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"Gheorghe Asachi" Technical University of Iasi, Romania

EDITORIAL

Green and Circular Economy at ECOMONDO 2021

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 2021* held, given the pandemic, in the sole digital format from the Italian Exhibition Group headquarter in Rimini, Italy, during 26 - 29 November 2021

(hiip://en.ecomondo.com).

Ecomondo is the one of largest European exhibitions in the field of *Green and Circular Economy*, which, in the 2019 edition (before the pandemic), hosted over than 100,000 delegates from 60 different nations along with 1350 companies exhibiting their products and processes in 135,000 square meters. Despite the pandemic, *Ecomondo 2021* hosted over than 90 conferences and workshops dedicated to policies, research and innovation, innovation funding opportunities, education, communication and entrepreneurship and international networking.

As with the previous editions, the aim of *Ecomondo 2021* 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 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 2021* also hosted events on the priorities of the Mediterranean macro-region, and in particular the water scarcity of the area, the Mediterranean Sea contamination (also due to marine litter) and its sustainable exploitation.

Ecomondo 2021 conferences hosted more than 700 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 mentioned technical and scientific conferences of *Ecomondo* 2021.

We believe that this collection of papers will be useful to people who could not follow the edition of *Ecomondo 2021*. 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 territories.
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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 250 scientific papers, 210 of which on medium/high IF peer-review international journals of industrial and environmental biotechnology and circular bioeconomy. He has 9769 overall citations, a h-index of 58 and an i10 index of 149 (Google Scholar) along with 205 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, ROUTES, MINOTAURUS, WATER4CROPS, ULIXES and KILL SPILL.
F. Fava served and is serving several national, European and international panels, by covering, among others, the following positions:

• Member of the Scientific Committee of the European Environmental Agency (EEA), Copenaghen, for the "Circular economy and resource use" domain (2021-);
• Italian Representative in the "European Bioeconomy Policy Forum" and the "European Bioeconomy Policy Support Facility" of the European Commission (2020-);
• Senior Expert of the Italian delegation to the Programming committee Horizon Europe, Cluster VI: Food, Bioeconomy, natural resources, agriculture and environment (European Commission, DG RTD)(2020-);
• Italian Representative and elected vice chair in the "States Representatives Group" della Public Private Partnership "Circular Biobased Europe" (CBE JU), Brussels (2022-);
• 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-);
• Italian Representative in the "Working Party on Biotechnology, Nanotechnology and Converging Technologies" of the Organization for Economic Co-operation and Development (OECD, Paris) (2008-);

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

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INTEGRATED ENVIRONMENTAL AUTHORIZATION: ODOUR MONITORING THROUGH UNMANNED AERIAL VEHICLES

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Abstract

To protect environment and public health, in the European Union industrial activity is subjected to Integrated Environmental Authorization (IEA), according to the provisions of the Directive 2010/75/UE. In Italy, the Legislative Decree n. 152/2006 regulates IEA procedure and states that ISPRA is responsible for the elaboration of a Monitoring and Control Plan (MCP) for large industrial plants, where odour impact assessment can be required.
Currently, odour monitoring is mainly carried out through dynamic olfactometry, which requires odour sampling. Such an activity can inevitably expose workers to occupational risks. So, to avoid/limit risks for workers involved in odour impact assessment, the authors investigated the scientific literature on Unmanned Aerial Vehicles (UAVs) through SciVal engine, recently recognized as a successful tool for different purposes. Hence, the paper's aim is evaluating the opportunity to use UAVs for odour monitoring and their influencing factors, as well as addressing further research in this field.

Key words: e-noses, IPPC, odour monitoring, UAVs

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1. Introduction

Even though industries are recognized to be a key component of economic well-being, there is scientific evidence that they can threat seriously both environment and public health (Patnaik, 2018). However, while industrial pollution can be considered a global phenomenon, different approaches have been developed to manage its issues in the world. For example, in the USA the Pollution Prevention Act (1990) demanded to EPA the establishment of a general source reduction program. In the European Union the Directive on Industrial Emissions (IED) stated a general framework further integrated with the Best Available Techniques (BAT) definition for each industrial sector (e.g. BAT Conclusions and BREF) (Vázquez et al., 2015).

According to the Integrated Pollution Prevention and Control (IPPC) framework (Directive 2010/75/EU), European operators must apply for an Integrated Environmental Authorization (IEA) to carry out industrial activities. The permit includes specific conditions for each installation, according to BAT Conclusions and national environmental laws or reference documents. Generally speaking, IEA is accounted to be valid for ten years. However, an ISO 14001 certificate or an environmental declaration according to EMAS Regulation can extend the deadline of the permit up to 12 or 16 years.

In Italy ISPRA elaborates a Monitoring and Control Plan (MCP) for installations of national concern (D.Lgs. 152/2006). A specific odour monitoring can be required in MCPs, according to the article 272-bis D.Lgs. 152/2006 and BAT Conclusions.

Such a request is due to evidence of many industrial activities (e.g. refineries, chemical plants, landfills etc.) causing odour emissions with nuisance

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and health disturbs (Guadalupe-Fernandez et al., 2021).

Just to illustrate this concept, it is sufficient to consider that in the (EU Decision 902/2016), concerning the BAT Conclusions on treatment and management systems for wastewaters and waste gas released by chemical industry, BAT 20 details the monitoring and control plan contents for odours (included in an Environmental Management System). This plan should contain:

- the identification of odour sources, the exposure assessment and the evaluation of the odour impact in a specific area and time range;
- the description of methods used to evaluate odour impact;
- preventive and protection measures to mitigate odour impact.

Actually, odour impact assessment is mainly carried out through dynamic olfactometry (EN 13725, 2004), which firstly requires odour sampling. However, as observed in some chemical plants, such an activity could expose workers involved in sampling operations to Occupational Health and Safety (OHS) risks, via inhalation or dermic contact with toxic substances.

Throughout the world, some research projects have been developed to test indirect methodologies, thus evaluating the opportunity to use technology for a continuous odour monitoring rather than the traditional approach included in EN 13725. Electronic noses could been accounted as a successful tool since 2010s, even though a few applications had been already known in the first years of the millennium (Cipriano and Capelli, 2019).

However, some researchers have tried to overcome the concept of terrestrial e-nose for odour monitoring by approaching to unmanned aerial vehicles recently (Allen et al., 2019). Just to illustrate this concept, in the U.S.A. a group of researchers are working to validate a palm-sized prototype of drone able to smell odours (the so-called "Smellicopter") (Anderson et al., 2021). In Spain, the prototype "Sniffdrone" has been developed to detect sources of odours in a wastewater treatment plant and it is going to be patented to assess odorous impact (Burgués et al., 2021).

Moreover, in Italy a civil protection network has been established since 2020 to promote the use of drones for environmental monitoring according to standard procedures. About 100 vehicles and 100 pilots are involved in this network and ISPRA is actually part of it (SNPA, 2020).

Hence, with the goal to improve the odour impact monitoring, scientific literature about Unmanned Aerial Vehicles (UAVs) was further investigated. More in details, this paper aims to provide a scientific and systematic review of the literature about UAVs for environmental monitoring to answer this question:

"Can we use Unmanned Aerial Vehicles to assess and monitor odour impact in Integrated Environmental Authorizations?"

The remainder of the article is organized as follows: in the next section, there is a description of materials and methods used to carry out the literature review; Section 3 shows the results of this research and discusses potential application of UAVs in environmental and odour monitoring; finally, section 4 concludes the paper and addresses further research work.

2. Materials and methods

Making a systematic review means to collect and analyse data from published scientific papers to answer a specific question, in a way that can be defined transparent and reproducible (Snyder, 2019). Generally, systematic reviews are carried out by searching for scientific articles indexed in Scopus, Web of Science, PubMed, etc., as they contain most of research products, whose value is recognized at an international level. In fact, publications indexed in one of these databases are subjected to a strict and double peer-review process.

However, Elsevier has recently released a new research engine called SciVal to help researchers in the evaluation of their scientific performances. As demonstrated by (Kolosok et al., 2021), such a tool can be used to make literature reviews too. In fact, the sources of data for SciVal are English-written outputs (peer-reviewed papers, conference proceedings, books, trade publications etc.) included both in Scopus and in ScienceDirect databases. Publications, authors and affiliation information available in SciVal are updated about every two weeks, while Scopus and ScienceDirect databases are updated monthly. In addition to this, SciVal is equipped with specific algorithms (related to automatic text mining methods), making easy the papers' selection, with reference to a specific research area (Elsevier, 2015).

Hence, considered the advantage of text mining algorithms included in SciVal, the systematic review about the use of UAVs/drones for odour monitoring was carried out according to the following procedure:

a) Pre-screening of the total database, concerning the definition of the Research Area in SciVal;
b) Screening of papers among those ones selected through the Research Area, according to specific selection criteria;
c) Publication Set Analysis, through abstract reading;
d) Full text analysis of papers, according to some quality criteria, partially derived from (Olsen et al., 2020) and stated in Table 1.

The definition of the "Research Area" was carried out according to the following steps:

1. Definition of the enter query string. This string should include some entering keywords, allowing text algorithms to calculate new related keywords.

For the stated purpose, the following enter query strings were considered:

a. "(UAV* OR drone*) AND (gas*OR odour*) AND (monitoring OR control)";
b. "(UAV* OR drone*) AND environment* AND (monitoring OR control)";

2. Evaluation of the papers' time range. As in Scopus, you can look for publications in a specific temporal period. This review was elaborated considering scientific papers published in the last five years (from 2016 to 2021);
3. Definition of key subject areas to make a first screening of information. In this case, Engineering, Environmental Science and Chemical Engineering were firstly selected;
4. Definition of organization types. In SciVal you can define the Research Area even through the category of the authors' organization (Academic, Government, Other etc.), as the main goal of this engine is to link researchers all around the world. However, as the main focus of this review was the content evaluation of research works, the authors' affiliation was not considered.

Once the research area was defined, the total amount of papers was further selected according to the following criteria:

5. Stage of the publication: only final articles were included;
6. Sub-subject areas: we selected only papers related to Environmental Science, as the main purpose of this review is related to environmental monitoring;
7. Type of publications: only articles and conference papers were considered.
8. Before evaluating full text of papers, a publication set analysis was carried out by reading abstracts.

In Fig. 1 the scheme of the entire procedure is provided.

3. Results and discussion

On the 11th of December 2021 the entry query string "(UAV* OR drone*) AND (gas*OR odour*) AND (monitoring OR control)" did not result in any kind of literature product, recognized by the above-mentioned databases (Scopus and Science Direct).

By contrast, on the same date, the SciVal engine produced results reported in Table 2, through the second input string "(UAV* OR drone*) AND environment* AND (monitoring OR control)".

Table 1. Quality criteria to assess full text papers

Quality Criteria	***Description***
Q1	The study addresses odour or gas emissions characterization through unmanned aerial vehicles
Q2	The research objectives are clearly defined
Q3	The context of the study is explained and gives an overview of existing research on the topic
Q4	The paper discusses and identify possible limitations in the reported research.
Q5	The study can be considered externally valid

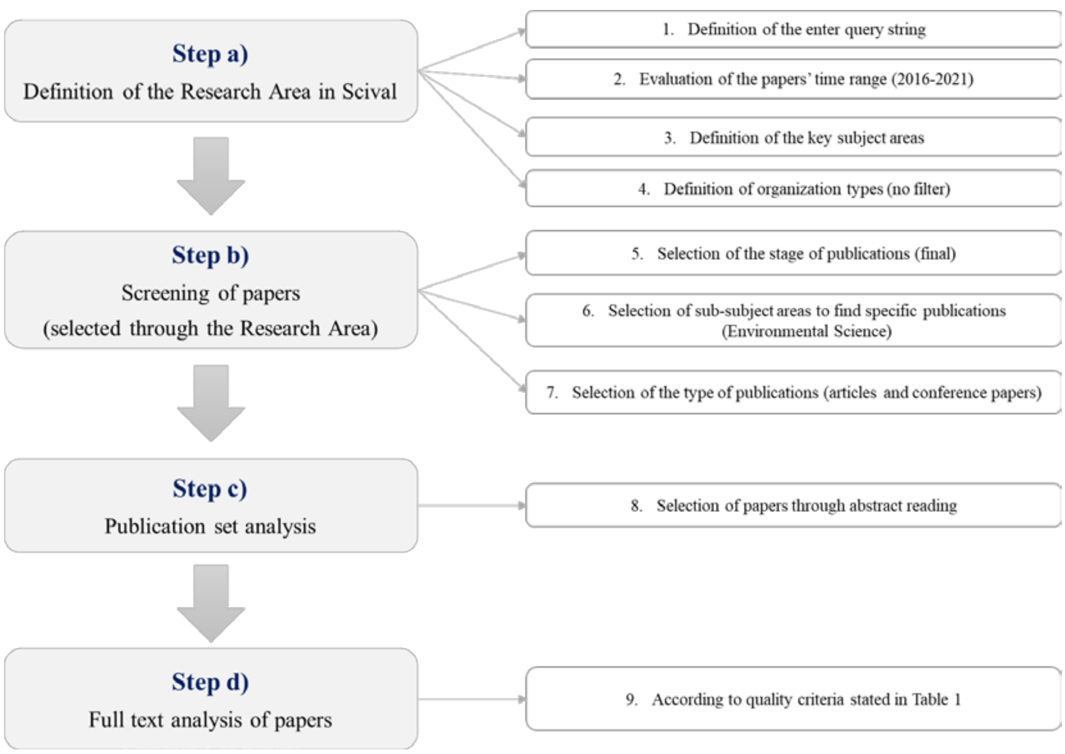

Fig. 1. The procedure developed to make the literature review

Table 2. Global results of the literature research

Time range: *2016 – 2021* ***input keywords string:*** *"(UAV* OR drone*) AND environment* AND (monitoring OR control)"*	
Step of the procedure	***Total number of papers***
Step a) Definition of the Research Area	Total matching publications (all subject areas): n. 5515 Matching publications with relevant subject areas for the stated purpose: n. 3661 1. Engineering: n. 3186 papers 2. Environmental Science: n. 542 papers 3. Chemical Engineering: n. 99 papers
Step b) Screening of papers	Phase of Step b): 5. Selection of the stage of papers: final (n. 3594) 6. Selection of Article and Conference Papers: n. 3359 7. Selection of the sub-subject area: Environmental Science (n. 474)
Step c) Publication Set Analysis (PSA)	• Papers rejected after PSA: n. 134 • Valid publications related to using UAVs for environmental monitoring: n. 340
Step d) Full text analysis (FTA)	• Papers submitted to FTA: n. 39 • Valid publications: n. 22

3.1. Results of the Publication Set Analysis (PSA)

3.1. Results of the Publication Set Analysis (PSA)

Before carrying out the Publication Set Analysis (PSA), the publication set was analysed with reference to key-phrases, elaborated by Scival engine from the input keywords string. Relevant key-phrases can be assessed directly in SciVal according to several variables (e.g. scholarly output, number of collaborations, citations etc.). In Table 3 an extract of such an analysis is reported with reference to scholarly outputs in the period 2016-2021. Then, the total amount of publications (n.474) extracted at the end of Step b) was selected through the Publication Set Analysis (PSA), which mainly consisted in abstract reading. The PSA was conducted through the means of:

- The SciVal engine, where abstract reading is directly available for each publication;
- Microsoft Excel tools, which allowed organizing the outcomes of Step b) in a table with the following columns: Title (Colum A), Authors (Colum B), Year of the publication (Colum C), Journal Title (Colum D), DOI (Colum E), Publication Type "Article/Conference Paper" (Colum F), Eligibility "YES/NO" for the Full Text Analysis (Colum G), UAVs application area (Colum H).

Hence, thanks to the PSA, the publication set was immediately divided in two categories: rejected papers and valid publications related to using UAVs for environmental monitoring.

In a second phase of the PSA, valid and rejected publications were identified for each year to evaluate, respectively, the cumulated distributions. Finally, all potential UAVs applications for environmental purposes were identified and papers were related to each one.

In the first phase of PSA, the main reasons to exclude papers were for example:

a) the paper only deals with technological issues of drones or UAVs, without highlighting information for specific environmental monitoring aspects;
b) The paper focuses the attention on the use of drones for security or safety issues;
c) The abstract does not allow the reader to distinguish key points of the publication;
d) The paper provides only a review of the state-of-the-art on UAVs, without any original application study;
e) The paper is focused on other topics, such as Geographic Information Systems, remote sensing platforms, elaboration models for remote sensing data etc., not related to specific applications of UAVs for environmental control.

In the second phase of PSA, cumulated distribution of publications related to environmental monitoring with unmanned aerial vehicles were elaborated with reference to the period 2016-2021. Such distributions were organized in histograms showing an increasing linear trend, both for valid papers (Fig. 2) and rejected ones (Fig. 3).

Then, every valid paper was related to a specific UAVs application area for environmental monitoring and global results were reported in Table 3.

Table 3. Top-three key phrases related to scholarly output

Scholarly output (results based on 474 publications)							
Keyphrases	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2016-2021**
Unmanned aerial vehicles	20	30	48	73	79	88	338
Drone	12	24	18	41	46	54	195
Unmanned vehicles	15	15	29	36	38	38	169

3.2. Results of the Full Text Analysis (FTA)

As mentioned above, none of the publications extracted with the second input keywords string allowed recognizing direct applications of UAVs for odour monitoring in the period 2016-2021. However, n.39 papers were submitted to the next Full Text Analysis (FTA), as related to applications of UAVs to air quality monitoring and, in a few cases, to industrial gas leaks control too. The first-mentioned research field was reasonably recognized the most related to odour monitoring. FTA was carried out in Scopus database by searching for those papers matching the quality criteria stated in Table 1.

During FTA, papers mainly related to particulate matter monitoring were excluded as not useful to answer to the question stated in the introduction. At the end of this phase, n. 22 publications were recognized as valid for discussion and distinguished in two categories: articles and conference papers. Moreover, reference publishers and journals were identified for such publication set. In Table 4 results of FTA are summarized.

3.3. Comprehensive discussion

As stated in section 2, results detailed in section 3.1 have been achieved through the use of text mining algorithms, which are a distinctive feature of Scival engine.

The automatic elaboration of other keywords from the input string allowed creating a publication set in short time, by integrating two databases (Scopus and ScienceDirect). Such opportunity can be considered a great advantage when you are required to make a literature review: in fact, it avoids the phase of removing duplicates identified in two databases.

Results achieved from Publication Set Analysis were interpreted through an histogram (Fig. 2) showing how applications of unmanned aerial vehicles in detecting environmental changes have been undoubtfully going up recently. Such increasing trend has not been related to a unique research field, but to several subject areas as reported in Table 5. These results can be also confirmed looking at the top-three key phrases analysis reported in Table 3.

However, results achieved through PSA and FTA demonstrated that applications of drones in gaseous releases monitoring are actually less usual rather than those ones concerning forest and vegetation monitoring, waste and contamination control or land monitoring. So, it could be argued that:

- some application areas are more developed than others (*i.e.* forest & vegetation monitoring);
- using drones in industrial areas still remains a very challenging task.

Table 4. Bibliometric features of the full-text analysed papers (Legend: A = Article; CP = Conference Paper)

<table>
<tr><th colspan="14">Full-text analysed papers</th></tr>
<tr><th colspan="2">2016</th><th colspan="2">2017</th><th colspan="2">2018</th><th colspan="2">2019</th><th colspan="2">2020</th><th colspan="2">2021</th><th colspan="2">2016-2021</th></tr>
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<tr><th colspan="14">Bibliometric features</th></tr>
<tr><th colspan="4">Publisher</th><th colspan="3">Type of papers</th><th colspan="7">Journal/Conference Proceedings</th></tr>
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<tr><td colspan="7">Environmental Pollution</td></tr>
<tr><td colspan="7">Journal of Environmental Management</td></tr>
<tr><td colspan="7">Ocean Engineering</td></tr>
<tr><td colspan="7">Waste Management</td></tr>
<tr><td colspan="7">Journal of Environmental Sciences (China)</td></tr>
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<tr><td colspan="4">Taylor & Francis</td><td colspan="3">A</td><td colspan="7">Journal of the Air and Waste Management Association</td></tr>
<tr><td colspan="4">Gh.Asachi Technical University of Iasi, Romania</td><td colspan="3">A</td><td colspan="7">Environmental Engineering and Management Journal</td></tr>
<tr><td colspan="4" rowspan="3">Institute of Electrical and Electronics Engineers Inc.</td><td colspan="3" rowspan="3">CP</td><td colspan="7">International Workshop on Metrology for AeroSpace, MetroAeroSpace 2020 - Proceedings</td></tr>
<tr><td colspan="7">International Conference on Environment and Electrical Engineering and 2020 IEEE Industrial and Commercial Power Systems Europe, EEEIC / I and CPS Europe 2020</td></tr>
<tr><td colspan="7">OCEANS 2017 - Anchorage</td></tr>
<tr><td colspan="4">EDP Sciences</td><td colspan="3">CP</td><td colspan="7">E3S Web of Conferences</td></tr>
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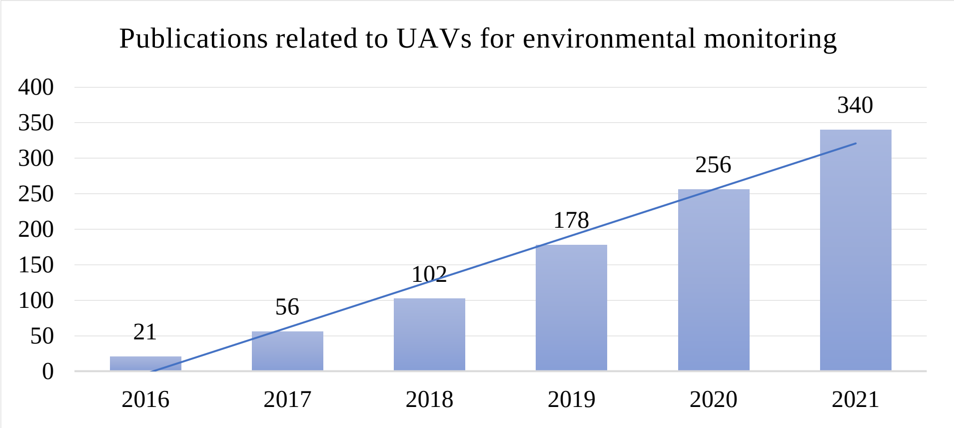

Fig. 2. Cumulated distribution of valid publications about using UAVs for environmental monitoring (2016-2021)

Table 5. Identified UAVs application areas through Publication Set Analysis

UAVs application areas *(based on 340* papers)*	***Short description***	***Number of publications*** *Time range: 2016 – 2021*
Forest and vegetation monitoring	This area concerns the application of UAVs to assess changes in forest and vegetation spectral conditions. Many applications have been related to marine vegetation too and required UAVs water-resistant.	83
Coastal surveying	This area concerns the application of UAVs to assess temporal changes in marine morpho-dynamics.	38
Air quality monitoring	This research area concerns the assessment of air pollution through unmanned aerial vehicles. Papers related to this field deal with particulate matter sampling, air pollutants dispersion etc. through drones equipped with e-noses.	35
Land and soil monitoring	This research field concerns the use of UAVs to evaluate soil health conditions as well as land use (residential, forest, for agriculture purposes etc.). Acquired imagery are further elaborated to assess variations in specific indexes, such as NDVI.	33
Waste and contamination monitoring	UAVs applications to assess shape and volume features of waste dumps and the extension of contaminated areas are here included. Many studies are currently about the use of drones to detect and characterize marine or beach littering. Other ones are related to the characterization of buried waste or illegal landfills.	31
Agriculture and farming practises	In this area papers regarding the use of drones to evaluate health conditions of cultivations or to assess farming practices are included.	30
Wildlife and animal control	Such research field includes papers addressing the use of drones to detect or control wild animals health conditions in large areas. Papers related to marine animals are available too.	23
Hydrology modelling	This research area concerns the use of drones for flood modelling, river sediment monitoring etc.	22
Quarries and dumps monitoring	Such area include articles addressing the use of drones for planning activities in dumps and quarries.	10
Urban environment monitoring	This area concerns the application of drones to civil infrastructures, such as highways, buildings etc. to assess their technical performances.	9
Cryosphere monitoring	This area includes articles about using UAVs to evaluate snow cover depth in glacial areas or to assess ice dynamics or dealing with typical factors of polar areas influencing the use of drones.	9
Radiation monitoring	This research area concerns the use of drones to analyze radiologic risk near nuclear reactors or areas contaminated by radioactive waste.	7
Industrial facilities control	This area mainly concerns the application of UAVs for leak detection and repair programs in industrial sites.	5

*n. 5 papers were accounted to be across two or more identified application areas

To better understand how research on drones could evolve with reference to odour impact monitoring in industry, some influencing factors related to the use of drones for air quality or industrial gas leaks monitoring were derived from the 22 selected publications and organized in some categories. The following categories were established: Operations management, Manpower, Environment and Machinery. Some factors, not mentioned in the selected papers (i.e. those ones related to “Manpower”), were derived from ISPRA and environmental Italian Agencies professional background about the use of drones. Then, all influencing factors on the use of drones for odour impact monitoring in industrial plants were organized through the means of an Ishikawa diagram. Published as a tool to assess quality in industrial processes, Ishikawa graph is now accounted to be one of the best logic instrument to evaluate cause-effect relationships. In fact, it shows a very flexible structure: for example, some applications of Ishikawa diagram have been reported to evaluate industrial sustainability (Mengistu and Panizzolo, 2021), waste management (Manojkumar and Rajayogan, 2021) or occupational health and safety (Górny, 2017). In Fig. 3 the final output of the above mentioned analysis is reported.

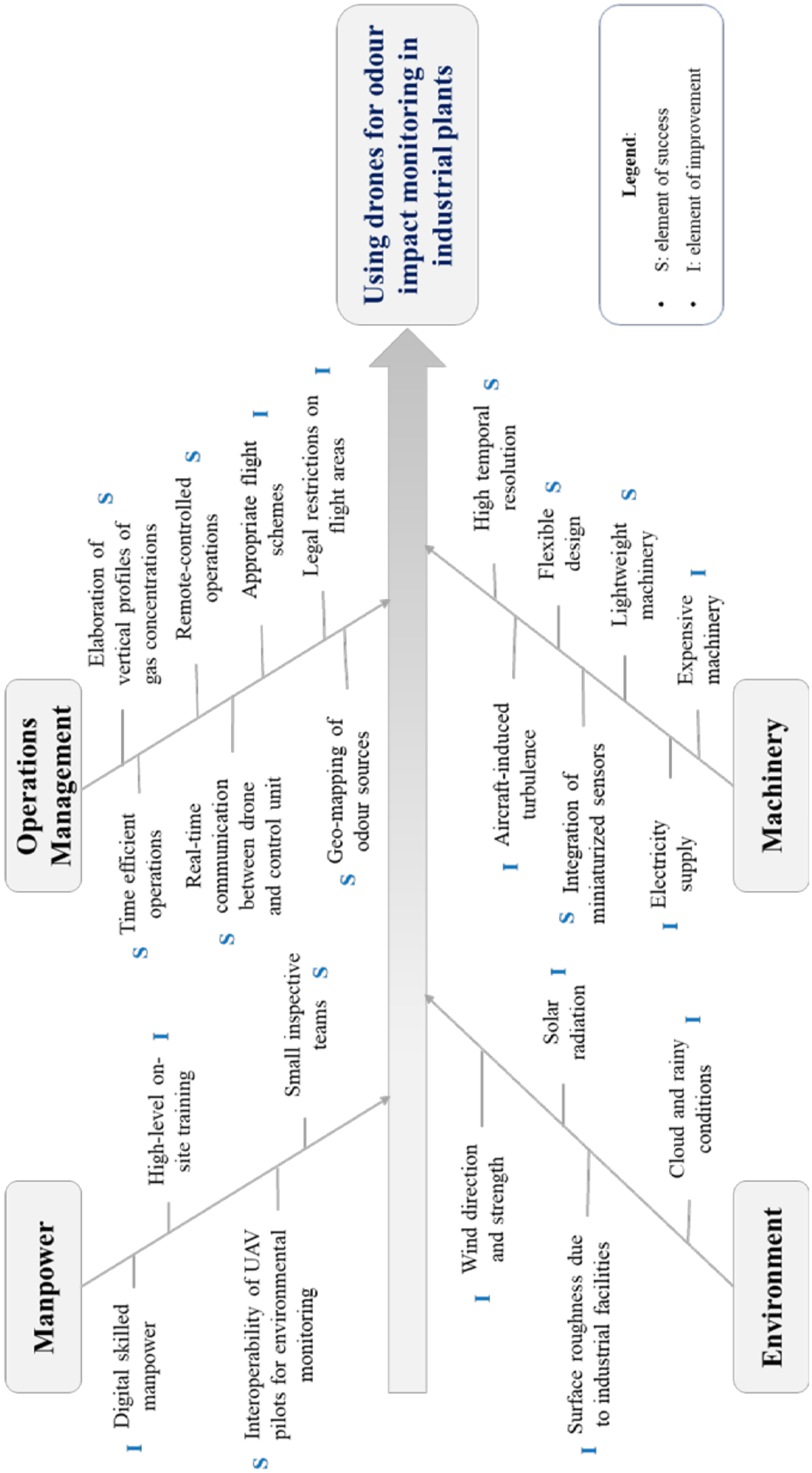

Fig. 3. Analysis of the influencing factors (Ishikawa graph)

Every factor was categorized as an element of success or improvement to better address the use of drones in such research field. Hence, the following results were achieved:

- the main successful factors are currently related to “Operations management” and “Machinery”. Drones can be considered a flexible and lightweight tool, but also a valuable measure to prevent workers involved in odour impact monitoring from OHS risks, as they do not require the direct contact/exposure to the sources of odours;
- improvements mainly concern “Manpower” and “Environment” categories, such as the need for digital skilled manpower and models to better control data uncertainty due to meteorological parameters and turbulence phenomena.

3.4. Study limitations

Even though this literature review pinpoints the recent state-of-the-art of drones for odour and environmental monitoring, some limitations were identified and are here discussed. Firstly, the review was highly dependent on the use of text mining algorithms to identify useful publications. Even though such tools allow selecting quickly a large amount of articles from two databases, they could lead to consider many off-topic papers with the increasing of literature production, as shown in Fig. 4.

Moreover, the study was aimed at defining current applications of drones with reference to the stated topic: so, publications were selected by considering only last five years. The choice of a short time period could be a limitation if you are interested in evaluating temporal changes in the specific subject.

Finally, another limitation is related to SciVal dependence on Scopus and ScienceDirect databases, powered by Elsevier. In this review, the largest amount of full-text analyzed papers were published by Elsevier. This result could be due to the automatic exclusion of papers indexed in other important databases (e.g. Web of Science, Google Scholar etc.).

4. Concluding remarks

A review of literature published in the last five years (from 2016 to 2021) on unmanned aerial vehicles for environmental monitoring was carried out to investigate the potential use of UAVs for odour impact monitoring in Integrated Environmental Authorizations, released to industrial plants according to Directive 2010/75/UE (in Italy, according to the Title III-bis of Legislative Decree n.152/2006). In fact, occupational health and safety issues for the operators involved in odour sampling were observed, addressing in this way the need to promote indirect methodologies to carry out odour impact monitoring.

Through the Scival engine, the study concludes that odour impact control through drones is still an open research field. In fact, in the period 2016-2021 no application were officially reported in SciVal engine with reference to such field, while only a few were accounted to monitor air quality and industrial gas leaks. Moreover, the authors discussed the initial question with an Ishikawa analysis of factors influencing the use of drones in odour monitoring to address further research in this field.

To sum up, with reference to IEA permits, this paper shows how environmental and health authorities may not agree on the use of UAVs for odour assessment, due to the lack of sufficient evidence. However, as demonstrated by current research projects throughout the world, the use of drones in odour monitoring could become a driver of innovation among researchers and professionals involved in such activities. For this reason, scientific experimental programs should be encouraged to better address the use of UAVs in the field of odour monitoring.

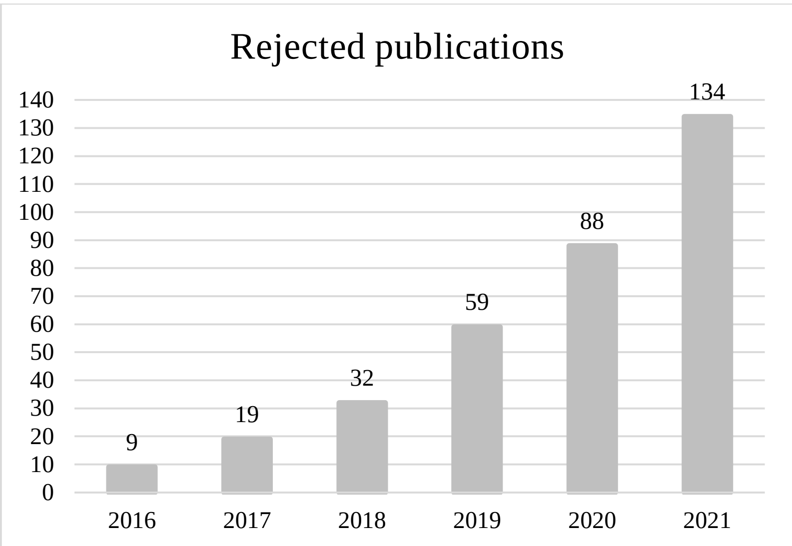

Fig. 4. Cumulated distribution of rejected publications through PSA (2016-2021)

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The authors declare no conflict of interest.

