of PCB-contaminated soil remediation using solvent extraction technology, *Journal of Environmental Monitoring*, **10**, 198-205.

Todaro F., De Gisi S., Notarnicola M., (2016), Contaminated marine sediments: waste or resource? An overview of treatment technologies, *Procedia Environmental Science Engineering and Management*, **3**, 157-164.

Todaro F., De Gisi S., Notarnicola M., (2020), Contaminated marine sediment stabilization/ solidification treatment with cement/lime: leaching behaviour investigation, *Environmental Science and Pollution Research*, **27**, 21407-21415.

Tony M., Wagner M., Khoury H., Rindress D., Papastavros T., Oh P., Goetghebeur M.M., (2011), Bridging health technology assessment (HTA) with multicriteria decision analyses (MCDA): Field testing of the EVIDEM framework for coverage decisions by a public payer in Canada, *BMC Health Services Research*, **11**, 329.

Tzeng G.H., Huang J.J., (2011), *Multiple attribute decision making. Methods and application survey*, CRC Press, Boca Raton.

UKEA, (1999), Cost and benefits analysis for remediation of land contamination, UK Environmental Agency, Midlands Region, P316, On line at: https://www.oecd.org/els/soc/handbookonconstructing compositeindicatorsmethodologyanduserguide.htm.

UNIDO, (2007), Survey of sediment remediation technologies, International Centre for Science and High Technology, On line at: https://clu-in.org/download/contaminantfocus/sediments/ Survey-of-sediment-remediation-tech.pdf.

US ACE, (2014), Economical treatment of dredged material to facilitate beneficial use, U.S. Army Engineer Research and Development Center, Vicksburg, 39180-6199, On line at: https://usace.contentdm.oclc.org/digital/collection/p266001coll1/id/3923/.

US EPA, (1988), Guidelines for conducting remedial investigation and feasibility studies under CERCLA, U.S. Environmental Protection Agency, Washington, On line at: https://nepis.epa.gov.

US EPA, (2004), Remediation and characterization innovation technologies, U.S. Environmental Protection Agency, Washington, On line at: https://nepis.epa.gov.

US EPA, (2005), Contaminated sediment remediation guidance for hazardous waste sites, U.S. Environmental Protection Agency, Washington, On line at: https://nepis.epa.gov..

US EPA, (2013), Use of amendments for in situ remediation at superfund sediment sites, U.S. Environmental Protection Agency, Washington, On line at: https://nepis.epa.gov..

Viana P.Z., Yin K., Rockne K., (2008), Modeling active capping efficacy. Metal and organometal contaminated sediment remediation, *Environmental Science and Technology*, **42**, 8922-8929.

Wessels Perelo L., (2010), In situ and bioremediation of organic pollutants in aquatic sediments, *Journal of Hazardous Materials*, **177**, 81-89.

Wu T.N., (2008), Environmental perspectives of microwave applications as remedial alternatives: review', *Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management*, **12**, 102-115.

Zhang C., Zhu M.Y., Zeng G.M., Yu Z.G., Cui F., Yang Z.Z., Shen L.Q., (2016), Active capping technology: a new environmental remediation of contaminated sediment, *Environmental Science and Pollution Research*. Springer Verlag, **23**, 4370-4386.

Zheng Z.J., Lin M.Y., Chiueh P.T., Lo S.L., (2019), Framework for determining optimal strategy for sustainable remediation of contaminated sediment: A case study in Northern Taiwan, *Science of The Total Environment*, **654**, 822-831.

Environmental Engineering and Management Journal October 2020, Vol.19, No. 10, 1905-1914
http://www.eemj.icpm.tuiasi.ro/; hiip://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

WASTE AND STANDARDS AT THE TIME OF THE ANTHROPOCENE. FOR AN URBAN ETHNOGRAPHY: THE CASE OF THE DALMINE WASTE-TO-ENERGY PLANT

Roberto Redaelli[1], Raffaella Trigona[2*]

[1]*ISIS Natta of Bergamo, Street Europa 15 - 24125 Bergamo, Italy,*
[2]*University of Bergamo, Place Rosate 2 - 24129 Bergamo, Italy*

Abstract

The focus of the research starts from a critical investigation of the environmental situation in Lombardy in the 1990s, linked to waste disposal and the related legislation produced by the Regional Council with the approval of the Regional Law of 1 July 1993, to analyse its evolution through the example of the construction of the waste-to-energy plant1 in Dalmine (Bergamo). The growing local urban socio-economic complexity, combined with the urgent global environmental problems produced by the ongoing ecological transition, called "Anthropocene", makes us reflect whether the Dalmine plant can actually be a model of sustainable development, i.e. capable of harmonizing economic growth with the balance of the territory and the current social dynamics.

Key words: anthropocene, complexity, environmental law, ethnography, waste-to-energy plant

Received: February, 2020; Revised final: June, 2020; Accepted: July, 2020; Published in final edited form: October, 2020

1. Introduction. Legal framework

The exclusive legislative competence of the State in matters of "protection of the environment, the ecosystem and cultural heritage" is provided for by article 117, second paragraph, letter s), of the Italian Constitution and according to the consolidated constitutional jurisprudence1 , it is up to the State to regulate the environment and the ecosystem as an organic entity, through a unitary and comprehensive discipline (inherent to a public interest of primary and absolute constitutional value) The aim is to ensure, as EU law requires, a high level of protection, which as such is mandatory under other sectorial disciplines.

The jurisprudence of the Italian Constitutional Court has elevated the environment to constitutional status as an organic entity inherent in a public interest of constitutional value primary and absolute in fact, the "competence entrusted exclusively to the State, pursuant to Article 117, second paragraph, letter s) of the Constitution" concerns the "environment in its entirety, as an organic entity that is inherent to a public interest of primary and absolute constitutional value".

The regulatory protection of the environment, to be effective, must be at supranational level, for this reason the European Union has promoted the prevention, reduction (in terms of quantity and quality) and reuse of waste with the EC Directive, (1975), later amended by the subsequent EC Directive, (1991), which recalls the guidelines introduced by the Fifth Action Programme for the period 1993/1997. It indicates the common path to follow by proposing guidelines such as: sustainable development in the field of waste management, prevention and minimisation of waste production, maximisation of recycling and recovery and promotion of compatible systems for waste treatment and disposal. The 1991 EC Directive introduces further principles such as: the need for common terminology and a definition of "waste"; the need to give priority to the prevention or minimisation of waste production and the recovery of material and energy over disposal; the introduction of

*Author to whom all correspondence should be addressed: raffaella.trigona@guest.unibg.it

a less strict and binding regime for recovery operations than for disposal.

The Sixth Environmental Action Programme of the European Union, (Decision N° 1600/2002/EC of the European Parliament and of the Council of 22 July 2002 laying down the Sixth Community Environment Action Programme) then defines the priorities and objectives of the European environmental policy on the management of natural resources, with the objective of ensuring that the consumption of renewable and non-renewable resources does not exceed the carrying capacity of the environment, decoupling economic growth from resource use, improving resource efficiency and reducing waste production.

The Commission initially presented proposals for new waste legislation in 2014, which were withdrawn and replaced by the improved, more circular and more ambitious proposals presented in December 2015 as part of the Commission's Juncker Circular Economy Programme (Massarutto, 2019). The proposals were then adopted and are now an integral part of the EU body of law. The new rules adopted today represent the most modern waste legislation in the world, an area where the EU is setting an example that others should follow. The proposals were then adopted and are now an integral part of the body of EU law.

These fundamental regulatory principles have been acquired and made their own in Italian law. The regulatory framework to better understand this work is highlighted below (Busi 2017; Dell'Anno 2018). Of particular interest for this research is "The Regional Plan for the management of waste of the Lombardy Region", which basically reproduces the provisions of LL, (2003), in the objectives of the regional waste management policy, with some additional indications such as the reduction of 20% of hazardous waste to be disposed of by 2010.

It should be noted that the quantities of residual urban waste, after separate collection, are essentially disposed of without or with a minimum recourse to landfill; the Plan highlights both the complement to the material recovery action implemented through separate collection, and the energy recovery implemented through the waste-to-energy plant for residual urban waste, in dedicated plants or with the production of fuel derived from waste. The Plan leads to the consequent combined production of electricity and heat (cogeneration) compared to the production of electricity alone; it also favours the supply of heat to residential centres (district heating), with consequent disposal of the relevant civil heating plants and the supply of electricity to industrial districts. We have chosen to highlight a number of milestones in the development of Italian and European Union legislation on the remediation of polluted sites and waste disposal. A complex and constantly evolving regulatory development, linked to the continuous transformations of socio-economic, territorial, political systems.

2. Objectives and methodology

The research questions by objectives are:

- how environmental protection is closely linked to the theme of the government of the territory of the Municipality of Dalmine, with the inclusive meaning of attention to the urbanistic aspect and also to the "political" action on the territory, i.e. the choice of a certain order of closely intertwined public and private, economic and social interests;

- how the legislation of the territory is evolving with the development of the urban socio-economic fabric, through the voices of some operators.

The research uses a qualitative methodology, for successive and recursive phases. First of all, a preliminary study of the territory of Dalmine was necessary through the available materials: the cartographic and plan metric data, the environmental information related to the Municipality and the neighbouring territories. This was followed by an analysis of EU and Italian legislation relating to the construction of the waste-to-energy plant, as well as an examination of regional legislation and administrative acts issued.

Table 1. Schematic overview of waste management and remediation of polluted sites

Legislation European Union	*Legislation Italian implementation*	*Object*
Directive implementing EC Directive, (2001), Directive 2001/77/EC of the European Parliament and of the Council of 27 September 2001, on the promotion of electricity produced from renewable energy sources in the internal electricity market	LD, (2003) 2003/387/IR of the Government of the Italian Republic	Standard for the promotion of electricity produced from renewable energy sources in the electricity market. National energy policy goes in this direction, supporting the increased use of renewable energy sources, including waste among the energy sources eligible for the reserved scheme. In particular, in Article 17 of Legislative Decree (2003), the Italian legislator reconciles the obligation to comply with the European directive (which classifies only the biodegradable fraction of waste as a renewable energy source and incentive) with the opportunity to start the thermos destruction of the residual part of waste only after separate collection and possible reuse (example of circular economy).

	A legislative decree – LD of Republic of Italy - IR- - is, according to Italian constitutional law, a legislative act having the value of a law adopted by the constitutional body which has the executive power by express and formal delegation of the constitutional body which has the legislative power (Parliament of the Italian Republic).
Legislation Italian	***Object***
LD (2006) 152/2006/IR of the Government of the Italian Republic	Italian framework law, considered the "Testo unico sull'ambiente", containing the main rules governing environmental legislation. The rule originates from an L, (2004). Since its promulgation, up to the date of today, it has undergone a series of amendments and additions, such as to adapt the legislation to the evolutions of the Italian socio-economic context and to the legal updates of the European Union. Italian legislation has over the years adapted to EU legal principles in particular: • the EC Directive, (2010) of the European Parliament and of the Council of 24 November 2010, on industrial emissions (integrated pollution prevention and control) on industrial emissions (integrated pollution prevention and control) • the EC Directive, (2014) of the European Parliament and of the Council of 16 April 2014 amending EC Directive (2011), on the assessment of the effects of certain public and private projects on the environment,
Rules on waste management and remediation of polluted sites	
Reference standard	***Object***
art. 237 bis LD (2006) 152/2006/IR of the Government of the Italian Republic	The standard sets out measures and procedures to prevent or, where that is not possible, to reduce the adverse effects of waste incineration and co-incineration activities in particular: • general technical criteria and standards concerning the design and functional characteristics and operating conditions of waste incineration and co-incineration plants, with particular reference to the need to ensure a high level of protection of the environment against emissions from the incineration and co-incineration of waste.
Brief quotes from the basic legal criteria o on environmental monitoring (https://www.arpalombardia.it/PublishingImages/Pages/Forms/AllItems/analisi%20anno%202019%20rev%2020191231_completo.pdf) (ISPRA, (2018), *Yearbook of Environmental Data*, State of the Environment.)	
Reference standard	***Object***
LD n.132, (2016) 132/2016/IR of the Government of the Italian Republic	The standard deals with the creation and regulation of the national network system for the protection of the environment and regulates the *Higher Institute for Environmental Protection and Research*. The Italian legislator in this way guarantees uniformity in the exercise of cognitive action (monitoring) and public control of environmental quality in Italy, establishing a national networked system for environmental protection. One of the objectives pursued is to identify the Essential Levels of Technical Environmental Performance (with the acronym LEPTA), in order to guarantee a homogeneous protection of the territory and citizens, following the model of what has been done in the health field.
Brief quotes from the basic legal criteria promulgated by the Lombardy Region in relation to waste disposal and environmental protection useful to understand this work	
Reference standard	***Object***
LR (1980) 94/1980 /LR, Lombardy Region Waste disposal regulations	This rule anticipates national legislation on waste disposal and environmental protection by two years. This law regulates the disposal of solid urban waste and special waste in order to adapt this activity to the needs of environmental protection; it promotes and defines the system of works and related services
LR (1993) 21/1993/LR, Lombardy Region	This standard represented a starting point for separate collection, in terms of quality and quantity (Lombardy municipalities exceeded the legal target quota of 10% and at the end of 1996 the 22% quota on a regional scale). The provincial plans of the following years have introduced the criterion of an integrated waste management system (abandoning the antiquated approach of the mere search for disposal solutions), promoting synergic phases of prevention that include all phases, from collection to recovery and final disposal. The law was repealed by LR (2003) 26/2003/LR, Lombardy Region
LR (2003) 26/2003/LR, Lombardy Region	Standards for waste management, energy, underground use and water resources.

Subsequently a specifically ethnographic methodology was used. In a second phase there was the meeting with some privileged witnesses, operators of the territory. The meetings were oriented through unstructured interviews, i.e. built in the interaction with the interviewee himself, to stimuli related to environmental issues related to the socio-economic history of the development of the territory. This methodological tool is often characterized by elements of informality (use of the first person, colloquial exchanges etc.) and out of pre-established schemes, but not for this reason with less "scientific" value. In fact, this tool has the value of bringing unforeseen stimuli and finding meanings that until then had escaped (De Sardan 2009). For this reason, the awareness of the partiality of this kind of knowledge makes anthropological knowledge a process that cannot have pretensions of exhaustiveness but can be a critical stimulus and can offer new and, at the same time, plausible interpretations of the object of study.