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AVAILABLE TOOLS AND METHODOLOGIES FOR SUSTAINABILITY ASSESSMENT IN PRODUCTION

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Abstract

The need for a paradigm shift toward a more circular, sustainable, and resilient economic model led to several attempts to better integrate sustainability metrics into the design and optimization phases of industrial processes. The specific focus, the reach, and means of application depend on the adopted tool and methodology. The goal of this paper is to discuss how the sustainability framework in the SMART-Pro project was created and to display how broad is the set of possible instruments that a company could choose from to promote a more sustainable and optimized business management, spanning from specific aspects of a process, the entire company, or the overall value chain up to the scale of industrial symbiosis contexts. All references have been characterized by taking a holistic approach to system analysis and relying on different criteria to stress complementarities, gaps and overlaps in areas of intervention.

Key words: smart production, sustainable production, sustainability metrics, system thinking

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1. Introduction

While the goal of continuous improvement has always existed, what changed through the years is the direction and breadth of such aim. In fact, several frameworks, methods, tools and concepts have been developed to promote performance improvements, at first in terms of production efficiency by maximizing produced units and economic growth, then also as organizational performances, waste reduction and eventually addressing the human component as well. When all these aspects are assessed together, the result is the inclusion of the sustainability perspective in the business strategy.

As of today, there are some standards that can be considered cornerstones in the field due to their completeness, extension and broad adoption, but a common characteristic to all of them, is that they depend on the underlying priorities of those who developed them. In fact, theories such as the Lean Manufacture (Shingo and Dillon,1989), for example, prioritize production efficiency over social aspects of the company performance, the Kaizen (or Continuous Improvement method) highlights also the need for proper communication and involvement within the company as a winning factor (Garza-Reyes et al., 2016), and the Taskforce for Climate-related Financial Disclosure (TCFD) guidelines (TCFD, 2017), keep at their core the economic perspective bound to Greenhouse Gasses (GHG) emission reduction, and so on. The idea at the base of this literature review and classification was to compare tools and give a more complete picture of the possible strategies to promote sustainability integration to the business management. The foundational idea at the base of sustainability for company management is that it is a multifaceted concept that is mostly expressed through the "Triple Bottom Line" principle, as it integrates economic aspects with the environmental and social dimensions, sometimes referred as the Triple P framework: People,

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Planet and Profit (Elkington, 1994, 1998) and that it has to fit inside the "Planetary Boundaries" as described by Chen et al. (2021).

This framework created in this research work analyses which are the overarching parameters and aspects that need to be monitored and integrated by companies, which more focused metrics are more frequently adopted, and introduces the identified gaps and difficulties with carrying out such assessments and following through with the improvement work. Prior to the actual evaluation, it was important to highlight the relationship between sustainability and the circular economy (CE), which can be considered as a sustainability-oriented industrial economy (Ghisellini et al., 2016). In particular, the introduction of CE on an industrial scale is often achieved by the adoption of several key actions aimed at improving the economic and environmental performance of spent resources and closing the loops for the valorization of wastes and their recovery into material and energy commodities (Kalmykova et al., 2017) but do not consider the social component with the same priority.

2. Materials and methods: definition of the classification framework

2.1. Literature sourcing, screening and categorization criteria

To ensure accuracy, objectivity and transparency in the research process, and obtain replicable and valid results, the authors decided to adopt a systematic literature review approach and followed the methodological guidelines proposed by Thomé et al. (2016). The general research question was: "which metrics play an important role in production sustainability?". The preliminary research on academic literature platforms like Scopus and Web of Science led, as suggested by the literature review by Pranugrahaning et al. (2021) to the need for expanding the research to the internationally recognized standards and reference documents already mentioned in the previous section.

Most of the scientific literature has been sourced basing on the keywords' combinations: environmental performances, organizational optimization methods, process efficiency, process optimization methods, smart production, social metrics, sustainability metrics, sustainable production, system thinking, and then screened by reading the abstract. In some cases, the entire document has been read to ensure clarity on the content. The material deemed useful to the framework has been collected in an Excel Spreadsheet that served as repository for the bibliographic references of the documents. Table 1 lists the screened references and how many metrics were identified for each one of them.

2.2. Structure of the classification framework

The goal of identifying meaningful metrics for sustainable production led to the adoption of the categories already mentioned and which will be described in more detail below. The scheme from Fig. 1 provides additional clarity on the structure of the classification framework.

Table 1. List of the screened references and classification

Screened references	*Type of literature source*				*Number of metrics per source*
	International standards	*Reports*	*Scientific papers*	*National standad*	
Amrina and Lutfia Vilsi (2015)			x		16
B Corp Lab (2021)	x				16
Baglieri and Fiorillo (2019)			x		26
CSR Lab (2010)		x			21
Frigerio and Matta, (2015)			x		1
Gong et al. (2019)			x		1
GRI standards 2021	x				49
Klemes (2012)			x		1
Kreitlein et al. (2015)			x		1
Li et al. (2020)			x		1
MCI (2020)	x				6
Mourtzis et al. (2012)			x		1
OECD (2011)		x			18
Pham et al. (2016)			x		1
RIVM (2018)	x				18
Sudhakara Reddy (2013)			x		1
Reich-Weiser et al. (2008)			x		3
TCFD (2017)	x				3
Thiede et al. (2012)			x		1
UNI (2021)				x	56
Wahren et al. (2015)			x		1
Winroth et al. (2017)			x		18
Zheng et al. (2021)			x		1
Total	**5**	**2**	**15**	**1**	**261**

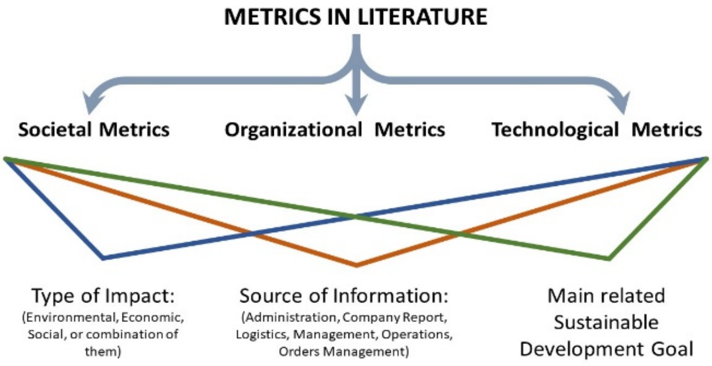

Fig. 1. Structure of the classification framework

2.2.1. Macro categories: Societal, organizational and technological metrics

The first major distinction for all the metrics identified via the literature review has been the clustering into the three following main aspects of sustainability, to capture its multifaceted nature even referring to industrial production systems:

- societal metrics - revolving around the human sphere,
- organizational metrics - influencing the economic, financial and organizational performance of the company,
- technological metrics – linked to the technical aspects of the production process, including the environmental aspects of the organization's activity.

2.2.2. Type of impact: Environmental, economic and social impact

Seemingly in opposition to what stated in the previous paragraph, the metrics involved in the performance assessment and improvement of a business practice can still be labelled basing on the conventional dimensions of sustainability and combination of them. Therefore, every metric has been sorted also based on the following sustainability impact categories: All; Economic; Environmental; Environmental and Economic; Environmental and Social; Social; Social and Economic.

The distinction between impacting the overall sustainability performance of the company, or combination of the three main dimensions: economic, environmental and social, becomes quite relevant to convey the cross-dimensional reach of several parameters and how sustainability should be approached holistically.

2.2.3. Source of information at company level

The source of information allows companies to understand where to source the data for that metric and which company figure should oversee its monitoring and evaluation. Therefore, according to Baglieri and Fiorillo (2019), the following categories have been identified to support the data sourcing:

- *Administration*: sources linked to the definition of policies, directives and objectives, planning and organizational functions.
- *Company Report*: every enterprise accumulates numerical data and information through the accounting records of purchases, sales, employees, banks and so on.
- *Logistics*: Company logistics consists of inbound logistics, internal production logistics, and outbound (distribution) logistics of produced goods.
- *Management*: sources that are linked to the management of the company.
- *Operations:* Business operations refer to the activities that businesses undertake daily to increase the value of the business and make a profit.
- *Orders Management:* Order management starts when a customer places an order and ends once they have received the package or service. It allows a company to coordinate the entire order fulfilment process.

2.2.4. Impact on the Agenda 2030

In terms of sustainability, the fundamental reference sources are the Agenda 2030 (UN, 2015) and the 17 SDGs (SDG, 2015) and related targets which create the roadmap to achieve sustainable development in a holistic and streamlined way. The goals encompass every aspect of sustainable development and therefore can be implemented by single individuals, companies, communities, and even whole countries. Hence, the relationship with the goals is being conjugated in many different forms and becoming paramount in every business strategy and performance assessment. It is important to mention that not all metrics assessed in this work are linked to the expected SDG and to the same Global Reporting Initiative (GRI) Standard as it is generally understood by the definition in the references (GSSB, 2021; SDG, 2015). The classification presented in this work is based on the authors' understanding of the link between the metric and the primarily affected SDG from an industrial perspective.

When it comes to businesses though, not all goals are relevant to the good stewardship of the company as: SDG 1 – No Poverty, SGD2 – Zero Hunger, SDG4 – Quality Education, SDG7 – Affordable and Clean Energy, and SDG17 – Partnership for the Goals, are not directly linked to the production process or service providing. Nevertheless, actions to support the achievement of those goals can still be carried out, and are encouraged, for brand positioning, reputation and for the higher reason to promote and support the wellbeing of the community. The goals identified in the literature review are: SDG 03: Good Health and Well-being; SDG 05: Gender Equality; SDG 06: Clean Water and Sanitation; SDG 08: Decent Work and Economic Growth; SDG 09: Industry, Innovation and Infrastructure; SDG 10: Reduced Inequalities; SDG 11: Sustainable Cities and Communities; SDG 12: Responsible Consumption and Production; SDG 13: Climate Change; SDG 14: Life Below Water; SDG 15: Life on Land; SDG 16: Peace, Justice and Strong Institutions.

One note on SDG 4 is that it refers to education as in the right of every child in the world to receive proper education regardless of discriminations. Child labour, minorities exploitation and work formation/training are included in SDG 8.

3. Data analysis and remarks on the findings

3.1. Societal, organizational and technological metrics

As described in the previous section, the metrics found in the literature have been screened and grouped into the three categories: Societal, Organizational and Technological. This resulted in a total of 261 metrics divided as in Fig. 2.

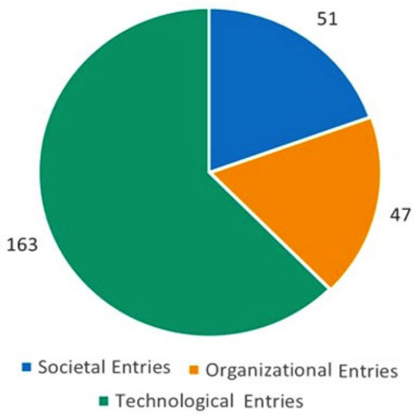

Fig. 2. Clustering of the metrics

This preliminary analysis is already an indication of the direction, or perspective, in which research has moved so far, as the disproportion of technically oriented indicators compared to the other macro-categories shows that technical (and environmental) parameters are both easier to monitor and improve, but at the same time a legacy to the industrial production mindset of the XX century where production volumes, times and profit were the only relevant metrics.

Nevertheless, it is possible to notice the clear low number of metrics collected in the organizational cluster and the societal metrics. The authors would like to go deeper into the research and analyze possible implementations that in the literature are often forgotten or omitted when considering productive sustainability due to a lower attention to human value.

3.2. Environmental, economic and social impact

An additional confirmation of the significant gap in representation that can be found between societal, organizational and technological metrics can be observed by looking at the distribution of indicators based on the three core dimensions of sustainability (Fig. 3). “Environmental and Economic” indicators are preponderant compared to the others, but this can be due to many of those indicators influencing the environmental performances of the company and require an economic investment or are supported by economic drivers like tax cuts or sanctions for missed reduction targets.

The paramount example is that CO_2 emissions reduction strategies are beneficial to the environment but to be implemented can require significant investment from the company to upgrade equipment, streamline processes and rely to other sources of inputs like renewable energy. At the same time, carrying on with business-as-usual leads companies to incur in sanctions, poor rating, and lower profit due to the ever-increasing attention to sustainability metrics by the consumers and lawmakers.

3.3. Source of information

The “source of information” is meant to suggest to companies the right direction for collecting information, while they try to navigate how to achieve more sustainable performances in their short-term and longer-term planning. As most of the identified metrics are technical in nature, the graph below (Fig. 4) further solidifies the observation that technological metrics are mainly related to the actual production process (operational source), while on the contrary, organizational and societal metrics can be directed to Company Reports, Operations and Administration sources.

The “company report” category refers to any sort of report that the business produces every year, regardless of it being purely internal, financial, or non-financial. Several of the metrics identified in the work are also referenced in the GRI Standards, which are the internationally recognized reference for Sustainability Reports. This type of reporting document details the vision, business performance, roadmap for the coming years, and financial performance of a business, often comparing them to the sustainable development goals of the 2030 Agenda (as described in section 3.4).

3.4. Impact on the Agenda 2030

Figure 5 shows how each one of the mapped-out metrics relates to the SDGs of the Agenda 2030. The one indicated in the graph is the main goal impacted by the indicator and as shown by the metrics distribution, the most prominent ones are SDG 12: Responsible Production and Consumption, SDG 13: Climate Change and SDG 8: Decent work and economic growth. While this is not surprising giving that the focus of the framework is on business sustainability performances, it shows the cross-dimensional nature of the SDGs as SDG 12 and SDG 9: Industry, Innovation and Infrastructure are found in all three macro-categories. The interdimensional nature of the SDGs is also shown from the consideration that although the graph shows the most prominent relationship between a metric and an SDG, in most cases action on one metric affects multiple SDGs at the same time. To give an example, improving gender equality (SGD 5) and minority representations (SDG 10) at all levels of the company brings additional perspectives to the decision table and enriches the conversation.

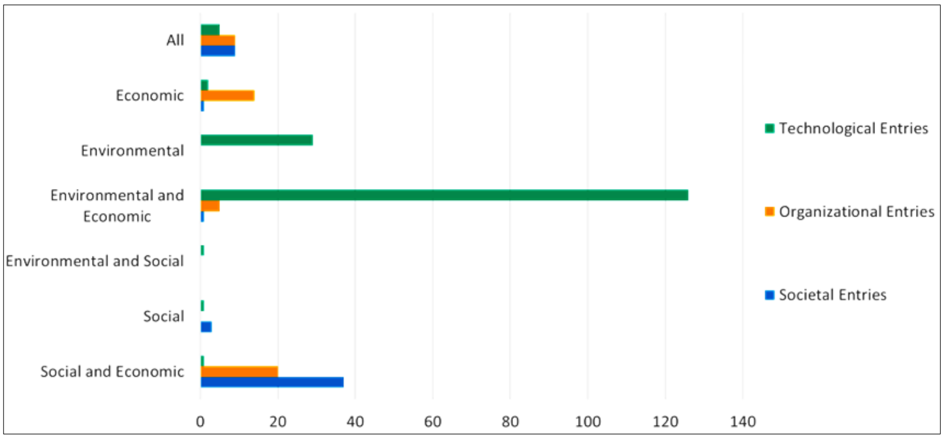

Fig. 3. Impact-based categorization referring to Triple Bottom Line

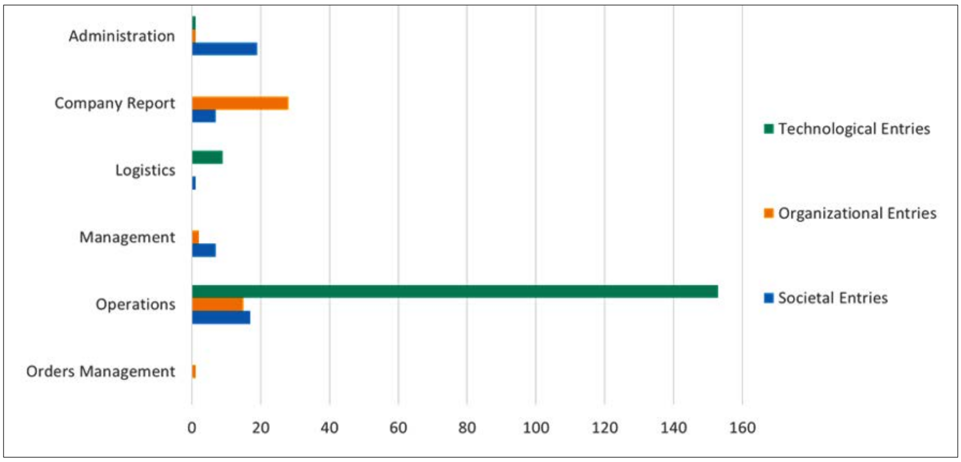

Fig. 4. Source of the metric information at company level

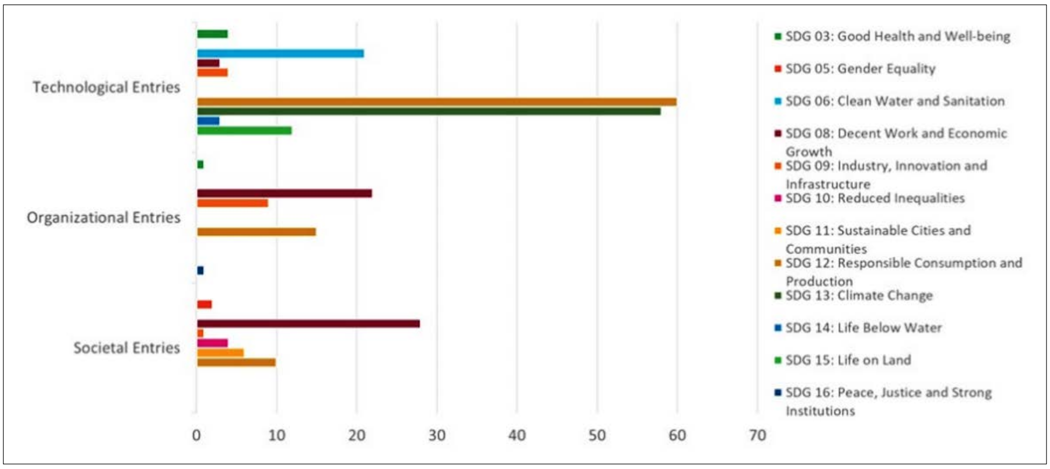

Fig. 5. Breakdown of the metric-SDG relationship

This way enabling to design better solutions for acting also on technological metrics. It is evident how some of the 2030 Agenda goals related to technology fall into SDGs related to conscious production, climate change and good health. On the contrary, organizational and societal metrics fall into similar goals often linked to the theme of decent work and economic development, conscious consumption and more responsible communities.

4. Conclusions

The research work has allowed us to reflect on the complexity of information for overall sustainability and the need for a common language at all stages of the manufacturing process for a comparable and additive outcome. In this sense, as the analyses in this paper show, the different aspects that can be linked to the same metric demonstrate how multifaceted and broad even historically established methods and metrics can be.

Furthermore, it showed how the SDGs are a pervasive and permeating aspect of our lives and that even conventional production processes should be reimagined to include them. The wealth of business-oriented scholarly work on the topic illustrates how sustainability can be approached from what is existing to completely revolutionizing a company's business model. Moreover, regardless of the size of the initial investment, integrating and promoting sustainability choices within the company or across the entire value chain pays off.

Furthermore, future developments could reflect on how companies could benefit from an industrial symbiosis by exchanging information, material and machinery and lower their environmental, social and economic impact. In this way, business performance can be effectively improved, future-proofing companies for unforeseen or impending changes as the world moves toward a more circular and fair economy.

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Tenebrio molitor: INNOVATIVE TOOL FOR FOOD LOSS AND WASTE VALORIZATION AND BIOPOLYMERS RECOVERY

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Abstract

Modern society is faced with a series of important challenges for its very survival, related to climate change, resource depletion, population increase, soil scarcity, and environmental pollution. It is now clear that the linear economy model, adopted up to now mainly by the most industrialised countries, is no longer sustainable, and urgent alternative solutions are required. The insects, and in particular Tenebrio molitor (TM), are a valid food alternative, and they can be used to valorise and reduce food loss and waste (FLW) in the Circular Economy perspective, converting FLW into high-value products including food, feed, pharmaceuticals, biomaterials, and lubricants. Furthermore, TM rearing waste provides fertilisers and bioproducts, such as chitin and chitosan, as well as biofuels and biochar. TM and its gut microbiota also represent a valid tool for plastic degradation, even though plastic pollution management using TM is quite controversial. Finally, TM can provide valuable assistance in the biological recovery of new biopolymers, such as polyhydroxyalkanoates (PHA) from plastic-producing microorganisms, (e.g. Cupriavidus necator), used as Single Cell Protein. In a circular system and following a bioeconomy approach, these microorganisms can be fed on FLW, produce PHA, and then be used as feed for mealworms to obtain PHA and, at the same time, protein biomass, as well as rearing waste (frass and exuviae) from which to obtain fertilisers for new crops and chitin/ chitosan for biomaterials.

Key words: agri-food by-products, bioplastics, circular bioeconomy, chitin and chitosan, plastic waste

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1. Introduction

Population growth is expected to reach 9.7 billion by 2050 (Worldometer, 2021). New protein sources must be exploited to cope with this population explosion, thus increasing overall food production by approximately 50-60% compared to world production in 2005/2007 (UN, 2019). Food systems throughout the supply chain are responsible for 34% of global greenhouse gas (GHG) emissions (Crippa et al., 2021). According to IPCC (2021), which examined different emission scenarios from 2015 to 2100, the global surface temperature will continue to increase until at least 2050, leading to global warming. This plight risks being aggravated by the increase in food production. Additional global warming can further exacerbate desertification, land degradation, sea-level rise, extreme weather events and natural disasters, thus exacerbating food insecurity conditions, malnutrition, and the gap between the richest and the poorest (FAO, 2016). In addition, the food system generates around 1.3 billion tons of food loss and waste (FLW) per year along the food chain (corresponding to one-third of world food production). Globally, production, post-harvest, and consumption stages contribute to over 80% of the FLW (Xue et al., 2017).

Generating FLW has associated an annual cost of over 1000 billion dollars, along with environmental impacts, including a carbon footprint of approximately 7% of total GHG of anthropogenic origin; a land-use

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of 1.4 billion hectares; a bluewater footprint of 250 km³ (Wohner et al., 2019). On the contrary, FLW reduction contributes to food sustainability, the efficiency of the food system, and food security (FAO et al., 2019). Added to these problems is plastic pollution. The use of plastic materials increases dramatically, primarily in the packaging sector. In 2019, plastic production was 370 million tons globally and 58 million tons in Europe (Plastics Europe, 2020). Parallelly, there is a tiny improvement in the management of plastic waste. Only 9% of plastic is recycled worldwide (UNEP, 2018). Plastic waste is now in the most distant and extreme environments and enters the food chain through marine fauna as microplastics (Cverenkárová et al., 2021). There is no doubt that plastic waste represents a great opportunity in terms of reuse and recycling from a circular perspective. Furthermore, plastic is now undeniably a necessary and irreplaceable material. On the one hand, therefore, it is urgent to find sustainable systems to manage and enhance plastic waste and, on the other, to seek solutions to produce recyclable non-fossil plastics with good performance, such as polyhydroxyalkanoates (PHA) (Mazhandu et al., 2020). Concerning this dramatic scenario, which raises serious concerns for the future, it is necessary to explore every remedy available.

The mealworm beetle TM represents an alternative source of high-quality proteins for food and feed. It has been recently authorized as the first insect as Novel Food in Europe (Commission Implementing Regulation 2021/882) and approved for feed in aquaculture, pets, pigs and poultry (European Commission Regulation 2017/893). Compared to meat livestock, TM has a high feed conversion ratio and elevated growth rate. TM production emits fewer GHG and requires less water and land (Oonincx et al., 2010; Oonincx and de Boer, 2012). However, the large-scale production of TM larvae (TML) is not yet fully sustainable and uncompetitive compared to conventional livestock. Moreover, the actual product of interest for both food and feed is TML flour/meal, which needs an additional energy-intensive phase for transforming the larvae into flour (FAO, 2021; Maillard et al., 2018). In this way, the environmental and economic costs of TML meals are not competitive compared to other protein meals like soybean meals or fishmeal (Le Féon et al., 2019).

The use of agri-food waste to feed TML increases its sustainability and, at the same time, help manage a great deal of FLW. TM rearing efficiently converts FLW into a wide range of high-value products, such as food, feed, fertilizers, chitin, chitosan, biomaterials, biofuels (Cadinu et al., 2020, Moruzzo et al., 2021a). TM degrades many substrates (Derler et al., 2021) and even plastics due to its highly differentiated microbiota (Przemieniecki et al., 2020). Furthermore, TM can release PHA by lysis of the cell walls of microorganisms by feeding on them (Murugan et al., 2016).

Figure 1 shows the role of TM in the circular bioeconomy. TM valorises FLW and plastic waste and recovers biopolymers from microorganisms. The exploitation of products deriving from TM rearing waste (chitin, fertilizers etc.) can improve production cost-effectiveness.

In this review, we examine the state-of-the-art relating to the use of TM in a circular bioeconomy perspective to solve the environmental and socio-economic problems described so far. We treat the valorization of FLW using TM and examine the different agro-industrial substrates studied to rear this insect. We critically discuss the ability of TM, along with its gut microbiota, to biodegrade plastic waste, on the one hand, and recover PHA biologically and cost-effectively, on the other. Finally, we explore the great potential of TM rearing waste (frass and exuvia) to have fertilizers and chitin/chitosan, respectively.

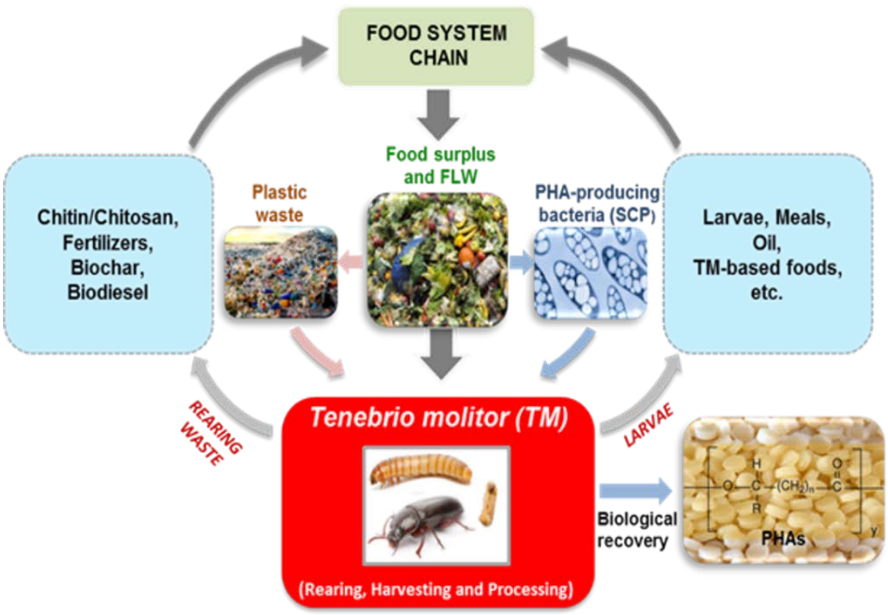

Fig. 1. TM in the Circular Bioeconomy

2. Valorizing and reducing food loss and waste by TM

As demonstrated by several authors, TM can transform low-value substrates into plenty of products with application in many sectors such as food, feed and biomaterials (Errico et al., 2021; Moruzzo et al., 2021a; Ojha et al., 2020). For this capacity, in recent times, TM has become particularly interesting from a circular economy perspective to achieve the zero-waste goal and close the loop of the food value chain (Cadinu et al., 2020; Sangiorgio et al., 2021b).

The use of FLW adds value to poor and environmentally impacting substrates and make TM rearing more sustainable. Indeed, although the TM rearing meets many of the Sustainable Development Goals, it is not yet entirely advantageous either in environmental or economic terms, especially on a large scale (Moruzzo et al., 2021b). Crop residues and food processing by-products are valuable and cheap feed resources (Ravi et al., 2020; Rovai et al., 2021).

The choice and management of the substrate are essential, especially if you want to use TM as food or feed. In this case, Regulation (EU) no. 68/2013 on the catalogue of feed materials requires that insects cannot feed on food contaminated by pathogens, as well as on animal by-products or catering waste. In addition, the use of food by-products must consider the potential contamination of waste with heavy metals, mycotoxins, pesticides or other hazardous materials (FAO, 2021). Moreover, the seasonality, transport, and storage of the substrate chosen for TM rearing are crucial aspects to consider (Sangiorgio et al., 2020). Finally, the choice of feed substrates should not cause competition with other animal productions from a food system sustainability perspective (Pinotti and Ottoboni, 2021). However, since TM rearing is conducted in controlled indoor conditions - requiring no specific geographic or natural environmental conditions - it can be placed close to substrate suppliers, thus reducing handling and costs to a minimum (Mancini et al., 2019). The research evaluates improvements in sustainability and cost-effectiveness of TM biomass production by new feed resources exploration. (Rumbos et al., 2020; Van Peer et al., 2021). Growth parameters, feed efficiency indicators and the nutritional value of TML are some of the parameters used to study the ability of TML to eat different substrates. As extensively reported in a previous review (Sangiorgio et al., 2021b), many feeding substrates have been studied, alone or in a mixture in different proportions:

- several fresh plant materials and fruit matrices, such as cabbages, carrots, oranges, apricots (Liu et al., 2020; Riudavets et al., 2020);
- various spent mushroom substrates such as those of *Pleurotus eryngii*, *Flammulina velutipes* and *Lentinula edodes* (Kim et al., 2014; Li et al., 2020);
- by-products of alcoholic beverage production, such as distillers dried grain, brewer's spent grain and beer yeast (Mattioli et al., 2021; Melis et al., 2019; Zhang et al., 2019);
- fruit and vegetable residues, such as peels of watermelon, banana, potato, carrot pomace, and beet molasses (Oonincx et al., 2015; Rovai et al., 2021; Tan et al., 2018);
- by-products from vegetable oil extraction, i.e. soybean meal, rapeseed meal, olive pomace (Rumbos et al., 2020; Ruschioni et al., 2020; Zhang et al., 2019);
- leftovers of bread and cookies (Mancini et al., 2019; Mattioli et al., 2021);
- cereal substrates (flour, non-flour and mill by-products) and legume flours (Rumbos et al., 2020; Tan et al., 2018);
- seed cleaning process of cereals and legumes (Riudavets et al., 2020; Rumbos et al., 2021);
- crop residues rich in lignocellulose, such as maize stover, rice bran and husk, straw of rice, corn and wheat (Stull et al., 2019; Yang et al., 2019b);
- various wastes of animal origin, such as hatchery waste, fish discards and even cattle and horse manure (Harsányi et al., 2020; Riudavets et al., 2020; Romero-Lorente et al., 2022).

Overall, the results of these studies indicate that larvae fed on nutrient-poor substrates show a reduced protein content but a higher fat fraction (Harsányi et al., 2020). In addition, high-protein diets lead to shorter development times and higher larval survival (Oonincx et al., 2015). However, several research studies have shown that TM can exploit the protein fraction of low protein substrates such as maize stover, concentrating it in its body biomass (Stull et al., 2019). Some plant by-products have a high level of defensive chemicals that can make them resistant to bioconversion based on insects; this is the case of wine and olive pomace, coffee and chocolate residues (Ruschioni et al., 2020). In these cases, selective breeding can be an effective tool to have adapted insects that, by detoxifying these chemicals, can feed on this kind of by-product (Jensen et al., 2017). Unfortunately, selective breeding focused on more efficient food waste reduction is still in its infancy and requires more funding and research.

Another way is to carry out successive conversion steps by combining two insects with different eating habits, such as TM and *Hermetia illucens* (black soldier fly), in a kind of multi-insect cascading biorefinery (Fig. 2). Pre-digestion of lignocellulosic-rich substrates with TM improved growth performance in the black soldier fly and led to a higher biomass production rate (Wang et al., 2017).

As pointed out by Derler et al. (2021), it is necessary to investigate the relationship between the protein content of the substrates and the growth performance/nutritional profile of TM and proceed with the standardization of TM rearing conditions to have comparable results. However, using FLW to make TM farming more sustainable has several limitations.

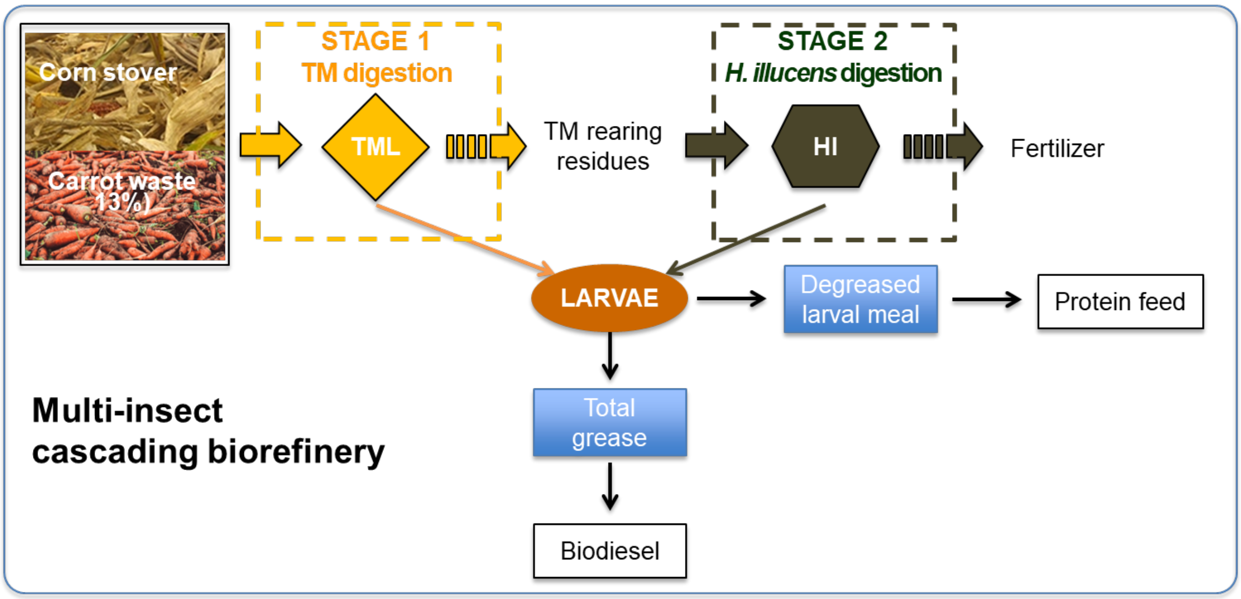

Fig. 2. Multi-insect cascading biorefinery (adapted from Wang et al., 2017)

Agro-industrial waste must not be affected by biological and chemical contaminations (e.g. pathogens, toxins, heavy metals). FLW must be low priced and of good quality. There must be no competition for the use of FLW between TM rearing and those of other animals. Finally, it is necessary to consider the seasonality of some agro-residues, together with the logistics and conservation systems for their management (Sangiorgio et al., 2021b)

Nevertheless, in the face of various limitations, there are various relevant advantages and opportunities in the approach of FLW valorization using TM. Agro-industrial waste is in large quantities and varieties. There is a large basin whence to select the optimal diet for TM growth. Furthermore, the peculiar characteristics of TM rearing allow its location close to the waste producer to reduce the costs of logistics and storage systems (Mancini et al., 2019).

Finally, the regulatory opening to TM-based products as novel food and as feed for pigs and poultry will increase the demand for TML production. Consequently, the research for beneficial and alternative feeding substrates for TM will grow.

3. Plastic degradation

The problem caused by oil-based plastics when they become waste is, as we all know, enormous. Regardless of these plastics use "in life" (most of them used for packaging), we observe that more than half (5 billion tons) of the plastics produced since 1950 by 2017 (no less than 9.2 billion tons) has become a waste that persists and exists on our planet (Plastic Atlas, 2019).

The need for new strategies to face the global plastic pollution concern is one of the most pressing problems for our society. In this perspective, entomoremediation, i.e. the use of insects for plastics degradation, has opened new opportunities to solve the problem of plastic pollution (Bulak et al., 2021).

In this article, we mainly review the scientific literature of the last few years on this topic based on a thorough previous work (Sangiorgio et al., 2021a). Several insects are capable of decomposing resistant lignocellulosic matrices (e.g. cardboard) and many plastics, such as polystyrene (PS), polyethylene (PE), polypropylene (PP) and polyvinyl chloride (PVC). Among these, TM is an effective solution for the bioconversion of plastics due to its intestinal microbiota, as demonstrated for the first time by Yang et al. in 2015. These authors established the role of the intestinal microbiota and a tight relationship between the bacterial strains present in the gut of larvae and their ability to degrade plastics. The biodegradation and subsequent mineralization of plastics occur starting from their chewing by the larvae. The shredded plastic then comes into contact with intestinal microorganisms and extracellular enzymes housed in the larval gut. This contact causes the decomposition of the long-chain molecules into lower molecular weight metabolites (Yang et al., 2015). TM can carry out plastic biodegradation through biodeterioration, bio-fragmentation, assimilation, and mineralization stages. The activity of its intestinal flora is confirmed by a recent review article on the currently available microbial technologies for degrading different types of plastics (Jadaun et al., 2022).

There is a mutually beneficial symbiotic relationship between the plastic-eating insect larvae and their intestinal microorganisms. To this aim, the larvae of various insects, including TM, were compared to determine their feeding capacities and survival rates, analyze the changes in the characteristics of their productions and determine the changes in the intestinal microbiota. According to this research, feeding on PS can change gut microbiota, causing the enrichment of the microorganisms responsible for plastic degradation. For TM, *Enterococcus*, *Enterobacteriaceae*, *Escherichia-Shigella*, and *Lactococcus* were the main responsible (Jiang et al., 2021).

Bulak et al. (2021) confirmed the ability of TM to degrade plastics (e.g. PS, two types of PU and PE), which, after 58 days of testing, showed a mass reduction efficiency of 46.5%, 41.0%, 53.2% and 69.7%, respectively (with a dose of 0.0052 g/larva for each type of plastic). According to these authors, also the adult stage of the insect (imago), in addition to the larva, can "eat" plastic (Bulak et al., 2021). However, the research by Palmer et al. (2022) showed that larvae are 50 times more capable of digesting expanded polystyrene (EPS) than adults. The same authors also highlighted how the environmental farming conditions represent a decisive factor influencing the degradation potential of TM. This potential is indeed conditioned by the type of farming substrate, the plastic pre-treatments and any additional nutrients eventually provided (Palmer et al., 2022).

TM's ability to degrade plastics has been extended to different polymers: rubber of tires (Aboelkheir et al., 2019), powder from fire extinguishers (Brandon et al., 2020), plastic waste present in electrical and electronic equipment. In this last case, TM proved to be less performing than G. mellonella larvae in degrading polymers (Zhu et al., 2022). Rigid PVC microplastic powders, used as the sole diet, were also degraded by TML, which reduced polymer weight, number, and size (33.4%, 32.8%, and 36.4%, respectively). Good depolymerization but limited mineralization of PVC was also observed. About 34.6% of residual PVC polymer and a small fraction of chloride (only about 2.9% of ingested PVC) were found in the excretion (Peng et al. 2020). Poor differences in the plastic-degrading ability of TM have also been observed concerning the geographic origin for PS (Yang et al., 2018) and confirmed for PS and low-density polyethylene (LDPE), but not for polyvinyl chloride (PVC), which is less easy to digest (Wu et al., 2019).

Several studies have provided a counter-proof of the action performed by intestinal microorganisms through the use of antibiotics (by suppression tests mainly with gentamicin) that have inhibited the degradation capacity (Yang et al., 2021). In this perspective, the study carried out by Tsochatzis et al. (2021) compared the adaptation of the intestinal microbiota of TM in response to different dietary strategies and the formation of degradation compounds (monomers, oligomers). Using diets with different bran/PS content (ratios 4/1 and 20/1), it was shown that the diet with a low bran/PS ratio leads to better results from the point of view of plastic degradation (Tsochatzis et al., 2021). Similarly, the addition of wheat bran to the diet of TM increases its degradation capacity of plastic (Jaduan et al., 2022). Another observed effect is the larvae body-weight loss when fed for a long time with only plastic.

If the plastic-based meal is supplemented with conventional food for larvae (bran, usually), a marked improvement in the degradation performance of plastics is observed: insects, thanks to the nutritional supply guaranteed by the food, attack plastics better. Obviously, by increasing too much the food/plastic ratio, the effect is lost (Urbanek et al., 2020; Wu et al., 2019). Gan et al. (2021) have reached similar conclusions. They confirm that the addition of conventional food to larvae diets causes an improvement rather than an antagonism in the PS degradation. Moreover, their frass can be used as a fertiliser in agriculture. Finally, the larvae fed on these substrates can be used for food and feed (mainly poultry and fish). However, these researchers question the use of insects is quite effective for the degradation of plastics and whether this can be considered a scalable natural solution (Gan et al., 2021). In their research on the polylactide (PLA) biodegradation using TM, Peng et al. (2021) verified that PLA-bran mixtures (10%, 20%, 30% and 50% PLA, w/w) lead to higher survival and lower cannibalism rates. Based on the results of their study and the literature data, the authors proposed a sustainable approach for PLA. The production comes from biological sources (agriculture), the waste PLA supports the production of proteins (TML) and TM rearing used for PLA demolition produces residues (frass) to exploit as a soil fertilizer for agriculture (Peng et al., 2021). Further authors support this approach (Lou et al., 2021).

From this observation derives an opportunity for the closure of the bioeconomic circle: to use FLW as co-feeding of plastics. This possibility can make the process more favorable and achieve two goals, i.e. the valorization of waste and the degradation of plastic (Sangiorgio et al., 2021a). The possibility of using TM for the bioremediation of plastics presents some critical issues. The first fact negatively affecting this possibility is the excessive costs to raise a large number of insects needed for the scaling-up: considering a degradative capacity of 0.22 mg of PE/larva/day, it takes 10 tonnes of larvae to treat 1 tonne of plastic (Billen et al., 2020). Khan et al. (2021) investigate the functionality of TM plastic degradation using much lower degradation rates than others researchers and not considering other compounds (as proteins) produced from insect farming. Despite a positive evaluation they asserted, Khan et al. state that, for effective exploitation of plastic waste, it is necessary a fast conversion of plastic into biomass and by-products, and the absence of microplastics or contaminants into the biomass, not to have environmental and safety problems (Khan et al., 2021). The justified concern about the safety of products derived from insects fed with plastics is, indeed, a problem to be explored. In this perspective, Zielińska et al. (2021) have highlighted that the consumption and degradation of polystyrene do not seem to influence the state of health of insects. However, at the same time, they admit the need for further analyses to confirm the absence of toxicity in the plastic degrading insects and so allow their use safe in animal or human nutrition.

It is now recognized that the key to plastic biodegradation is the larvae intestinal microbiome. This potential needs to be exploited to upgrade it to full-scale use. For this reason, further research is needed to replicate intestinal processes and the conditions in which they occur to fully understand the synergistic actions between the digestive system of larvae and microbial metabolism and, finally, better characterise the enzymatic systems involved in the biodegradation of plastic. These results could inspire a new biotechnological approach to solve the problem of plastic waste and microplastic pollution (Pivato et al., 2022).

4. PHA recovery

Some microorganisms (e.g. *Aeromonas, Azotobacter, Cupriavidus, Clostridium, Methylobacterium, Ralstonia, Pseudomonas, Syntrophomonas*, etc.) can produce PHA as an energy reserve, mainly when they suffer growth limitations (Khan et al., 2021). PHA represents a group of natural biodegradable polyesters used for degradable bioplastics production to replace many petroleum-based plastics. The global PHA market value has been estimated at $ 215.2 million in 2020 and $ 327.3 million by 2026 (360 Research Reports, 2020). This review examines the TM contribution to PHA recovery.

The use of PHA for bioplastics production has an effective potential for further development, but some elements limit their use. Among these, one of the main limitations is the high cost of production, particularly for the lysis of the microbial cells that synthesise it and the subsequent recovery from the matrix (Li et al., 2016). Usually, the recovery of PHA is carried out through the use of solvents (chloroform, acetone, methylene chloride) or with enzymatic digestion, with heavy environmental and safety costs (Bhola et al., 2021; Ong et al., 2018a).

The use of small animals has been proved to avoid these systems. Small animals feed on cells containing freeze-dried PHA, allowing their intestine system to digest the cells and release the PHA granules with their faeces (Murugan et al., 2016). The animal model commonly used is the murine one. In recent years, insects have been preferred to rats, as they perform the same functions but require minimal resources and space and show breeding facilitation. Insects are currently used as a biorefinery for PHA recovery principally where highly pure PHA is not required (Ong et al. 2018b). In particular, the PHA recovery by TML is considered one of the best available techniques.

Even the bacterial lysis method with bacteriophages, frequently used to free PHA from cellular deposition, reveals strong criticalities compared to the use of rats or TM (Kourmentza et al., 2017). In fact, compared to bacteriophage-mediated lysis, the digestive system of TM is considered more efficient, both for ecology and for economy, downstream strategy (Haddadi et al., 2019). The comparison of the qualitative characteristics of the PHA granules obtained from TM's biological recovery with those produced with conventional methods - carried out with TEM and SEM micrographic techniques- reveals that the PHA TM-produced granules retain their sphericity and morphological traits (Ong et al. 2018a). These researchers have also shown that bacterial cells are easily consumed by TML. PHA recovery by TM fed with freeze-dried *Cupriavidus necator* cells appears the best modality since TM larvae digest cells but not PHA granules. A simple treatment with water, detergent and heat is sufficient for the purification of the PHA granules from the excretion. The entire process does not cause the loss or the morphological deformations of the molecules, as demonstrated by electron microscopy and dynamic light scattering measurements (Murugan et al., 2016).

Supplementing agri-food by-products can increase the sustainability of the TM biorefinery system for PHA recovery. Moreover, if the PHA-producing microorganisms feed on FLW, they turn a problem into a resource. Once freeze-dried, microorganisms can become a single-cell protein source and feed for TML, which, in turn, can recover PHA and release it in their frass (360 Research Reports, 2020; Zainab-L and Sudesh, 2019). In addition to the release of PHA and providing protein biomass, the larvae produce also waste from their rearing (frass, chitin, etc.) with a very high value and different applications. The conceptual scheme of the entire circle is shown in Fig. 3 (Sangiorgio et al., 2021).

In this circular bioeconomy perspective, there are a lot of wastes that can be a carbon source for PHA-producing microorganisms. Some recent works highlight how the diversity of by-products usable for the nourishment of microorganisms is very vast, including oils and serums from different matrices (Dutt Tripathi et al., 2021; Kalia et al., 2021; Surendran et al., 2020). The efficacy of the process and the ability of TM to extract PHA from various types of bacterial cells has been confirmed using *Pseudomonas mendocin* grown for 72 hours in a medium containing liquid biodiesel waste (2% v/v). The recovered PHA by TM showed high purity and higher molecular weight than that recovered by conventional extraction with chloroform (Chee et al., 2019). Another line of research is the study of the efficiency of the recovery system using TM to reduce production costs, e.g. improving TM's consumption of PHA-containing cells. Zainab-L and Sudesh (2019) have proposed a simple washing method to reduce the level of mineral salts (deriving from the culture medium) in the lyophilised cells, thus increasing their palatability for TM. Consequently, the quantity of PHA recoverable in the frass increases with a simultaneous increase in the protein fraction (79%) and a reduction in the fat content (8.3%) of the larvae (Zainab-L and Sudesh, 2019).

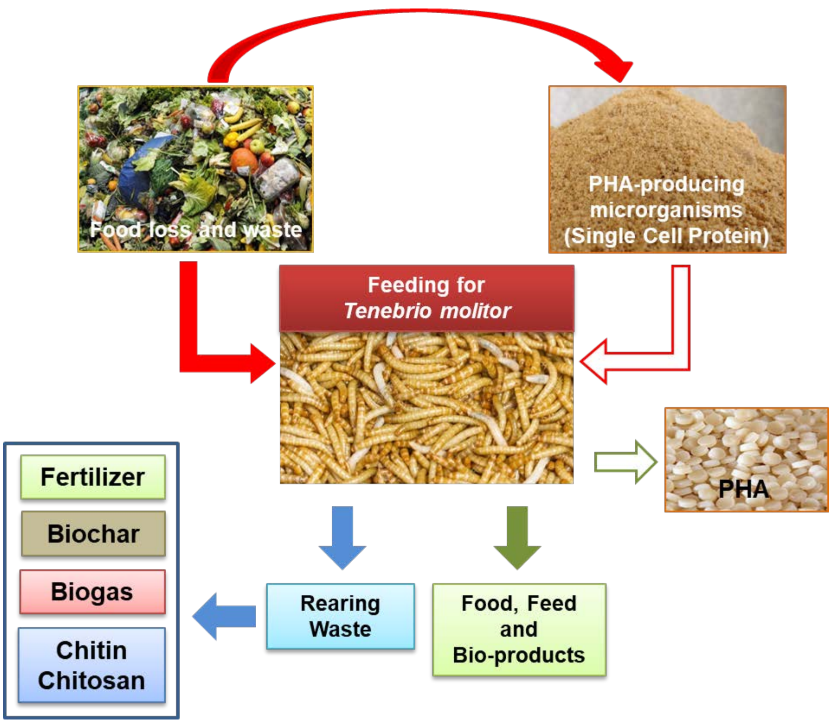

Fig. 3. TM in a circular strategy for PHA recovery, food/feed production, FLW and rearing waste valorization

5. Valorization of TM rearing waste

The TM rearing waste includes frass, dead insects, exuviae, and uneaten feed residues, commonly destined for incineration or landfill disposal. Nevertheless, to start a TM large-scale production, appropriate strategies should be made for the valorization of insect waste (Wang et al., 2017). TM frass (insect faeces) can be upcycled as fertilizing products (e.g., organic fertilizer, compost material, or soil improver) that could replace nitrogen- and phosphorus-based fertilizers obtained from conventional processes (e.g., mining and fossil-based processes). TM frass can be also converted into biogas and biochar. Instead, the TM exuviae can be exploited to obtain chitin and chitosan (Shin et al., 2019).

The global demand for products obtained from insect rearing waste is predicted to increase in the coming decades. The global markets for alternative fertilisers, chitin, and chitosan should reach, respectively, \$14.7, \$2.48, and \$21.4 billion by 2027 from \$ 4.5, \$ 1.5, and \$6.8 billion in 2019, at a compound annual growth rate (CAGR) of 14.1%, 11,3%, and 24,7% from 2020 to 2027 (Sangiorgio et al., 2021b). Therefore, setting up a large range of products from TM rearing waste can create new value chains and employment opportunities.

5.1. Potential TM frass exploiment as biofertiliser

It is possible to obtain 4 g of insect biomass and 180 g of frass and residues, respectively, from TML fed with 220 g of food. The volume of frass and residues is thus more than 40 times that of the produced insects (Poveda, 2021; Wang et al., 2017). In the perspective of large-scale production of TM, it is, therefore, necessary to valorize the large volume of insect frass produced. TM frass includes valuable macro-and micronutrients, such as N, P, K, C, S, Ca, Mn, Fe, Mo, and Mg, needed by plants for their growth. Huai et al. (2003) reported that TM frass use as an organic fertilizer increases the seed weight of beans (*Phaseolus vulgaris*) by 18%. Li et al. (2013) highlighted how aqueous extracts produced by using TM frass increase the germination of wheat (*Triticum aestivum*) seeds by 4%.

A recent study on chard plants (*Beta vulgaris* var. *cicla*) by Poveda et al. (2019) showed that the TM frass application as biofertiliser increases in these plants the chlorophyll content, the fresh weight, the length of the aerial part, and the width of the basal part of the stem. Research by Poveda et al. (2019) is the first study to report the potential use of TM frass to induce plant resistance to abiotic stresses, such as salinity, drought, and flooding, partly due to the presence of microbes acting as plant growth-promoting (PGP).

PGP-microbes exhibited several multifunctional abilities (Pattnaik et al., 2021; Yadav et al., 2017):

- N_2-fixation, and solubilization of micronutrients (phosphorus, potassium, and zinc);
- production of siderophores, phytohormone, enzymes, antagonistic substances, antibiotics, auxin, and gibberellins;
- secretion of exopolysaccharides (EPS), volatile compounds, and 1-aminocyclopropane-1-carboxylate (ACC) deaminase;
- maintenance of osmolytes and antioxidants;
- regulation of stress-responsive genes etc.

The microbiome present in TM excrement includes communities of fungi, primarily dominated by *Ascomycota*, and bacteria consisting mainly of *Firmicutes*, followed by *Proteobacteria*. The predominantly present fungi family belongs to the *Aspergillaceae*. As regards bacteria, *Streptococcaceae, Clostridiaceae, and Bacillaceae* families are prevalent. In TM frass, *Aspergillus* represents the most abundant fungi genus, while the *Bacillus*, *Lactococcus*, and *Clostridium* are the most common bacterial genera found (Poveda et al., 2019).

Several research studies have reported the beneficial effect of the *Aspergillus* genus on plants. This genus of fungi showed good phosphate solubilising ability (Bhavsar et al., 2008; Pradhan and Sukla, 2006; Richardson et al., 2002) and great potential as a biocontrol agent (Soliman et al., 2012). Among the bacteria content in TM frass, also *Bacillus* can act as a biocontrol agent (Balabel et al., 2013; Borriss, 2015; Grosu et al., 2015), as well as promote seed germination (Widnyana and Javandira, 2016), root development (Aziz et al., 2015), nutrient assimilation (Shi et al., 2014), and degrade toxic waste in soils (El-Helow et al., 2013). Some strains of the genus *Lactococcus* can mineralize and either solubilise inorganic and organic phosphate sources: such as calcium phosphate, aluminium phosphate, rock phosphate, and phytate. Furthermore, the lactic acid produced by *Lactococcus* can perform an antimicrobial activity, resulting in positive effects on plant growth indirectly (de Lacerda et al., 2016). Bacteria of the genus *Clostridium* are classified as PGP due mainly to their ability to nitrogen-fixing and gibberellin-producing (Febri Doni et al., 2014).

Moreover, some scientific research performed on insects other than TM (Poveda et al., 2019; Tanga et al., 2022) have concluded that the use of insect frass as organic fertilizer can:

- contribute nutrients to the soil, mainly nitrogen, easily assimilated by plant tissues;
- add biomolecules and PGP-microbes;
- increase tolerance to abiotic stresses and resistance to pathogens and pests thanks to different compounds and microorganisms contained in insect frass.

Then, the application of organic fertilisers instead of chemical ones can represent an environmentally sound long-term approach to sustainable agriculture (Poveda et al., 2021).

Currently, the insect as a fertilizer is not clearly defined in Regulation (EC) No 1069/2009 of the European Parliament and the Council laying down health rules on animal by-products and derived products not intended for humans, even in the consolidated version of June 2019. As a result, some EU countries classify insect frass generically as manure, allowing its use as organic fertilizer after heat treatment. By contrast, other EU countries think of insect frass as a "category 2 material", different from manure, as it does not consist only of faeces. They require previous pressure sterilization before its marketing.

In both cases, the treatments carried out on insect frass cause the loss of microorganisms supporting plant health. Therefore, it is essential to establish suitable treatment processes capable of preserving the microbiological properties of insect frass (IPIFF, 2019).

5.2. Other potential TM frass uses

Besides being used as an organic fertilizer, TM frass can also be converted into biogas - specifically biomethane - via a mesophilic anaerobic digestion process. Research studies by Bulak et al. (2020) suggested that the biomethane potentials obtained from insects rearing waste (*Hermetia illucens*, *Tenebrio molitor* and *Gryllus* spp.) are like those obtained from the most used substrates for anaerobic digestion: mink, cattle and poultry manure, fruit and vegetable waste, ryegrass, switchgrass, wheat, and sewage sludge. Thus, anaerobic digestion can be considered a new method to valorize TM frass.

Finally, other research studies have suggested another method for exploiting TM frass, such as the elaboration of biochar via an insect waste pyrolysis process. Then, biochar can remove heavy metals, including Pb (II), Cd (II), Cu (II), Zn (II) and Cr (VI) (Yang et al. 2019b).

5.3. Chitin and chitosan from insects

Chitin is an inert macromolecule composed mainly of repeating N-acetyl-D-glucosamine units $(C_8H_{13}O_5)_n$. These units are linked together by β-(1,4)-glycosidic bonds (GlcNAc, 2-acetamido-2-deoxy-D-glucopyranose). Its estimated annual production is approximately 10^{10}–10^{12} tons (Ahmed et al., 2016; Han et al. 2020; Li et al. 2019; Zainol Abidin et al., 2020), thus representing the second most abundant natural biomass after the cellulose. From a process of chitin N-deacetylation, it is generally possible to produce chitosan, a copolymer composed of β-(1→4)-linked 2-acetamido-2-deoxy-d-glucopyranose and 2-amino-2-deoxy-d-glucopyranose units (Ahmed et al., 2016).

The chitosan, discovered by Charles Rouget physiologist in 1859, is the primary chitin derivative (Maddaloni et al., 2020). Generally, three routes can be used to recover chitin and obtain chitosan: chemical, biological, and green (or physical) (Fig. 4).

Chitin and chitosan are of great commercial interest thanks to their significant characteristics, such as biocompatibility, biodegradability, low toxicity and allergenicity (Jiang et al., 2020; Maleki and Milani, 2020), and biologiocal activities, such as anti-inflammatory, antioxidant, antimicrobial, antitumor, hypolipidemic, hypocholesterolemic, anticoagulant activities etc. (Chiu et al., 2019; Kim, 2018). These macromolecules are suitable for applications in numerous fields: in agriculture, chemistry and agrochemistry, in the food, medical, pharmaceutical, cosmetic, textile and paper industries etc. (Errico et al., 2022).

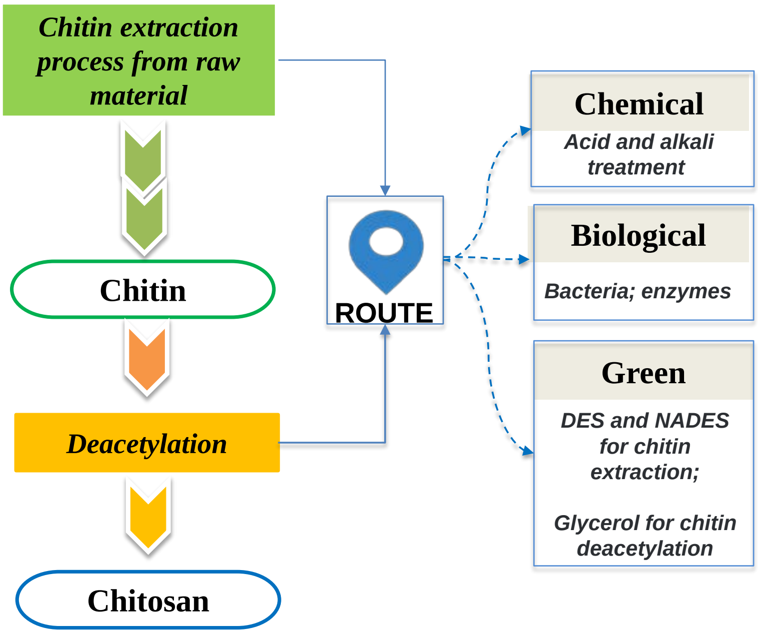

Fig. 4. Recovery processes of chitin and chitosan

The shells of marine crustaceans, such as lobsters, crabs, shrimp, krill, and crayfishes, are the primary commercial sources of chitin and chitosan. The chitin content into these animals exoskeleton is 15-40%, even if it varies widely according to the species used (quality and freshness of the shell) and the season (Morin-Crini et al., 2019). Various fungal phyla, such as Basidiomycota, Ascomycota, and Zygomycota, contain 1-15% chitin in the cell wall and represent the second chitin source (Yang et al., 2019a). Currently, insects represent a research area of considerable interest as an alternative and promising source of chitin. They produce, on average, 10-15% chitin (Costa-Neto et al., 2016).

The insects' chitin acts as a support material for: - fibrous exoskeleton cuticles; - head capsule, trachea, foregut, hindgut; - the peritrophic membrane lining the midgut lumen. (Yang et al., 2019c). It also protects insects from food abrasion and external invasion. Several scientific studies are underway relating to the extraction of chitin, and the consequent production of chitosan, from insects belonging to many different orders: Coleoptera, Diptera, Hemiptera, Hymenoptera, Lepidoptera, Odonata, Orthoptera, etc. Insects show several advantages over crustaceans:

- they are very numerous as they represent approximately 80% of the world's species (Zainol Abidin et al., 2020);
- their supply is not subject to seasonality;
- their fertility and reproductive rate are high. For this reason, insects can easily be rear.
- insect rearing facilities have been made worldwide;
- insect chitin contains less than 10% inorganic material comparing crustacean shells (20% –40%). Therefore, its extraction can be performed via a more ecological, economic, and sustainable process (Hahn et al., 2020);

Figure 5 shows the characteristics of chitin and chitosan obtained from different insects. TM chitin and chitosan have low toxicity, antimicrobial (against fungi, gram-positive and gram-negative bacteria), and anti-inflammatory properties (Shin et al., 2019; Son et al., 2021). Experimental studies by Shin et al. (2019) showed for the first time that TM chitosan has antimicrobial activity against pathogenic bacteria, such as *S. aureus*, *B. cereus*, *L. monocytogenes*, and *E. coli*. Several works of literature analyse the action mechanism of chitosan against microorganisms, as shown in Fig. 6 (Li and Zhuang, 2020; Qin et al., 2010; Wu et al., 2016).

In addition, research performed by Son et al. (2021) showed excellent TM chitosan anti-inflammatory effects in the lipopolysaccharide (LPS)-induced murine macrophage cell line. Other research studies attributed the anti-inflammatory effect to also peptides, proteins, and unsaponifiable matter of the oils from TM, and not only chitosan (Chang et al., 2019; Chou et al., 2003; Son et al., 2020). Therefore, TM chitosan can be exploited in different fields, such as in medicine, in industries of textiles and food preservation, and others. Compared to other insects, TM waste can be considered a better resource for chitin and chitosan recovery thanks to the stable supply of raw materials and low cost (El Knidri et al., 2019).

6. Conclusions

In a circular economic perspective, insects such as the mealworm *Tenebrio molitor* (TM) are valid alternatives for valorizing and reducing FLW and converting them into high-value products. At the same time, fertilizers for crops and chitin/chitosan for biomaterials can be obtained by using TM rearing waste (frass and exuviae).

Order	Matrix /sources Species	Characteristics	References
Coleoptera	*Tenebrio molitor, Zophobas morio, Allomyrina dichotoma*	Low-toxicity	Shin et al., 2019
Coleoptera	*Holotrichia parallela*	Biocompatibility Biodegradability Non-antigenicity	Liu et al., 2012
Coleoptera	*Omophlus sp., Melolontha sp.*	Adsorbable	Kaya et al., 2016
Coleoptera	*Tenebrio molitor*	Anti-inflammatory	Son et al, 2021
Coleoptera	*Tenebrio molitor, Zophobas morio, Allomyrina dichotoma*	Antimicrobial (antibacterial, antifungal)	Shin et al., 2019
Dictyoptera	*Blattella germanica*		Basseri et al., 2019
Coleopter Orthopter Diptera	*Zophobas morio, Pterophylla beltrani, Chrysomya megacephala*	Antioxidant	Soon et al., 2018 Torres-Castillo et al., 2015 Song et al. , 2013
Diptera	*Musca domestica, Lucilia sericata, Chrysomya albiceps*	Antitumoral	Hasaballah et al., 2019
Orthoptera	*Schistocerca gregaria*	Wound healing	Marei et al., 2016
Lepidoptera	*Clanis bilineata*	Antiageing Hypolipidemic	Wu et al., 2011 Xia et al., 2013

Fig. 5. Characteristics of chitin and chitosan from different insects

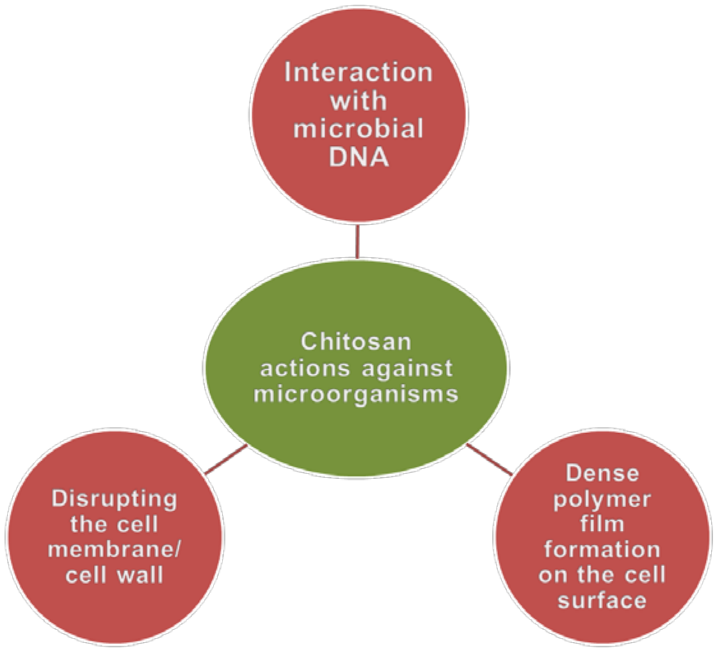

Fig. 6. Some action mechanisms of chitosan against microorganisms

The problem of plastic degradation is undoubtedly strongly much felt, and public authorities are becoming increasingly sensitive to the subject. The use of TM to degrade various types of plastics is becoming increasingly popular in the scientific literature. However, managing plastic pollution with TM does not seem to be a viable option. There are very critical authors about it. On the other hand, TM is still an insect with many interesting characteristics. It is, therefore, desirable to have more studies to highlight other TM capabilities, perhaps still unknown or little known, which can allow TM use in this sector, possibly also in combination with or in support of other solutions. For example, TM microbiota offers a valuable source of plastic-degrading microorganisms and might be exploited for this purpose in next future.