The operational lines of research will deal with the following:

1. the analysis of European Union, Italian, regional and local environmental legislation on waste disposal and site remediation;
2. the study of the case of the Dalmine waste-to-energy plant in relation to the urban, economic and social context, through the voice of some privileged informants;
3. the final observations that highlight the possible critical issues to be addressed also thanks to awareness raising actions for a sustainable development of the area in question the possible critical issues that emerged from the environmental emergency combined with the current health emergency.

3. Case study: the Dalmine waste-to-energy plant in relation to the urban, economic and social context. An urban ethnography through the voice of some privileged informers

Dalmine is a town in the province of Bergamo, located in the centre of a strategic industrial area, between Bergamo and Milan and close to important communication routes such as the Milan-Venice motorway, the Bergamo-Treviglio-Milan railway, Orio al Serio airport. The provincial road 525 crosses the territory connecting the entire industrial area. The urban model of Dalmine is that of a factory town (Dematteis and Lanza, 2016; Ferrara, 2016) following the 19th century example of Crespi d'Adda and numerous European and world cities such as Detroit, Toyota, Togliattigrad, Stuttgart, Wolfsburg, Essen and Turin. This model was born from the positivist idea for which man is conceived as a producer: the man-worker, his family, his material and spiritual life take place within a single industrial space.

Leaving behind the Crespi d'Adda model and differentiating itself from nearby Zingonia, over the last fifty years Dalmine has evolved and transformed itself into an innovative urban reality, but not without a problematic development.

This, in particular, if seen in the light of the most urgent environmental issues produced in the Anthropocene, literally "the age of man", i.e. the time in which man, as a species, is able to alter the ecological cycles of all natural species and human activities are considered the main causes of the territorial, structural and climatic changes of the planet (Bougleux, 2015; Ceruti, 2018; Crutzen and Stoermer, 2000; Ferrara, 2016; Morton, 2018; Trigona, 2018). The study of Dalmine's case is an opportunity to explore the human-environment relationship, demonstrating how the problem of the environment cannot be in any way detached from the experience of the people who inhabit and live the territory.

3.1. Interview with Viviana Lazzarini

The head of the ecology office of the Municipality of Dalmine (Fig.1) Viviana Lazzarini receives me in her office and explains her task as head of the Ecology Service since 2011. She is an expert in environmental science and deals with environmental issues, as shown by her curriculum. She has a degree in environmental sciences and her previous assignments have always dealt with ecological and environmental issues.

I would ask you to describe exactly what your office is dealing with. The environmental and land protection service is structured as follows:

1. Manages waste disposal;
2. Performs all pest control operations;
3. controls air and water pollution and noise and electromagnetic pollution;
4. It takes care of municipal gardens (28 public gardens) and greenery (2 orchards, 2 woods);
5. It plans and proposes sustainable development actions with the Agenda 21 Association, in line with the European 2020 programme;
6. Collaborates within the PLIS - Local Park of Municipal Interest of the lower course of the Brembo river.

Viviana highlights points 5 and 6 and the active collaboration with other territorial realities and municipalities:

- With regard to Agenda 21, with the so-called "Isola Bergamasca" municipalities and with Zingonia.
- As regards the Local Park, with the municipalities of Boltiere, Bonate Sotto, Madone, Filago, Osio Sopra and Osio Sotto.

The most recent and ongoing actions by the Municipality are:

1) The "plastic free" project, to raise awareness among citizens and/or non-profit associations and avoid plastic containers: for example, the use of plastic during Church-related events;

2) The projects on sustainable mobility, in particular the electric one; four years ago, the first electric column, followed by six others, in addition to the one installed by the Province and that of REA; there is the facilitation of parking and circulation for electric or hybrid vehicles thanks to the agreement with the Municipality of Bergamo.

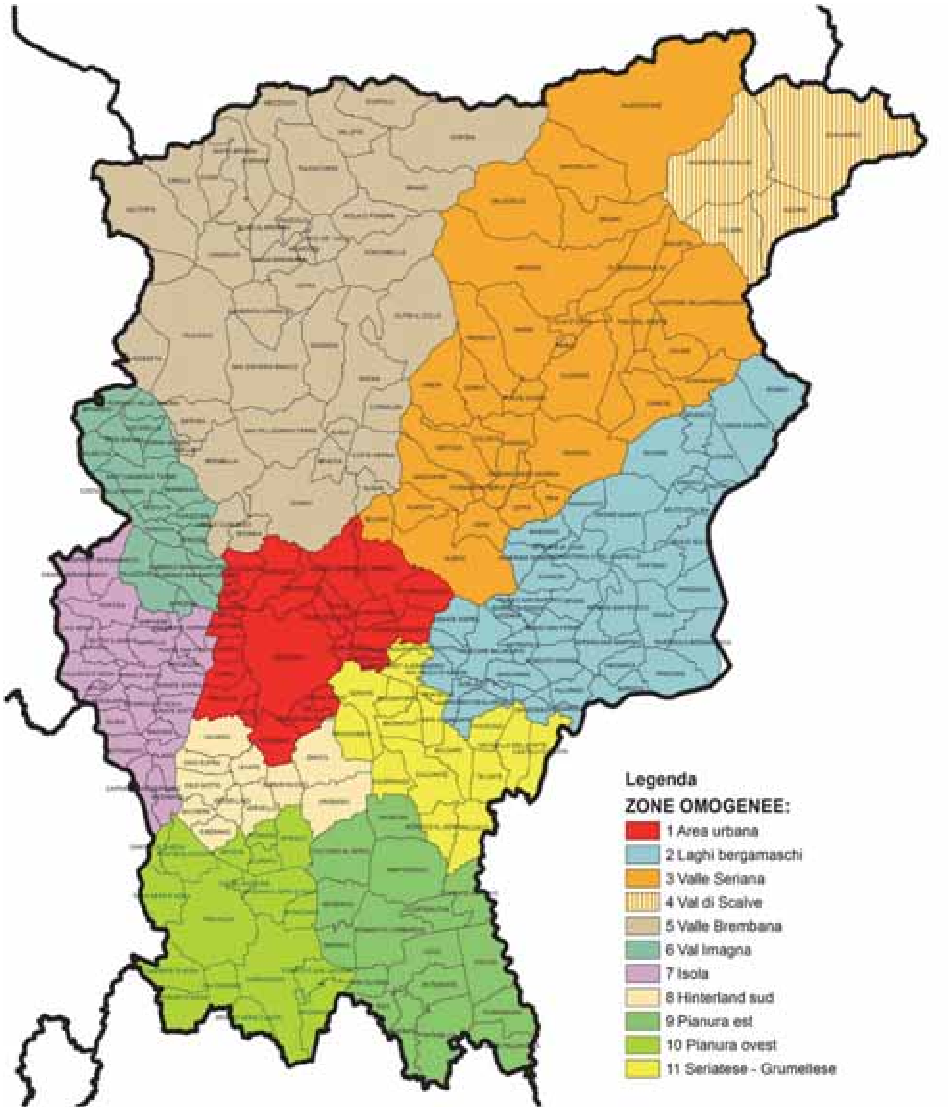


Fig.1. Lombardy territory of Dalmine (web site Municipality of Dalmine)

I then turn to Viviana for environmental education. The Municipality is also very active in this field:

- two study rooms have been set up: the Belvedere river classroom and the geology classroom;
- environmental education courses are active with the cooperative Il Picchio Verde and Il Sogno;
- there is a collaboration with REA for the development of environmental education courses at ENAIP or other high schools in Dalmine.

At this point I have to dig deeper and ask about the Dalmine REA waste-to-energy plant.

Viviana shows me some archive data that help us to reconstruct a brief history of the design and construction of the waste to energy plant (located in Dalmine, via Dossi, 12). The interesting part is that the design of the waste to energy plant was started just at the end of the nineties and thanks to art. 32 of the Regional Law no. 21 of 1 July 1993. Also in the Dalmine area the 90s were fundamental for the realization of possible solutions for waste disposal with the construction of what have been called "incinerators".

The regulatory references, as explained above, did not actually provide for the construction of the plant in Dalmine, as this was not provided for in the regional planning, except for direct agreements with the municipal administration.

Short Chronological History of the Waste-to-energy Plant REA DALMINE S.p.A.:

- 1 January 1997: first agreement between REA (Fig. 2 and Fig, 3) and the Municipality of Dalmine for the construction of the plant, as provided for by the regional law;
- January-September 1998: operating agreement with precise agreements between REA and the Municipality;
- years 2001-2003: testing and construction of the plant.
- subsequent legal amendments until 2019.

AMENDMENT OF THE TERRITORIAL AGREEMENTS, SIGNED AND SUBMITTED DURING 2003, FOR THE MUNICIPALITIES OF:

- **BERGAMO** signed on 10/7/2003 and registered with the same municipality in date 10/07/2003 to No 48881
- **AZZANO SAN PAOLO** signed on 28/11/2003 and registered with the same municipality on 04/12/2003 to No 17432
- **BONATE SOPRA** signed on 28/11/2003 and registered with the same municipality on 04/12/2003 at no. 15120
- **BONATE SOTTO** signed on 28/11/2003 and registered with the same municipality on 04/12/2003 under no. 9788
- **CURNO** signed on 28/11/2003 and registered with the same municipality and on 04/12/2003 at no. 22072
- **DALMINE** signed on 28/11/2003 and registered with the same municipality on 09/12/2003 under No 27375

Fig. 2. Amendment 2016 (Source: Public acts of authorisation for the construction of the REA plant in Dalmine from the Archive of Renato Daminelli

REA DALMINE S.p.A. manages waste-to-energy plants in the national and European panorama thanks to its qualifying points: the ITR NOY 400 waste-to-energy plant located in Dalmine (BG). ITR NOY 400 is considered a reference:

- it guarantees flue gas emissions with very low pollutant values, reduced on average by 80% compared to the limits of the European legislation, thanks to its innovative flue gas treatment line.
- does not use water at any stage of the process, conserves a vital resource and has no liquid discharges
- achieves high efficiency with efficiencies in excess of 27%.

The plant is able to treat a wide range of wastes

- municipal waste as downstream of separate collection
- municipal waste
- dry fractions from mechanical sorting plants
- waste derived fuel
- biomass
- dewatered biological sludge of civil origin
- hospital waste

Fig 3. REA DALMINE S.p.A.

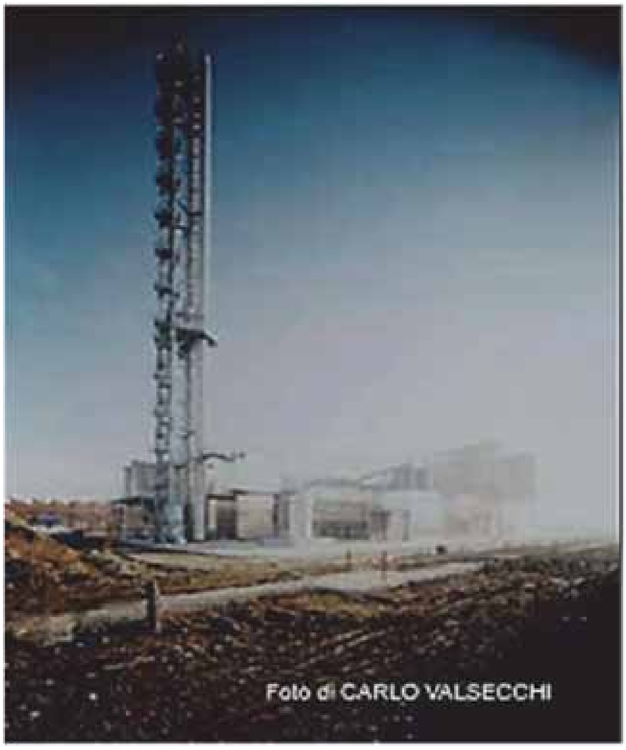
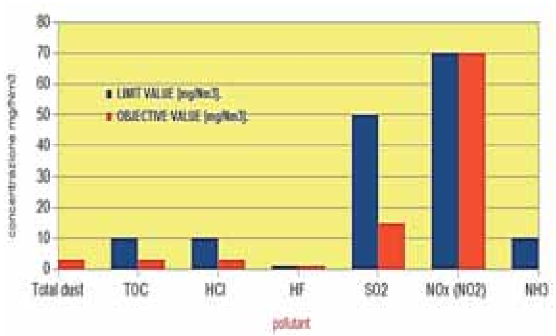
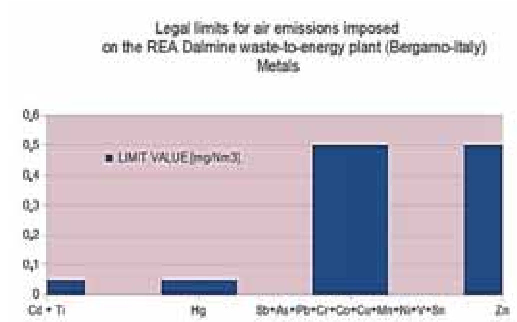


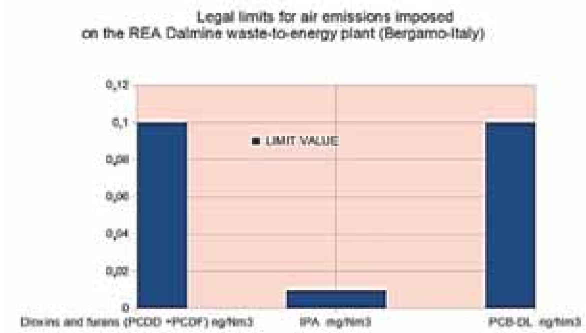
Fig. 4 - REA DALMINE S.p.A (from the Archive of Carlo Valsecchi)



(a)



(b)



(c)

Fig. 5. Legal limits for air emissions imposed on the REA Dalmine waste-to-energy plant (Bergamo-Italy) (ARPA Lombardy): (a) - Air Emission limit values for pollutants: total dust, TOC (total organic carbon), HCl (hydrochloric acid), HF (hydrofluoric acid), SO2 (sulphur dioxide), NOx (oxides of nitrogen), NH3 ammonia); (b) - Air Atmospheric emission limit values for metallic pollutants; (c) - Air Emission limit values for pollutants: dioxins and furans (PCDD +PCDF), hydrocarbons aromatic polycycles (IPA), polychlorinated biphenyls (PCB-DL)

An important part of the conversation with Viviana concerns the relationship between REA Dalmine S.p.A. and the Municipal Administration. The relationship has gone through alternating phases of collaboration and misunderstanding, in particular on some points of the agreement ignored by REA Dalmine S.p.A. and related to the economic benefits for the Municipality. A legal dispute is still open concerning the agreement signed in 1998 between the company and the Municipality. On this issue, some interesting questions have been raised about the functions of the plant and the concrete benefits for Dalmine and the citizens who live there.

Today the plant is among the most virtuous in the Region, according to the data provided by ARPA Lombardy (Fig. 4 and Fig. 5) as regards the relationship between the quantity of waste disposed of and the emission of harmful gases. Controls are carried out by ARPA both on a scheduled and random basis and have always provided data within the permitted limits according to the parameters indicated by the Region.

There is at least one important unresolved issue: the construction of a cogeneration section for the development of district heating, as seen in the original convention. This change was approved and finally implemented in recent months, also thanks to the collaboration with A2A S.p.A. of Brescia. The new part of the plant and the consequent production of thermal energy as well as electricity will bring a series of advantages: a further reduction in emissions, a strong energy recovery, a possible improvement in the heating systems of private housing units and public buildings, with a direct benefit for the resident population. It is precisely at this point that another protagonist appears: the industrial plant of Tenaris S.p.A.. This is the steel company par excellence of the territory, known by the inhabitants and the rest of the province as "La Dalmine". A historic company that has been producing steel pipes for over a century - the first pipe was built in 1909. The characteristic of Tenaris is the production of a complete range of seamless and welded tubular products.

So, my question to the manager is: "How does this industrial reality fit into the problems concerning the environment and the territory of Dalmine? We begin to understand that the situation is increasingly complex and that there are many actors whose interactions can be crucial points for further research.

Tenaris S.p.A (Fig. 6), in fact, is subject to frequent controls on environmental impact carried out by the Lombardy Region, which issues the company with an integrated environmental authorization but with constant monitoring of possible sources of pollution. After examining some of Tenaris's parameters regarding its impact on the environment, some relevant data emerge:

- impact in substantial equilibrium with regard to emissions;

- criticality with respect to noise pollution, on the other hand.

Precisely on this second aspect Tenaris has been called to improve the noise emitted during processing and night production and in the transport of materials. Sustainable mobility is in fact one of the most critical aspects for noise impact.

Fig. 6. Tubular products - Tenaris Dalmine (web site Tenaris Dalmine)

But let's come to the conclusions of this interview, in which some interesting and unexpected aspects emerge: problems not directly related to pollution produced by industrial plants, but above all related to the complexity of critical factors present in the territory, such as the road system, a constant source of air and noise pollution in industrial areas.

According to the latter observations, the main sources of pollution would be: the road traffic of the provincial road 525, which crosses the Municipality of Dalmine, and that of the A4 motorway, one of the main communication routes of the Region and Northern Italy. With respect to these infrastructures, the attention is now focused through the redevelopment plans with the SEAP - Sustainable Energy Action Plan.

3.2. Interview with Renato Daminelli

We meet Renato Daminelli in a room of the Kilometro Rosso in Stezzano, the place of technological research by definition in the province of Bergamo. Renato is a middle school art history teacher, now retired, and one of the historical figures linked to the events of the waste disposal plant (REA) in Dalmine. In fact, he was a town councillor in the nineties.

At the end of the decade the Municipal Administration was in favour of the construction of the plant, while within the Municipal Council there was a lively debate on its necessity. The debate was also heated among the population and the "Citizen Committee against the incinerator" was created to promote numerous awareness raising actions. Renato is an environmentalist and an activist of the Committee and has provided us with numerous archival documents.

The Association's opposition was essentially based on an analysis of the territory (Fig. 7), identified as an area of industrial degradation, already saturated with waste disposal plants and not requiring further plants - with reference to the Bergamo and Brescia plants, the Trezzo plant and the special waste plant in Filago.

Fig. 7. Flyer of the "Committee against incineration" of Dalmine, year 2000 (Neighborhood magazine from the Archives of Renato Daminelli)

According to this complaint, the choice to build the REA plant did not derive from the overall needs of the area, but from an assessment conditioned by a logic limited to the local economy, separated by the complexity of the environmental and social factors of the sector. A choice, therefore, oriented by a vision of development of an industrial economy in the wake of the "factory cities", which grew up around the large metallurgical industry of Dalmine spa, and by a dense network of industries distributed throughout the territory. Starting from this testimony, important as a direct testimony, we can get closer to some partial conclusions, which open rather than solve further issues. The focal point under discussion does not seem to be the functioning of the REA plant: the data provided by ARPA Lombardia show that the plant fully respects the parameters set by the Region (Figs. 4-5).

On the other hand, there are a number of other critical issues relating to pollution in this area, which have already been highlighted in the past:

- air pollution resulting from road traffic and due to the concentration in a relatively small area of industrial activities and the related traffic of goods and road vehicles;
- the inadequacy of housing structures with obsolete heating systems;
- noise pollution;

- the consumption of land for housing and industrial activities at the expense of green areas;

- lack of public awareness and attention to the "common" environment.

3.3 Final remarks

All these factors in their complexity highlight a critical environmental condition of this part of the territory for those who live there, despite the respect of legal parameters and compliance with current regulations.

The case of Dalmine represents an interesting "litmus paper" to outline possible development scenarios, which take into account the intertwining of critical factors:

- the adaptation of the existing plant with the district heating line, as foreseen since its original construction, and consequently an investment for the renovation of housing structures with other heating systems;

- an improvement of the road infrastructure for road traffic, a source of daily air pollution;

- the development of various waste disposal policies, such as increased separate collection and "plastic free" administrative policies;

- the extension of green areas and the preservation of existing ones;

- raising awareness among citizens to cultivate a collective awareness of the environment in which everyone lives and not just of "their own private garden";

- environmental education as a useful tool in schools and training places;

- constant monitoring, not only by the authorities in charge, but also the social attention of the community through the implementation of good actions.

4. Conclusions

To think that the problem of waste management can be solved satisfactorily, using appropriate disposal technology and legal compliance, is a simplistic vision, belonging to a positivist and linear development model that is no longer sustainable.

The issue, in the age of the Anthropocene, is not only of a technological or normative nature, but rather cultural, social and structural. For this reason it is increasingly necessary to take alternative paths in a systemic and complex perspective, in which economic initiatives, the development of services and the design of plants and infrastructures are harmonised.

This conclusion, finally, cannot fail to take account of the health emergency that we have and that we are going through. It is precisely this emergency that triggers a series of other emergencies, certainly including the environmental one. It must be said, however, that one of the effects of the emergency, as the word itself suggests, is that of "bringing out" aspects of reality and life previously under the surface: weak signals, unresolved issues, apparently local and negligible problems. What emerges, therefore, on an environmental level, in relation to the case of the Dalmine territory examined so far?

Certainly a model of adaptation and resilience is a possible response to the changes imposed by the emergency. In this sense, the strengthening of the use of technologies and the activities carried out at a distance represent an attempt at adaptation: more "virtual" technology less "real" pollution. However, the adaptive model is reactive, it is not able, for example, to anticipate events but only, by definition, to adapt to them. When the level of complexity of the emergency/crisis cannot be traced or addressed by remaining in the individual/interpersonal dimension but becomes a community, environmental, systemic fact, the adaptive model is no longer adequate. We therefore argue, on the basis of the work done, that a model of a more complex order and of a different quality level is needed.

We really need an alternative vision, to be thought of but where the role of local communities and small social groups as the only possible actors of change is central. Groups and communities that grow spontaneously in a self-organized form, made strong thanks to the difficulties encountered.

This is why the small community of Dalmine - one of the centres of the Italian and Bergamo pandemic - can grow as a virtuous example in rethinking its model of industrial and economic growth and development.

References

Bougleux E., (2015), Issues of Scale in the Anthropocene, *Archivio Anthropologico Mediterraneo*, **17**, 67-73.

Busi O., (2017), *Commented Waste Code*, Maggioli, Publisher, Rimini, Italy.

Ceruti M., (2018), *A Community of Destiny at the Time of Complexity*, Franco Angeli, Milan, Italy, 17-22.

Crutzen P.J., Stoermer E.F., (2000), The Anthropocene, IGBP Newsletter, On line at : http://www.igbp.net/download/18.316f18321323470177580001401/1376383088452/NL41.pdf

De Sardan J-P.O., (2009), *Field Politics*, In: *Living Ethnography*, Cappelletto F. (Ed.), Seid Publisher, Milan, Italy, 27-63.

Dell'Anno P., (2018), *Environmental Law*, Cedam Publisher, Padova, Italy.

Dematteis G. C. Lanza, (2016), *The Cities of the World*, *An urban Geography*, Utet Publisher, Milan, Italy.

EC Directive, (1975), Directive 1975/442/EC of the European Parliament and of the Council of 15.7.1975 on waste, Annex *Official Journal of the European Communities*, L.194/18 25.7.975, Brussels.

EC Directive, (1991), Directive 91/156/EC of European Parliament and of the Council of 18.3.1991, Annex *Official Journal of the European Communities*, L. 78/34/26.3.1991, Brussels.

EC Directive, (2001), Directive 2001/77/EC of the European Parliament and of the Council of 27.9.2001, *Official Journal of the European Communities*, L. 283/27.10.2001, Brussels.

EC Directive, (2010), Directive 2010/75/EU of the European Parliament and of the Council of 24.11.2010.

EC Directive, (2011), Directive 2011/92/EU of the European Parliament and of the Council of 13.12.2011.

EC Directive, (2014), Directive 2014/52/EU of the European Parliament and of the Council of 16.4.2014, amending the previous Directive 2011/92/EU of the European Parliament and of the Council of 13.12.2011.

Ferrara E., (2016), Anthropocene theories and practices. History and geology of human impact on the environment (in Italian: Teorie e pratiche antropocene. Storia e geologia dell'impatto dell'uomo sull'ambiente), *Cultures of Sustainability (Culture della Sostenibilità)*, http://doi.com/10.7402/CDS.18.01.

Massarutto A., (2019), *A World without Waste?: Journey in a Circular Economy* (in Italian), Il Mulino Publisher, Bologna, Italy, 1-218.

Morton T., (2018), *Being Ecological*, (in Italian), Laterza Publisher, Bari-Roma, Italy.1-213.

Trigona R., (2018), *Through the Anthropocene: Cultures*, *Right*s, *Practices* (in Italian: *Attraverso l'Antropocene: culture, diritti, pratiche*), Pontecorboli Publisher, Florence, Italy.

Environmental Engineering and Management Journal

October 2020, Vol. 19, No. 10, 1915-1926
http://www.eemj.icpm.tuiasi.ro/; hiip://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

UTAQ, A TOOL TO MANAGE THE SEVERE AIR POLLUTION EPISODES

Fabrizio Ferrari*, Giuseppe Maffeis[1], Johannes Flemming[2], Roberta Gianfreda[1]

[1]TerrAria srl, via Melchiorre Gioia 125, Milan, 20125, Italy
[2]European Centre for Medium-Range Weather Forecasts, Reading, RG2 9AX, UK

Abstract

The Urban Tool for Air Quality (UTAQ) is a project funded by CAMS (Copernicus Atmosphere Monitoring Service) - ECMWF (European Centre for Medium-Range Weather Forecasts). UTAQ is a web-based tool with a user-friendly interface that allows users to evaluate current and forecasted air quality for the following 4 days at urban scale with high resolution (10-50 m). UTAQ, in the mobile version, allows citizens to evaluate and then to limit their air quality exposition thanks to the personal position tracking of the mobile device. UTAQ, in the decision makers' version, allows local authorities to evaluate and find the best traffic limitation strategies to be implemented in the short-term to manage emergency conditions of air quality exceedances. To support this process, UTAQ produces high-resolution maps of air quality both on the current situation and on the forecasted next 4 days. These maps are the combination of (1) the background concentrations supplied by the European CAMS ENSEMBLE model in real time analysis and 4-days forecasts (2) the peak concentration due to traffic through specific hourly source-receptor functions, to make the calculation fast and reliable even at high resolution (3) observed air quality data monitored by urban stations. UTAQ supports the authorities to increase the degree of awareness of its citizens communicating the air quality forecasts and the benefit obtained thanks to the emission abatement strategies adopted. A first version of UTAQ has been trained and validated on a 10x10 km^2 domain close to Monza in Lombardy region, including 7 municipalities (for a total of 180 thousand of inhabitants) with the air monitoring station of Meda (ARPA Lombardia). This work describes an improved version of UTAQ, trained and validated on a domain centered on the metropolitan area of Milan.

Key words: air pollution episode forecast, CAMS, mitigation strategy, source-receptors models, traffic limitation policies efficiency, urban dispersion modelling

Received: February, 2020; Revised final: June, 2020; Accepted: July, 2020; Published in final edited form: October, 2020

1. Introduction

Despite significant improvement of air quality in Europe in recent decades, air pollution still causes about 400,000 premature deaths every year and more than 75.000 in Italy alone (EEA Report, 2019). In the past, exceedances of air quality thresholds occurred across larger areas of the continent. In recent years, the exceedances are only found confined to heavily urbanized areas such as the Po Valley, southern Poland and Benelux in terms of particulate matter concentration and big cities in terms of nitrogen dioxide (Kiesewetter et al., 2013). The transport sector is the main source for the emission of many primary pollutants, which lead to poor air quality, particularly in urban areas with high road traffic volumes (Fig. 1). The EU threshold for the annual average of nitrogen dioxide (40 μg m^{-3}), one of the most critical air pollutants which is typically associated with emissions of road vehicles, has been widely exceeded in 2017, with 86% of exceedances observed at monitoring stations close to road infrastructures (EEA Report, 2019).

The infringement procedure by the European Commission against Italy, because of the persistent excess of PM_{10} daily limit values in many regions in

* Author to whom all correspondence should be addressed: e-mail: f.ferrari@terraria.com

May 2018 (IP/18/3450, 2018), and the decision of the European Commission decision to refer Italy to the EU Court of Justice, for failure to respect limit values for nitrogen dioxide (EC Case, 2019), are both clear signs of how serious the Italian air quality problem is.

An example of the severe situation occurred in the first months of 2020 in northern Italy (Fig. 2) when high anthropogenic emissions combined with the frequent wintertime air stagnation and a long period without rainfall caused high concentrations of particulate matter, mainly PM10 in the Po valley. Even if emissions will be reduced because of a regional air quality plan in the future, it could be expected that climate change will lead to a shift of precipitation patterns and to the decrease of winter rainfall (ISPRA Report, 2019) and thereby maintaining occurrence of air pollution events in the Po Valley during winter.