On the contrary, TM proves to be an effective and advantageous means to recover new biopolymers such as PHA from plastic-producing microorganisms. This fact could make it very interesting in the bioplastic sector.

However, in addition to the great potential, there are criticalities. TM must be produced on a large scale to meet protein needs and manage the problems of plastics and bioplastics. Unfortunately, TM industrial rearing is not yet economically and environmentally competitive.

A possible solution is to use FLW as a feed (or as a co-feed in case of plastic degradation) to reduce economic and environmental costs and, at the same time, to valorize worthless waste that represents a problem/cost. Closing the loops is another way: exploiting the waste from TM rearing and the wide range of bioproducts obtainable from the entire TM supply chain can give more value and make TM rearing advantageous.

Finally, the exploitation of TM-based products, in a sort of "entomo-refinery", could ensure the creation of new value chains and employment opportunities. Even if a lot has already been written about it over the years, TM is probably an insect that can still reserve many surprises and constitute a valid resource to be used in the best ways.

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Tenebrio molitor AS A NEW PROMISING ALTERNATIVE IN THE PRODUCTION OF FEED AND FOOD

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Abstract

The global population is growing and the ever-increasing need for proteins from sustainable sources requires urgent actions. The insects represent an alternative solution for several reasons: their nutritional profile is comparable to that of meat from other meat livestock; they can be easily and sustainably reared due to high fertility and reproductive rate; insect rearing facilities can be realized everywhere worldwide; reared insects' availability is not subjected to seasonality; they can grow on low-value substrates such as agri-food by-products. Among these good-to-eat insects, *Tenebrio molitor* (TM) is gaining rising attention from academia and the business world, also in the light of the recent favourable opinion of EFSA and the even more recent approval by the European Commission for the use of mealworms as a Novel Food.

Despite the enormous potential of TM, some aspects related to the impacts on human health have yet to be analysed and some regulatory, psychological and cultural barriers have yet to be overcome in the Western countries. On the other hand, the feed production from TM larvae will be more significantly promoted, since TM feed, already used in Europe for pets and aquaculture, has been approved for monogastric terrestrial animals and poultry at the end of 2021.

Key words: alternative protein sources, circular bioeconomy, edible insects, food safety, *Tenebrio molitor* rearing

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1. Introduction

The demand for more food connected to the increase in the planet population places the world of research in front of a fatal challenge. Indeed, it is necessary to limit the negative impacts on the environment and climate generated by the conventional food production system and, at the same time, ensure an increase in the availability of healthy and nutritionally balanced foods. Therefore, it is necessary to stop the present unsustainable productions and frame the new sources of nutrients, especially proteins, in a sustainable circular economy perspective. The new strategies implemented to meet this challenge consider the use of insects as one of the most promising opportunities due to their peculiar characteristics that make them suitable for the role of alternative sources of proteins and other valuable substances (Ordoñez-Araque and Egas-Montenegro, 2021). In this context, *Tenebrio molitor* (TM) can represent a very interesting and promising alternative.

From this point of view, 2021 can be considered the year of TM, a beetle of the Tenebrionidae family. It was the first insect approved by the European Commission (EC) for human consumption, in June 2021, after receiving the favourable opinion of EFSA in January of the same year (EC, 2021a; EFSA NDA, 2021). Europe's interest in insects as alternative sources of protein is demonstrated by the subsequent approval of the

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Locusta migratoria in November 2021 (EC, 2021b) and of *Acheta domesticus*, in February 2022 (EC, 2022). At this moment, TM is the only insect approved by EC for using larvae (also known as “mealworm”) in human nutrition, while the other two insects are approved for using adults.

Authorization as Novel Food involves compliance with certain regulatory restrictions in Europe. A proposer who wants to produce and market a new product in Europe must apply to the EC, which takes advice from certain relevant bodies (EFSA - European Food Safety Authority, is involved in food). After the favourable opinion of the relevant body, the EC can approve or reject the application.

The approval is valid only for that specific product and all the conditions detailed in the dossier. Anyone wishing to produce the same food can either become a partner or contractor of the proposer or submit a certification to the EC, which guarantees compliance with all the approved conditions and parameters.

For whatever changes, even minimal, they must submit a new application to the EC, as if they wanted to produce and market a completely different product and wait for EC approval. All this ferment, especially in EC, is due to the need to find valid alternative sources of protein, given the growing demand and the exponential increase in the world population (Derler et al., 2021). There are relevant innovations on TM use also in the production of feed. Already used for pets feed and aquaculture since 2015, it was approved in August 2021 as feed for poultry and monogastric terrestrial animals (EC, 2021c). In this review, we summarize the state-of-the-art on TM larvae (TML) products and on their possible uses. Furthermore, we make an analysis of the challenges to face for the full use in Western countries of this interesting matrix.

In fact, while the scientific and the business communities are increasingly interested in this insect both as an alternative source of good quality protein and in the use of many of its derivatives, there are still many challenges to be faced. Obviously, the massive use of TM and its products requires a large-scale TML rearing. At the moment, neither of these activities is sustainable, neither environmentally nor economically, unless specific measures are taken, which we will discuss in more detail in the dedicated paragraph.

One proof of this is that despite the many beneficial effects of TML derivatives, there is currently no product or drug based on TML derived peptides on the market, probably because it is still too expensive to produce them. Another crucial aspect is related to health and food safety. If rearing and production are not conducted under certain conditions, the risk of contamination is very high. Last but not least, cultural and legislative barriers still need to be overcome, the latter only in part recently contained.

2. TM products: sectors of use and biological effects

2.1. Nutritional aspects of Tenebrio molitor

Because TM has an excellent nutritional profile and very attractive characteristics, it has recently been greatly re-evaluated. Its products are an excellent alternative to meat and valuable for many other uses (Errico et al., 2022). In fact, TML are rich in protein, fat and micronutrients, which include sources of copper, iron, zinc, magnesium, potassium and phosphorus (Ghosh et al., 2017; Wu et al., 2020); mealworms are also rich in vitamins such as E, B12, B3, B2, B5 and H (Costa Rocha et al., 2021; Moruzzo et al., 2021b). In addition, two valuable antioxidants are in TM oil: tocopherol (Vitamin E) and polyphenols (Son et al., 2020). According to Ghosh et al. (2017), TML's iron and zinc contents are found to be higher than those found in other animals, such as chicken, pork, and beef (Costa Rocha et al., 2021). TML have a nutritional profile with an average of 50% crude protein (on dry matter, DM) and 30% crude fat (Hong et al., 2020; Van Broekhoven et al., 2015). Nutritional profile's value changes depending on the rearing environment, the life stage and the substrate used to feed larvae, where the value of fat varies above all (Mancini et al., 2019a; Van Broekhoven et al., 2015). The lipid content is very rich in monounsaturated fatty acids (MUFA), such as palmitoleic (C16:1) and oleic (C18:1) acids, saturated (SFA) and polyunsaturated (PUFA) fatty acids, such as linoleic acid (C18:2). TML also meet the demand for essential amino acids (EAA) as they are rich in leucine, isoleucine, lysine, tyrosine, valine and methionine (Gkinali et al., 2022).

2.2. Sectors of use and biological effects

TML products are oil, flour, protein, peptides, chitin, chitosan and frass: this review will deal mainly with the use of proteins, peptides, oil, and flour. According to Regulation (EU) 1017/2017, TML can be used dried or frozen for livestock or live (in a few EU member states). They can be used as flours and oils and partially replace some conventional ingredients, such as soybean-fish-wheat meal/oil. Several authors have evaluated animals' growth and health performance after the inclusion of TML meal and oil in feed, and the results have been satisfactory. In aquaculture, for example, TML-based feeds have been evaluated positively for rainbow trout, tench-bream and European sea bass (Moruzzo et al., 2021b).

In addition, TM meal and oil have been used as an alternative to soybean meal and oil in the feeding of broilers (Sedgh-Gooya et al., 2021), free-range soy and rabbits (Gasco et al., 2019) with good results. TM oil can be used as a substitute for palm oil in multiple products, poultry feed, and many other health applications due to its anti-inflammatory properties and Omega 3 content (Errico et al., 2022). Benzertiha et al. (2019) evaluated the effects of replacing palm oil and poultry fat with TM oil. These authors note a significant reduction in liver size, triglyceride and total cholesterol concentration, and an increase in n-3 and n-6 fatty acids in the breast muscle tissue of chickens that can be attributed to the high PUFA content in TM oil. TM fat may also be an excellent alternative to soy fat in rabbit diets. Indeed, Dabbou et al. (2020) saw a change in FA profile in diets with the highest MUFA value by supplementing the feed with TM fat. This supplementation proved to be very useful in increasing animal welfare, probably because insect fat plays an important role in containing pathogen growth (Errico et al., 2022), although further studies are needed on the impact of TML meals on microbial activity and gut microbiota of rabbits (Dabbou et al., 2020).

Other possible applications of TML meal are in the industrial sector and as food (supplement in food, snacks, bakery products, meat products). The proteins obtained can be used in food because they contain all the EAA (Costa Rocha et al., 2021). Thanks to their high nutritional value and sustainable production, insects could be an excellent alternative for human nutrition, partly satisfying the growing demand for food (Van Huis et al., 2017). Degreased worm powder can be used as a functional ingredient in food due to its high antioxidant capacity (Moruzzo et al., 2021b). One of the applications of TM flour is in bakery products, replacing wheat flour with percentages between 5 and 10%. The doughs and bread obtained in this way show more digestibility and better nutritional characteristics. They gave good results also in terms of volume, softness and colour (Gkinali et al., 2022). In addition, TML in the form of whole or pre-treated flour can be used for the preparation of meat products, such as sausage emulsions, by replacing 10% pork with untreated, defatted or acidified TM flour (Kim et al., 2016). According to Son et al. (2020), TM oil is very similar to vegetable oil and usable in nutrition, as it is rich in bioactive nutrients, such as ɣ-tocopherol, an antioxidant, and polyphenols, while the cholesterol content is shallow.

The scientific world is particularly interested in TM proteins and peptides, besides food and feed, because of their further considerable applications in pharmaceuticals and their nutritional and health effects. Some of the possible applications of proteins and peptides are mainly in the medical field for their anti-diabetic, anti-ACE, anti-microbial, anti-thrombotic, antioxidant and anti-inflammatory, anti-freeze and hepatoprotective properties (Errico et al., 2022). In their study, Seo et al. (2017) investigated the effects of TML extracts on the possible reduction of adipogenesis and obesity for their possible use as replacement of currently used drugs which are effective but have many side effects. The tests were conducted in vivo on mice fed different percentages of TML. They demonstrated the anti-obesity capacity of TML extracts by assessing parameters such as in vitro cytotoxicity, intracellular lipid accumulation, intracellular triglyceride content, gene expression and protein production. TM oil is rich in MUFA and PUFA and has excellent anti-inflammatory properties. It has a significant impact on cardiovascular disease, may also promote brain development of children during pregnancy and have beneficial effects on lactation (Errico et al., 2022). Lee et al. (2021) studied the effect of TM meal supplementation on hind limb atrophy in rats, particularly on the soleus muscle. They saw a stimulation of muscle protein synthesis and an inhibition of muscle protein degradation after 5 weeks of dietary supplementation, a promising result in combating sarcopenia.

2.3. TM Bioactive compounds and biorefinery model

Insect products have been shown to have remarkable biological properties due to some special molecules: bioactive compounds. These can interact with components of living tissue to produce a positive effect on human health. Insect-based bioactive compounds include mainly peptides and lipids, and TM products are an interesting natural source of them (Fig.1).

In addition, some TM peptides have antioxidant and anti-inflammatory activity against hypertension and diabetes. Moreover, some authors, such as Navarro del Hierro et al. (2020) demonstrated the inhibitory effect on pancreatic lipase using bioactive extracts of mealworm obtained by pressurized liquid extraction using aqueous ethanol as solvent. In similar research, Wu et al. (2020) obtained natural anticancer chemotherapeutic agents from the lipid fraction of TM. Table 1 shows some studies about possible positive effects of TML extracts and oil on human health. Costa Rocha et al. (2021) introduces the concept of biorefinery applied to edible insects and specifically to TM. Similarly to a refinery, in fact, from TM is possible to extract high added-value molecules using green technologies, such as non-conventional eco-friendly extraction methods (Costa Rocha et al., 2021).

The application of this concept can generate environmentally sustainable products, with high economic value, through innovative technologies, starting from the collection of organic waste and arriving at the final consumption, in a circular economy perspective. Various products can be obtained from oil and extracted protein by applying the biorefinery concept. For example, it can produce biodiesel from oil extracted with supercritical fluid extraction (SFE-CO_2) (Fig. 2). Additionally, thanks to bioactive compounds, other extraction products can be used as food and feed components; for example, the protein fraction obtained by the same process can be used in animal feed. TM fat for biodiesel production could be an alternative and sustainable resource that could decrease the cost of this product (Moruzzo et al., 2021b). The concept of biorefinery related to the recovery of high value-added products in insects is still in the embryo and needs more attention, as well as deeper studies.

Fig. 1. Properties of bioactive peptides from *Tenebrio molitor* larvae (in vitro studies) (adapted from Errico et al., 2022)

Table 1. Possible positive effects of *Tenebrio molitor* larvae extracts and oil on human health

Possible positive effects	***Bibliographic reference***
Protection against hepatocellular carcinoma	Zepeda-Bastida et al., 2021
Inhibition of BACE-1 enzyme activity related to accumulation of β-amyloid	Youn et al., 2014
Cardiovascular protection, promotion of fetal brain development, positive effects on breastfeeding	Koletzko et al., 2008
Obesity-alleviation (in vitro and in vivo)	Seo et al., 2017
Anti-thrombosis, antioxidant and hemolytic activities against human red blood cells	Pyo et al., 2020
Promotion of platelet aggregation	Pyo et al., 2020
Antioxidant capacity and anti-inflammation activity	Son et al., 2020
Antioxidant and tyrosinase inhibitions activities, perhaps also skin-whitening effects	Kim et al., 2018
Prevention of muscular atrophy	Lee et al., 2021
Prevention of lipid oxidation in free radicals and hydroperoxides in foods	Son et al, 2020

3. Challenges in Western countries

3.1. Sustainability of TM rearing

According to several authors, the production of farmed insects is more sustainable than livestock raised industrially to produce meat (Oonincx and de Boer, 2012). Rearing insects is considered sustainable also due to their higher Feed Conversion Ratio (FCR) and edible portion than other farmed animals (van Huis et al., 2013).

Land used to produce 1 kg of edible protein with TM is 10% of that needed for beef (Baiano, 2020; Flachowsky et al., 2017). Oonincx and de Boer (2012) estimated the land use for 1 kg of fresh TM larvae based on economic allocation. This value is split between 3.03 m^2 for mixed grains, 0.51 m^2 for carrots and only 0.01 m^2 for TM farm.

The consumption of water for livestock farming is under the attention of FAO (Baiano, 2020), as it is an important parameter to assess the breading sustainability. TML can absorb water through the cuticle in environments with high humidity (Punzo and Rosen, 1984): breeders exploit this characteristic to feed TML plant sources of water, in addition to the dry diet, instead of water as such. The decision to provide a plant supplement to the diet is justified because the increasedavailability of free water increases growth and reduces development times (Liu et al., 2020; Özsoy, 2019).

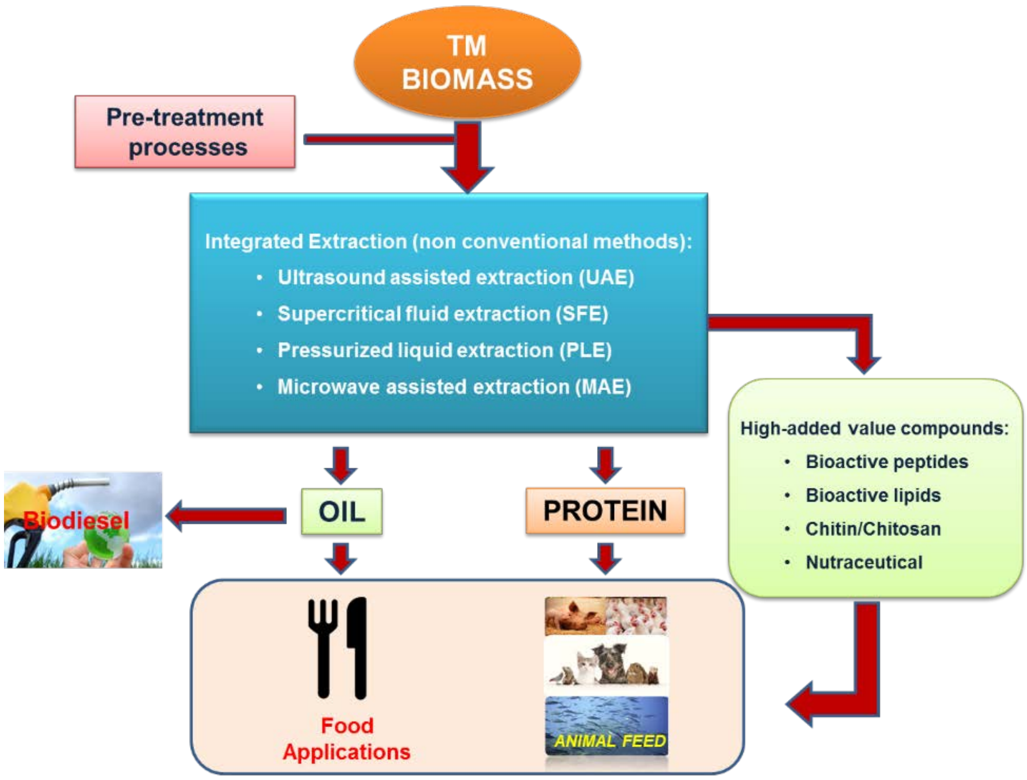

Fig. 2. Flowchart of biorefinery concept applied for *Tenebrio molitor* (adapted from Costa Rocha et al., 2021).

In farming, mealworm grows using carrots as a water source (Dreyer, 2021), but other vegetables such as potatoes and cabbages are also used (Liu et al., 2020; Rumbos et al., 2021). The water footprint was estimated at 112 L/g protein for beef and only 23 L/g protein for mealworms, mainly included in the feed production phase (Miglietta et al., 2015). Thus, the water footprint strongly depends on the diet type fed to the insects. Dreyer et al. (2021) performed an LCA on a small-scaled TML production located in an Austrian mountainous area about 1,000 m above sea level. According to their studies, heating-related energy consumption is highly relevant for the mealworm production site in a cold Country. Additionally, the heating demands increase more in winter due to a potential decrease in outdoor temperatures. On-farm energy demand related to the use of electric appliances (heaters, humidifiers, wacker plates, vacuum cleaners) and feed processing equipment (mill and mixing machine) represents a hot spot (Dreyer et al., 2021).

Due to mealworms poikilothermic nature, they do not use the energy in feed to maintain a constant body temperature, but instead to grow (Nakagaki and Defoliart, 1991). Although poikilothermy decreases feed consumption, insects' body temperatures are affected by ambient temperature. Thus, local climatic conditions directly influence the energy consumption of mealworm rearing. In contrast, cooling-related energy consumption could be relevant in a hot country, particularly in the summer season.

Therefore, energy demands are strictly dependent on the country's latitude and climate.

Nonetheless, insect farming will be more sustainable using substrates without competing with feeds for other farmed animals (Pinotti and Ottoboni, 2021). Insect farms generally use commercial substrate (Oonincx et al., 2015), mixed grains (Oonincx and de Boer, 2012), chicken feed (Bordiean et al., 2020; Harsányi et al., 2020) and wheat bran mixed with corn seeds (Dreyer et al., 2021). Sustainability would increase with higher use of wheat bran (a by-product of the transformation of wheat) and less consumption of seeds for human and animal nutrition. Among other things, wheat bran appears to be more suitable than chicken feed in the TM reproduction phase (Naser El Deen et al., 2021).

A considerable increase in the environmental and economic sustainability of the TM rearing can result from the use of agro-industrial by-products as feed (Pinotti and Ottoboni, 2021; Derler et al., 2021). Bioconversion of wet by-products and waste through insects is more feasible with *Hermetia illucens* L., while expired bakery products could be better bio converted by mealworms (Ites et al., 2020). Suitable moist by-products such as brewery by-products require dehydration to prepare TM feed, thus negatively affecting energy consumption (Dreyer et al., 2021). Brewer's spent grain has been tested alone or in combination with other by-products (van Broekhoven et al., 2015). Compared to residual cookies, it induced significantly faster larval growth, higher larval protein content and lower fat content (Mancini et al., 2019a). Brewer's yeast as a wheat bran supplement (at doses of 30% and 50%) significantly improved the weight gain, specific growth rate and reduced larval period (Kim et al., 2019). Among the most widespread agro-industrial by-products, inclusion of olive pomace up to 25% in wheat middlings diet represents the best compromise between larval growth performance and their nutritional properties (Ruschioni et al., 2020). Rovai et al. (2021) tested carrot pomace and proposed an optimized diet with dry carrot pomace (36%) balanced with wheat bran.

Among the cultivation residues, spent mushroom substrates can be advantageously mixed in standard diets for TML. Diets supplemented with <40% of spent *Lentinula edodes* (Berk.) substrate produce performance (larval weight and larval survival) like that of conventional diet (Li et al., 2020). The fungus species influences the larval performance which is better for *Flammulina velutipes* (Curtis) than for *Pleurotus eryngii* (DC.) substrates (Kim et al., 2014). Crop residues rich in lignocellulose were also tested. Rice bran, rice straw and corn straw have supported larval growth, but their low protein content limits their use in diets. However, the results show that mealworms can partially degrade cellulose, hemicellulose and lignin (Yang et al., 2019). Often the use of by-products in diets must include multiple substances for the optimal feed. A methodological approach based on self-selection by TM was used by Morales-Ramos et al. (2020) to select the best diet composition.

In a circular economy framework, it is also fundamental to evaluate the use of by-products from an economic point of view. Rumbos et al. (2021) reared TML on different seed cleaning process by-products, combining FCR and Specific Growth Rate (SGR) to Economic Conversion Ratio (ECR). This method showed that the wheat bran and yeast control diet (9:1) had 2-3 times higher ECR values than lupine, triticale, barley and oat by-products. This result suggests that each feed must be evaluated based on economic efficiency, although the cost of other local factors such as energy and labour must also be considered.

Integrating TM rearing into a broader circular economy context could help reduce costs and increase sustainability. Valorizing the residues of TM rearing is one way of closing the cycle. As shown in Fig. 3, insect waste streams prove to be promoters of crop and soil health (Torgerson et al., 2021). Used as fertilizers and bio stimulants, they can re-enter the primary crop production, which, in turn, generates waste usable for feed for mealworms. Exploiting all the products that may derive from rearing waste can give more value to the entire chain. Exuviae and dead insects (larvae or adults) are excellent sources of chitin and chitosan. These macromolecules have numerous applications in various sectors such as chemicals, food, pharmaceuticals, textiles and cosmetics (Errico et al., 2022). All this confirms the potential and multifunctionality of all products derived from TM, including waste products.

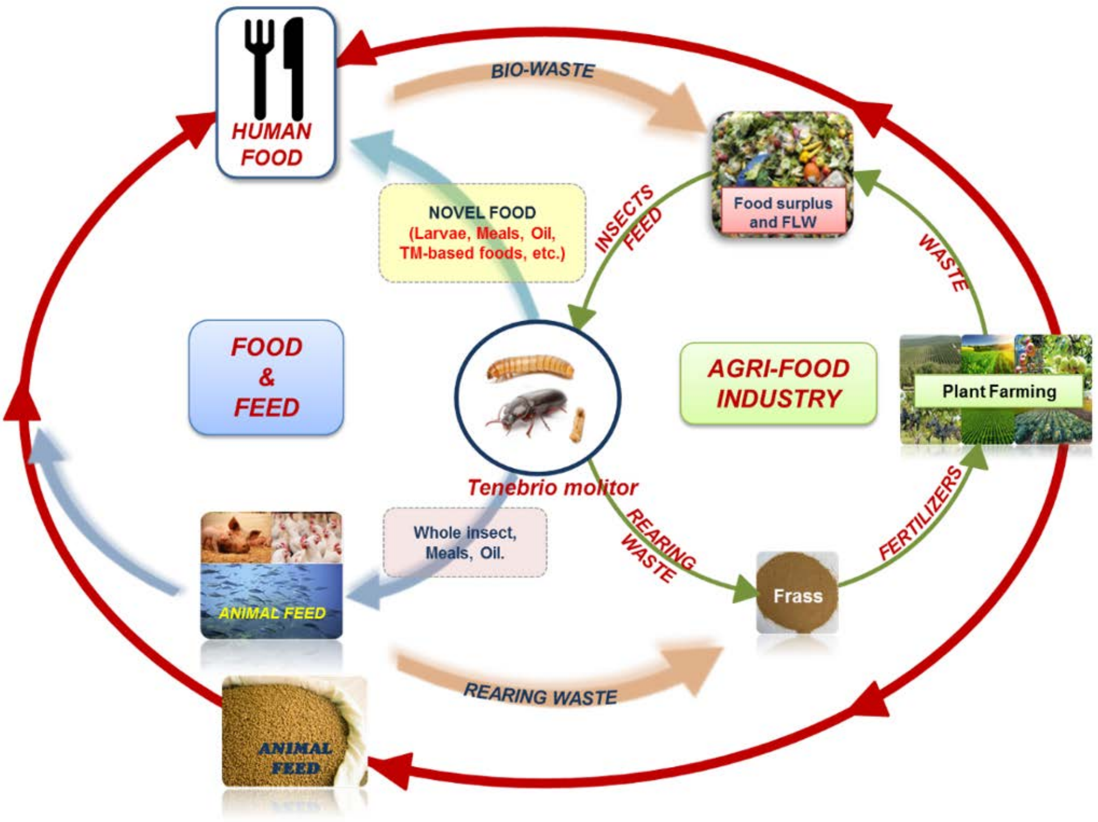

Fig. 3. *Tenebrio molitor* in the Circular Bioeconomy

3.2. Safety

Whole edible insects and their insect-based foods, given their high nutritional profile and a high degree of sustainability, represent an excellent source of bio-compounds and protein. These can be used as valuable substitutes or supplements to traditional protein sources even if their food safety is one of the main obstacles to the acceptability of insects as food and feed, especially in Western countries (Imathiu, 2020).

Edible insects, in addition to hidden exogenous (farming conditions, harvesting and processing, etc.) and endogenous (insect itself or its food, etc.) risks to human and animal health (EFSA, 2015; EFSA NDA, 2021), are responsible for potential food safety hazards. The main hazards associated with them can be grouped into microbial, chemical, toxic, allergenic and zoonotic hazards (Rumpold and Schlüter, 2013a, b), as shown in Fig. 4.

3.2.1. Microbial risks

Consumption of fresh larvae is often associated with contagions from foodborne pathogens, whereas consumption of insect-based foods is often related to contagions from sporulated pathogens resistant to industrial food treatments and can grow during the storage period (Messina et al., 2019; Vandeweyer, 2020).

Observing the data shown by Garofalo et al. (2019), the main microbial risks of fresh and processed edible insects are represented by: high total count of aerobic bacteria, some also responsible for food alteration (*Bacillaceae*, *Enterobacteriaceae*, *Enterococcaceae*, *Staphylococcaceae*), presence of sporogenous bacteria potentially sensitive to heat treatments, yeasts and moulds.

Taking all those measures leading to the inactivation of the gut microbiota of the insect can minimize most microbial risks. To this end, according to some authors, various treatments may be effective: fasting, in particular, performed before any transformation treatment (Garofalo et al., 2019); the using sterilized feed during rearing (Chung et al., 2013); the various pre- and post-processing heat treatments (Bellucco et al., 2013; Vandeweyer et al., 2020), in particular, those that ensure the survival of the bacteria responsible for beneficial effects (Grau et al., 2017). Microbial surveillance, also extended to feed used in insect farms, can reduce their transmission and this was verified for *Salmonella* sp against TML (Wynants et al., 2019). When agro-industrial by-products serve as feed, it is critical to apply strict microbial surveillance in the production and storage of these substrates, thus blocking the introduction and spread of these contaminants within the supply chain (FAO, 2021). Currently, insects and their derived foods are of low dietary risk only towards determinate food pathogens such as hepatitis A virus, hepatitis E virus and group II norovirus. However, the same authors recommend extending the research to other species using more innovative methods (Vandeweyer et al., 2020).

3.2.2. Chemical and toxic hazards

As observed by Houbraken et al. (2016) and Imathiu (2020), insects can present several chemical and toxic risks, including:

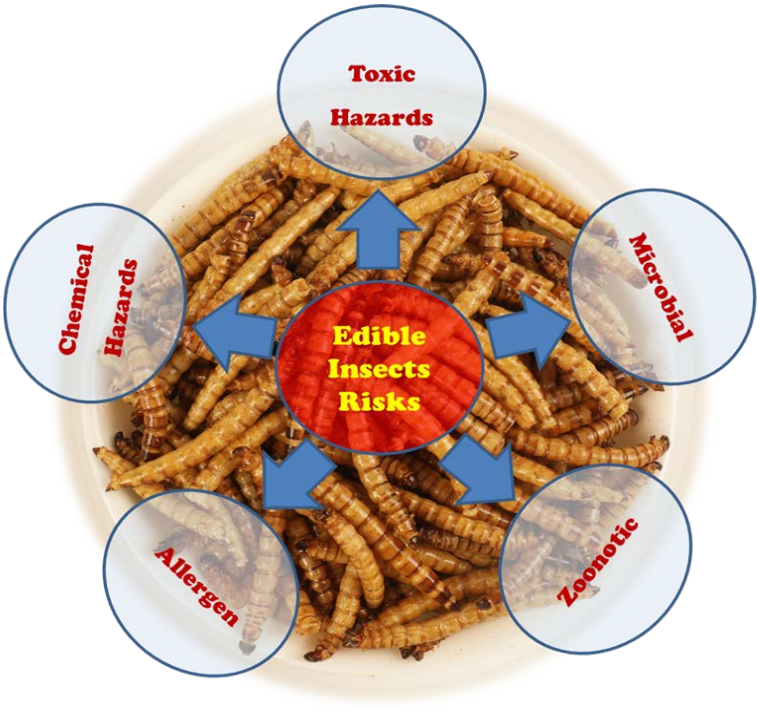

Fig. 4. Safety risks of edible insects

- antinutrients (tannin, oxalate, cyanide, phytate, saponins, alkaloids, and heat-resistant thiaminases),
- species-specific synthesized toxins, produced in response to hazards or sequestered directly from the plants they feed on,
- heavy metals (selenium, cadmium, lead, mercury, and arsenic) and other harmful chemicals such as pesticides accumulated using contaminated feed.

There is no evidence of mycotoxin accumulation (van der Fels- Klerx et al., 2018). Antinutrients in edible insects are not toxic but reduce the absorption of essential nutrients in the body, thus decreasing the nutritional value of the food (Ekpo, 2010; Iduwu et al., 2020). In contrast, heavy metals can be of concern, as some authors have found a tendency for TML to accumulate selenium and cadmium beyond acceptable levels for food consumption (van der Fels-Klerx et al., 2018; van der Spiegel et al., 2013). Kooh et al. (2020) have recently introduced a downstream HACCP protocol for the entire insect supply chain, from rearing to consumption, to reduce biological and chemical contamination and assess the risks associated with the different manufacturing processes of TML powders intended to produce various foods.

3.2.3. Allergen risks

This topic involves both consumers of insects (Ribeiro et al., 2017) and employees of insect rearing facilities exposed to inhalation or contact with materials contaminated with possible insect allergens (Grau et al., 2017). As arthropods, insects contain allergens like tropomyosin (Ayuso et al., 2002), arginine kinase (Binder et al., 2001), and glutathione S-transferase (Galindo et al., 2001).

These allergens are responsible for cross-reactivity to insects for consumers allergic to house dust mites or crustaceans (Broekman et al., 2016; Verhoeckx et al., 2014). In addition, chitin allergenicity has only been confirmed by inhalation and is not related to direct consumption (van der Fels-Kelerx et al., 2018). Various authors have investigated the possible effect of insect processing methods in reducing allergenicity. It appears that heat treatments such as blanching, boiling, frying or baking affect the solubility of TM meal allergens, but their degree of allergenicity remains unaffected (Broekman et al., 2016; van der Fels-Kelerx et al., 2018). Since the presence of gluten on the surface of TML and in their intestines could limit their inclusion in products labelled "gluten-free," a great deal of attention is being paid to the relationship between TML and celiac disease. Data from Mancini et al. (2020) showed that washing and fasting could effectively reduce the levels of gluten carried by TM to below 20 ppm. Introducing clear information and warnings on insect-containing food packages is fundamental and highly recommended to mitigate or eliminate allergenicity risks (van Huis et al., 2021).

3.2.4. Zoonotic risk

Given the current historical moment marked by the SARS-CoV-2 pandemic we are experiencing, the zoonotic risk is now more in the consumer spotlight. Though studies show that insects and feed do not contribute to the transmission of SARS-CoV-2 and other coronaviruses (Dicke et al., 2020), Khalil et al. (2021) showed a significant decrease in willingness to consume insect-based foods after the COVID-19 outbreak.