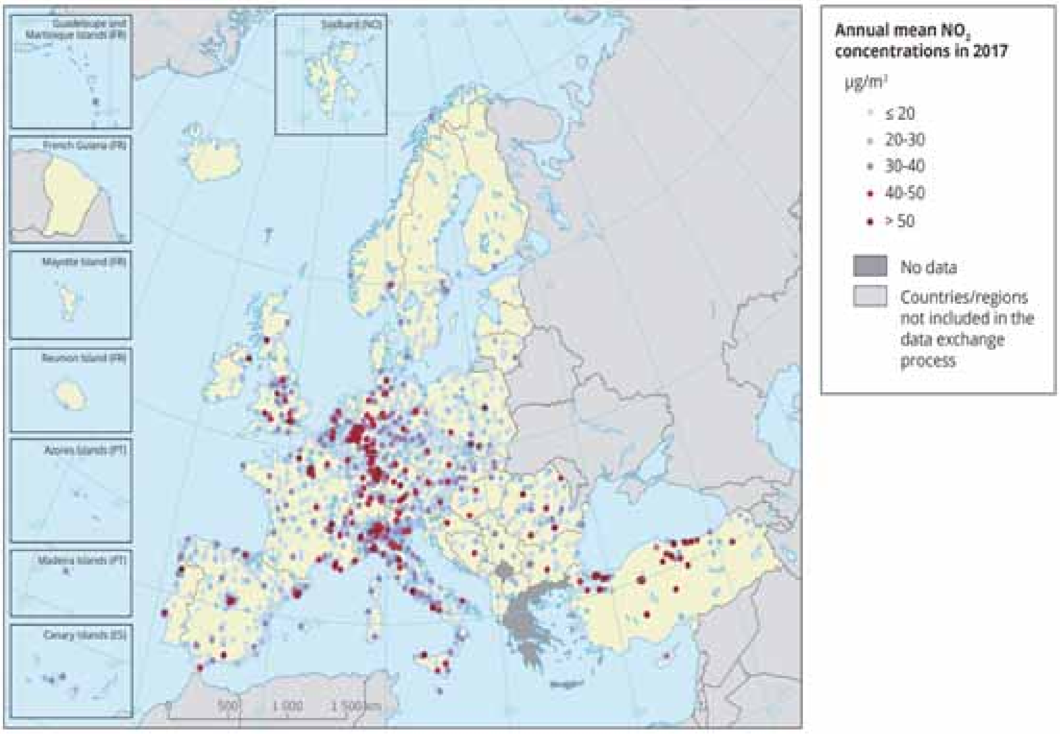


Fig. 1. Observed concentrations of NO_2 in 2017. Dots in the highest two colors categories correspond to values above the EU annual limit value: 40 μg m^{-3} (EEA Report, 2019)

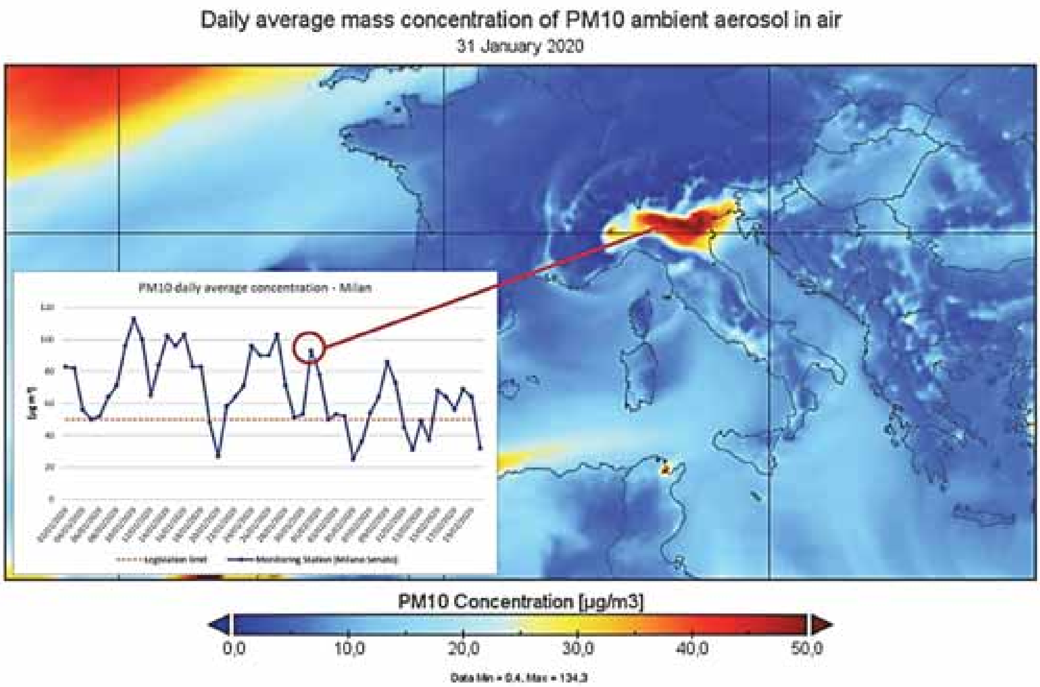


Fig. 2. An example of a severe PM_{10} episode. CAMS (Copernicus Atmosphere Monitoring Service) ensemble analysis for 31 January 2020 (daily average): in dark red values over PM_{10} legislation limit (50). In the chart, PM_{10} daily average concentration trend measured by the Milano Senato air quality monitoring station (ARPA Lombardia)

The EU air quality standards, adopted by the member states in 2008 (EC Directive, 2008)), require that each state establishes an action plan defining the measures to be taken in the short term to reduce the population exposure to the concentration exceeding the limit, for the main pollutants affecting urban areas, such as NO_2, PM_{10} and O_3.

To comply with the short-term limit values set by the legislation and to reduce the dangerous concentration peaks, actions must be planned at least one or two days before. The actions to be taken could be effectively led by air quality forecasting systems such as the one implemented in UTAQ. Furthermore, according to EU directives, local authorities must provide information to the public on the air quality status and on the forecasted trend for the following days.

Mitigation measures are often taken because of measured concentrations and weather forecasts, when the air quality critical episode has already occurred and the efficacy is strongly limited. The availability of a reliable urban air quality forecasting system could help decision-makers to plan abatement measures in time, minimizing both health costs as well as the costs connected to the unnecessary restrictions on economic activities.

The Urban Tool for Air Quality (UTAQ) presented in this paper is such a tool that will support air quality management by local authorities and will be instrumental to provide air quality information to the public.

A first version of UTAQ (Ferrari et al, 2019) has been trained and validated on a 10x10 km^2 domain close to Monza in Lombardy region, including 7 municipalities (for a total of 180 thousand of inhabitants) with the air monitoring station of ARPA Lombardia in Meda. In this first version of UTAQ, 48 hours before observation was assimilated in the computation. This paper describes an improved version of UTAQ trained and validated on a domain centered on the metropolitan area of Milan, with a new computation of the total concentrations with data assimilation performed with observations of 24 hours before.

2. Methodology

2.1. UTAQ architecture

UTAQ is a web-based tool with a user-friendly interface which provides: (1) a Web version for policy makers helping them to define the best strategy to reduce urban air quality pollution peak episodes by traffic limitation measures, (2) a public Web version with maps of the current and the predicted air quality status, (3) a public mobile version in which, through the device GPS position, citizens can inquire about the current and forecasted air quality at their position.

UTAQ represent air pollution as combination of regional, urban and street level contributions (Fig. 3, adopted from Harrison, 2018) in the following way:

I. the regional background concentration (green part) are obtained from the estimates of the European scale model ENSEMBLE of the regional Copernicus Atmosphere Monitoring Service (CAMS) retrieved from the European Centre for Medium-Range Weather Forecasts (ECMWF) which provides four days of hourly concentrations forecasts of several pollutants, including in particular nitrogen dioxide NO_2 and particulate matter PM_{10} (Marécal et al, 2015) - paragraph 2.5;

II. the city increment (light blue-lilac part) is obtained from the pollutant concentration measured on the day before from one or more air quality monitoring stations, therefore taking into account the temporal urban accumulation of pollutants (Maffeis, 1999) - paragraph 2.6;

III. the street level increments (red-yellow part) in terms of PM_{10} daily average and NO_2 hourly average (in compliance with the observations available) are calculated using local traffic emissions through specific hourly source-receptor functions (hourly kernels), in order to make the calculation fast and reliable even at high resolution (20x20 m^2). Thanks to the support of the JRC in Ispra, this approach is borrowed from the SHERPA-City project (Degraeuwe et al, 2018), where the annual kernels have been used to calculate the PM_{10} and NO_2 annual averages - paragraph 2.4.

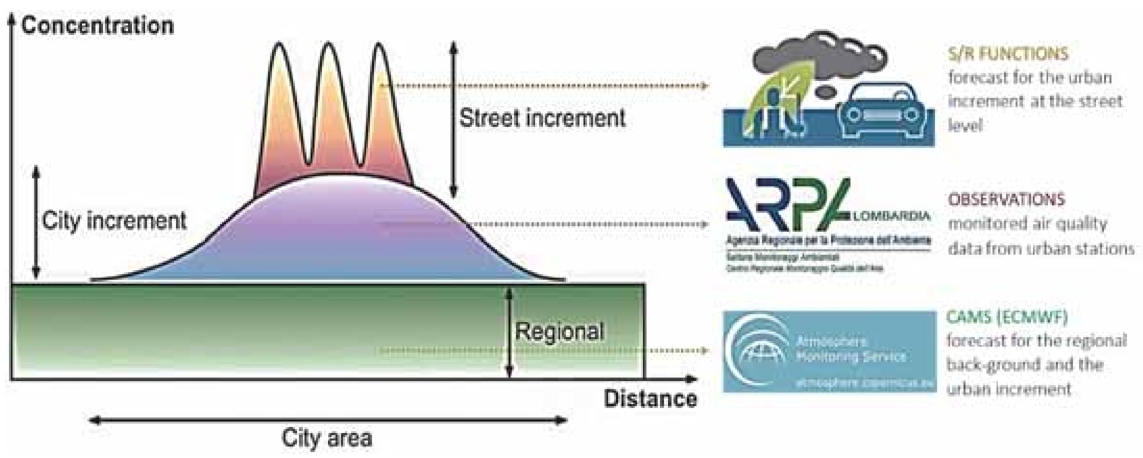


Fig. 3. Urban pollution schematic profile (adopted from Harrison, 2018)

The integration of these three contributions guarantees both scientific validity and efficient computation time allowing a web operation during the model computation of the efficiency of traffic limitation policies chosen by the decision maker.

As described in more detail in the next paragraph (2.6), the integration method makes sure that double counting of the CAMS emission contribution in steps II and III is avoided.

The operation diagram of the UTAQ system is shown in Fig. 4: starting from the definition of the calculation domain, different road traffic emission scenarios can be applied. Next, using the weather forecast of the IFS (Integrated Forecasting System)-ECMWF model and the relative hourly source-receptor functions (kernels), the measured air quality data and the ENSEMBLE model forecasts, concentrations maps for the different scenarios of air quality are produced and made available to policy makers and citizens.

2.3. Emissions calculation

Due to the overwhelming contribution of the traffic to air pollution in the city of Milan (Fig. 5), UTAQ street increment focuses only on traffic sector.

The emissions are calculated on a 20x20 m^2 grid in the chosen domain, starting from the road graph and the related traffic volumes used for the estimation are taken from OpenTransportMaps (Jedlička et al., 2016) and the macroscopic model OmniTRANS (de Graf, 2015), respectively.

Roads are divided into five categories, from highways to neighborhood streets and for each road segment the annual average daily traffic (AADT) is estimated. The calibration of the emission model has been carried out adjusting the AADT in order to be consistent with the estimation of the local traffic emissions inventory provided by INEMAR Lombardia (Caserini et al., 2012).

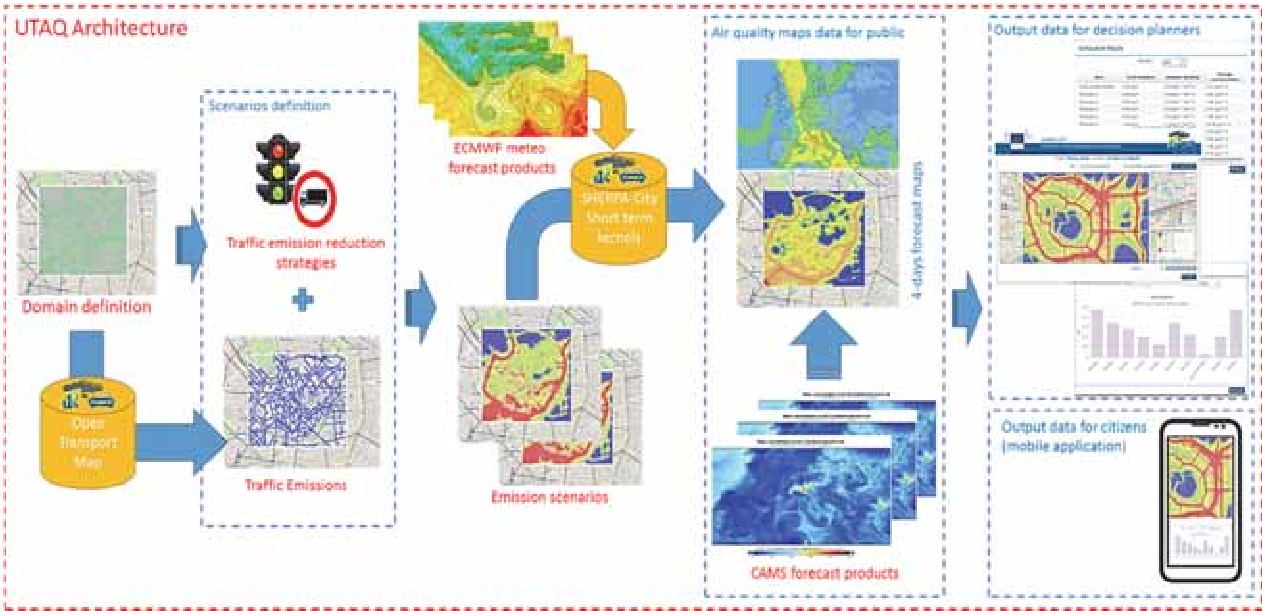


Fig. 4. UTAQ architecture

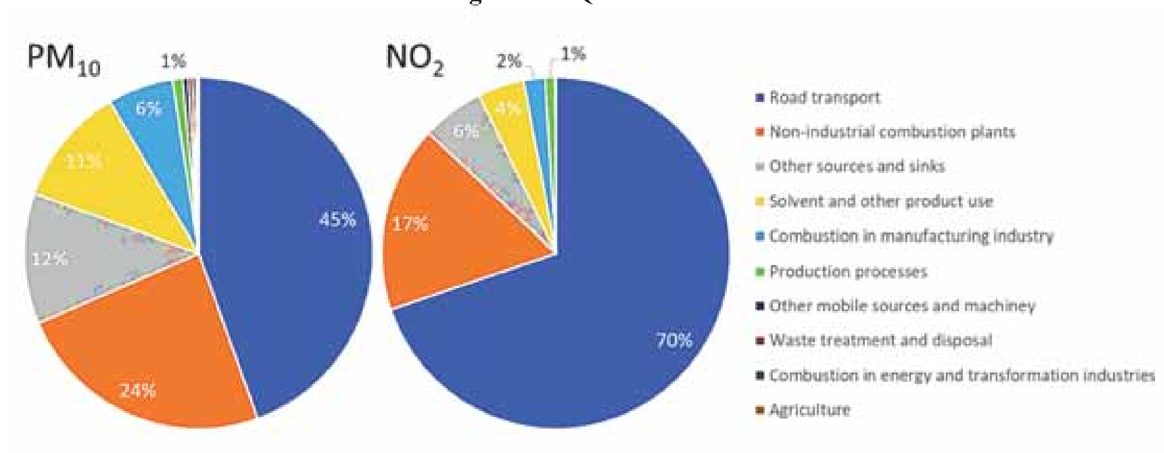


Fig. 5. Emission distribution by CORINAIR SNAP1 sector in 2014 for Milan municipality (INEMAR, 2018)

UTAQ grid emissions are estimated using the average distribution by vehicle type according to the COPERT4 classification (Gkatzoflias et al., 2012) with the vehicle emission factors specified by road type (urban, rural and motorways) and by pollutant (PM, NO_2). Emission factors were taken from JRC DIONE traffic model database (Thiel et al., 2016) which incorporates data collected in the European research project TRACCS (Papadimitriou et al., 2013). A temporal disaggregation is applied based on a typical daily profile to obtain hourly emissions.

2.4. Local traffic contribution

Based on previous experience within the project SHERPA-City (on an annual time scale), it was decided to adopt hourly Gaussian source-receptor functions (*kernels)* to ensure reduced computational time from an input emission grid. Each kernel, representative of a different weather condition, depicts the concentrations Gaussian matrix obtained by simulating the dispersion of 1 kg/h of a given pollutant with the Gaussian model IFDM (Lefebvre et al., 2013).

Therefore, different hourly weather and traffic conditions can be simulated by model kernels requiring weather variables such as wind speed, with direction, temperature and the incident solar radiation. In UTAQ weather values came from the Integrated Forecast System (IFS) of ECMWF.

UTAQ is then able to calculate for each cell and hour the local “street” contribution, responsible for increased PM_{10} and NO_2 concentrations (contribution III in Fig. 3).

In order to consider the variability of European weather conditions which affects the main parameters influencing atmospheric dispersion (wind speed and direction, solar radiation and temperature), a contingency table has been pre-built using weather data of the ERA-Interim data set (ECMWF, 2012). ERA-interim has spatial resolution of 0.75° of latitude and longitude and a temporal resolution of six hours. The following meteorological parameters have been used:

- Wind speed (0-1 m s-1, 1-2 m s-1, 2-3 m s-1, 3-4 m s-1, 4-5 m s-1, 5-6 m s-1, >6 m s-1);
- Wind direction (8 direction classes);
- Solar radiation (Night, <300 W m^{-2}, 300-600 W m^{-2}, >600 W m^{-2});
- Temperature (<-10°C, -10-0°C, 0-10°C, 10-20 °C, 20-30 °C, >30 °C).

Four European macro-regions have also been considered: Northern Europe, Western Europe, Eastern Europe and Southern Europe.

The combination of all the meteorological classes is equal to 5,376 cases (7 wind speed classes, 8 wind direction classes, 4 solar radiation classes, 6 temperature classes and 4 European macro-regions). 4,510 kernels have been trained on hourly basis representing combinations with at least one occurrence. The trained kernels are used by UTAQ according to the area in which the chosen domain is.

2.5. CAMS regional background contribution

As previously described, UTAQ uses as regional background concentration the CAMS ENSEMBLE forecasting model (Marecal et al, 2015) which is based on the integration of the outputs of seven models on a European scale (Table 1). The adoption of forecast based on ensemble products reduces the uncertainty of individual models and consequently improves the reliability and accuracy of the final results (Leutbecher and Palmer, 2007). The regional CAMS models use the same (i) weather parameters (derived from the IFS-ECMWF global model, the same used by UTAQ), (ii) boundary conditions of the chemical compounds (CAMS IFS-MOZART global model) and (iii) emissions (CAMS-REG).

The ENSEMBLE analysis carried out for the CAMS products produces forecast concentration maps for up to 4-days with a spatial resolution of about 10-20 km (0.1 degrees of latitude and longitude).

Table 1. Models within the CAMS ENSAMBLE model

Model name	*Institute*	*Spatial resolution*
CHIMERE	INERIS (France)	0.15°x0.1°
EMAP	MET Norway (Norway)	0.25°x0.1 25°
EURAD-IM	RIUUK (Germany)	15 km
LOTOS-EUROS	KNMI, TNO (The Netherlands)	0.25°x0.1 25°
MATCH	SMHI (Sweden)	0.2°
MOCAGE	METEO-FRANCE (France)	0.2°
SILAM	FMI (Finland)	0.1°

2.6. UTAQ concentration calculation

The UTAQ resulting concentration given by the integration of the three contributions (regional background, city increment and road increment) shown in Fig. 3 may be expressed as (Eq. 1):

$$C_{tot}(t) = CAMS(t) + C_{local}(t) + \varepsilon ...(a_s)^{\beta \cdot t} \quad (1)$$

where:

- $C_{tot}(t)$ is the UTAQ resulting hourly concentration at hour t;
- CAMS(t) is the regional hourly concentration provided by CAMS at hour t (contribution I);
- ε is the urban background term that takes into account the local contribution through the measured concentrations (contribution II);
- α_s and β are coefficients (the first varying with the season s) to take into account the pollutants’ urban accumulation term that is decreasing with longer predictions.

• $C_{local}(t)$ is the local traffic concentration (contribution III) computed as (Eq. 2):

$$C_{local}(t) = (C_{traff}(t) - C^{avg}_{traff}(t)) \quad (2)$$

where:

• $C_{traff}(t)$ is the traffic concentration calculated through the kernel at hour t;

• $C_{traff}^{avg}(t)$ is the spatial average traffic concentration on the domain at hour t (the difference represents the local redistribution of the CAMS concentration, aimed avoiding the double counting of the emission already considered in regional CAMS concentration);

Every day the UTAQ run is initialized (*t=0*) by computing the ε based on the daily mean measured concentrations of the day before of the air quality monitoring station located in the domain (Eq. 3):

$$\varepsilon = C^*_{obs}(t-1) - CAMS^*(t-1) - C^*_{local}(t-1) \quad (3)$$

where the different contributions refer to the daily average of the day before.

Using the observed concentration values for a one-year period the seasonal adjustment coefficients α and β are estimated with an optimization procedure minimizing the absolute error between the UTAQ daily average concentration and the measured daily average observation during the training period.

This new formulation implemented in UTAQ foresees the computation of the total concentrations on the base of the error ε estimated respect to the 24 hours before observation, attenuated over time thanks to the β exponent.

3. Results and discussion

This section reports the first results obtained from calibration and subsequent validation of the UTAQ model considering PM_{10} on a domain set on the urban area of Milan. A first assessment of the tool for $PM_{2.5}$ and NO_2 was done during COVID19 outbreak in Milan (AMAT, 2020).

3.1. Calibration on Milan domain

The system has been trained for the year 2018 using alternatingly one of the four ARPA air quality stations present in the 10x10 km^2 domain centered on the metropolitan area of Milan: Marche, Pascal, Senato and Verziere (Fig. 6). Pascal station is classified as background station, while Marche, Senato and Verziere stations are classified as traffic stations. The α_s and β coefficients computed in the training period are applied in the validation period (first half of 2019) considering each air quality monitoring station individually as the reference used in equation (3) in order to evaluate which configuration give the best performances.

To evaluate with which monitoring station the adjustment coefficient ε produces the best result, R^2 and the Root Mean Square Error RMSE are taken into account (Fig. 7). The graph shows that good results were obtained for all monitoring stations using Milano Senato station because higher R^2 and lower RMSE were reached. In contrast, lower R^2 and higher RMSE values were obtained when using Milano Verziere station. The α coefficient estimated using Milano Senato station measured concentrations in winter and summer (Table 2).

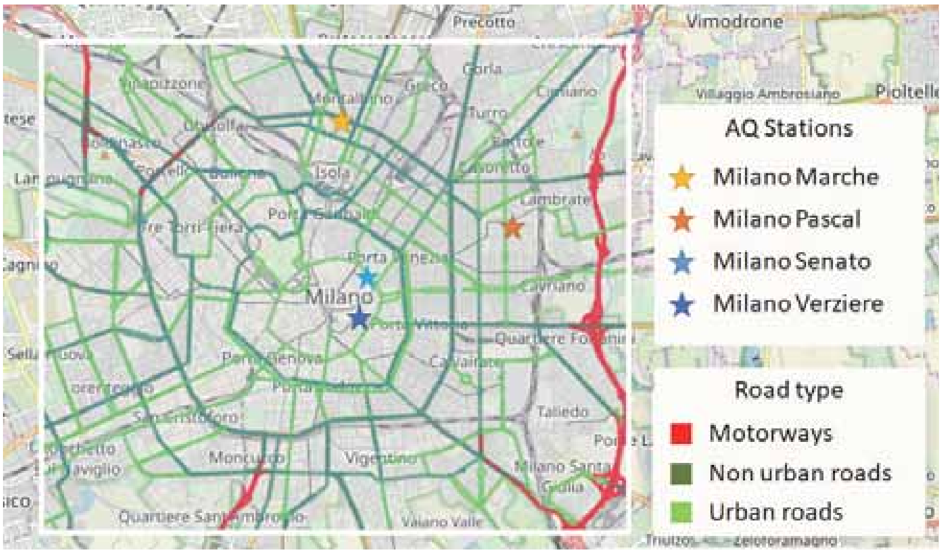


Fig. 6. The domain used for the training and validation of UTAQ model. The first three levels of the roads are represented in the map with the 4 ARPA air quality monitoring stations

Table 2. α and β coefficients of Senato station

Semester	*Period*	*α*	*β*
Winter	October 15 - April 15	0.9365	0.2
Summer	April 16 - October 14	0.8423	0.2

Based on these α and β coefficients estimated with the Senato station (the one with the best performance), the final concentration has been calculated for every hour of 2018. UTAQ's performance in the calibration year are summarized in Figs. 8 -9.

They show the aggregated modelled PM_{10} concentration and the daily observed data. In addition to the UTAQ evaluation, the CAMS ENSEMBLE forecast has been included in the analysis. Overall, the modeling system implemented in UTAQ reproduces the summer and winter trends better than the CAMS model specially in wintertime thanks to the introduction of the observed data and the higher spatial resolution.

Fig. 9 shows UTAQ January 2018 simulation compared with the measured concentrations detailing the three different contributions described in paragraph 2: the regional background concentration obtained from CAMS (I), the urban contribution (II) and the street level contribution (III). Compared to the annual average, the contributions respectively contribute 82%, 14% and 4%, meaning that on the average CAMS is the principal contribution, while the urban contribution (City) is dominating the peak days of January.

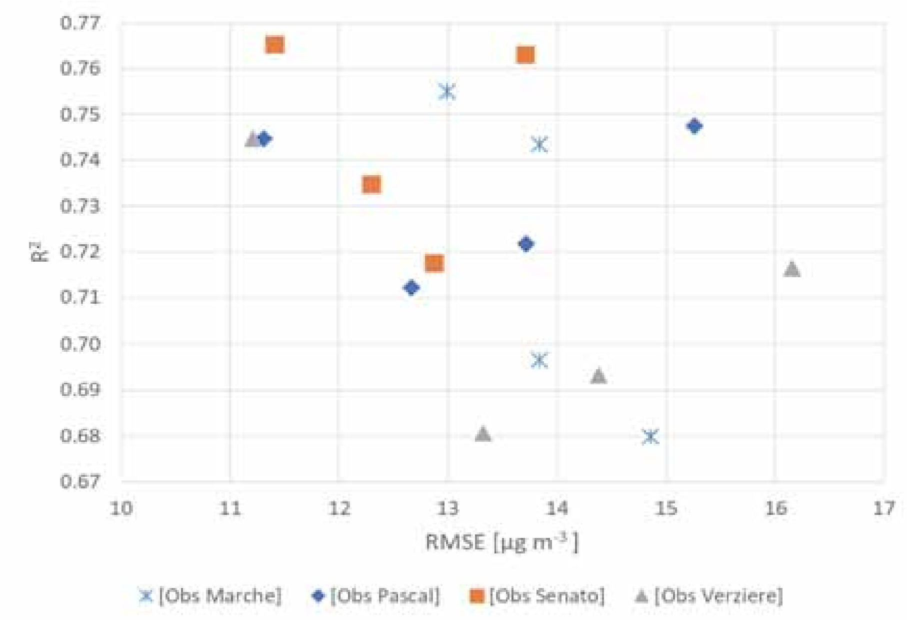


Fig. 7. R^2 and RMSE values in 2019 (first half) using each of the 4 ARPA's stations