Some authors argue that, unlike livestock, insects do not pose a high zoonotic risk due to their evolutionary distance from mammals (Dicke et al., 2020). They cannot accumulate mycotoxins (Niermans et al., 2019; van Broekhoven et al., 2017), pathogenic viruses, and prions, but can act only as "zoonotic vectors" (van der Fels- Klerx et al., 2018). So, when raised and processed in controlled environments, their food safety is high (Klunder et al., 2012; Rumpold and Schlüter, 2013a, b), and the risk of zoonosis is extremely low (EFSA, 2015). However, this does not mean that the risk can be eliminated. Recent studies have shown that prion diseases (transmissible spongiform encephalopathies) are lethal neurodegenerative diseases that affect humans and livestock (Grau et al., 2017). Furthermore, insects are a reservoir of a high diversity of RNA viruses, whose potential risk to human health is still unexplored (Käfer et al., 2019).

EFSA's recent statement regarding the safety of TM for the proposed levels and uses (cookies, pasta, snacks, bars) confirmed many scientific data found to date in safety terms (EFSA NDA, 2021).

3.3. Cultural barriers

Until last year alone, many studies reported that about 2 billion people (3000 ethnic groups), distributed in 113 countries around the world, included in their daily diet the approximately 2,000 species of edible insects usually collected in nature or reared (del Mastro, 2021; Deroy et al., 2015; Tao and Li, 2018; Thrastardottir et al., 2021; van Huis et al., 2021). A very recent study by van Huis et al. (2022) radically re-examines the economic, cultural and social profile of those defined as "insect-eaters". The author strongly questions the exact estimate of the total global population that consumes insects. It may only be a few "hundreds of millions" of people who "really" eat insects instead of the 2 billion (25% of the world population) as presented in the FAO/WUR report and by IPIFF (IPIFF, 2020; van Huis et al., 2013;). Therefore, the value used so far could only be considered an overestimate of the actual number of insect consumers (van Huis et al., 2022). The interest in insects, both as food and feed, has grown exponentially in the last 10 years (van Huis, 2021).

However, the process of economic and cultural globalization is generating negative repercussions towards the view of "insects as food". For example, in the Tropics, territories considered of choice for insect consumption, there has been a lower consumption of insects as food in recent years because of an increased rejection by the population. The causes of this phenomenon are the westernization of the eating habits and the depopulation of rural centres where the consumption of insects is more rooted and widespread (Hlongwane et al., 2020; Muller, 2019; Niassy et al. 2016). On the other hand, the Western people, despite the enormous attention devoted by the scientific community to "edible insects" (803 articles in the decade 2011-2020) (van Huis et al., 2021), still seems very reluctant to eat insects and manifests much difficulty in changing its eating habits (De Carvalho et al., 2020; Hartman et al., 2015).

Therefore, this reluctance to eat insect-based foods is no longer a Western prerogative but a "universal" one. So, it is urgent and of paramount importance to implement all strategies to foster change in the attitudes and behaviour of the entire world population towards edible insects (van Huis et al., 2021) if the goal is to introduce at least partial insect consumption into the human diets.

The big challenges in recent years have been to add more detail and better define the profile of the "insect eater of the future" and to study the key factors that most influence the perception and acceptability of especially Western consumers towards insect foods (Hartmann and Bearth, 2019; Kauppi et al., 2019; Rumpold and Langen, 2019; Wendin and Nyberg, 2021). The result that emerges from these studies is a rather complex picture, composed of very different but at the same time firmly correlated factors that may vary throughout an individual's lifetime (Moruzzo et al., 2021a; Ngo and Moritaka, 2021). The main barriers to Western consumer acceptance of insect food products appear primarily psychological, cultural, and age-related (House, 2019).

In most Western populations, the mere thought of consuming insects as food essentially generates behaviours of pure "food neophobia" and "deep disgust". Insects are not "familiar to them as food" (Sidali et al., 2019) and are associated with "negative personal experiences" (Moruzzo et al., 2021a). They are especially linked in a "generalised" way too contaminated, dirty, unhygienic environments, deteriorating organic matter, and represent a public health hazard (De Foliart, 1999; Deroy et al., 2015; Looy and Wood, 2006; Shelomi, 2015). These sometimes illogical and inconsistent behavioural responses to insects as food are dictated, according to Deroy et al. (2015), by so-called "environmental confound", the consideration of insects as a "one-size-fits-all" category, and, most importantly, a lack of awareness and knowledge of the existence of "insect varieties" (e.g., edible and inedible) (Looy et al., 2014; Shelomi, 2015).

Older people tend to be more neophobic than younger people (Jaeger et al., 2021). Children and adolescents - the segment that should be strongly targeted - show a more possibilistic approach and greater willingness about insects' consumption (Geertsen, 2019; Nyberg et al., 2021; Scaglioni et al., 2018).

Western consumers are not used to eating insects, so it is important to find strategies to explain their hygienic safety, environmental sustainability and goodness for health (van Huis, 2021). An effective way to make insects such as TM less unfamiliar and repulsive is to increase their degree of familiarity by including them in known food products (meat products, bakery goods, snacks, milk, etc.), thus making them "invisible" (Azzollini et al., 2018; Çabuk and Yilmaz, 2020; Cho et al 2018; Choi et al.,2017; González et al., 2019; Petrescu-Mag et al., 2022 Tello et al., 2021; Zielińska and Pankiewicz, 2020) and pleasant taste (Çabuk, 2021; Cicatiello et al., 2020, Wendin et al., 2021; Żołnierczyk et al., 2021).

Many studies have shown how exposure to insect-based foods, through sensory evaluation tests, and its frequency decrease the disgust factor among participants and increase their willingness to try to eat them (Barton et al., 2020; Mancini et al., 2019b; Woolf et al., 2019). The participant's education level and gender, together with the context (location, type of participants, the notoriety of the organizers, etc.) in which insect foods are offered, affect both the number of attendees and the degree of acceptance. Males of young age and higher education are the most willing to eat insect-based foods (Arena et al., 2020; Videbæk et al., 2020). All contexts characterized by positive emotions shared with friends (such as in pubs, food festivals, etc.), new trends launched by well-known chefs (Dion-Poulin et al., 2021) or famous television programs, manage to address consumer choices differently (Arena et al., 2021; Motoki et al., 2020).

Schools could play a key role in increasing their awareness and moving toward including insects and their products in their diets (Jones, 2020; Nyberg et al., 2021). Consumers need increasingly qualified information about several aspects of insect consumption, including food safety, possible health benefits, sustainability, and environmental protection (Legendre et al., 2019; Mancini et al., 2019b; Palmieri et al., 2019).

Young consumers, as they become more aware and attentive to topics such as sustainability, environment and health, are more likely to change their diets towards more sustainable food choices (Guiné et al., 2021; Henault-Ethier et al., 2020; Saric et al., 2020; Sogari et al., 2020). Conversely, in adult consumers, environmental consciousness does not necessarily translate into a greater likelihood of consuming insects (Chang et al., 2019; Hartman and Siegrist, 2017; Lammers et al., 2019).

In contrast to the reluctance of the population to embrace this change in their diets, the scientific community has lately paid great attention to this issue, so much so that it is present in both the goals proposed by the "Agenda for Sustainable Development 2030" and in some strategies of the European Green Deal, such as Farm-to-Fork (EC 2019; 2020). Moreover, there is now a large amount of scientific information available on insect-based foods as a sustainable alternative to traditional protein sources (Gkinali et al., 2022; Sangiorgio et al., 2021).

Insect-enriched foods and beverages have begun to appear on the European market since 2014 but since 2018 there has been an acceleration leading to 82 insect-based products on the market in 2021. They include products like pasta, bread, crackers and energy bars (Khalil et al., 2021). Interventions to improve their commercialization can increase the recruitment of new consumers. These include the reduction of supply and storage distances, the presence in local supermarkets and not just online sales (Florença et al., 2021), appropriate marketing campaigns, such as their name, image, and price reduction (Hwang and Choe, 2020; Van Thielen et al., 2019).

These sectors, especially in Europe, are currently heavily penalised because they are limited by the European regulations still in force on edible insects and their products (Guiné et al., 2022). In other parts of the world, however, insects are increasingly being marketed as a protein and sustainable alternative for humans and as feed for livestock and aquaculture (Glaros et al., 2021).

4. Conclusions

Last year, 2021, saw the approval by the European Commission of the use of TM (for the first time in Europe) as Novel Food, opening new strong growth perspectives for its direct production and for its various derivatives. On the other hand, the approval of TM as a Novel Food subjects this insect to restrictive regulations that should be evaluated in further analysis, as they could inhibit a wider use of insects in human nutrition and better sustainability.

In addition to improving the sustainability of TM farms, scientific research will have to address concerns about food safety and possible effects on consumer health, as well as the elimination of cultural and psychological barriers that substantially inhibit the correct exploitation of TM. The scientific community has long proposed TM as an alternative protein source, although some regulatory obstacles have only recently been overcome. There are certainly many cultural barriers to get over, especially in the Western countries. However, it would seem that Europeans disgusted by foods containing insects are less and less, enticed by the nutritional characteristics, but only if the insects are no longer distinguishable on the dish and their presence is clearly marked among the ingredients or on the package. With the recent approval from the EC of TM for human consumption, the producers' market is also making substantial investments in this nutritional alternative source.

Tenebrio molitor is undoubtedly a very interesting insect that could have a central and innovative role in the nutrition of many Europeans in the not-too-distant future. This, however, provided that some critical issues are overcome, and that studies and investments continue to make its rearing fully sustainable.

Finally, it is essential to enhance and make effective communication that disseminates knowledge on the nutritionally beneficial effects and environmental benefits that can be obtained from the insects' farming in a context of circular bioeconomy. Only good information can change consumers' position for this new food source and modify their behaviours in favour of its regular consumption.

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IMPORTANCE OF KNOWING WHAT YOUR CUSTOMERS KNOW TO EFFECTIVE CIRCULAR DESIGN

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Abstract

Circular Economy, as the counterargument to the 'take-make-dispose' linear model, is an approach that includes a variety of schools of thoughts looking at environmental, economic, and social sustainability. In turn, it leads to a variety of strategies and often confusion when it comes to choosing the right action to implement efficient circular economy (CE) strategies, especially by companies. In particular, due to the close interplay of circular product design, business model and social responsibility, companies often struggle to develop strategies that comply with all three triple-bottom-line criteria. An analysis of a case study conducted with the University of Bayreuth and the ISPO correlating aspects of material choice in product design, labelling and technological innovation with customer preferences and education about specific material and technology features, revealed those attributes of the consumers' environmental awareness that directly translate into an increase of purchase power - primarily connected with individual preferences regarding the sport activity and technical knowledge. Continuing from the results achieved in this latter case study, the authors of this paper researched on the potential value of a questionnaire reserved for manufacturing companies that considers inherent company assets, as well as, subjective parameters, such as customer awareness, focused on CE and sustainability. The suggested output is a tool that provides a score guiding companies to material and technology choices for circular product design, while considering business model and communication strategy to the attentive customers. Current research highlights the importance of consumers' WTP and purchase power, therefore, such a questionnaire could underline the knowledge about the company's and employees' awareness about CE, as well their awareness of their customers. Resolving potential concerns highlighted in result of the questionnaire would support the development of more effective circular design strategies, while simultaneously increasing customers' trust and loyalty. In fact, while this paper primarily carries out an analysis of gaps, limitations, and future research needed in this field, it looks to potentially develop a tool as support for companies to identify their limitations, while improving communication to their consumers who have purchase power and can lead demand towards more ecologically pronounced products.

Key words: awareness, circular design, circular economy, sports, sustainability, willingness to pay

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1. Introduction

Attention to sustainability has increased as manufacturing companies are under pressure to sustain the environment in which they operate (Bour et al., 2019). A pressure that can bring result in higher profits, since it has been identified that sustainability practices result in significant positive margins with respect to company revenues. Additionally, regulatory bodies and governments push towards sustainable business practices through regulations, leading a need to rethink how we design and manufacture products (IPCC, 2021). In fact, on an environmental standpoint reducing the negative impact of consumption is key to comply with international standards (OECD, 2002; OECD, 2004; UNEP, 2007). Compliance to ISO

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standards has increased and it is demonstrated that certified companies with environmental ISO standards, such as ISO 14001, were able to improve their performance as compared with non-certified organizations (Kwon et al., 2002; Honk and Ruzzier, 2017; Neves et al., 2017; Treacy et al., 2019). In consequence, there is an increased awareness and pressure from multiple stakeholders to pursue more sustainable practices towards environmental benefits (Li et al., 2019).

Therefore, it appears companies have no other choice than transitioning towards higher sustainable standards for their products, services, and/or processes (Brömer et al., 2019). Simultaneously, they still need to remain profitable and for this design their offerings in such a way that they resonate with the consumers' demand for sustainability that is reflected in their willingness to pay (WTP) for those offerings. Since the WTP is connected to personal attitudes, preferences, and level of understanding for sustainability, investigating these motivations could direct practical guidelines for the design and development of successful products and services. The latter supposes the company's ability to apply effective circularity and awareness of what their customers' want and meet their increasing demands, in addition to achieving employee well-being and sustainable society. Hence, this logically requires the integration of creative problem-solving activities translating customer demands into opportunities for sustainable processes and products (Alhawari et al., 2021). Echeverrìa et al. (2022) demonstrate that when adding a social, and sustainable, dimension to a product the mean WTP was 7.5% higher than a standard price. Similarly, Zander and Feucht (2018) demonstrated that among different Members States of the European Union (EU) consumers were WTP for more sustainable products, especially when the applied trusted standards were well communicated. The same is observed also when applying circular economy (CE) strategies, where the WTP was higher for products where the circular economy strategies applied were correctly communicated to the consumer (EEA, 2016; 2017).

As the relationship between consumer and industries strengthens, it becomes more crucial to implement effective CE strategies and to comprehend how the transition is observed by consumers who are also placed in the forefront to sustainable development (Buerke et al., 2016; Betancourt Morales and Zartha Sossa, 2020) directing demand and purchase power.

The aim of this publication is therefore to shed light on the interrelation between corporates' awareness of circularity and circular product design strategies, in relationship to a firms' awareness of their customers' knowledge and WTP for a specific product when it is designed applying circular design. The latter awareness and knowledge should be researched through a structured questionnaire directed to manufacturing companies that considers inherent company assets as well as subjective parameters, such as customer awareness, focused on circular economy and sustainability. The outcome is a scoring system that provides guidance for material and technology choices for circular product design, while considering business model and communication strategy to the customers.

2. Literature review

2.1. Bibliometric analysis

Generating an understanding of corporate awareness and application of circular design, requires an overview of the current result discovered in literature. An initial research on Scopus with the authors' key words "circular economy" AND "consumer" AND "willingness to pay" yielded 9 results.

The most relevant results investigate the application and consumer behaviour in view of specific CE strategies, such as leasing *vs.* selling (Boyer et al., 2021) second-hand clothing (van Loon et al., 2017) arguing that manufactures lack models to navigate circular business models.

In the case of the research carried out by Sabbaghi and Behdad (2018) they found that there was value both for manufacturers and consumers to repair phones and even higher for manufacturers when consumers chose not to turn to repair services. Therefore, identifying the power that consumer choice has in the potential decision the company can take to implement a CE strategy or not, also identified the researched by Mansuy et al. (2020) who identified WTP varying based on product, but also consumer-type. A similar analysis and result by Stelick et al. (2021) who identified within cereal bars that sustainability information (upcycled ingredients) appeared affecting WTP more than the products' nutritional-value.

Pretner et al. (2021) demonstrated that for products labelled CE (e.g., recycled and reused) the WTP was low, unless an efficient communication was provided to consumers, and the companies' market abilities. Similarly observed in Magnier et al. (2019) who contributed to the theoretical understanding of consumer responses to products made of recycled ocean plastic and the ability of company to direct specific campaigns to sell such products effectively. To the authors' knowledge these latter and former appear to be the only two papers effectively connecting the company's ability to launch a product so that it can be comprehended by the consumer. This further reinforcing the power of increased consumer understanding of what they purchase leading to increased WTP for specific products. In fact, this is observed in the analysis by Shen et al. (2019) of optimal product line design for green and non-green products in terms of quality differentiation, identifying that consumers' WTP based on high responsibility impacts the value of green *vs.* non-green production. Moreover, if the consumers' WTP is based on low responsibility the quality of green products vs. others would not matter.

CE and sustainability are already gaining more attention at the policy level (Brennan et al., 2015; Geissdoerfer et al., 2017). As particularly evident with the European Circular Economy package (European Commission, 2015; 2020a; 2020b; 2021) and the Chinese Circular Economy Promotion Law (Lieder and Rashid, 2016). Companies are also understanding the benefits from applying CE (EMF, 2013). However, as identified, there are struggles by manufacturers to not only effectively implement CE strategies (Sabbaghi and Behdad, 2018; van Loon et al., 2017), but the same are required to successfully and clearly communicate the strategies implemented to the consumers (Magnier et al., 2019; Pretner et al., 2021), which WTP is based on several other factors (Magnier et al., 2019; Shen et al., 2019). Therefore, this literature review underlies the need to investigate where are the gaps within a company's understanding of CE business models and of their consumer's behaviour to indirectly impact WTP. Thus, as the gaps have been identified this research is crucial because it looks to underline that while struggles could be made by companies to implement CE strategies – that provide sustainability and wellbeing to society, as well as the planet – it could be less powerful when consumers are not WTP for the same.

2.2. Circular economy and consumer awareness

CE strategies are being applied as way to close the loop and reduce environmental impact, in fact, the objective of CE is to lower material input and reduce waste production (EEA, 2016) which involves strategies that help preserving products, their parts, the used materials (Ghisellini et al, 2016). CE is gaining traction in various sectors, such as academia and among policymakers (Geissdoerfer et al., 2017).

In recent years, CE has also been promoted not only to minimize burden on the environment, while stimulating the economy (Moraga et. al, 2019; European Environment Agency, 2017; Walzberg et al., 2021, Kalmykova et al., 2018) generating annually 1 trillion USD versus linear economy (Korhonen et al., 2018).

Since a CE system makes sure that there is as little, or none, waste or pollution produced as a "…framework for an economy that is restorative and regenerative by design." (Moreno et al., 2016; Morseletto, 2020), the EC is looking to improve the durability of the products, increasing recycled content, enabling product remanufacturing, restricting single-use, introducing bans on unsold durable goods, incentivizing product-as-a-service, increasing digitalization, and providing reward based on sustainability performances. Most importantly, it wants to empower consumers and public buyers to provide them with cost-saving products that can be sustainable. Data collected in the report highlights the public's purchasing power represents 14% of the EU GDP and it can also serve as a powerful driver for demand. Therefore, if it is taken into consideration the policy pressures and the consumer demand, companies must take part in this environmental shift and the EC adds in its plan the importance of the circularity in production processes that can generate extra value and thus unlock these economic opportunities.

As previously mentioned, defined as an umbrella concept, CE is a method to promote the responsible and closed-loop use of resources. (Moraga et al., 2019). However, as the same authors identify and highlight, the exact definition is ambiguous, and the attempt of a single definition is merely unachievable. (Korhonen et al., 2018). Furthermore, these various definitions and approaches to CE have not been challenged (Betancourt Morales et al., 2020). Such inability to provide a standard definition, could make it harder and more confusing for companies to implement CE strategies. A confusion shared also when investigating the connection between CE business models and sustainability and it could be harder for small and medium enterprises, especially, to innovate in this direction. Thus, while the economic growth is understood, it is unclear how it can also support the environment (Awan and Sroufe, 2022).

As identified by Boyer et al. (2021) it should be the researchers, policymakers, and other involved stakeholders' responsibility to provide the infrastructure to facilitate the transition to effective circular business by using realistic CE labelling systems, which, as seen above, affects the consumers' WTP. The same study highlighted that while labelling products as more circular can impact consumer's WTP, it should not be confused with products who have undergone only partial CE strategies. One example are products that are labelled circular when the only strategy applied is to integrate a certain percentage of recycled material. Attention therefore should be placed on terminology and possible misuse by companies, also widely referred to as green washing (Kärnä et al., 2001; Self et al., 2010; Schaltegger et al., 2010; Schmuck et al., 2018).

Hence, in this research, the authors focus on that part of the value that can be generated by efficiently moving consumers towards a higher WTP for circular products. Furthermore, as results also identified that customers may exhibit a lower WTP for certain circular products of even 75% due to the stigma that products made of recycled products has lower quality, the educational level plays a crucial role to encourage customers to purchase products with higher circularity scores (Diddi and Yan, 2019). This makes it clear that education and awareness about CE principles play an important role in the acceptance and purchase decisions for circular products. To this point, research demonstrates that while consumers do not have a clear understanding of the term CE their intentions and demand already point in that direction (Sijtsema et al., 2019) and therefore it is crucial to integrate the knowledge about the consumers into the product development processes.

If a company cannot clearly communicate how they their products are approaching circularity, then it could become highly challenging for the consumer to know what they are buying and if they are willing to pay for it due to its additional CE qualities and trust the company selling it. An existing overview of the literature on CE terminology (Camacho-Otero, et al., 2018) already identified by analysing a specific set of papers that, "…consumption in the circular economy is anonymous, connected, political, uncertain, and based on multiple values, not only utility." It is further highlighted that WTP is based on values and can vary from consumer to company, as well as between countries. It is quite relevant also the research by Kirchherr et al. (2017) who noticed a general research gap in addressing the consumer perspective towards CE, the authors identify that it is quite essential to investigate consumer awareness and knowledge of circularity and sustainable features of products.

3. Case study: Consumers pay more for sustainable products in the sports' sector

How do "green" consumers differentiate sustainability-related features in sporting goods is a question that not only brands have to ask when bringing new sustainable products to the market but also something that needs to be clarified at the early stages of product design.

A case study conducted with the University of Bayreuth and the world's largest trade fair for sporting goods and sportswear (ISPO) revealed those attributes of the consumers' environmental awareness that directly translate into an increase of purchase power - primarily connected with individual preferences regarding the sport activity and technical knowledge (Thormann and Wicker, 2021).

The quantitative study was implemented with the help of a choice-based conjoint analysis. In the first step, participants could choose between skis, snowboards, and surfboards as generally high-priced sports products with comparable features. Subsequently, questions were made regarding specific product features in comparison to megatrends, such as customization and digitization in the sporting goods industry, while applying a monetary value that the respondents would pay for these same features. Hence, it was possible to distinguish correlate the value of the benefits resulting from sustainable product features with the value of customization and digitization options based on the WTP of the respondents. The result was a significantly higher WTP for the sustainable feature, which was driven by personal preferences and the customer's knowledge about sustainable materials. Based on this outcome, we constituted a product development approach starting from an analysis of companies' individual perception towards sustainable product features as well as their awareness about CE enabling materials and technologies. This follows the argumentation of Barros et al. (2021), which confirms the importance of internalizing circularity principles horizontally across all company divisions to maximize the efficiency of circular product design practices in terms of environmental and economic benefits.

Assessing this awareness becomes therefore key for choosing those environmentally friendly product concepts that resonate with the customers' education regarding material choices and drive their WTP for "greener" products. When it comes to measure WTP in sports, research highlighted that WTP was positively determined by environmental consciousness and educational level. Some studies discuss that as CE must apply a triple-bottom-line value system (Geissdoerfer et al., 2017; Ghisellini et al., 2016; Kirchherr et al., 2017) including economic, environmental and social sustainability, there is a demonstrated interest of sports companies to shift to sustainable solutions with CE models achieved through: optimizing material-technical loops, transforming product ownership into services, sharing resources, and shaping symbiotic ecosystems. However, despite how conclusive this research is, it highlights that there is a concerning switch not only by companies, but also researchers overall in the terms "circular economy" and "sustainable". A sustainable strategy is not necessarily circular; hence this latter study identifies that as companies, such as Patagonia are trying to move towards circularity their business model remains within the sustainability arena, which frequently holds an unclear terminology. Rattalino (2017) in their research of Patagonia's business model in connection with circularity advantage explored ways in which the pursue of economic, social, and environmental objectives can embrace circularity. Thus, this case study functions to further identify the complexity of providing CE strategies that are sustainable and highly influenced by the particular consumer groups, as could in sports' industry.

4. Measuring CE awareness and knowledge of consumer behaviour and communication

4.1. Preliminary interviews

To investigate the measurement of awareness CE and develop a corresponding quantitative approach the first a literature review was carried out in conjunction with direct open-question interviews (n=33) about the application, understanding, and measurement of CE within companies from different industries, such as textile, technology and electronics, construction, and research. The aim of the open-question interview was to preventively comprehend CE awareness. Thereby, the following key challenges have been identified that reflect also those exposed in Moreno et al., (2016) and Morseletto (2020):

- A large quantity of information on CE application and strategies exists online but it lacks a systematic strategical focus on the various types of industries;
- A general interest in the topic is found among all sectors, but awareness on the true potential and applicable strategies is missing at all corporate levels. Generally, the interest is focusing on specific departments (e.g., sustainability experts, CSR etc.);

- The general consumer trend towards CE is overall acknowledged but systematic quantification is restricted to various independent sustainability aspects not integrally correlated with CE;
- Many who already have acquired some kind of sustainability certifications are not actively involved in measuring further indicators for CE due to a lack of clear standards and frameworks;
- Finally, a plethora of accredited sustainability assessment tools are available, which address specific products and sectors. CE labelling or measuring, on the other hand, is very fragmented as are the methodologies.

These interviews further highlight the confusion and challenges in the application of successful CE strategies and innovation towards this direction.

4.2. Importance of companies' and consumers' awareness

As the initial open-question interviews identified, to effectively realize circularity in product design, it is necessary to internalize the CE principles within the company. Additionally, also provide higher knowledge that reflects into clearer communication about CE application to consumers, as expressed in the literature identified. Therefore, the first step is to assess the level of knowledge and awareness. The authors decided to develop a quantitative scoring system that measures the companies' awareness of circularity along the different CE processes. The aim was to deliver a preliminary indicator that allows companies to identify the internal knowledge gaps on CE, and the gaps in regards to research about consumer behaviour, to develop targeted communication strategies needed to create a common understanding both internally and on the customer side. The goal is to turn individual knowledge into organizational intelligence, which can determine a company's innovative spirit and help to design more effective circular products (Castaneda and Cuellar, 2020). Currently the empirical knowledge is little and requires further analysis (Liakos et al., 2019).

The purpose of this circularity assessment is to provide an evaluation with short- and long-term perspectives to assist product developers, and/or decision-makers within companies with an overview of which actions should be taken to create circular product concepts that resonate with the customers (Tscheikner-Gratl et al., 2021). As previous research of sustainable product features demonstrated, the higher the consumers' awareness and company's product transparency, the higher the probability that consumers develop a high WTP. Hence, the paper's goal with the questionnaire is to transfer the potential outcomes on circular product design and implement customer preference translated into education analysis into a circularity assessment tool that considers inherent company assets as well as subjective parameters, such as awareness. The outcome provides guidance for companies on the areas of improvement for internalizing CE principles and by this determine more effective material and technology choices, while considering business model and communication strategy to the attentive customers.

4.2.1. The questionnaire and scoring methodology

The growing awareness about CE significantly increases the interconnection between industry and the general public, because efficient circular design heavily involves the consumer side (Garbie, 2015). A questionnaire is required to identify awareness gaps within a company regarding user and company approach and understanding in regard to CE. The questionnaire draws questions from a study conducted by Hörisch et al. (2019) who identified that knowledge on factors that can support the increase of corporate sustainability action is of crucial importance. Especially, since they look at the influence of feedback and awareness of consequences on the development of corporate sustainability action. Therefore, identifying those awareness gaps in corporations becomes also essential with regard to circularity (Talbot et al., 2020). A study on the awareness of sustainability in corporate organizations conducted by Garbie (2015) looked at how corporations were aware of sustainability in general, environmentally, socially, and economically. The same author states that yet the concepts are not fully understood by all stakeholders. Therefore, it is understood that clearer communication to the public is not only needed, but crucial for CE development, then the first step must come from the industry that should be aware of CE aspects and how those can be realized in product design. As another study suggested, CE is driven by economic and not environmental considerations, since the application of practices remains within a firm rather than across the supply chain (Masi et al., 2016; Sacco et al., 2021). It means that maximizing the economic benefits through for example an increasing WTP on the consumer side, is equally important to drive CE as it is when optimizing supply chains. Thus, all stakeholders within a supply chain should be included.

In view of aforementioned research mentioned, this paper integrates those findings in the development of the questionnaire (Fig. 1), which provides a set of closed questions (Annex I), researching firstly in the user's role in the company, age, educational level, and daily sustainability behavioural actions. It subsequently provides questions regarding the user's awareness of the company's actions on the company's transparency towards other stakeholders, and the company's application of sustainability and CE strategies during its supply chain and at the product's end-of-life. The specific questions are drawn from the aforementioned literature to tackle the various objectives determined in the questionnaire's framework (Fig.1). The "level of awareness" is used as the measured variable and the confounding variable being the user's age, gender, role in the company, and personal belief and actions of sustainability (Haan et al., 2018; Smol et al., 2018).

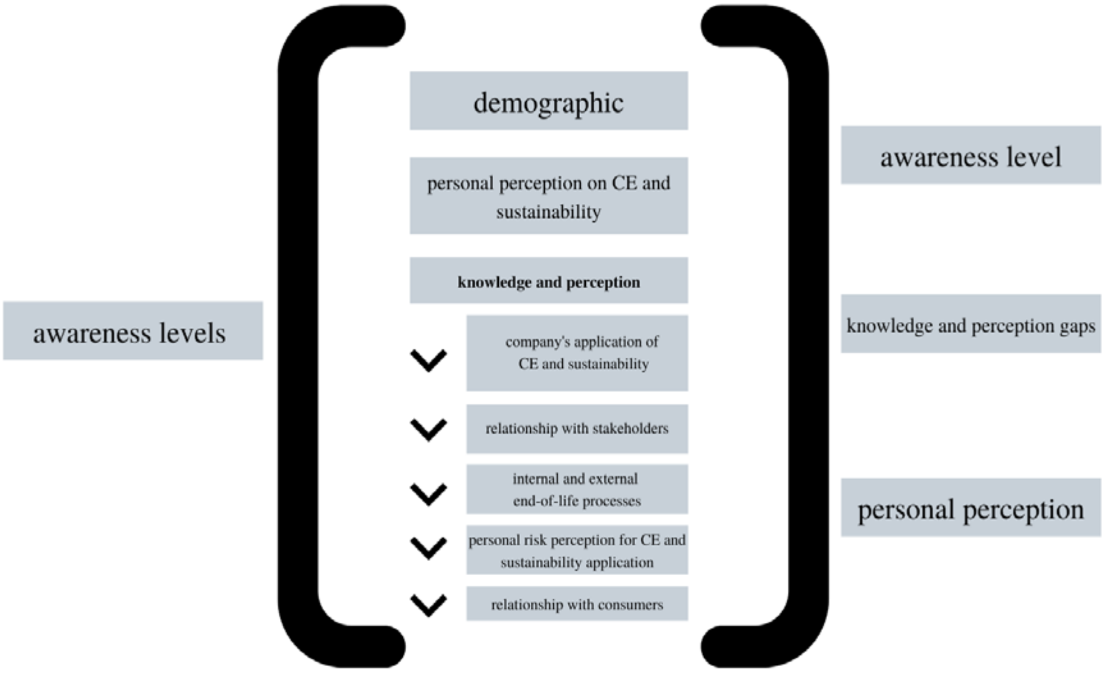

Fig. 1. Questionnaire structure and overview

The aim is questioning whether a higher awareness of sustainability, and CE, could translate into a more effective implementation of circular design. In regards to the score, every answer was given a weight between 0-3 and the final result is meant to group which weight is observed more frequently. This defines the level of awareness based on how confidently also the user was responding. For example, definitely yes and no answers were given the highest score (3) since the user is clearly sure of that particular answer. It looks to tackle data that is not numerical and can identify and highlight gaps within the corporate mindset of circularity (Maranesi and de Giovanni, 2020). The assumptions are that this method does not currently provide an overall awareness level and, being in its introductory phase, it is not directly looking at the company's circularity performance itself, rather the impressions and awareness about CE application.

4.2.2. Preliminary results

A preliminary analysis of the results (n=15) collected highlighted some gaps that further research should tackle. The questionnaire was shared online and additionally to the same companies who carried out the interviews for a period of 5 months for a preliminary analysis of potential results.

Considering the paper's aim to identify gaps and potential future research using this questionnaire, only partial questions were selected. The most visible change is that "definitely not" is generally an answer not provided, it appears "I don't know" is chosen.

As observed (Fig. 2), when asked about feedback opportunities and transparency, the answers were quite balanced, hence showing that it varies among companies, yet that the same could have a positive impact if it were properly transparent. Furthermore, when it comes to the application of these CE strategies, most respondents found that it was risky, but necessary, in view that they were also thought that the consumer would probably choose a sustainable product over not which is not.

The results provided from this questionnaire highlights that further attention should be brought to the relationship that companies have with their stakeholders, employees, and consumers. Thus, it also confirms the potential that education and knowledge can bring into effective CE application (Millette et al., 2020).