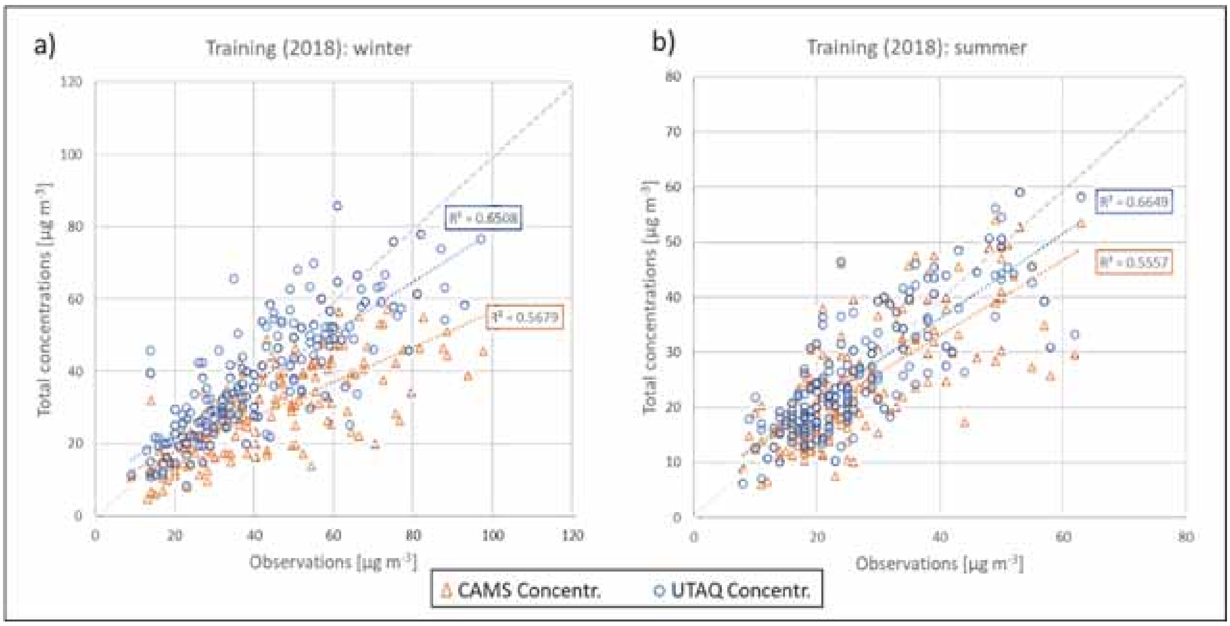


Fig. 8: scatter plot between observed daily average PM_{10} concentrations (Milano Senato ARPA air quality monitoring station - Year 2018) and CAMS/UTAQ data in wintertime (left part) and in summertime (right part) from the training data set

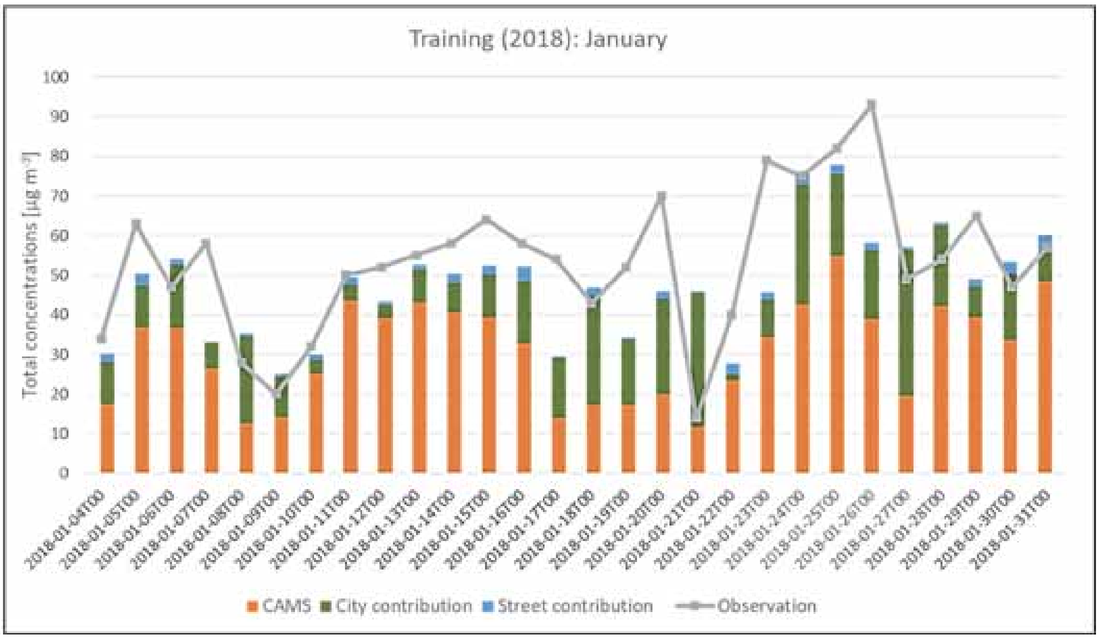


Fig. 9. Observed daily average PM_{10} concentrations in Milano Senato ARPA station and UTAQ modelled data split into the three contributions from the training data set

3.2. Validation of the model

To evaluate the actual performance in the predictive phase, UTAQ has been validated on the same domain from January to June of 2019 with the summer and winter α coefficients estimated on 2018 data. As for the calibration phase (Fig. 8), CAMS model performance of the CAMS ensemble was also evaluated (Table 3 and Fig. 10).

As in the case of calibration, UTAQ tool improves CAMS performances, which underpredicts the severe events of local pollutants accumulations, especially in winter because of its regional-scale resolution (10 km). CAMS ensemble underestimates the PM_{10} concentrations during the first day of forecast (average bias equal to -14.2 µg m^{-3} and RMSE equal to 21.8 µg m^{-3}) and the following forecast days (average bias over to 12.9 µg m^{-3} and RSME over to 20.5 µg m^{-3}). UTAQ improves CAMS forecasts because of the use of air quality observations and of the benefit of detailed high-resolution traffic emission data. Considering the UTAQ performance in more detail, the model underestimates the PM10 concentrations with values that increase for the forecast days following the first day0 (average bias from -1.6 for day0 to 7.3 µg m^{-3} for day3 and RMSE from 12.3 µg m^{-3} for day0 to 15.8 for day3) but with R^2 fairly constant (from 0.73 for day0 to 0.65 for day3).

Table 4 is a contingency table, which shows the success, and failure rates of predicting the exceedance of the daily PM_{10} threshold (50 µg m^{-3}) by UTAQ and CAMS models. As presented below, for the first forecast day (day0) UTAQ correctly predicts an exceedance in 64% of cases and a non-exceedance in 93% of cases (rates are respectively 20% and 100% for CAMS model) and in the last forecast day (day3) respectively in 51% and in 100% of cases (31% and 100% for CAMS model).

4. UTAQ tool application

A web application has been developed to present in a user friendly interface the results of UTAQ modeling system, which is available on the website www.utaq.eu and which is accessible for both public and authorized users (for the run of the traffic limitation measures).

4.1. Web application

UTAQ application is an online accessible tool with a user-friendly interface designed for non-specialist users and it has been entirely developed with open source technologies. The tool incorporates: a Web-GIS (Geographical Information System) with visualization functions (zoom in, zoom out, pan, etc.) to help the user selecting the inputs and displaying the outputs. The maps show hourly concentrations and time series in graphs and diagrams for the 4-days forecast. The UTAQ web application consists of:

• a login module that allows the “decision-making/planner” user to access the UTAQ application and to decide and to apply traffic limitation policies;

• a module to define new emission scenarios and new policy measures (for instance: limitation of certain categories of vehicles such as diesel, heavy vehicles, Euro 1/2/3 or the closure of particular city areas to create Low Emission Zones);

• a module to present outputs through grid maps (emission and air quality index maps), tables and bar graphs (Fig. 11).

Table 3 PM_{10} UTAQ model performances compared with CAMS model in Milano Senato monitoring station – year 2019

Forecast day	*BIAS [μg m^-3]*		*RSME [μg m^-3]*		*R^2*	
	UTAQ	*CAMS*	*UTAQ*	*CAMS*	*UTAQ*	*CAMS*
day0 [forecast hours 1-24]	-1.65	-14.16	12.29	21.84	0.73	0.52
day1 [forecast hours 25-48]	-4.34	-13.82	14.82	21.36	0.63	0.52
day2 [forecast hours 49-72]	-6.15	-13.41	15.19	20.72	0.65	0.56
day3 [forecast hours 73-96]	-7.27	-12.97	15.81	20.50	0.65	0.55

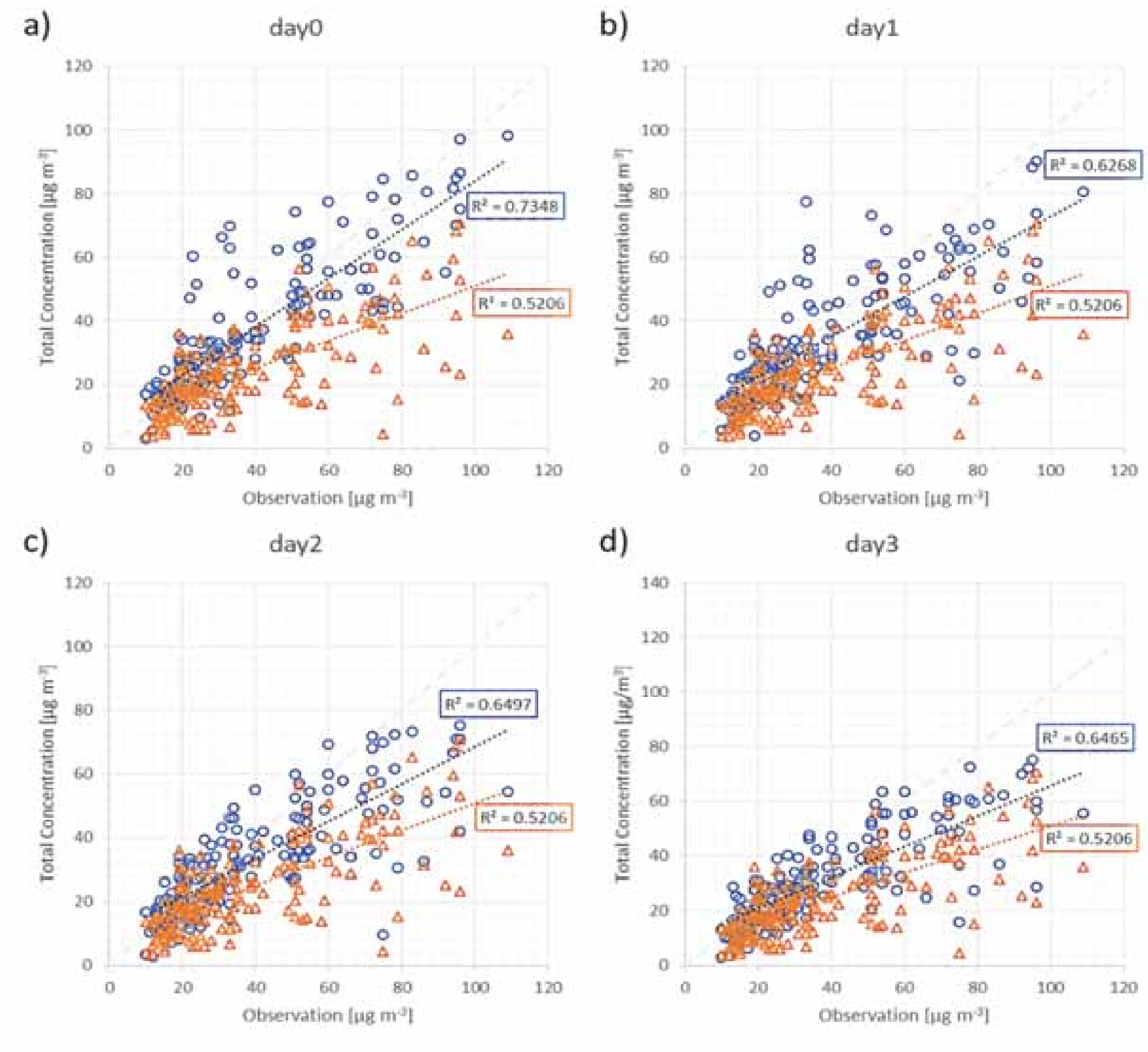


Fig. 10. Validation: scatter plot between observed daily average PM_{10} concentrations (ARPA Milano Senato station and modelled data for forecast day0 (upper-left), day1 (upper-right), day2 (bottom-left) and day3 (bottom-right)

Table 4. Contingency table of PM_{10} legal threshold exceedances (50 μg m^{-3}) considering observed data (ARPA air quality monitoring station located in Milano Senato. Year 2019) and UTAQ and CAMS models for each forecast day. The percentage in parentheses represents the number of occurrences in the models compared respect to the ones in the observations

PM_{10} daily average observed data		*UTAQ model*		*CAMS model*	
		Exceedance	*Non exceedance*	*Exceedance*	*Non exceedance*
day0	*Exceedance*	32 (64%)	18 (36%)	10 (20%)	40 (80%)
	Non exceedance	8 (7%)	104 (93%)	0 (0%)	112 (100%)
day1	*Exceedance*	28 (57%)	21 (43%)	14 (29%)	35 (71%)
	Non exceedance	7 (6%)	106 (94%)	0 (0%)	113 (100%)
day2	*Exceedance*	26 (53%)	23 (47%)	11 (22%)	38 (78%)
	Non exceedance	1 (1%)	112 (99%)	0 (0%)	113 (100%)
day3	*Exceedance*	25 (51%)	24 (49%)	15 (31%)	34 (69%)
	Non exceedance	0 (0%)	113 (100%)	0 (0%)	113 (100%)

The tool has been designed to ease the work of decision makers, by making available (i) the road graph within the urban area, (ii) the traffic volume and (iii) the related emissions and the 96-hours pollutant concentration forecast.

4.2. Mobile application

The UTAQ open mobile application (Fig. 12) allows users to evaluate the estimated air quality forecast for the following 4 days thanks to an intuitive interface. The service is freely accessible for the analyzed domains and provides real time air quality concentrations (with a spatial resolution of 20x20 m^2) at the users' position (obtained via the smartphone GPS device).

5. Conclusions

The paper presents a new version of the tool UTAQ used to forecast and eventually avoid the severe air pollution episodes in a high-resolution urban environment.