5. Relevance

The relevance of the tool in the context of the circular design process comes from the understanding that effective circular design derives from not only efficient business models that take into consideration additional services (e.g., take back) but also consumers' awareness about CE principles. For example, as demonstrated by Elzinga et al. (2020) there is a clear preference for take-back management models over leasing. Additionally, habits and consumer opinion regarding payment structures have a large influence on which circular business model to choose.

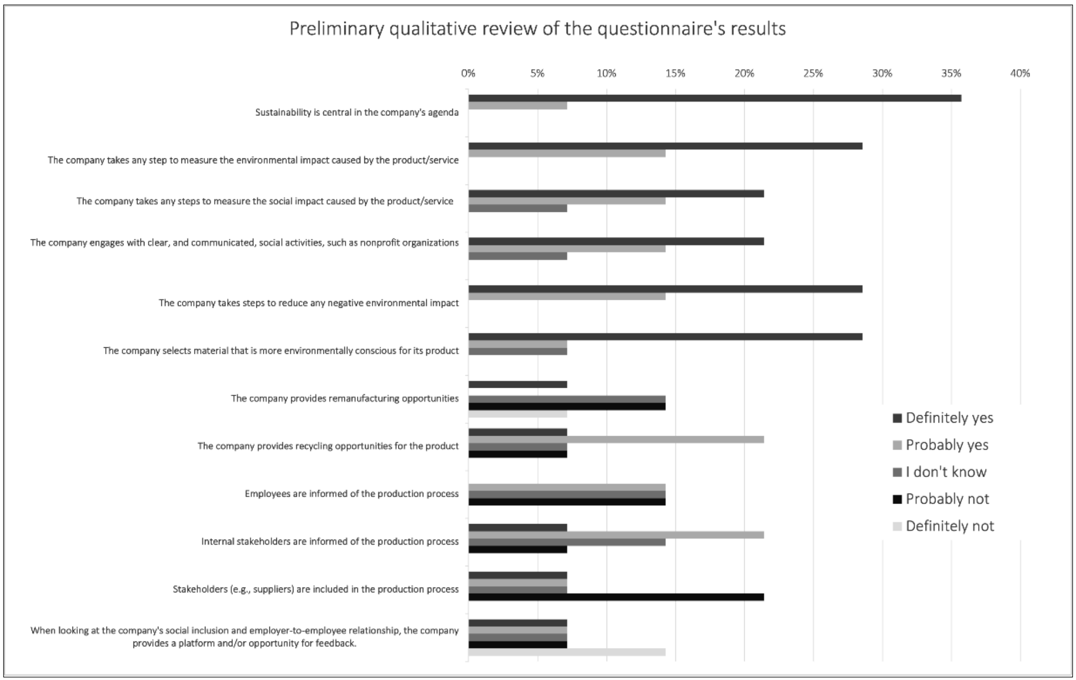

Fig. 2. Representation of partial results showing the % of answers per question on corporate governance, agenda, and application. While respondents were certain that sustainability is central to the company's agenda, there is an increase of indecision regarding application, inclusivity, and stakeholder relationship.

However, if the company is unaware of its circularity limitations it cannot tackle improvements within the design of their products that lead to a holistic approach of circular design. Companies must take into consideration consumer preferences to create complete business models for CE (Kirchherr et al., 2017; Lewandowski; 2016; Ölander and Thogersen, 1995; Planing, 2018; Rexfelt and Hiort af Ornäs, 2009). In particular, as our case study presented, consumers are being drawn more frequently to products that take CE and sustainability into consideration, when they are aware of the distinct CE strategies and then exhibit a higher WTP. The objective of this paper was to provide a tentative structure of awareness and CE assessment that could identify that corporations should take consumers into their model and strategies.

In particular when it comes to the sports sector, it appears, to our knowledge, that there is little about the sports sector and the implementation circular design strategies. Therefore, if we also consider that sports goods manufacturers play an important role in regional economic development, and yet cause environmental pollution (Huang and Chen, 2022), circular design could be a solution to reduce this number and its secondary inevitable effect on the environment. (Nandy et al., 2022).

Therefore, companies in the sports sector, and not only, should choose effective CE strategies by being transparent, educate, and communicate with all its stakeholders, including consumers who not only are at the forefront of sustainability development, but also WTP more for products designed with circular strategies.

6. Limitations and further research

The first limitation is that research for this paper was mainly carried out looking specifically at CE and while review highlights that there is a connection between awareness, WTP, and knowledge to drive effective circularity, lesser attention was given to specific industries or specific CE strategies. The second limitation has to do with one point raised during interviews regarding assessment tools that can be cumbersome, and that for companies it is not always easy to collect information about consumers and other stakeholders. Therefore, the authors of this paper are aware of the challenges that come with identifying the main efficient applications for sustainable CE. Due to this limitation, the scoring system could not take into consideration other methods if the company was able to collect all the required data. Furthermore, the scoring system presented in this paper does not want to become an absolute key for measurement, rather an entry step to identify a company's gaps in various categories and act on it, to gather further awareness on consumers to drive environmental and ecological changes on circular design.

Regarding the questionnaire, further limitations could be caused by the user's misinformation, bias, or unaware of what CE actions entitle affecting the results. Additionally, to be representative for a specific sector, a larger and adequately sample responses is needed also to validate and further test the questionnaire's potential. Finally, companies may be unwilling to critique themselves and social desirability bias may be evident.

Further analysis and study of this questionnaire is required. However, to our knowledge no other study provides a quantified correlation between WTP and CE awareness to achieve efficient circular design highlight the crucial importance of communication among stakeholders.

7. Conclusions

A comprehensive knowledge of CE business models is required to strengthened the ability to implement effective circular product design strategies. It is understood and aware also in the literature that consumers play a crucial role by choosing what to purchase, and if they are willing to pay more for one product against another. Moreover, this occurs also when choosing a product designed according to CE strategies. Furthermore, consumers can also be at the forefront of sustainable development when effectively involved in the design process for circular product concepts.

To measure their involvement and effectively drive the awareness about CE strategies for the deployment of circular products, the author researched to develop a preliminary method that looks to assess a company's circularity awareness and measures it with an awareness scoring system. The questionnaire contributes to the guidance of companies through their areas of improvement for internalizing CE principles and by this determine more effective material and technology choices. The authors believe that this questionnaire is necessary as demonstrated with the previously carried out research in the sports industry, highlighting that not only are consumers important in driving particular decisions, but WTP for environmentally sustainable products. The latter is relevant since it provides significance that when consumers are more WTP for a particular product, firms may be directly interesting to implement certain strategies to create that same product.

To this point, the questionnaire's outcome helps to gain information about the firm and the level of circularity awareness on the organizational level, which in turn would lead to a stronger understanding of consumers collected by the firms. Hence, the questionnaire is a necessary starting point that can support the internalization of CE concepts and translate them into effective circular product design that the consumer understands and is willing to pay. The relevance of this latter statement regards the crucial element that the absence of such investigation within firms could result in products manufactured in a poorly closed-loop system that consumers are still not willing to pay for them, and are thus, not achieving the goal to pressure manufacturers to sell products that are socially, environmentally, and economically sustainable.

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ENVIRONMENTAL PROFILE OF ANAEROBIC AND SEMI-AEROBIC LANDFILLS WITHIN SUSTAINABLE WASTE MANAGEMENT: AN OVERVIEW

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Abstract

The new perspective of circular economy accelerates the efforts to increase reuse and recycling of products and reduce the need of resources. Although the quantity of waste reaching the end-of-life has decreased, landfills can't be eliminated from the waste management systems (WMS) since the current treatment processes still produce unrecyclable materials. Anaerobic landfills have great environmental impacts due to the long-term emissions, therefore, to reach a more sustainable waste management less impacting alternatives are being implemented. Semi aerobic landfills can reduce the environmental burdens by enhancing waste stabilization with natural air flow inside the landfill body through the leachate collection pipes. The presence of aerobic areas implies biogas with less methane and leachate with lower pollutant concentrations. The research goal is to deepen the evidence that the semi-aerobic landfills are environmentally preferable to traditional anaerobic landfills, by considering the scientific information published in international peer-reviewed journals from 2000 to 2022. To obtain comprehensive answers to the research question, papers using the life cycle assessment (LCA) methodology are included in the review, with the aim of understanding what the environmental profiles of traditional and semi-aerobic landfill are when all life cycle phases are considered. The results clarify what the main contributions to environmental impacts of these two types of landfills are. The review only partially demonstrates the environmental convenience of semi-aerobic landfill. Instead, it reveals a lack of papers analyzing the comparison between different landfill technologies, suggesting new research perspectives to optimize the sustainability of final treatment solutions in WMS.

Key words: environmental impact, life cycle assessment, semi-aerobic landfill, waste management systems

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1. Introduction

In recent years the European Union (EU) is moving from a linear economy, in which the resources are considered available and plentiful, to a more sustainable and circular economy in which the generation of waste is minimized by keeping the materials and resources in the loop as long as possible (Barreiro-Gen and Lozano, 2020). The concept of circular economy derives from the will of reaching a sustainable development by reducing treatment and disposal and prioritizing the reduction, reuse, and recycling; this can be achieved through a sustainable and effective waste management system (WMS) (Cherubini et al., 2009). The increasing complexity and quantity of waste represent a challenge for a sustainable WMS (Christensen et al., 2020).

When choosing the most suitable solutions for a city or region's waste treatment system, it is not sufficient to consider only technical and economic aspects, but the environmental impacts should be included in the choice (De Feo and Malvano, 2008). The selection of a technology over another can't be generalized and it is strictly related to the case study

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and local conditions; recycling is one of the less impacting choices although the benefits depend on different factors like the type of material to recycle and the recycling efficiency (JRC, 2011). Moreover, different surface and population density, per capita gross domestic product and per capita municipal solid waste production determine different options in WMS (Calabrò et al., 2015). Given the high position of recycling in the waste hierarchy, it is often perceived as the solution for the waste management criticalities by politicians and public opinion (Cossu et al., 2020). For this reason, the focus has been on increasing the recycling rate and the separate waste collection, meanwhile reducing the quantity of waste going to landfills that, on the contrary, are seen as negative for the environment. The European Union and other developed countries have already set a limit to the quantity of waste that can be disposed in landfills; in these countries the conventional landfills are mostly controlled sanitary landfills to reach the sustainability (Interreg Europe, 2020). The policy change also includes the closing of old landfills and consider them as a source of alternative raw materials (Muica et al., 2021).

The WMS changes dramatically in less developed or developing countries where the sustainable management is one of the biggest challenges due to the rapid increase of waste produced given by the population growth and the rising standard of living (Ahmadifar et al., 2016). Generally, the integrated WMS of developing countries is less organized, incomplete, and insufficient due to the lack of infrastructures and weaker technical skills; complex waste treatment technologies have too high construction costs for those countries and frequently resources are not available for skilled personnel, appropriate equipment and infrastructure and their proper maintenance (Iqbal et al., 2020; Guerrero et al., 2013). It is also recognized that the WMS of developed countries are counterproductive for developing countries due to the lack of connection to the local social and economic conditions (Marshall and Farahbakhsh, 2013). Moreover, in developing countries separate waste collection is difficult to obtain, due to the lack of customer commitment (Calabrò and Satira, 2020). For these reasons, most of the waste produced in these countries ends up in open dumps and uncontrolled landfills (Ferronato and Torretta, 2019).

In case of such complex circumstances, landfills would have a lower effect on the environment: in every case even the landfills are always a better alternative than an uncontrolled waste disposal (Maalouf et al., 2020; Manfredi et al., 2011). The landfill cannot be avoided, due to unrecyclable residual flow, so the concept should be remodeled to reduce the negative impact on the environment and to act as a sink to close the material loop and fulfil its role in the circular economy strategy (Cossu et al., 2020). In the aim of doing this and given the still elevated quantity of landfills around the world, new technologies are being designed and analyzed. One of these is the semi-aerobic landfill, also called “Fukuoka method landfill”, from the Japanese university in which it was originally designed (Hanashima et al., 1981).

The Life Cycle Assessment (LCA) methodology can help give a comprehensive estimation of the environmental impacts associated to each phase of product’s life cycle, from cradle to grave (ISO, 2020a). LCA is frequently adopted to quantify the environmental impacts associated to products, services, and technologies (ISO, 2020a). This methodology is widely recognized as a decision support tool in the field of integrated WMS since it provides relevant information to evaluate, by weighting the benefits and drawbacks, the environmental preferability of one alternative over another (JRC, 2011; Manfredi et al., 2011).

A particular importance should be given to the LCA of landfills given their need and their great impact on the entire WMS. Due to the many factors influencing the performance of the landfill a comparative assessment between types of landfills should be performed to select the best option for each specific situation.

Semi-aerobic landfills are characterized by a different design which enables natural air intrusion into the waste body and the consequent contemporary presence of anaerobic and aerobic spots that enable very specific conditions for enhanced and accelerated waste stabilization processes. As a consequence, the quality of landfill leachate and biogas emissions is enhanced as well (Huang et al., 2008). Although it is a convenient technology, there is a lack of a systematic literature analysis on the environmental convenience of the semi-aerobic compared to the traditional anaerobic landfill technology.

Hence the purpose of this paper is to verify that semi-aerobic landfills are environmentally preferable for the final disposal of waste, to identify the best solutions for the last step of the waste hierarchy. To understand the environmental performances of different alternatives in the WMS, the scientific evidence published in peer-reviewed journals derived by LCA studies related to traditional and semi-aerobic landfills are analyzed and discussed.

2. Background

2.1. Waste management systems

The WMS includes all the treatments and technologies used from the waste collection to the final disposal; it can vary greatly depending on the waste composition, geographical characteristics, and cultural patterns (Christensen et al., 2020). The WMS should follow the waste hierarchy that puts prevention and recycling as a priority and indicates the landfilling as the least preferable option. The prevention has the highest priority since it avoids the impacts of the waste and its treatments on the environment (JRC, 2011).

The waste produced can undergo different treatment technologies; the most frequently considered in scientific studies are recycling for materials like plastic and glass, composting and anaerobic digestion for organic waste, thermal treatment for high calorific waste and landfilling for the unsorted, unrecyclable, and residual waste (Laurent et al., 2014). Although the recycling is widely agreed to be the most sustainable option, the actual environmental benefits depend on the type of waste; in addition, some recycled material cannot be compared to the virgin material since it can be used as a replacement only for a limited extend or for a reduced amount of time (Rigamonti et al., 2018). For this reason, it is important to quantify these benefits and compare them with the advantages of other technologies to choose the most sustainable option for each case study (Ripa et al., 2017).

The recyclability and the final treatment option depends on the state and composition of waste. Homogeneous waste facilitates the recovery of materials and increases the efficiency of treatments having higher quality outputs; unsorted waste instead ends up in the landfill (Bakas et al., 2018). Examples of treatment technologies for homogeneous waste are the composting and anaerobic digestion of the organic fraction. An alternative option to recycling is the thermal treatment; through combustion of waste with a high calorific content, it is possible to stabilize it, decrease its volume and produce electricity obtaining significant environmental benefits (JRC, 2011; Mendes et al., 2004). While from recycling the benefits are given by the avoided impacts for extraction of new virgin material, the waste incineration with energy recovery avoids the impact of energy production (Cherubini et al., 2009; Scipioni et al., 2009). As final option in waste hierarchy, the landfill can be realized with ad-hoc technical solutions to reduce the environmental impacts associated to its operability.

2.2. The role of landfill in the waste management systems

The recycling and thermal treatments are usually preferred over landfilling which has the worse environmental performance (Laurent et al., 2014). On the other hand, the performance depends on the type of waste; the landfills can even be the best environmental solution, with the lowest environmental impacts, in case of inert waste that might need further processing and long-distance treatment (JRC, 2011).

Landfills are also parts of the WMS and cannot be avoided but only minimized and, if possible, made more sustainable (Vaverková, 2019). The great quantity of emissions produced from the waste disposed in landfills makes them the least preferable options. Although the public opinion and politics are pushing for the minimization of landfills, they are still necessary and integrated in the WMS. This is very important for countries with a poor management in which due to the inadequate infrastructure most of the waste produced is either uncollected or badly disposed (Idowu et al., 2019). The collected waste mostly ends up in open dumps and poorly controlled landfills. This means that the waste is directly disposed on the ground without any emission control system to prevent and stop the pollution on the environment resulting in a damage of the groundwater, soil and air quality as well endangering the public health; the priority in this case is to upgrade the disposal method to more controlled and engineered landfill that is easily implemented and managed to reduce and control the pollution (Lavagnolo, 2019).

While in developing countries most of the waste is still disposed in landfills, in more developed countries the quantity of landfills is minimized (Laurent et al., 2014) but still present; active measures have been taken to remediate the open dumps and substitute with engineered sanitary landfills. The modern landfill can play a fundamental role in SWM strategies, serving as a geological repository to close the material cycle (Khan et al., 2022). In developed countries, like the EU, the most frequent landfill technology is the sanitary anaerobic, often called traditional or conventional landfill (Interreg Europe, 2020). In this type of landfill, the waste is anaerobically degraded, partially converted in biogas, with a high percentage of methane, and in leachate, with high pollutant concentration. As represented in Fig. 1, in the traditional landfills most of the measures are taken to control and collect the biogas and leachate, with the purpose of reducing the uncontrolled emissions, but little is done to actively increase the waste stabilization (Manfredi and Christensen, 2009). The multi-barrier principle was introduced to highlight the benefits of a combination of features, including waste pre-treatment and measures to enhance waste stabilization processes in the landfill body, to effectively control landfill long term emissions (Cossu, 2018). In this perspective, semi-aerobic conditions enable the acceleration of waste stabilization processes and the enhancement of leachate and biogas quality; for these reasons they provide an effective barrier to contaminant release into the environment.

2.3. Semi-aerobic landfill

Also known as the Fukuoka method, the semi-aerobic landfill combines the presence of aerobic and anaerobic areas to improve the waste degradation; this method allows to have aerobic areas without the needs of additional aeration (Ahmadifar et al., 2016). This combination allows to decrease the landfill life and therefore decrease the pollution on the environment; the shorter life is given by the faster waste stabilization due to the characteristics of this technology (Huang et al., 2008).

The method consists of inserting large, slotted pipes on the bottom of the landfill to collect the leachate by gravity (Fig. 1). The pipes in the landfill are designed to not be filled of leachate to also allow the natural air flow in the landfill body (Huang et al., 2008).

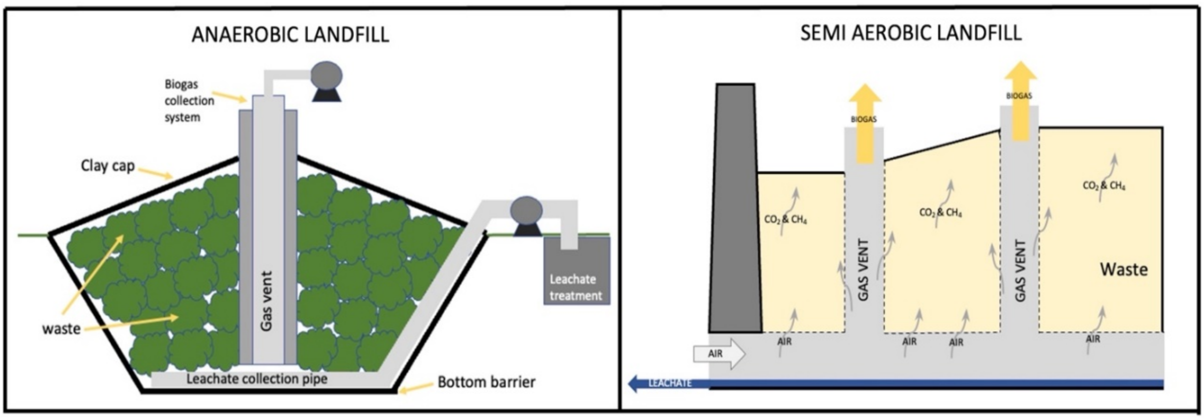

Fig. 1. Anaerobic and semi-aerobic landfill schemes comparison

They are also connected with the gas vents in the landfill body directly connected to the atmosphere, this allows the aeration of the waste in every part of the landfill body (Matsuto et al., 2015). The natural airflow is induced from a chimney effect resulting from a difference in temperature between the landfill body and the outside air (Ahmadifar et al., 2016). The aerobic degradation of the waste increases the temperature making the gas rise and creating a negative pressure inside the landfill body that draws the outside air in the waste from the leachate pipes (Matsuto, et al., 2015). The temperature in the landfill body was proven to remain high during the landfill life. Although the temperature difference is the main driver for the waste aeration, other factors such as the composition and compaction of the waste and the characteristics of the cover materials, have been proven to be influencing it; the efficiency of this technology also depends on the location of the landfill since a warmer climate will reduce the temperature difference (Matsuto et al., 2015).

Regarding the biogas produced, the quantity of methane is negligible respect to the percentages of it in the biogas of the traditional landfill. Instead, the biogas produced is high in CO_2 and N_2 (Manfredi and Christensen, 2009). Due to the low concentration of methane the biogas produced is usually not used for energy recovery; the biogas is often directly released in the environment. The use of biofilter and bio covers were also proven, by Bacchi et al. (2018), to be effective in reducing the CH_4 emissions, when energy recovery is not a feasible option, and to be a sustainable alternative to further decrease the environmental impacts given by the release of the biogas. Beside accelerating the waste stabilization, this methodology allows to quickly reduce the concentration of both organic substances and ammonia in the leachate if compared with the leachate of a traditional landfill; the quality of the leachate increased rapidly, therefore requiring fewer treatments (Huang et al., 2008). Leachate from traditional anaerobic landfills normally requires intensive and expensive biological and chemical treatments off site for a long time after landfill closure. On the contrary, semi-aerobic landfill leachate is expected to show lower concentration of solutes and it could be treated by means of less costly and purposely designed systems (Aziz et al., 2010). Furthermore, the collection of the leachate by force of gravity, that makes the construction of the landfill and its operation easier, allows to avoid the use of pumps and the consumption of electricity for their operation that are instead needed in the traditional landfill.

2.4. The LCA methodology in WMS

A helpful instrument to better understand the impacts associated to the waste treatment technologies and to take actions to implement more sustainable solutions in WMS is the life cycle assessment (LCA) methodology (De Feo and Malvano, 2008). The LCA methodology can be used to understand the consequences of human choices on the environment by modeling the cause-effect relationships in the environment (Mazzi, 2020).

To support the practitioners in the conduction of a thorough LCA study, two international standards are present: the ISO 14040 (ISO, 2020a) which contains the general principles and the ISO 14044 (ISO, 2020b) with more specific requirement. The methodology consists of 4 phases, namely goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA) and results interpretation. During the first phase of LCA, the goal of the study and its scope must be explicated; coherently the functional unit and the system boundaries have to be defined, in order to clearly decide which processes, inputs and outputs are included in the study. Secondly, in LCI, all relevant information about input and output flows associated to each process included in the boundaries are collected, in terms of material and energy consumption, product and byproduct flows and emissions to air, water and soil. The environmental impacts are calculated in the life cycle impact assessment (LCIA) phase, using ad-hoc environmental impact assessment methods and indicators, with the support of LCA software. The result obtained by the LCIA is the environmental profile of the product: environmental hotspots and critical points are identified aiming at the subsequent interpretation phase, in which additional deepening of LCIA results enable a better understanding of the contribution of each life cycle stage and of specific materials and substances to the total environmental profile (Mazzi, 2020; Silva, 2021).

Different features, like the life cycle perspective, the coverage of an extensive range of environmental issues and its quantitative and science-based nature, make the LCA a complete support tool for sustainable commitments of corporations and markets (Bjørn et al., 2018). According to Hellweg and Mila` i Canals (2014) to support companies internal decision-making for products eco-design, optimizations of processes and supply-chain management, many LCA analyses are being done. The LCA approach can be a valuable tool in all consumption sectors through the display of information on a variety of impact categories in product labeling (Toniolo et al., 2019).

The LCA methodology for WMS, often called "waste LCA", is widely used to evaluate and compare the end-of -life of products (Bakas et al., 2018). It can be used to calculate the environmental impacts and to help choosing the less impactful treatment technologies, to optimize the environmental performance of waste separation and recycling, or to design new WMS solutions at local level (Christensen et al., 2020; Ripa et al., 2017). Many papers on waste LCA analyze the benefits and advantages of the recycling technologies for different materials given the importance of it in the waste hierarchy (Mazzi, 2021). Given the great influence of site-specific data on the WMS, the LCA can help identifying the critical aspects and suggest improvement by reproducing local condition and taking them into account in the impact calculation (Laurent et al., 2014).

In the waste LCA the functional unit is usually expressed in terms of the system input like the quantity of waste to be treated or disposed (Cherubini et al., 2009). The waste LCA has mostly a comparative nature and consequently it has a different system boundary than a product LCA; indeed, the previous stages before the collection of the waste are not included (Bakas et al., 2018; Barreiro-Gen and Lozano, 2020).

Generally, when applying the LCA in waste management, the zero-burden assumption is considered; the waste it's not assumed to be already associated with any environmental impact when it enters the system (Laurent et al., 2014). Except for the entering waste, all the input and output of the system boundaries are transformed in environmental impacts through an impact assessment method. When comparing different alternatives for WMS, it is important to include in the system boundaries the materials needed for the construction and operation and the possible additional waste flows (Mazzi et al., 2022).

According to Cherubini et al. (2009) to have a consistent information on the impact assessment of the system considered, several assessment methods should be used. When analyzing possible scenarios, it is possible that the improvements are not proportional in all the impact categories therefore it is advised to carefully analyze the results and the benefits before decision making to avoid a burden shift situation (Ripa et al., 2017). According to Christensen et al. (2020) the waste LCA have different applications to support the management of solid waste which are the understanding of the impacts of the entire WMS and its improvement, the comparison of different technologies and the development of new ones. Other important functions are the reporting and the policy making development.

3. Material and methods

From the overview presented in the introduction section, some considerations emerged, and further insights must be verified, as research hypotheses that can be confirmed or denied through the literature review.

• In the international scientific debate, LCA studies can be conducted to evaluate the potential impacts on the environment caused by the final treatment solid waste through the use of different landfill technologies.

• It is plausible that the scientific discussion analyzes the convenience of semi-aerobic landfill compared to the traditional one.

• A comprehensive quantification of the environmental profile of semi-aerobic landfill can be obtained using the LCA methodology.

• The environmental convenience of semi-aerobic landfill in WMS has to be demonstrated in particular in developing countries, where the alternative final treatment could be the open dumps.

To verify the research hypotheses, qualitative research based on a systematic literature review is conducted, exploring the research topic in scientific papers published during the last 20 years. In line with the methodology suggested by Luederitz et al. (2016) and Mazzi et al. (2016) the research is structured in four steps, detailed in Table 1:

- Step 1 – Screening: preliminary survey with international databases, using specific research keywords and ad-hoc inclusion and exclusion criteria.
- Step 2 – Cleaning: selection of relevant papers, on the base of their consistency with the research topic and the research hypotheses.
- Step 3 – Classification: analysis of the selected papers in terms of type of publication, type of landfill, and other LCA characteristics.
- Step 4 – Discussion: deepened overview of the LCA results, to verify the research hypotheses and to obtain answers to the research question.

4. Results and discussion

4.1. LCA studies related to landfill

From the steps of screening and cleaning, 29 papers, published from 2000 and 2022 and related to the LCA of landfill, are identified: these papers, listed in Table 2, are further analyzed in the steps of the classification and discussion. To reach the goal, the review is limited to the LCA studies of landfill technology; other LCA studies on WMS published in the last 20 years are therefore not considered in this research.

Only studies comparing the landfill on its own, and not included in the solid waste management, are included in the study. If the landfill impacts are considered separately, also the papers comparing the landfill to other treatments are assumed to be relevant for the research.

Articles analyzing only parts of the landfill, like the leachate or the biogas treatment, are integrated in the literature review if considerate significant. The papers describing the waste characteristics are included in the study, due to great impact that they have on the resulting emissions of the landfill (Manfredi et al., 2010b).

Table 1. Objectives, contents, and criteria of the research steps

Research step	*Objectives*	*Source of inputs*	*Criteria*
Step 1 – Screening	Obtain a preliminary list of papers discussing the LCA of landfills in WMS	Firstly, Scopus and Google Scholar's and the editors' libraries (Emerald Insight, Science Direct, Springer Library, Wiley Library)	Search through the keywords "LCA" and "landfill" in title and abstract Only papers published in peer-reviewed journals Only papers in English Years of publication 2000 – 2022 (last access on August 31st 2022)
Step 2 – Cleaning	Select only the papers consistent with the research goal and scope	The preliminary list of papers obtained by the Step 1 Deepen analysis of abstract and text of papers	Selection of papers that report results of LCA studies related to landfill, both anaerobic and semi-aerobic
Step 3 – Classification	Classification of studies on the base of the main characteristics of landfill and LCA	All papers selected in the Step 2 Deepen analysis of papers' contents	Case studies analyzed in terms of: - Year of publication - Journal of publication - Landfill technology - Geographical location - Steps of life cycle included - Impact categories considered
Step 4 – Discussion	Comparison of the LCA results and verification of research hypotheses	All papers selected in the Step 2 Deepen analysis of papers' contents	Case studies discussed in terms of confirmation or deny of research hypotheses

Table 2. List of papers exploring the environmental profile of landfill technologies

Reference	*Title*	*DOI*
Xiao et al., 2022	Comparative environmental and economic life cycle assessment of dry and wet anaerobic digestion for treating food waste and biogas digestate	hiips://doi.org/10.1016/j.jclepro.2022.130674
Ouedraogo et al., 2022	Life cycle assessment of gasification and landfilling for disposal of municipal solid wastes	hiips://doi.org/10.3390/en14217032
Mazzi et al., 2022	Environmental performance of semi-aerobic landfill by means of life cycle assessment modeling	hiips://doi.org/10.3390/en15176306
Ferrans et al., 2022	Life cycle assessment of management scenarios for dredged sediments: environmental impacts caused during landfilling and soil conditioning	hiips://doi.org/10.3390/su142013139
Wang et al., 2021	Life-cycle assessment of a regulatory compliant U.S. municipal solid waste landfill	hiips://doi.org/10.1021/acs.est.1c02526
Sauve and Van Acker, 2021	Integrating life cycle assessment (LCA) and quantitative risk assessment (QRA) to address model uncertainties: defining a landfill reference case under varying environmental and engineering conditions	hiips://doi.org/10.1007/s11367-020-01848-z
Sauve and Van Acker, 2020	The environmental impacts of municipal solid waste landfills in Europe: a life cycle assessment of proper reference cases to support decision making	hiips://doi.org/10.1016/j.jenvman.2020.110216

Henriksen et al., 2017	Linking data choices and context specificity in life cycle assessment of waste treatment technologies a landfill case study	10.1111/jiec.12709
Di Maria et al., 2016	Treatment of mechanically sorted organic waste by bioreactor landfill: experimental results and preliminary comparative impact assessment with bio stabilization and conventional landfill	hiips://dx.doi.org/10.1016/j.wasman.2016.03.033
Yang et al., 2014	Environmental impact assessment on the construction and operation of municipal solid waste sanitary landfills in developing countries: China case study	hiips://dx.doi.org/10.1016/j.wasman.2014.02.017
Khoo et al., 2012	Projecting the environmental profile of Singapore's landfill activities: comparisons of present and future scenarios based on LCA	hiips://doi.org/10.1016/j.wasman.2011.12.010
Damgaard et al., 2011	LCA and economic evaluation of landfill leachate and gas technologies	hiips://doi.org/10.1016/j.wasman.2011.02.027
Manfredi et al., 2010a	Environmental assessment of low-organic waste landfill scenarios by means of life-cycle assessment modelling (easewaste)	hiips://doi.org/10.1177/0734242x09104127
Manfredi et al., 2010b	Contribution of individual waste fractions to the environmental impacts from landfilling of municipal solid waste	hiips://doi.org/10.1016/j.wasman.2009.09.017
Niskanen et al., 2009	Environmental assessment of Ämmässuo landfill (Finland) by means of LCA-modelling (easewaste)	hiips://doi.org/10.1177/0734242x08096976
Manfredi and Christensen, 2009	Environmental assessment of solid waste landfilling technologies by means of LCA-modeling	hiips://doi.org/10.1016/j.wasman.2008.02.021
Kirkeby et al., 2007	Modelling of environmental impacts of solid waste landfilling within the life-cycle analysis program easewaste	hiips://doi.org/10.1016/j.wasman.2006.06.017
Ménard et al., 2004	Comparative life cycle assessment of two landfill technologies for the treatment of municipal solid waste	hiips://dx.doi.org/10.1065/ica2004.09.180.6
Nikkhah et al., 2018	Hybrid landfill gas emissions modeling and life cycle assessment for determining the appropriate period to install biogas system	hiips://doi.org/10.1016/j.jclepro.2018.03.080
Beylot et al., 2013	Life cycle assessment of landfill biogas management: sensitivity to diffuse and combustion air emissions	hiips://dx.doi.org/10.1016/j.wasman.2012.08.017
Voronova et al., 2011	Environmental assessment and sustainable management options of leachate and landfill gas treatment in Estonian municipal waste landfills	hiips://doi.org/10.1108/14777831111170876
Ouedraogo et al., 2021	Comparative life cycle assessment of gasification and landfilling for disposal of municipal solid wastes	hiips://doi.org/10.3390/en14217032
Demetrious and Crossin, 2019	Life cycle assessment of paper and plastic packaging waste in landfill, incineration, and gasification-pyrolysis	hiips://doi.org/10.1007/s10163-019-00842-4
Grzesik, 2017	Comparative environmental impact assessment of the landfilling and incineration of residual waste in Krakow	hiips://doi.org/10.5277/epe170411
Nabavi-Pelesaraei et al., 2017	Modeling of energy consumption and environmental life cycle assessment for incineration and landfill systems of municipal solid waste management - a case study in Tehran metropolis of Iran	hiips://dx.doi.org/10.1016/j.jclepro.2017.01.172
Al-Fadhli, 2016	Assessment of environmental burdens of the current disposal method of municipal solid waste in Kuwait vs. waste-to-energy using life cycle assessment (LCA)	hiips://doi.org/10.7763/ijesd.2016.v7.806
Assamoi and Lawryshyn, 2011	The environmental comparison of landfilling vs. Incineration of MSW accounting for waste diversion	hiips://doi.org/10.1016/j.wasman.2011.10.023
Abduli et al., 2010	Life cycle assessment (LCA) of solid waste management strategies in Tehran: landfill and composting plus landfill	hiips://doi.org/10.1007/s10661-010-1707-x
Mendes et al., 2004	Comparison of the environmental impact of incineration and landfilling in São Paulo city as determined by LCA	hiips://doi.org/10.1016/j.resconrec.2003.08.003

The selected studies are then analyzed and classified; several elements are examined for each paper and reported. The issuing year and the country and the journal in which they are published, are checked to get a summary view. The main characteristics of the LCA studies are summarized: the goal and functional units are initially evaluated to assess the pertinency of the paper. The characteristics of modelled landfill are reported, in terms of life cycle phases included, the landfill lifetime, and the system boundaries. Concerning the impact assessment phase, the selected papers are analyzed in terms of methods, impact categories and software used to calculate the environmental hotspots. A summary of the LCA results is considered to conclude the review, including possible sensitivity analyses.