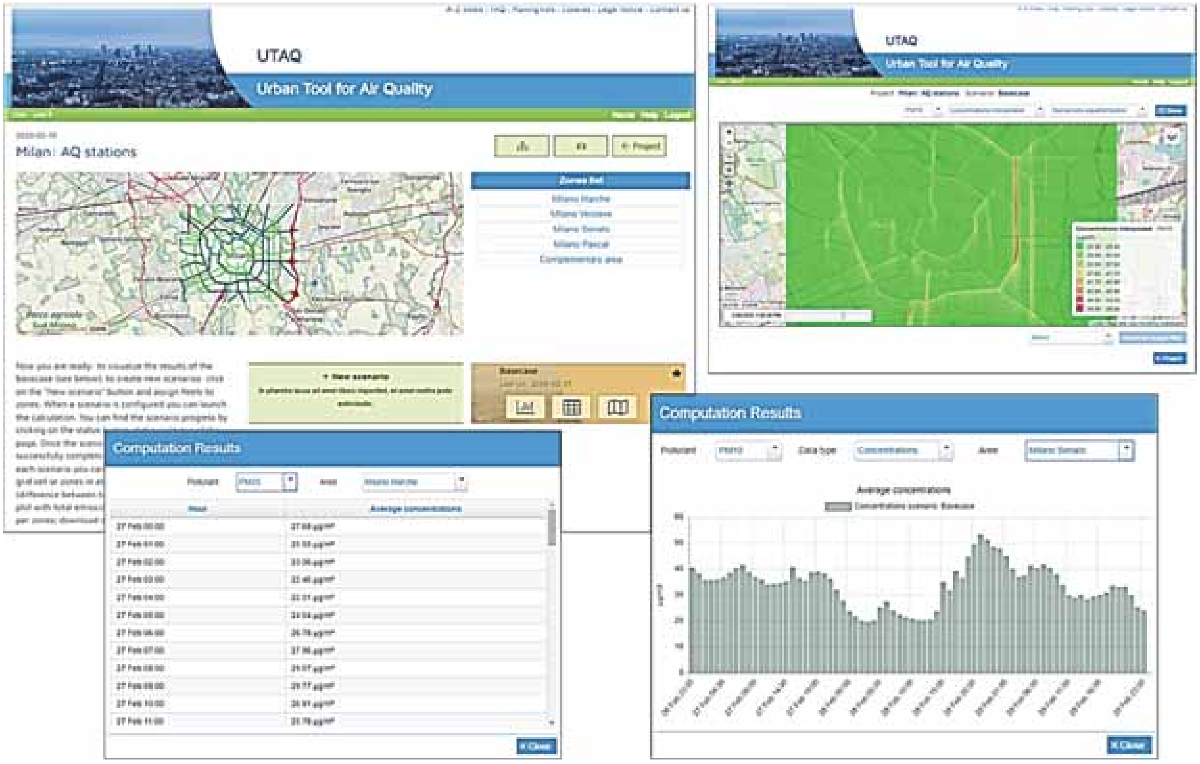


Fig. 11. UTAQ Web application screenshots

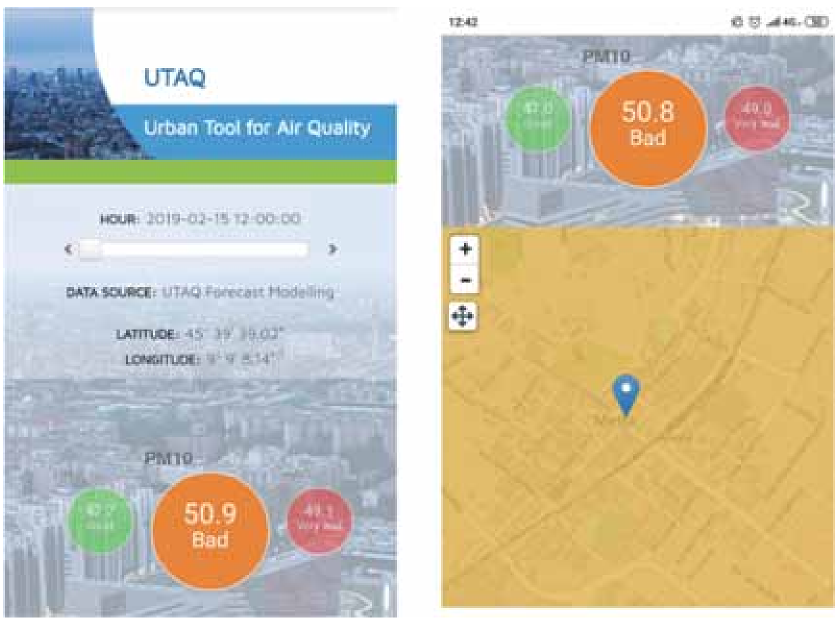


Fig. 12. UTAQ Mobile application

UTAQ has been implemented as web and mobile application to support policy-makers and local authorities to evaluate and establish the best traffic limitation strategies to be implemented in the short-term, therefore satisfying regulatory requirements and potentially enabling such limitation policies before air quality conditions become more severe.

UTAQ could also support local authorities to increase the awareness of citizens, spreading the air quality forecasts and communicating the benefit of short-term mitigation measures.

Current regional or Europeans forecast models, such as the CAMS ENSEMBLE, cannot fully reproduce local pollution events in the urban environment especially related to winter accumulation, because of their low spatial resolution and the lack of more detailed local emission inventory. The high spatial resolution representing the street level, the evaluation of traffic policies and the use of observations are the benefits of UTAQ compared to forecast on larger scales. On the contrary, UTAQ simplified formulation cannot replace the long-range transport and physical and chemical transformations of pollutants considered in a CTM. Two limitations of UTAQ current version is that it does not take into account street configuration (e.g. street canyon) and local variation of the fleet composition and consequently of the emission factor.

The UTAQ results for PM10 are promising and encourage the future development of the modeling tool, the web application and the mobile app too. The availability of CAMS ENSEMBLE and OpenTransportMaps data all over the Europe allows an easy implementation and calibration of UTAQ to other urban areas.

Acknowledgements

We thank: Bart Degraeuwe and Enrico Pisoni (JRC ISPRA) for scientific discussions on the methodology and on the kernels calculation; Angeliki Tsapatsari and Giulia Bonetti (ECMWF) for the valuable suggestions in using CAMS tool and improving UTAQ graphical interface; Simone Paleari and all the staff of the INNOVA21 agency for facilitating dialogues with stakeholders and the helpful feedbacks about the identification of the UTAQ added values for the local authorities.

References

AMAT, (2020), The results of two studies on the reduction of air pollution levels in Milan during the lockdown have been published (in Italian), On line at: https://www.amat-mi.it/it/notizie/33/.

Caserini S., Angelino E., Antognazza F., Fossati G., Lanzani G., Marongiu M., Moretti M., (2012), *Atmospheric Emissions in Lombardy: Findings from the INEMAR Emission Inventory, SIDISA 2012 Sustainable Technology for Environmental Protection*, Int. Symp. of Sanitary and Environmental Engineering, 9th Edition, On line at: https://www.researchgate.net/publication/259590912_Atmospheric_emissions_in_Lombardy_findings_from_the_INEMAR_emission_inventory.

Degraeuwe B., Peduzzi E., Pisoni E., Thunis P., (2018), SHERPA and SHERPA-city: screening tools for air quality modelling in Europe. The European Commission's Science and Knowledge Service (JRC), On line at: https://www.feem.it/m/events_pages/2018-04-12-pisoni.pdf.

De Graf S., (2015), Transport Modelling: OmniTRANS, On line at: https://www.dat.nl/en/solutions/transport-modelling-omnitrans/

EC Directive, (2008), Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008, on Ambient Air Quality and Cleaner Air for Europe, *Official Journal of the European Communities*, L 152/1/16.6.2008, Brussels.

EC Case, (2019), Case C-573/19. Action brought on 26 July 2019 – European Commission v Italian Republic, Official Journal of the European Union, C 305/29, 9.9.2019, Brussels.

EEA Report, (2019), Air quality in Europe - 2019 report, Publications Office of the European Union, No. 10/2019, Luxembourg, On line at: https://www.eea.europa.eu/publications/air-quality-in-europe-2019.

ECMWF, (2012), ERA-Interim Project, Single Parameter 6-Hourly Surface Analysis and Surface Forecast Time Series. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory, Dataset, On line at: https://rda.ucar.edu/datasets/ds627.2/.

Ferrari F., Gianfreda R., Maffeis G., (2019), UTAQ, a tool to support and manage the severe air pollution episodes (in Italian), *Environmental Engineering*, **6**, 183-193,

Gkatzoflias, D., Kouridis, C., Ntziachristos, L., Samaras, Z., (2012), COPERT IV: Computer Programme to Calculate Emissions from Road Transport, User Manual (Version 9.0), European Environmental Agency, On line at: http://www.emisia.com.

Harrison R.M., (2018), Urban atmospheric chemistry: a very special case for study, *Climate and Atmospheric Science*, **1**, 20175.

INEMAR, (2018), Air Emission Inventory: 2014 emissions in Lombardy Region - final data, (in Italian), ARPA Lombardia, On line at: http://www.inemar.eu/xwiki/bin/view/Inemar/HomeLombardia.

IP/18/3450, (2018), Air quality: Commission takes action to protect citizens from air pollution. Press release, On line at: https://ec.europa.eu/commission/presscorner/detail/en/IP_18_3450.

ISPRA Report, (2019), Climate indicators in Italy in 2018, EditionXIV, State of Environment 88/2019, Roma. , On line at: https://www.isprambiente.gov.it/en/publications/state-of-the-environment/climate-indicators-in-italy-2018-edition-xiv.

Jedlička K., Hájek P., Ježek J., Kolovský F., Mildorf T., Charvát K., Kozhukh D., Martolos J., Sťastný J., Beran D., (2016), *Open Transport Map: Open Harmonized Dataset or Road Network*. Int. Symp. on Computer-Assisted Cartography, AutoCarto 2016, Albuquerque, vol. 1, 72-84.

Kiesewetter G., Borken-Kleefeld J., Schöpp W., Heyes C., Bertok I., Thunis P., Bessagnet B., Terrenoire E., Amann M., (2013), Modelling compliance with NO2 and PM10 air quality limit values in the GAINS model. TSAP Report #9, IIASA, Luxemburg.

Lefebvre W., Van Poppel M., Maiheu B., Janssen S., Dons E., (2013), Evaluation of the RIO-IFDM-street canyon model chain, *Atmospheric Environment*, **77**, 325-337.

Leutbecher M., Palmer T.N., (2007), Ensemble forecasting, ECMWF Technical Memoranda 514, On line at: https://www.ecmwf.int/en/elibrary/10729-ensemble-forecasting.

Maffeis G., (1999), Prediction of carbon monoxide acute air pollution episodes, Model formulation and first application in Lombardy, *Atmospheric Environment*, **33**, 3859-3872.

Marécal V., Peuch V.H., Andersson C., et al., (2015), A regional air quality forecasting system over Europe: the MACC-II daily ensemble production, *Geoscientific Model Development*, **8**, 2777-2813.

Papadimitriou G., Ntziachristos L., Wüthrich P., Notter B., Keller M., Fridell E., Winnes H., Styhre L., Sjödin A., (2013), TRACCS. Final report. Transport data collection supporting the quantitative analysis of measures relating to transport and climate change, On line at: https://traccs.emisia.com/.

Thiel C., Drossinos Y., Krause J., Harrison G., Gkatzoflias D., Donati A.V., (2016), Modelling electro-mobility: An integrated modelling platform for assessing European policies, *Transportation Research Procedia*, **14**, 2544-2553.

Environmental Engineering and Management Journal
"Gheorghe Asachi" Technical University of Iasi, Romania
73 Mangeron Blvd., 700050, Iasi, Romania
Tel./Fax. +40-232-271759, PO 10, BOX 2111,
URL: http://omicron.ch.tuiasi.ro/EEMJ/
e-mail: eemjournal@yahoo.com, eemj.office@gmail.com

INSTRUCTIONS FOR AUTHORS

1. Introduction

Environmental Engineering and Management Journal (EEMJ) is an international medium for publication of Original Papers, Reviews, Case Studies, Book Reviews on the fundamentals, applications in environmental engineering and technologies, applied environmental sciences, environmental health, management, sustainable development, education for sustainability. Advertising is also accepted with contractual payment forms.

Submission of a manuscript implies that the work described has not been published before (except in the form of an abstract or as part of a published lecture, or thesis); that it is not under consideration for publication elsewhere; that its publication has been approved by all coauthors, if any, as well.
Papers, books for review, offers to review, suggestions and commercials (advertising) should be submitted to the *Editor-in-Chief* All papers will be published in English. Non-English speaking authors should seek the advice of a professional language expert or an English speaker to help translate the paper.

2. Legal requirements

The author(s) guarantee(s) that the manuscript is/will not be published elsewhere in any language without the consent of the copyright holders, that the rights of third parties will not be violated, and that the publisher will not be held legally responsible should there be any claims for compensation.
Authors wishing to include figures or text passages that have already been published elsewhere are required to obtain permission from the copyright holder(s) and to include evidence that such permission has been granted when submitting their papers. Any material received without such evidence will be assumed to originate from the authors.
The author(s) are encouraged to transfer the copyright of the article to the publisher upon acceptance of an article by the journal, using the Authors' Warranty and Assignment of Copyright agreement. This transfer enables the Editor to protect the copyrighted material for the authors, but does not relinquish the author's proprietary rights. The publication of an article is conditioned by the signature of the author to whom correspondence should be addressed on this Authors' Warranty and Assignment of Copyright that is provided by the Editor.

Ethics in Publishing

For information on ethics in publishing for journal publication see
hiip://omicron.ch.tuiasi.ro/EEMJ/plagiarism.htm

Conflict of interest

All authors are requested to disclose any actual or potential conflict of interest such as any financial, personal or other relationships with other people or organizations concerning the submitted work that could inappropriately influence, or be perceived to influence, their work.

3. Editorial procedure

For original papers, an upper limit of 7000 words is recommended (including Abstract, Keywords, References, Figures and Tables), processed with MS editing facilities.

For review papers (critical evaluation of existing data, defined topics or emerging fields of investigation, critical issues of public concern), an upper limit of 15000 words is recommended (including Abstract, Keywords, References, Figures and Tables).

Manuscripts should be written in English (American or British usage is accepted, but not a mixture of these) and submitted **electronically**, in .doc format (please do not use .docx) to the *Editor-in-Chief*, at one (and only one) of the following e-mail addresses: **eemjournal at yahoo dot com**; **eem_journal at yahoo dot com**; **eemjeditor at yahoo dot com**; **eemj_editor at yahoo dot com**; **eemjournal at gmail dot com**; **eemjeditor at gmail dot com; eemjoffice at gmail dot com.**
Please be sure to include your full affiliation and e-mail address (see Sample manuscript).