4.2. Main characteristics of LCA studies related to landfills

The cases studies included in the review (as in Table 2) are distributed during the years as reported in Fig. 2. More than 50% of papers are published in the last 10 years; however, in recent years, the papers focusing on landfill don't follow the same increasing trend as the other WMS LCA studies, probably due to the decreased interest on this solution in the waste hierarchy and the reduction of its use, especially in developed countries. Out of the selected papers, 20 are comparative studies, while 3 studies analyze only some parts of landfill life cycle. Most of the studies although analyzed the traditional anaerobic landfill for municipal solid waste and either compared it with another typology or with different types of leachate and gas treatments. Most of the waste LCA studies compare different technologies to apply in the WMS; the comparison is usually made between the recycling or the thermal treatment with a traditional anaerobic landfill.

Although the developed countries are decreasing the landfill use, the geographical distribution in Fig. 3 shows that the majority of the LCA studies are from European countries. Only 5 studies were done in developing countries, of which most of them were done to compare the landfill with other treatment to prove their preferability over the landfill's. Over 40% of the analyzed papers specifies the ISO 14040 and ISO 14044 standards as methodological framework to conduct the LCA study. In two papers published before 2006 the references for LCA study are the standards published before the present version. However, almost 50% of the papers found did not specify the use of any standard to perform the study.

By virtue of the selection criteria used (first step – Screening), all papers are published on peer review international journals, but there is a particular concentration of papers in few journals.

In LCA studies about landfills, the functional unit (FU) is usually the landfilling of a certain amount of waste. Most of the studies use as FU a reference value of waste, like 1 ton or 1 kg, to be landfilled; this also sometimes includes characteristics of the type of waste and of the type of landfill and the lifetime. Some papers instead use as FU the total quantity of waste to be disposed or the quantity of electricity and heat produced form the landfill biogas. Although the waste fraction and characteristics assumed are different for each study, they are all considered to be from the municipal solid waste collection with average characteristics form the country or city where the landfill case study is located; only one study includes contaminated soil and construction and demolition waste to be disposed in the landfill.

As shown in Fig. 4 the attention of authors in LCA studies is not always referred to the entire life cycle of the landfill. Out of the selected papers, few cases only report the impacts related to all the landfill life cycle stages, from cradle to grave; frequently operation phase is included in the analysis, rather than the construction, closure or aftercare phases, that are considered by only few LCA studies.

In comparison with other treatment plants, which have immediate direct emission, the landfills release small concentrations of pollutants for a very long period of time. Because of the difficulties in considering the long-term emissions from the landfill, a hundred-year period is usually assumed in the landfill LCA studies. About 10% of the studies in literature assume 30 years to assess only the phase with the highest emissions while another 10% considered 140 years to evaluate the impact of the landfill for longer time.

During a LCA study, different choices that can affect the results have to be made; to assess the influence of those assumptions a sensitivity analysis can be performed. In the LCA of landfills many factors can be analyzed; according to Kirkeby et al. (2007) one of the most affecting elements is the waste type assumed. Only 8 studies among the selected papers included the sensitivity analysis. The analysis was done on input parameters like the energy consumed, the biogas collection and the gas production.

Due to the many assumptions that have to be made when analyzing the landfill, the results of the studies could have many uncertainties. To test those uncertainties the Monte Carlo uncertainty analysis can be done; only 2 papers performed this analysis.

When assessing the landfill impact on the environment through a life cycle methodology, all the steps of the landfill life should be considered, which includes all the materials needed for the construction and the energy used even after the landfill's closure. About 60% of the studies include the construction of the infrastructure or at least the fuel for the disposal of the soil and waste. Only about 40% of the studies include the waste transportation to the site due to the low influence on the results and due to the defined system boundaries. The leachate and biogas treatment are not always included as well. The leachate treatment is assessed in only 11 papers, while 5 of them only partially include it by assuming a removal efficiency but without the energy and materials to do the treatment itself. The biogas management instead is present in almost all the analyzed cases. Regarding the software used in waste LCA studies, the EASYWASTE is the preferred since it is used in 9 papers; probably because this software includes a landfill model that allows to use defaults datasets for conventional landfills. In few papers information about the software used for the impact assessment is reported: SimaPro is used in 4 papers, GaBi software in 3 studies, and EASETECH in 1 study.

The impact assessment method adopted in the LCIA step is declared in 20 studies only: the EDIP method is the most frequently named, followed by TRACI and CML. Otherwise, in all the studies a multicriteria impact assessment model is used to quantify the environmental impacts, through several impact categories, as represented in Fig. 5. The global warming potential is always included in the LCA studies. Moreover, acidification, ecotoxicity, eutrophication, human toxicity and ozone depletion are generally adopted to quantify environmental impacts of landfills. Some impact categories are not frequently used, and several categories are very rarely considered to quantify the environmental profile of landfills.

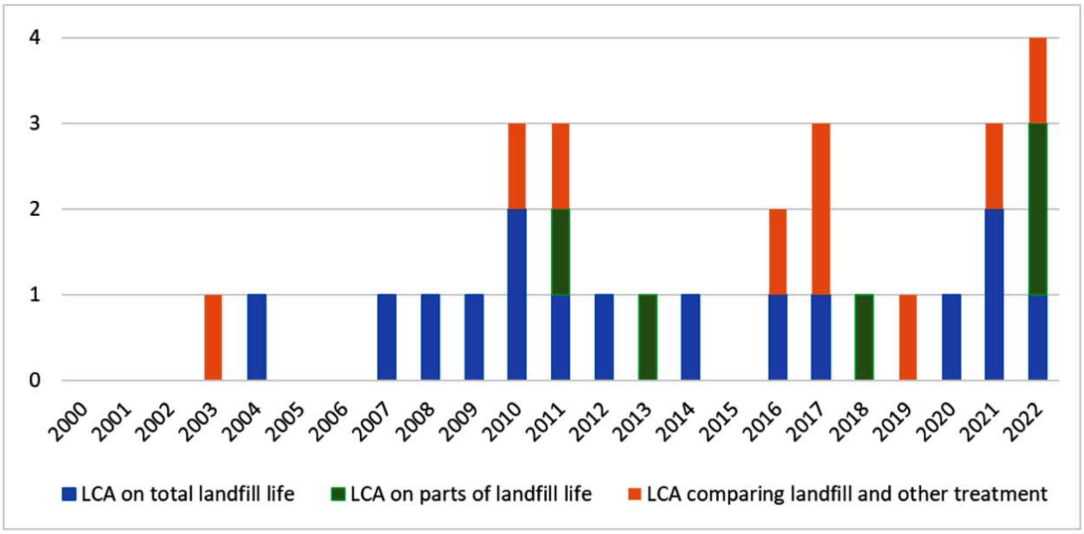

Fig. 2. Studies distribution in time divided by type of study

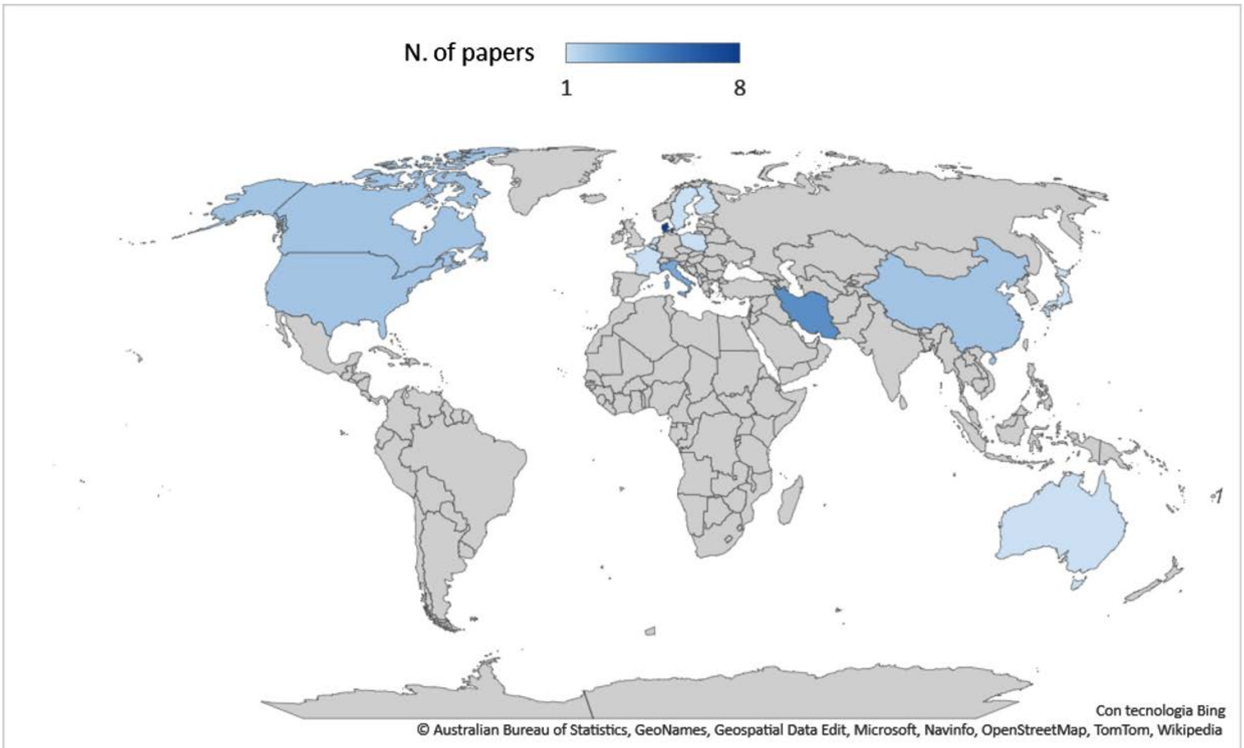

Fig. 3. Geographical distribution of landfill LCA studies

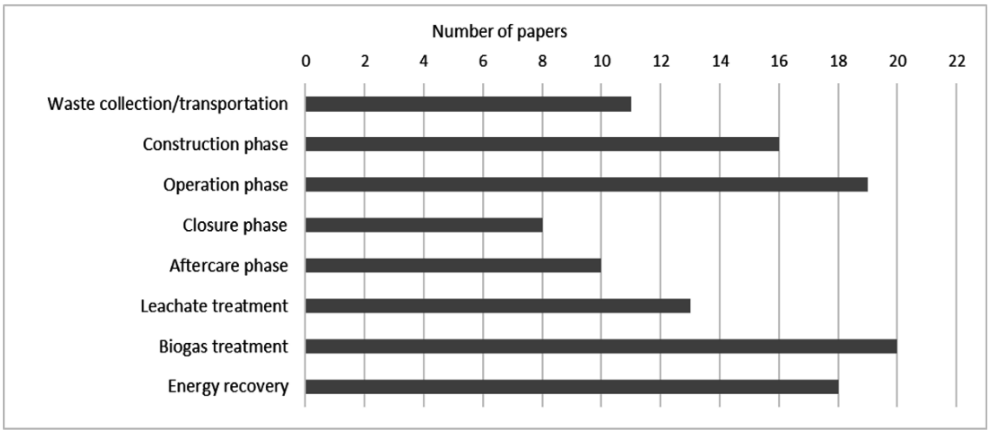

Fig. 4. Distribution of papers per life cycle phases included in the system boundaries

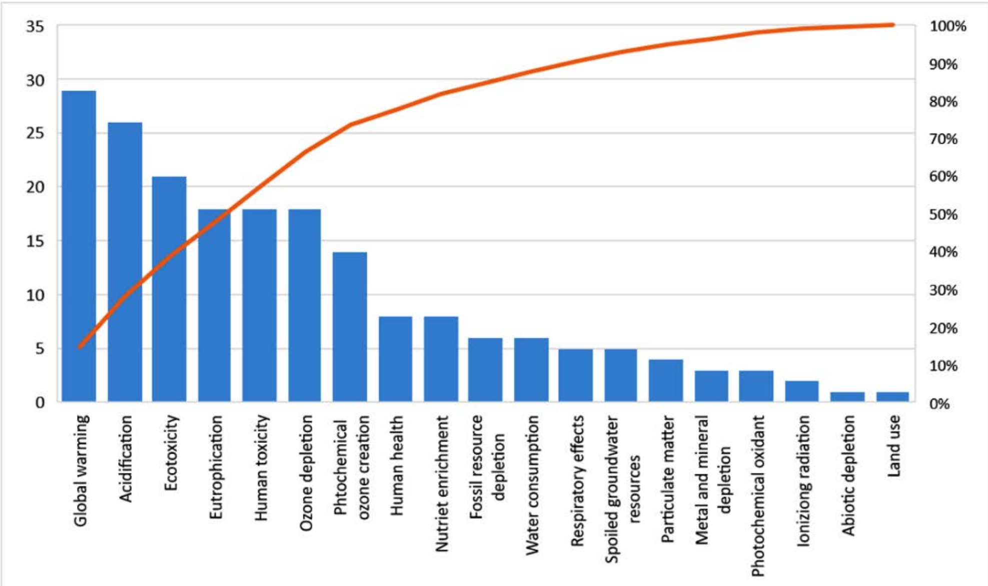

Fig. 5. Impact categories used in landfill LCA studies

4.3. Environmental performances of landfill

Different types of landfills are analyzed through the LCA methodology in scientific literature. The open dump, the conventional, the hybrid, the bioreactor landfill and, in only two studies, the semi-aerobic landfill were included.

The open dump is the worst alternative since it is defined as an uncontrolled disposal and there are no measures to stop the emissions of the waste on the environment. The studies addressing the problem of open dumps from a LCA point of view appears to have similar results; the dump shows to have a much higher impacts on global warming, human toxicity and ozone depletion potential compared to traditional landfill with leachate and biogas collection and treatment. These results prove the importance of the control of the emissions and the collection of biogas and leachate to significantly reduce the landfill impacts and improve its environmental performance (Damgaard et al., 2011). According to Beylot et al. (2013) the open dump has the worse impacts than the traditional landfill on the climate change, ozone depletion, human toxicity and ecotoxicity impact categories.

The most analyzed landfill type is the anaerobic landfill due to its wide use around the world. When compared with other WMS technologies it results to be the worse alternative due leachate and biogas emissions and the lack of material recovery. The production of biogas and leachate lasts for a long time with high concentrations of pollutants. According to Wang et al. (2021), the normalized results show that the traditional landfills mostly impact on the global warming potential due to the gas emission. From the results of the study of Kirkeby et al. (2007) emerges that the landfill biogas also has a relevant impact on human toxicity and photo chemical ozone. While the biogas can be collected and utilized for energy production, the leachate must go through numerous treatments to reach the legislative limits concentration. Both the direct long-term emissions from the leachate pollutants and the emissions of the treatment plant have relevant impact. As can be seen from the paper of Sauve and Van Acker (2021) wastewater treatment has a great impact on the ecotoxicity and human toxicity potentials.

Although it is not always considered, the construction of the landfill site can be one of the major contributors of the total impacts like in the case of Yang et al. (2014); the diesel used for daily operations appears to have a great influence on all the impact categories.

An advantage of this type of landfill is the possibility, when a high percentage of methane is produced, to use the biogas as an energy source. The energy recovery is highly influenced by the landfill design and composition of waste: the gas extraction can be done for a limited amount of time after which other possibilities have to be employed (Kirkeby et al., 2007). This benefit is limited, other than the period of high methane production and extraction, to the energy production already used in the area and that the landfill biogas would substitute. According to Manfredi and Christensen (2009) the energy recovery from the landfill gas allows to have avoided impacts greater than the landfill direct emissions on the global warming potential impact category when the electricity is produced in a coal fired power plant. This is because the green house generated in the power plant are higher than the ones emitted by the landfill to produce the same electricity. In this case, the energy recovery is also beneficial on impact categories like human toxicity (via soil and water), acidification, nutrient enrichment, and photochemical ozone formation; the negative contribution to the total impact of each category is although not enough to outbalance the impact from the direct emissions as seen in Fig. 6 (Manfredi and Christensen, 2009).

The waste composition also greatly influences this benefit; an example is given by Manfredi et al. (2010a) who analyzed the landfilling of low organic waste which resulted in poorer production of methane and lower avoided impact from energy recovery. Benefits of the energy recovery given by the high presence of organic waste are also proven by the paper of Manfredi et al. (2010b).

Different studies address the impacts of hybrid landfills respect to the traditional one; the results from those studies all agree to the better environmental performance of the hybrid landfill due to the active measures to stabilize the waste.

4.4. Environmental performances of the semi-aerobic landfill

From the literature review, two studies report the application of the LCA methodology to semi-aerobic landfills. Despite the limits related to these case studies, it is notable to analyze the main results because of the relevant information available, concerning the environmental profile associated to the semi-aerobic landfills. Moreover, they report important recommendations to support consistent evaluations about the environmental impacts related to the life cycle of a landfill.

The first study, published in 2009 by Manfredi and Christensen, compares the environmental performances of semi-aerobic and other type of landfills. The second one, recently published (Mazzi et al., 2022) quantifies the impacts associated to the entire life cycle of a semi-aerobic landfill, including construction, filling, aftercare, closure, and conversion.

Manfredi and Christensen (2009) compared 6 different types of landfills, from the worse option which is the open dump to newer technologies like the bioreactor and the semi-aerobic landfill. According to this study the semi-aerobic landfill total impact is lower than open dumps and are also slightly better than the traditional and bioreactor landfill (Fig. 7).

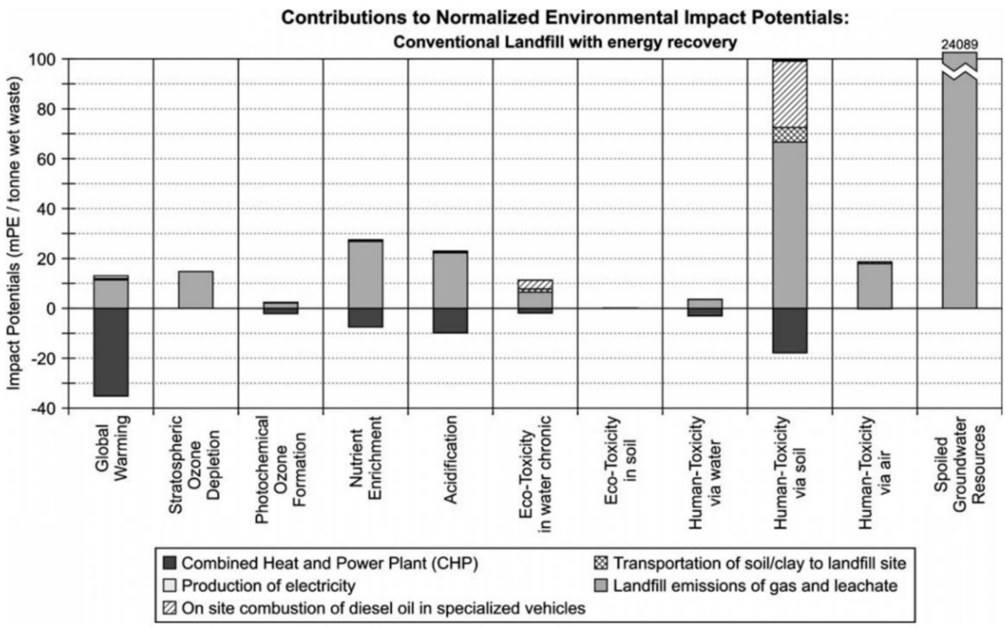

Fig. 6. Environmental impacts of conventional landfill (Manfredi and Christensen, 2009)

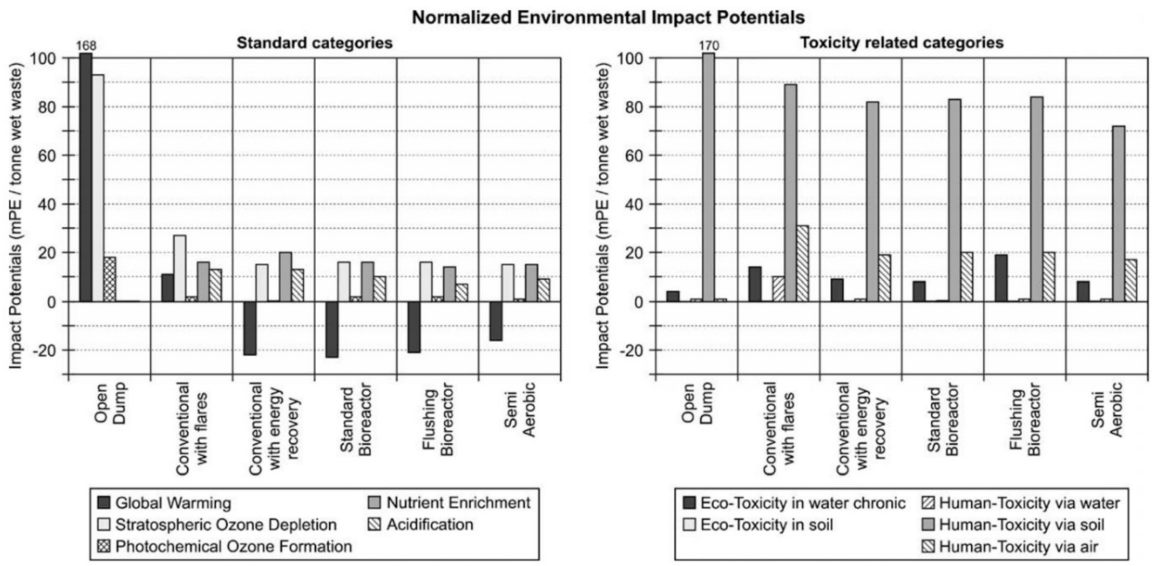

Fig. 7. Comparison of 6 landfill type's normalized impacts potential (Manfredi and Christensen, 2009)

According to the model used, Manfredi and Christensen (2009) took into account both anaerobic and aerobic conditions expected in the semi-aerobic landfill and they assumed that gas management and utilization for energy recovery was carried out for the first 8 years; in the same period leachate recirculation was carried out as well. Afterwards, an artificial air flow was activated to start waste aerobic degradation processes; as a consequence, methane concentration in the gas was assumed to drop to 5%.

From the results of the study by Manfredi and Christensen (2009) (Fig. 7) it was found that the semi-aerobic landfill had lower impacts in all the toxicity related impact categories in comparison to the other technologies analyzed while in the standard categories the benefits are less evident but still present.

Manfredi and Christensen (2009) demonstrate the main benefits of the semi-aerobic landfill compared to the traditional landfill. The direct emissions are lower than a traditional landfill due to the aerobic areas. The faster waste stabilization allows to decrease the impact of the biogas since the quantity of methane in it is low. The higher presence of CO_2 in the biogas decreases the global warming potential. A further benefit of this technology is the avoided impacts due to the leachate collection by gravity as the use of pumps can be avoided. The fast stabilization of the waste, that reduces the need for costly leachate treatment, makes this technology a great opportunity for both developed and developing countries. A disadvantage is the very limited possibility for energy production from the landfill biogas due to the low concentration of methane. The disadvantage is although limited to the country energy source for electricity production. Mazzi et al. (2022) assessed the potential impacts and the environmental performance of the semi-aerobic landfill technology through the LCA, using project data of an Italian pilot plant. All the life cycle phases were included into the system boundaries, from landfill construction to filling, aftercare, closure and conversion for future use. The results show that the overall environmental impacts associated to semi-aerobic landfill are primarily due to filling and aftercare phases, and secondly to construction and closure phases (Fig. 8).

The results of case study in Mazzi et al. (2022) show that the biggest share in the total impact is given by the leachate: even if its pollutants concentrations are below the concentration limit, the volumes released are significant and, consequently, the impact on the marine and freshwater ecotoxicity are relevant. Methane emissions reduction through enhanced methane oxidation would have a lower impact reduction than improving the efficiency of leachate treatment. The impact of landfill construction, filling and closure, in terms of material use and transportation, cannot be neglected as it can be comparable to impacts caused by emissions. From the normalization of impact assessment results, it is possible also to recognize what are the environmental categories on which the impacts of the landfill fall most: primarily marine and freshwater ecotoxicity, followed by land use, human carcinogenic and non-carcinogenic toxicity, and terrestrial ecotoxicity; other impact categories can be considered negligible in the overall environmental landfill profile.

The Italian case study analyzed in Mazzi et al. (2022) demonstrates the relevance of comprehensive analysis, including all the life cycle stages of landfill plant, from cradle to grave: as underlined by these results, materials used in landfill construction, filling and closure significantly contribute to the environmental profile of semi-aerobic landfill. From these results, it is notable that when assessing the impacts of a landfill, the analysis should not only focus on the biogas and leachate but should also include all the materials used during the landfill life cycle.

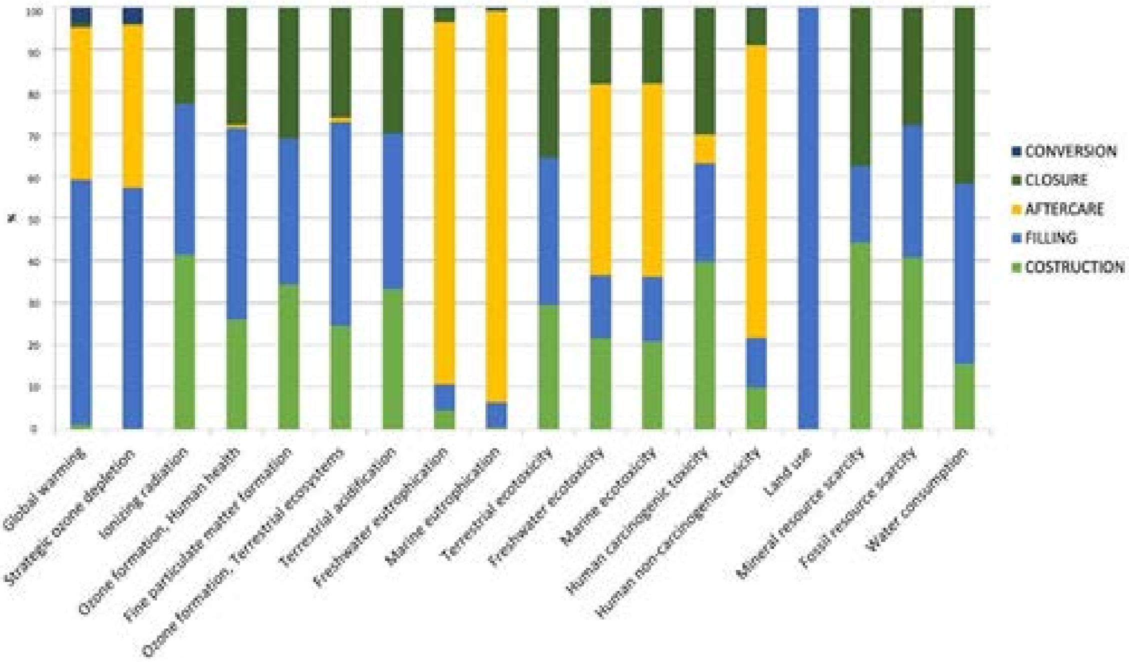

Fig. 8: Impact assessment results of life cycle phases of semi-aerobic landfill (Mazzi et al., 2022)

5. Conclusions

A literature review on different waste LCA studies, based on English paper from peer review international journals available online, has been performed to analyze the environmental profile related to landfill construction, filling, closure and aftercare. Different types of landfills have been taken into consideration. Strong focus has been placed on the impact assessment of municipal solid waste disposed in traditional landfill; different options for leachate and biogas treatment were compared in the reviewed studies. From the comparison of open dumps with other technologies emerged the importance of the control of the emissions to diminish the impacts. Active measures to increase the waste degradation, like in the bioreactor or hybrid landfill, was observed to improve of the landfill's burden on the environment in various impact categories.

The benefits of the semi-aerobic landfill were described and its preferability was partially proven by the scientists. The semi-aerobic landfill was found to be effective in reducing the direct and indirect impact of the traditional landfill; indeed, it allows to reduce the biogas and leachate emissions, reaching waste stability in shorter times and leaving out the need of pumps and specific treatments. The waste stabilization is shortened by the aerobic areas that, at the same, reduce the methane concentration in the biogas limiting the energy recovery and its avoided impacts. Due to faster waste stabilization, the management of the landfill is shorter and easier making this technology viable also by developing countries. From the results published in these papers it is possible to state that the semi-aerobic landfill, decreasing the time its emissions have a concerning environmental impact, helps to move forward a more sustainable solid waste management.

Although the environmental benefits related to the semi-aerobic landfill are clear, evidences are limited by the lack of studies on this topic; only two papers in last 20 years focus the attention on the semi-aerobic landfill, and quantify the environmental profile associated to the entire life cycle of this technology. Further studies should be conducted to better analyze the total impacts of the semi aerobic landfill throughout its life. Newer research comparing different landfills, also inserted in the total solid waste management system performances should additionally be done including the sensitivity analysis varying the waste composition and landfill location.

These additional comparisons are helpful to further prove the preferability of this technology, in both developed and developing countries. Moreover, possible conversion into semi-aerobic conditions might be considered for closed traditional landfills.

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PLANETARY HEALTH: AN INTERDISCIPLINARY PERSPECTIVE

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Abstract

This paper addresses the issue of planetary health under a multidisciplinary profile. It starts with defining the scope of planetary health, retracing its most salient historical points. It then reflects on the socio-political changes needed to achieve transformational change in society. The concepts of health literacy and environmental health literacy are explored as a useful means of disseminating and raising awareness about planetary health. Finally, a case study related to heart disease is explored to demonstrate why this approach is more necessary today than ever.

Key words: climate change, climate justice, environmental medicine, planetary health

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1. An introduction to planetary health

Planetary health is a rapidly emerging field that provides a unifying framework for many of the most urgent challenges of the coming decades. It focuses on understanding and quantifying the human health impacts of global environmental disruptions, including climate change, food-systems collapse, rapid biodiversity loss, and widespread pollution, among other urgent threats to human lives and livelihoods (Myers, 2017; Whitmee et al., 2015). Planetary health also advances the development of solutions that will allow humanity and nature to thrive into the future (PHA Website, 2022). The planetary health framework is foundational for a new, broad-based societal awareness that the wellbeing of humanity is deeply connected to the state the biosphere and bold solutions are urgently needed to safeguard human health and well-being, and the rest of life on Earth, now and into the future (Haines and Frumkin, 2021; Myers, 2017; Myers and Frumkin, 2020; Myers et al., 2021; Wabnitz et al., 2020; Whitmee et al., 2015; WHO, 2021). Driven by rapid population growth, even steeper growth in per capita consumption, and industries with large environmental impacts, the scale of the human enterprise now surpasses the planet's capacity to absorb wastes or to sustainably provide the resources used across all sectors of society. Human activities are driving changes to earth systems and the living world at rates that are much steeper than have existed in the history of our species (Myers and Frumkin, 2020; Steffen et al., 2015).

These unprecedented changes include: 1) anthropogenic climate change; 2) widespread pollution of air, water, and soil; 3) rapid biodiversity loss; 4) reconfiguration of biogeochemical cycles for carbon, nitrogen, and phosphorus; 5) pervasive changes in land use and land cover, and 6) depletion of fresh water and arable land (Haines and Frumkin, 2021; Myers and Frumkin, 2020; Steffen et al., 2015; Whitmee et al., 2015). Each of these alterations interacts with the others in ways that undermine the foundational conditions needed for human health, including air and water quality, and the production of food.

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These global scale environmental changes also influence the emergence and spread of infectious diseases, the increase and severity of extreme weather events, and the habitability of many parts of the world. These transformations impact every dimension of our health and wellbeing (Haines and Frumkin, 2021; Myers and Frumkin, 2020; Whitmee et al., 2015).