When submitting the manuscript, it is mandatory to include a cover letter to the editor. The cover letter must state:

- that all authors mutually agree that the manuscript can be submitted to EEMJ;
- that the manuscript contains the original work of the authors;

- the novelty in results/findings, or significance of results;
- that the manuscript has not already been published, or is not under consideration for publication elsewhere.

Manuscripts are evaluated first in the Editorial Office (as a preliminary condition for acceptance) in terms of meeting the requirements of the journal, including attempts of plagiarism. The authors are responsible for the accuracy of the whole paper and references. Authors will be notified about the registration of their contribution. Only those contributions, which conform to the following instructions, can be considered for the peer-review process. Otherwise, the manuscripts are returned to the authors, with observations, comments and annotations.

The peer review process is decisive for paper acceptance. It could be done in several stages, depending on the revision quality of the manuscript in accordance with the requirements of paper evaluators.

Please do not transmit electronic data or requirements to the publisher until your manuscript has been reviewed and accepted for publication. Please follow the instructions below.

A minimum of four suitable *potential reviewers* should be provided by the authors. Please provide their name, email addresses, and institutional affiliation. When compiling this list of potential reviewers please consider the following important criteria: they must be knowledgeable about the manuscript subject area of the manuscript; they must not be from the authors' own institution or country; they should not have recent (less than five years) joint publications with any of the authors. However, the final choice of reviewers is at the editors' discretion.

4. Manuscript preparation

General:

Authors must follow the Instructions for authors strictly, failing which the manuscripts would be rejected without review. Editors reserve the right to adjust the formatting style to conform to the standards of the journal.

Manuscripts should be concise, in 1.5 line spacing, and should have 2 cm all over margins. The font should be Times New Roman of size 12 points. The numbering of chapters should be in decimal form. Ensure that each new paragraph is clearly indicated, using TAB at 1.25 pts.

The text layout should be in single-column format. Keep the layout of the text as simple as possible. Most formatting codes will be removed and replaced on processing the manuscript. However, do use bold face, italics, subscripts, superscripts etc. Add line numbering and page numbers. To avoid unnecessary errors it is strongly advised to use the 'spell-check' and 'grammar-check' functions of your word processor.

Title page will contain:

- A concise and informative title (Times New Roman bold, all caps of size 14 points); the maximum length of the title should be maximum 100 letters and spaces; The full name(s) of the author(s) (first name, then last name, with Times New Roman bold 12 points) should be written below the title. The affiliation(s) and complete postal address(es) of the author(s) will be provided immediately after the full name of the authors and will be written with Times New Roman 12 points. When the paper has more than one author, their name will be followed by a mark (Arabic numeral) as superscript; for the corresponding author, an asterix will be added using *Word_Insert_Reference_Footnote_Symbol* sequence. Also, the full and e-mail addresses, telephone and fax numbers of the corresponding author will be provided in the footer of the first page, as: Author to whom all correspondence should be addressed: email….., Phone…….., Fax…………
- **Abstract:** each paper must be preceded by an abstract presenting the most important results and conclusions in no more than 250 words. Do not include citations in the Abstract.
- **Keywords:** three to five keywords should be supplied after the Abstract for indexing purposes, separated by comma, **ordered alphabetically,** using American spelling and avoiding general and plural terms and multiple concepts (avoid, for example, "and", "of"). Be sparing with abbreviations: only abbreviations firmly established in the field may be eligible.
- The text of the paper should be divided into **Introduction, Materials and methods (**or **Experimental), Results and discussion, Conclusions, References** (for papers dealing with environmental management, policy, education etc., the Experimental part can be replaced by case-studies presentation).

1. Introduction

State the objectives of the work and provide an adequate background, avoiding a detailed literature survey or a summary of the results.

2. Material and methods (or 2. Experimental)

Provide sufficient detail to allow the work to be reproduced. Methods already published should be indicated by a reference: only relevant modifications should be described.

3. Results and discussion

Results should be clear and concise. Discussion should explore the significance of the results of the work, not repeat them. Avoid extensive citations and discussion of published literature.

4. Conclusions

The main conclusions drawn from results should be presented in a short Conclusions section. Do not include citations in this section.

Formulae, symbols and abbreviations: Formulae will be typeset in Italics (preferable with the Equation Editor of Microsoft Office 2003) and should be written or marked as such in the manuscript, unless they require a different styling. The formulae should be numbered on the right side, between brackets:

$$a^3 = 3M / 4N \qquad (1)$$

Always refer in the text to Equations as (Eq. 1), Eqs. (1-4) etc.
The more complex Chemical Formulae should be presented as Figures.
Abbreviations should be defined when first mentioned in the abstract and again in the main body of the text and used consistently thereafter.

SI units must be used throughout.

Footnotes should be avoided.

References:
The list of References should only include works that are cited in the text and that have been published. References should be cited in the text in brackets ***(Harvard style)*** as in the following examples:

(Chisti, 1989), (Gavrilescu and Roman, 1996), (Moo-Young et al., 1999).
References should be alphabetically listed at the end of paper, with complete details, as follows:

Books: Names and initials of authors, year (between brackets), chapter title, title of the book (italic), editors, edition, volume number, publisher, place, page number:
Mauch K., Vaseghi S., Reuss M., (2000), *Quantitative Analysis of Metabolic and Signaling Pathways in Saccharomyces cerevisiae*, In: *Bioreaction Engineering*, Schügerl K., Bellgardt K.H. (Eds.), Springer, Berlin Heidelberg New York, 435-477.
Faber K., (2000), *Biotransformations in Organic Chemistry – A Textbook*, vol. VIII, 4th Edition, Springer, Berlin-Heidelberg-New York.
Handbook, (1951), *Handbook of Chemical Engineer*, vol. II, (in Romanian), Technical Press, Bucharest, Romania.

Symposia volumes: Names and initials of authors, year (between brackets), paper title, symposium name, volume number, place, date, page numbers:
Clark T.A., Steward D., (1991), *Wood and Environment*, Proc. 6th Int. Symp. on Wood and Pulping Chemistry, Melbourne, vol. 1, 493-498.

Journal papers: Names and initials of authors, year (between brackets), full title of the paper, full name of the journal (italic), volume number (bold), first and last page numbers:
Tanabe S., Iwata H., Tatsukawa R., (1994), Global contamination by persistent organochlorines and their ecotoxicologcial impact on marine mammals, *Science of the Total Environment*, **154**, 163-177.

Patents: Names and initials of authors, year (between brackets), patent title, country, patent number (italic):
Grant P., (1989), Device for Elementary Analyses. USA Patent, No. *123456*.

Dissertations: Names and initials of authors, year (between brackets), title, specification (PhD Thesis, MSc Thesis), institution, place:
Aelenei N., (1982), *Thermodynamic study of polymer solutions*, PhD Thesis, Institute of Macromolecular Chemistry Petru Poni, Iasi, Romania.
Star K., (2008), *Environmental risk assessment generated by natural hazards*, MSc Thesis, Institute of Hazard Research, Town, Country.

Legal regulations and laws, organizations: Abbreviated name, year (between brackets), full name of the referred text, document type, author, URL address:
ESC, (2007), Improving access to modern energy services for all fundamental challenge, Economic and Social Council, ENV/DEV/927, On line at: hiip://www.un.org/News/Press/docs/2007/envdev927.doc.htm.
EPA, (2007), Biomass Conversion: Emerging Technologies, Feedstocks, and Products, Sustainability Program, Office of Research and Development, EPA/600/R-07/144, U.S. Environmental Protection Agency, Washington, D.C., On line at: hiip://www.epa.gov/Sustainability/pdfs/Biomass%20Conversion.pdf.
EC Directive, (2000), Directive 2000/76/EC of the European Parliament and of the Council of 4 December 2000, on the incineration of waste, Annex V, *Official Journal of the European Communities*, L 332/91, 28.12.2000, Brussels.
GD, (2004), Governmental Decision No. 1076/2004 surnamed SEA Governmental Decision, regarding the procedure for strategic environmental impact assessment for plans or programs, *Romanian Official Monitor*, Part I, No. 707 from 5th of August, 2004.

Web references
The full URL should be given in text as a citation, if no other data are known. If the authors, year, title of the documents are known and the reference is taken from a website, the URL address has to be mentioned after these data:
Burja C., Burja V., (2008), Adapting the Romanian rural economy to the European agricultural policy from the perspective of sustainable development, MPRA, Munich Personal RePEc Archive, On line at: http://mpra.ub.uni-muenchen.de/7989/1/MPRA_paper_7989.pdf

Web references must not be listed separately, after the reference list.

All references must be provided in English with a specification of original language in round brackets.

Citation in text
Please ensure that every reference cited in the text is also present in the reference list (and vice versa). Do not cite references in the abstract and conclusions.
Unpublished results, personal communications as well as URL addresses are not recommended in the references list..
Citation of a reference as "in press" implies that the item has been accepted for publication.

Papers which have been accepted for publication should be included in the list of references with the name of the journal and the specification "in press".

References style

Text: All citations in the text may be made directly (or parenthetically) and should refer to:

- *single author:* the author's name (without initials, unless there is ambiguity) and the year of publication: "as previously demonstrated (Smith, 2007)"; "as Smith (2007) demonstrated"
- *two authors:* both authors' names and the year of publication: (Arnold and Sebastian, 2008; Smith and Hansel, 2006; Stern and Lars, 2009)
- *three or more authors:* first author's name followed by "et al." and the year of publication: "As has recently been shown (Werner et al., 2005)…", "Kramer et al. (2000) have recently shown ...."

Citations of groups of references should be listed first alphabetically, then chronologically.

Examples: "…..as demonstrated (Aden, 1996a, 1996b, 1999; Allan and Jones, 1995; Han et al., 2007; Weiss and Schmidt, 1988)".

Abbreviations

Define all abbreviations at their first mention in the text. Ensure consistency of abbreviations throughout the article.

Acknowledgements

Include acknowledgements in a separate section at the end of the article before the references and do not, therefore, include them on the title page, as a footnote to the title or otherwise. List here those individuals who provided help during the research (e.g., providing language help, writing assistance or proof reading the article, funding supports etc.).

Footnotes

Footnotes must be avoided. Do not include footnotes in the Reference list.

Table footnotes

Indicate each footnote in a table with a superscript lowercase letter.

Tables

Draw the Tables in grid format using a basic, solid line style without shadows.

Ensure that the data presented in Tables do not duplicate results described in Figures or elsewhere in the paper.

Figures

Number Figures consecutively in accordance with their appearance in the text. All illustrations should be provided in camera-ready form, suitable for reproduction, which may include reduction without retouching. Photographs, charts and diagrams are all to be referred to as Figure(s) and should be numbered consecutively, in the order to which they are referred.

Figures may be inserted preferably as black line drawings. They should be pasted on, rather than taped, since the latter results in unclear edges upon reproduction.

Ensure that each illustration has a caption, placed below the Figure. Supply also captions separately, not attached to the figure. A maximum limit of 8 Figures are allowed per manuscript.

A caption should comprise a brief title (**not** on the Figure itself) and a description of the illustration. Keep text in the illustrations themselves to a minimum but explain all symbols and abbreviations used. Multiple Figures can be expressed as one Figure (for e.g. 1a, 1b, 1c etc...), while retaining the maximum limit of 6.

ALL Figures must be submitted in either .jpg or .tiff format with a very good resolution (but do not submit graphics that are disproportionately large for the content).

Figures and Tables must be embedded in the text.

Proofs

Proofs will be sent to the corresponding author (by e-mail) and should be returned within 72 hours of receipt. Corrections should be restricted to typesetting errors; any other changes may be charged to the authors.

Paper in Electronic Format:

Authors are asked to submit their final and accepted manuscript as an attachment to one of the above-mentioned e-mail addresses. Use the **.doc** format (not .docx !).

5. Page charge

There is no charge per printed page for regular papers.

6. Reprints

The corresponding author will be provided with a .pdf file of the paper via e-mail, free of charge. A hard copy Of the issue containing the paper can be provided on request, for a fee. This request will be formulated when the final form of the manuscript (the electronic one) is provided.

7. Additional procedures for the editorial management of *Environmental Engineering and Management Journal*

Starting with volume 13/2014, the members of the Scientific Advisory Board and the Corresponding authors will receive each issue of the journal in electronic .pdf format. Printed copies can be delivered on request.

An author cannot appear on more than two papers per regular issue. An author cannot appear on more than three papers in a Guest Editor/ Conference issue.

The evaluation/peer-review process of manuscripts submitted for Guest Editor / Conference issues published according to journal *Editorial Procedure and Policy* will be handled and evaluated as with regular manuscripts, so that only consistent papers will be published. The manuscripts must be sent at least six months before the presumed data of publication. Those manuscripts which do not fulfill the journal requirements

will be rejected. This is to discourage superficiality in the development of the manuscript, from formal and scientific points of view. No amount of money will be refunded following the rejection of manuscripts.
No more than 160 pages and no more than 20 papers are acceptable for regular issues. No more than 180 pages and no more than 25 papers are opportune for special issues. The number of pages is based on the published version of an article, not on the submitted version (for instance, when page breaks are changed and when images are enlarged for easier viewing).
An issue can include, as an exception, a number of 25-30 papers as a maximum. This situation could appear when the authors of an already accepted paper need and ask for early publication, from the position in the list of accepted papers. In this circumstance, a yearly submission to our journal (500 Euro) will be asked for each already accepted paper, for its publication in advance.
A newly-received manuscript can be evaluated by priority, when a deposit of 200 Euro shall be paid by authors in advance. If the manuscript is deemed unsuitable for publication, the authors will not be eligible for a refund.
Failure to pay mandatory charges may result in the paper being withheld from early publication.

In all cases, the corresponding author will sign an agreement with the *Editor-in-Chief*, and the *Director* of the *EcoZone* Publishing House according to journal *Editorial Procedure and Policy.*

Automated software is used for checking against plagiarism. In order to avoid false results, the generated reports are cautiously checked and confirmed by journal staff. We do not send plagiarism reports to authors. Any manuscripts which do not prove to be at least 90% original will be rejected. The rejection for plagiarism may arise at any phase of the editorial / review process, even if the manuscript was accepted for publication. The authors are solely responsible for the originality of their submission. Therefore, any manuscript should be carefully checked for such inconsistencies before submitting to EEMJ.
The authors are required to follow academic publishing rules, to adhere to the principles of scientific ethics and to sign the Authors' warranty and Copyright transfer.

Detailed information concerning these issues may be found of the EEMJ website, under *Editorial Procedure and Policy.*