The harms associated with global environmental change do not fall upon all people equally. They exploit the fissures in human societies that social and racial inequities create and, at the same time, global environmental changes also create conditions that favor more inequity and injustice. Activities that degrade Earth’s natural systems tend to benefit the privileged, while the world’s poorest people, indigenous communities, people of color, and future generations disproportionately bear the associated health burdens. As such, equity and justice concerns form the basis for understanding and addressing global environmental change and health (Haines and Frumkin, 2021; Myers and Frumkin, 2020; Myers et al., 2021; Redvers et al., 2022; Whitmee et al., 2015; WHO, 2021).

To provide for a healthy, just, and sustainable world, there needs to be an awareness and understanding of the human health impacts of global environmental changes and to use this knowledge to develop solutions that will allow humanity and the natural systems our society depends on to thrive. The Great Transition (Raskin, 2016; Spratt et al., 2010) is a term used to describe the societal transformation to a world that optimizes the health and well-being of all people and the planet. To safeguard the future of humanity and all life on Earth, there needs to be rapid and deep structural changes across all dimensions of society (Myers et al., 2021; Whitmee et al., 2015). It will require a transition to a new set of values that incorporate diversity, equity, and inclusion of all people as well as respect and recognition that the health of people are dependent on and interconnected with Nature (Haines and Frumkin, 2021; PHA Website, 2022).

A cornerstone of planetary health is that it is a community forged in urgency, hope, and action. Two examples of actions include a planetary health pledge for health professionals (PHA Website, 2022; Wabnitz et al., 2020) and the São Paulo Declaration on Planetary Health (Myers et al., 2021). The proposed planetary health pledge is based on the Declaration of Geneva for the medical profession and is a way to bring planetary health principles and values into the culture, education, and practice of health professionals. The authors also urge other professions to adapt the pledge to their occupations to stimulate the transformative changes needed to achieve planetary health (Wabnitz et al., 2020). The São Paulo Declaration on Planetary Health was launched in 2021 and is the first document of its kind from the global planetary health community outlining what actions are necessary to achieve the Great Transition. It was produced by the planetary health community at the 2021 Planetary Health Annual Meeting and Festival in São Paulo, Brazil (PHA Website, 2021), concluding with a global consultation of nearly 350 participants from 70+ countries. It outlines recommendations for planetary health action across 19 sectors, including governments, private sector, civil society, and the general public (Myers et al., 2021).

The strength of the planetary health framework is that it focuses the many individual conversations and activities about climate, biodiversity, oceans, global food systems and pollution into a single discussion about the survival of humanity and all life on Earth, with an emphasis on social justice. It addresses the scale and urgency of both the current societal challenges and the solutions needed to achieve the Great Transition. The evidence base that comes from the planetary health field can be used to develop and inform the growing social movement calling for action to equitably harmonize human development gains while protecting the planet’s natural systems and all life on Earth.

2. Socio-political changes needed for planetary health – a reflection

The planetary limit approach, first established in 2009 (Planetary health alliance website), has captured the imagination of scientists and politicians. But a technical approach to planetary threats has limitations. A neglected area is the quality of socio-political and economic institutions that provide answers to the dangers identified by Rockström and others (Myers, 2017). How we organize the actions of society in the face of threats is more important than the threats themselves. Science is an example. Science has made enormous contributions to understanding planetary threats. But a new planetary perspective for our difficult situations invites us to rethink the way knowledge is produced and used by society.

Currently, knowledge exists mainly within closed systems. It was generated within the institutions we call universities. Universities are organized into narrow academic disciplines that work with short-term funding and are focused on publishing research articles in largely inaccessible journals. Scientists set their own research agendas, keeping their knowledge system closed. Planetary health requires more open knowledge systems where grounded knowledge comes from many societal sources, where universities are organized according to the problems facing society, where investments are long-term and the products of research are at available to all in the forms that meet the needs of the various public communities. What is needed today is an investigation into the threats to human civilizations and our survival from perturbations of planetary systems. We need to go beyond the global health manifesto and instead adopt a planetary view of human health. As Jared Diamond wrote in his 2005 book, Collapse, “For the first time in history, we face the risk of global decline. But we are also the first to enjoy the opportunity to learn quickly from developments in societies anywhere in the world today“. The global health task is not finished. But now it needs to be integrated with a new perspective on our future-health of the planet” (Diamond, 2005).

In this vision, the goal of protecting and promoting health and well-being, to prevent disease and disability, to eliminate conditions that damage health and well-being and to promote resilience and adaptation, become one with the sustainability concept. In achieving these goals, our actions must respond to the fragility of our planet and our obligation to safeguard the physical and human environments within which we exist. A strong reaffirmation of primary prevention, indeed a true historical nemesis in the proper sense of the term that recalls in Greek and Latin mythology an act of compensatory or restorative justice for what, exceeding the right measure, disturbs the order of the universe.

With the current pandemic, we are also facing infectious zoonotic disease increasing, and we see mental health effects associated with eco grief, and other disruptions. With all of this change we see civil strife and trauma, forced displacement and migration, all of this which impacts human well-being and the ability for us to live with a wellness into the future. So, in other words we've mortgaged the health of our future generations to realize economic and development gains in the present. This statement comes from the 2015 Rockefeller Lancet Commission’s Report on planetary health (Myers, 2017), which called for action to address these urgent issues. It called for creating a transdisciplinary field focused on the evidence base connecting human health and environmental disruption, and it called for creating an entity to galvanize the community of planetary health practitioners.

Already in 2013, Richard Horton, a member of the aforementioned Commission, reflecting on "global health" wondered if this new and powerful discipline, born in the last decade mainly from the Millennium Development Goals, was able - with its definition and its purposes - to answer the questions our societies currently pose. Global health has included in the concept of health that of equity among peoples, social justice and solidarity, indicating the path of transnationality and interdisciplinarity but has not kept - according to Horton - the substratum in which we live, the planet itself.

Our planet is under pressure, and not only for the additional 2 billion people who will inhabit it between now and 2050. The post-2015 era will be characterized by "sustainability", the idea that not only human and natural systems are interdependent, but also that nonlinear transformations in such systems could be catastrophic for our future. The planet's potential to support our species is slowly declining. The most important post-2015 idea is that global sustainability is the prerequisite for human health, survival and prosperity. Horton also introduces the concept of planetary boundaries, the idea that our species must live within an operational space of security, and citing Johan Rockström specifies that this space is much more than climate change, it includes dangers such as ocean acidification, depletion of the ozone layer, disruption of nitrogen and phosphorus cycles, depletion of freshwater resources, land system change, biodiversity loss, atmospheric aerosol load and chemical pollution. If these limits are transgressed, the survival of our species will be compromised and this represents the ultimate threat to global health.

3. Towards a new approach: health literacy and environmental health literacy

Climate and health education should play an important role in health promotion. Planetary health goes far beyond the concept of climate change and, therefore, requires a communicative approach to illustrate adequately the connection between our health and that of the planet. The field of climate change communication can inform such an approach given the large body of environmental communication research. One of the most prominent climate change communication approaches is the use of a series of “frames”, or interpretative narratives that help specific populations understand why information is relevant in specific contexts (Nisbet, 2009). The health frame (a subset of the social progress frame) is functional and effective for communicating climate change information because it addresses the primary difficulty of climate change communication, namely the fact that climate change is perceived as something distant in space and time (Nisbet 2009). Health is instead something close and personal, and we have direct and immediate negative consequences if we do not safeguard it (Maibach et al., 2010; Myers et al., 2012).

3.1. Health literacy (HL)

In the last twenty years, the meaning and dimensions of health literacy (HL) have grown progressively to include the ability to access, understand, and use health information from numerous and different sources. HL as a key element of health promotion and public health was defined by the WHO in 1998 to encompass those cognitive and social skills that determine people's motivation and ability to access information, understand it, and use it to promote and maintain good health (WHO, 1998). This definition encompasses three domains of health literacy: functional health literacy, interactive health literacy, and critical health literacy.

Functional health literacy refers to the basic skills of reading, writing, basic numeracy, and general literacy that allow people to understand communications concerning health and the use of services in healthcare contexts. Examples include the ability to adhere to medical therapy (correct timing, dosage, and administration method) and schedule appropriate medical examinations and visits. Interactive health literacy is the set of communication and social skills that enables someone to extrapolate and understand meanings from different forms of communication and to apply new knowledge to changing circumstances. Examples include communicating with a doctor about care pathways and exchanging health knowledge and information with contact networks via verbal interactions or online discussions. This form of literacy promotes the development of personal skills in a supportive environment. Finally, critical health literacy is a higher level of cognitive and social critical analysis that enables greater control over life events and situations. Critical health literacy is necessary for empowering effective individual and collective action to address the social, economic, and environmental determinants of health.

People with adequate HL are empowered to understand their rights, to act as informed consumers, and to promote individual and collective action for health improvement through active participation in society (Kanj and Wayne, 2009). Such empowerment is encapsulated in the right to vote, the right to participate in social movements, and the right to demand environmental protections collectively through social organizations like neighborhood committees.

This concept of a community health appears within the definition of another type of health literacy, that of public health literacy, the set of skills necessary to understand that choices have an impact not only on the health of the individual, but also on that of the entire community (Gazmararian 2003; Freedman 2009). Following an extensive review of the literature, the European Health Literacy Consortium developed an integrated definition of health literacy that summarizes its evidence-based dimensions and acknowledged the awareness and skills necessary for making informed decisions and judgments about disease prevention and health promotion to maintain or improve quality of life. (Sørensen et al., 2012). Knowledge, skills, and motivation constitute the heart of this HL definition, distinguishing it from notional knowledge acquisition or skills achieved through training. This definition envisions health literacy as the ability to access, understand, evaluate, and act on health information throughout the course of life. These abilities are associated with three domains, namely care, prevention, and health promotion, and they represent a progression from the individual to the collective perspective, encompassing both a clinical and a public health perspective. According to this integrated definition, numerous antecedent factors influence individual- and population-level HL, including age, gender, level of education, general literacy, previous illness experiences, socioeconomic level, employment, language proficiency, cultural background, the presence of physical disabilities or cognitive impairment, and impaired vision or hearing, in addition to family, social, and environmental determinants. Just as these factors influence HL, HL influences health behaviors and the use of health services, and consequences are measured in terms of health outcomes and costs for the individual and the community. This perspective identifies health literacy as a determinant of health that impacts the equity and sustainability of health systems as well as opportunities for improving the quality of life of individuals and populations.

HL, therefore, is a set of cognitive and social skills that may in part be developed through health education and information acquisition. However, developing these skills also requires exposure to different forms of communication and effective messaging, rather than relying solely on individual cognitive abilities (Nutbeam, 2009). If health messages and the communication modality are not aligned with a recipient’s needs, the information will not be easily accessible or comprehensible, and those with low HL levels may experience health inequalities.

3.2. Environmental health literacy

Environmental health literacy (EHL) is a new HL subset born from the fusion of the principles of HL, risk communication, environmental sciences, communication research, and safety culture. EHL is the comprehension of connections between environmental exposures and health with a focus on actions that exert positive impacts on individuals, communities, and the environment. EHL may be understood as "the wide range of skills and competencies that people need in order to seek out, comprehend, evaluate, and use environmental health information to make informed choices, reduce health risks, improve quality of life and protect the environment" (Society for Public Health Education 2008, as cited in Finn, 2017).

EHL is comprised of the same three domains as HL but with an environmental focus (Gray, 2018). The first domain concerns how the socio-cultural dynamics and the environments to which we are exposed affect our health, whether in the context of the relationship between environment and health or a specific environmental pressure. The second domain is derived from social cognitive theory and focuses on decision-making, competence, and self-efficacy with respect to influencing one's own health and that of one's community. The third domain involves individuals or groups applying their knowledge and agency to protect collective health. In this case, both individuals and groups use self-efficacy to implement behavioral change to reduce harmful environmental exposures and improve collective health.

As with HL, communication is important for EHL. For example, social media may play a role in disseminating information about environmental risks. Individual- and population-level EHL has numerous determinants, including objective factors like literacy, the ability to understand health-related numbers (functional HL), and access to "quality" information sources, and subjective factors like emotions and individual motivations that can affect environmental exposure risk perception of things like the imminent construction of an incinerator in an area close to one's home or news regarding the spillage of harmful wastewater near places secularly considered "sacred", such as schools and kindergartens.

The complexity of information about the relationship between health and environment made available to the public continues to grow. While information sources have become easier to access, they often report conflicting information and increase perceived uncertainty around the results of scientific studies (Fischhoff and Davies, 2014). Non-experts (i.e. the general population) tend to be less familiar with the concept of uncertainty and probability and usually think of things in absolute terms (e.g. good/bad), which produces distortion in the perception of health risks (Politi et al, 2007). Numeracy is particularly important for understanding uncertainty. But understanding uncertainty also requires knowledge gained from previous life experiences, emotional involvement, and the ability to accurately assess risk-benefit ratios in the short, medium, and long term (NASEM, 2017). HL and EHL can play important roles in understanding risk and uncertainty related to health problems.

Following are three examples of the intersection of HL and uncertainty. The emergency nature of a pandemic is necessarily uncertain because the nature and severity of the illness is unknown, as are the probability with which adverse outcomes occur and the effectiveness of preventive actions. Communicating this uncertainty is essential for maximizing the confidence and empowerment of the population to accept those interventions that experts indicate to be most effective (NASEM, 2017). Communicating the uncertainty of science during public health crises is complex and if it is not well managed, the resulting ambiguities can damage public trust in the reliability, credibility, and adequacy of the information the public encounters, while confusion, disorientation, and vulnerability increase. These problems exploded during the Covid-19 pandemic when communication chaos imperiled prevention measures and medical treatment, illustrating that “a pandemic is a communication emergency as much as a medical crisis" (Duhigg, 2020). Thus, HL – even in the specific forms of digital HL and media literacy – can help people access and navigate reputable information. Interventions that increase HL, digital HL, and basic literacy can help users distinguish accurate content from inaccurate content and limit exposure to inaccurate messaging (Rapp and Salovich, 2018). Investigations into the role of HL in understanding uncertainty in a pandemic are still very scarce, but a 2018 study of 2700 subjects to whom a hypothetical pandemic scenario was described found that the individuals with low HL were less able to process uncertainty in health messages (Han 2018).

A second example testifies to the association between health literacy and uncertainty in the case of genetic predisposition. The evolution of diagnostic techniques has made possible the identification of genetic predispositions or susceptibilities to certain pathologies. Understanding the implications of the results of these tests is difficult for laypeople because the tests are complex and because the results a person receives can impact their emotions and their individual risk perception (Kaphingst et al., 2018). An individual’s level of health literacy can affect how they process genetic test results, and patients with low HL may require support to understand these results (Mason et al. 2017). Healthcare professionals who communicate information like this should be trained how to deliver it to subjects with low HL (Rowlands and Nutbeam, 2013).

Finally, uncertainty also plays a fundamental role in EHL and how environmental risks are perceived. Risk maps are a widely used tool for communicating environmental exposure and health risk. While studies of the role of HL and EHL in understanding environmental risk maps are rare, such studies indicate that individual HL and EHL levels are associated with the ability to understand risk maps and uncertainty associated with potential health impacts (Stieb et al., 2019). Risk maps, therefore, may provide a potential element for increasing individual and community EHL across all three EHL domains, including the relationship between environment and health, the decision-making competence to condition individual and community health, and the application of health protection knowledge to improve collective health (Gray, 2018).

4. An example of impact: cardiovascular disease

Cardiovascular disease is the leading cause of worldwide morbidity, more than cancer. However, recent analyses showed that cardiovascular disease is the leading cause of death in middle- and low-income countries, yet in high-income countries cancer causes twice as many deaths as cardiovascular disease (Dagenais et al., 2020). This proportion related to income is maintained except during the current pandemic era where Covid-19 is the main cause of death in the presence of a significant and abrupt reduction in cardiovascular diagnostic testing across the globe (Einstein et al., 2015).

Cardiovascular disease is one of the main comorbidities in anesthesia and intensive care. Of note, several days after major surgery myocardial infarction occurs in surgical patients without any kind of cardiac injury as well as in people at high risk of morbidity due to coronary artery disease. It is known that the onset of perioperative myocardial infarction may be related to several conventional risk factors (i.e., cigarette smoking, diabetes, hyperlipidemia, and hypertension) as well as perioperative withdrawal of cardiovascular pharmacotherapy (Lionetti et al., 2020). Recently, the exposure to climatic and environmental factors is emerging as new perioperative risk factor (Sarkar et al., 2020). This is a relevant original issue since heart diseases have implication for the more than 300 million people undergoing non-cardiac surgery worldwide every year. What climatic and environmental factors have the greatest impact on the perioperative period? New further investigations are needed, although the pathophysiology of perioperative myocardial infarction remains unclear despite the last 20 to 30 years of studies. To date, we know that a small proportion of nonmodifiable risk factors are due to aging and genetic alterations, but more than 70% of cardiovascular disease worldwide is caused by modifiable risk factors. Among the latter, the main ones are metabolic risk factors (i.e., a large waistline, a high triglyceride level, high fasting blood glucose), the second ones are other factors related to our lifestyle, such as tobacco use, hypertension, physical activity, social relationship, cognitive activities or psychosocial stress (Yusuf et al., 2020). The climatic and environmental factors are emerging as the third modifiable risk factors leading cardiovascular disease in the worldwide population, such as the global warming, heat events and air pollution (Nature Reviews Cardiology, 2021).

A recent study conducted among Chinese adults demonstrated that the long-term exposure to temperature variability from plus 5 to plus 15 degree Celsius increased the estimation of the risk of cardiovascular disease (Kang et al., 2021). Moreover, people less tolerant to this climate-disease relationship are older people (Giang et al., 2014). For cardiovascular disease, stroke and coronary artery disease, the percentage of lost disease-free years are progressively reducing below 16 years old. Although it is possible to identify a population that is much more at risk of cardiovascular diseases, the leading causes are not the same around the world (Yusuf et al., 2020). Recently, The Lancet published a study - the PURE study (Dehghan et al, 2017) - that showed as the proportion of cardiovascular disease cases and the cardiovascular mortality change in different countries like low-income, middle-income and high-income countries (Yusuf et al., 2020). Indeed, we cannot ignore that exposure to household air pollution is much more related to cardiovascular disease morbidity in a low-income rather than in high-income country: that's why we need global strategies to take a local and a tailored approach in each country. We should be much more focused on tailored regulation of primordial prevention in each country.

Air pollution means long-term exposure to particulate matter that have different dimension: 1) less than 0.1 micron, 2) equal or less than 2.5 micron and 3) equal or less to 10 micron. It is well known that the particular matter with the size less than or equal to 2.5 micron is the killer of our cardiovascular cells and the magnitude of injury is related to their concentration and exposure time (Liang et al., 2017). Interestingly, the low-income countries have a higher concentration as microgram per cubic meter (i.e. North Africa, Bangladesh, India, Pakistan, some area of China). This finding depends on the regulatory policy setting limits on certain air pollutants in each country. If you consider the threshold of the WHO targeting Particulate Matter (PM) 2.5, the limits are smaller in the US compared to the EU or India. Since the exposure to air pollutants over the threshold leads to higher risk of cardiovascular disease, the primordial prevention will require strict setting of threshold for PM 2.5 to prevent no communicable diseases (Peters and Schneider, 2021). Another evidence supporting environment/health relationship for the onset of cardiovascular diseases has been observed in China. As showed in a recent map of China, the brown and darker area means that population is exposed to higher concentration of PM 2.5, higher concentration of air pollutants, which corresponds to higher cardiovascular disease incidence and death (Liang et al., 2017). This original relationship further supports the occurrence of higher incidence of cardiovascular major events during the perioperative time in countries experienced worst air pollution. To date, we cannot ignore that air pollution may induce an effect - a dramatic effect - on perioperative care. Moreover, climate change is another relevant emerging risk factor of perioperative myocardial infarction and should be considered by anesthesiologists (Roa et al., 2020).

We know that the long-term exposure to different air pollutants induces an inflammatory response and oxidative burst affecting the heart as well as the brain through the immune-mediated dysfunction of the autonomic system and the release of mediators leading to inflammation, cell death or hypercoagulable state. In fact, the activation of coagulation factors trigger clots formation into the coronary microcirculation leading to myocardial ischemia (Rajagopalan et al., 2018).

Yet, what are the underlying mechanisms induced by particulate matters? Till now, scientists were focused on progressive oxidative-based cell injury leading to mitochondrial dysfunction and endothelial injury, which impair the myocardial perfusion up to the onset of diastolic and systolic dysfunction. In the last years, the better understanding of epigenetic mechanisms, which regulate gene expression without altering DNA sequence, suggested the hypothesis that chronic exposure to higher concentration of air pollutants may interfere with the epigenetic life of each of us even before our birth (Micheu et al., 2020). It is conceivable that exposure to high concentration of PM 2.5 during early embryonic and fetal development, and lactation, may induce the expression of genes associated with adult-onset heart disease susceptibility. Cardiovascular disease susceptibility may depend on the maternally provided environment (i.e. living and working place) and it can be transmitted up to the third generation. Therefore, we can assume that environmental health conditions human health, such as the healthiness of the place where you stay much more time during the day, similarly to intake of medications, drugs, junk food or alcohol, or the exposure to tobacco or asbestos.

Of course, it is a suggestive new medical hypothesis supported by growing scientific evidences. It is more than plausible that the exposure to a safe or unsafe environment can affect your health status and well-being. If you are exposed to safe environment you have much more opportunity to have a normal development during your pre-birth life, or you can have a healthy aging during your adult life by avoiding the susceptibility to metabolic diseases (i.e.: diabetes mellitus, obesity) or mental illness. Although the exposure to harmful environment can induce cardiovascular disease during your adult life, it is much more important the exposure time during your life in order to understand the pathophysiological impact of epigenetic modifications, which will be stably transmitted to subsequent generation when affect germinal cells or embryo (Aguilera et al., 2010).

Epigenetic mechanisms affect gene expression at transcriptional, post-transcriptional and post-translational level through chemical modifications (i.e.: de-/methylation, de-/acetylation, ubiquitylation, de-phopshorylation) or the expression of microRNAs, which are small single-stranded non-coding RNA molecules (containing about 22 nucleotides), acting on different area of the chromatin or in the cytosol to modulate mRNA expression and protein degradation (i.e., sumoylation, ubiquitylation, glycosylation) or activation (i.e., phosphorylation, acetylation). It is established that epigenetic signatures related to air pollution involve process of DNA methylation of some area of chromatin. Indeed, DNA methylation at levels of specific promoter may alter the expression of pro- or anti-inflammatory genes rather than pro- or anti-oxidant ones leading to subclinical vascular injury, such as atherosclerotic plaque, or cardiomyocyte apoptosis without evidence of symptoms up to the onset of myocardial infarction and severe heart failure (Suades et al., 2019).

An interesting experiment demonstrated that the exposure of endothelial cells to PM 2.5 at increasing concentrations progressively reduces their viability. It results like a bombing effect on the endothelium by particulate matters leading to myocardial infarction (Zou et al., 2021). Other study has also demonstrated a gene-mediated effect. In particular, the nuclear levels of specific transcriptional factors are increased following the exposure to PM 2.5 and it means that are activated. Interestingly, the activator signal is the interleukin-6 (Dai et al., 2016), the same pro-inflammatory cytokine rising in Covid-19 patients.

We can conclude that the cardiovascular tissue is altered following inhalation of particular matters in a time and dose dependent manner, as demonstrated in human beings and animal models (Kunovac et al., 2021). It is established that the long-term exposure to air pollutants may induces the death of cardiomyocytes (Yang et al., 2019). The loss of cardiomyocytes progressively decreases the cardiac contractility as you have less contractile cells and larger deposits of collagen until the onset cardiac remodeling and heart failure (Lionetti et al., 2014). The heart enlarges and develops thin walls that are not able to contract and relax properly and defects of myocardial repolarization even occur (Wold et al., 2012). The risk of lethal arrhythmias increases in population exposed to higher concentration of PM 2.5/PM 10, like atrial fibrillation and other disorders of myocardial repolarization (Zhang et al., 2021). Moreover, peripheral organs (i.e. brain, kidneys) are also affected by less blood perfusion due to decay of cardiac function. In order to define mechanisms, previous study already mapped genes up- or down-regulated by the exposure to air pollutants compared to people not exposed to same environment (Kunovac et al., 2021). For example, NFkB, an established transcriptional factor leading to the expression of interleukin 1b, interleukin 6, TNF- alpha, regulates the inflammatory response that extent increases during septic shock. Levels of angiotensin II increased as well as during a systemic inflammation, infection and during arterial hypertension. Conversely, other cardioprotective genes, such as antioxidant proteins, superoxide dismutase type one or VEGF type a, are significantly downregulated (Kunovac et al., 2021).

In order to understand underlying epigenetic mechanisms, a recent study has demonstrated that exposure of pregnant to high concentration of pollutants increased levels of DNA methylation in specific area of chromatin silencing some microRNAs involved in the angiogenic response and pro-survival pathways (Tsamou et al., 2018; Ferrari et al., 2019). Other epigenetic modifications are involved. For example, the acetylation of lysine 9 of histone H3 induced the expression of two relevant gene related to progenitor cells activity; while, the methylation of lysine 4 of histone H3 increased expression of STAT3, a pro-inflammatory transcriptional factor, and HIF1alpha, a transcriptional factor modulating the response to hypoxia. Therefore, we can assume that during our epigenetic life, when we are still in uterus, and our mom is exposed to air pollutants that enrich the air (i.e. particulate matter, nitric oxide donors or metals or CO_2) the expression of our genes is modified without changing DNA sequence (Breton et al., 2019). Air pollutants interfere with activity of different enzymes leading to several patterns of chromatin remodeling that induce the expression of “bad” genes or down regulate the expression of “good” genes. These modifications may underlie higher or lower susceptibility to different disorders like cardiovascular diseases.

We refer to transgenerational inheritance, where epigenetic modifications cause transgeneration inheritance of resistance or susceptibility to disease. For instance, someone inherits a predisposition to diseases that do not belong to the family following the chronic exposure to environmental pollutants. What are the perspectives? Recently, *Circulation,* one of the main lead journal of cardiovascular science, the official journal of the American Heart Association, published an interesting perspective article suggesting the need to expand the framework of environmental determinants of cardiovascular health from climate change to planetary health (Chang et al., 2021). It means much more regulatory policy and studies focused on impact of environmental risk factor and climate change on human health. Indeed, climate change cause different type of disasters, including global warming and heat waves, may increase risk of heart diseases in the presence of air pollution. Of note, older and fragil people are more vulnerable to this type of synergy exposure. Age is a critical determinant of the socio-economic status of population. However, healthy aging in a contaminated place may be unrelated to the salary, intake of good food, co-medications or quality of healthcare system, which might be not enough to defend frail population from climate and environmental changes. Indeed, elderly people with comorbidities are less tolerant to risk factors of cardiovascular diseases compared to others.

Everyone are exposed everywhere to climate and environmental synergy. Of course, people living in poverty, women and children and elderly, outdoor workers, patients with chronic diseases are the most vulnerable to effects of long exposure to climate and environmental factors. In order to counteract the climate change and air pollution synergy, we should promote program of translational multidisciplinary research and education in faculty of medicine, and new regulatory policy in order to design more effective primordial and primary prevention.

5. Conclusions

Planetary health is an increasingly vast field of study, which attracts increasingly varied and complex contributions. This complexity has been illustrated in the paper in question, which does not pretend to be exhaustive, but which aims to provide some keys to understanding the new concept of planetary health.

In the future, it will be increasingly important to understand how environmental sciences, medical sciences, social sciences and other fields of knowledge must work together to solve the challenges we now, as mankind, are called to face. This is because ecological challenges and climate change pose multidimensional questions, both in space and in time, which risk condemning generations that have not been the cause of the problems present today. Interdisciplinarity will be a key point to complete this path, as academics and as human beings.

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INDUSTRIAL SYMBIOSIS POTENTIAL ON SPECIFIC AGRI-FOOD AND METALLURGICAL VALUE CHAINS IN LOMBARDY REGION

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Abstract

This paper focuses on the project activities carried out by ENEA on Industrial Symbiosis (IS) as part of the CREIAMO project, funded by CARIPLO Foundation, aimed at identifying and promoting new destinations and economic opportunities for by-products and waste deriving from the olive and wine sectors, under a circular economy perspective. Due to the pandemic, the ENEA's methodology for promoting and implementing IS has been adapted in order to perform from remote all the activities with the companies involved. An engagement campaign was carried out in the territory of Brescia with the support of several local associations. The IS – Operative Meeting (OM) with enterprises was held remotely on 19 February 2021. About 100 potential synergistic actions have been identified, mainly involving material resources. Following an initial processing of data, summary reports were prepared, one for each company. Significant resource flows were selected according to the quantities involved and to their economic value. As an output of this work, two technical handbooks have been drawn up for companies that are willing to transform synergies from theory to practice.

Key words: eco-innovation, industrial symbiosis methodology, residues, resource valorizations, synergies

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1. Introduction

By 2050, it is expected that the world will have a minimum of 9 billion habitants and our common desire is to ensure a comparatively high level of prosperity and welfare for all. This goal is not achievable using the present linear mode of economy, because the natural resources of the Earth are already being depleted. A profound shake-up is required and a whole re-thinking of the Western industrial system and economy needs to happen (Sacchi et al, 2021).

Circular economy aims to replace the linear economy concept, where the value of products and materials is maintained as long as possible (Korhonen et al. 2018). It is not just a question of eliminating or minimizing the production of waste, but of radically changing the conflicting vision between economic and environmental interests, traditionally considered in antithesis, with a new and broader concept of well-being, which includes both. The circular economy represents a radical paradigm shift, within which to develop new sustainable business models, able to increase the potential closure of production cycles and the efficient use of local resources.

As part of the strategies and tools for closing resource cycles, there is an increasing interest in IS, which aims at transferring and sharing of resources (raw materials, water, waste, energy waste, services,

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skills, tools etc.) between companies and / or other operators present in nearby areas (CWA 17354, 2018). This approach constitutes not only a potential competitiveness factor for industrial activities, but also an enrichment factor for the area, which sees all of its resources valued locally and not dispersed, delegated or given away to third parties.

The European Commission has attributed a strategic role to industrial symbiosis (IS) for the efficient use of resources, clearly identified in various programming and funding documents (e.g., European Resource Efficiency Platform, COM 571, 2011; COM 398, 2014; COM 614, 2015). Interest in IS was also registered in Italy, with the development of several projects dedicated to the closure of resource cycles and with the inclusion of IS in some regional planning tools (Notarnicola, 2016; Simboli, 2014, 2015).

ENEA is responsible for implementing and promoting IS using a validated methodology as result of decades of experience on this issue. In 2011 ENEA started the development and the implementation of an IS network model thanks to three projects in three Italian regions: the “Eco-Innovation Sicily” project (Cutaia et al., 2014a, 2015; Luciano et al., 2016); the "Green Project - Industrial Symbiosis" in Emilia-Romagna (Cutaia et al., 2016; 2014b); and the "Industrial Park of Rieti-Cittaducale" project in Lazio (La Monica, 2016).

The CREIAMO project, financed by CARIPLO Foundation, has as its partner the University of Brescia in the role of coordinating the activities, the University of Milano Bicocca and ENEA, which dealt with aspects relating to the circular economy, the IS, and the promotion of intersectoral synergies in particular.

This article, as part of the aforementioned project, illustrates the activity carried out by ENEA to identify and promote new destinations and economic opportunities for by-products and waste deriving from olive and wine supply chains, under a circular economy perspective. By achieving this objective, the competitiveness of companies operating in the Lombardy Region, and in Brescia province specifically, will consequently be increased, also thanks to the creation of new business models. The project adopted a system eco-innovation strategy through the creation of a network of IS in Lombardy, through which enterprises will be able to achieve economic, environmental and social benefits.

Moreover, the project represents the first structured attempt to implement IS in the region and involved various productive sectors in addition to the one directly involved in the project (olive and wine supply chain). Two different supply chains have been studied in the project: the agri-food industry, with a focus on the production of oil and wine, and the metallurgical industry, with a focus on steel production from Electric Arc Furnace (EAF).

Waste resources coming from these two sectors, respectively organic (olive and grape marc, Olive Mill Wastewater - OMWW) and inorganic resources (EAF slag), were considered for the implementation of specific valorization strategies. The choice of synergies to be implemented was guided by the characteristics and quantities of the resources made available by the companies involved in the project.

2. The potential of circular economy in agri-food chain and other industries in Lombardy

The agri-food chain includes the primary sectors of agriculture, animal husbandry and fishing, the food industry that deals with the transformation of raw materials and the production of beverages, the industry for the enhancement of by-products and waste, the distribution and commercial phase. In the Communication of the European Commission "Roadmap to a Resource Efficient Europe", the waste produced along the agri-food chain is mentioned as one of those on which to intervene primarily (European Commission, 2011).

The circular economy model aims to overcome the limits of the current system, increasing production performance and simultaneously generating an improvement in the quality of the soil, water and air. This is achieved by exploiting the reuse of agricultural residues, finding the right application for each type of residue, through a series of sequential processes. The companies must identify the actual potential of all substances that do not constitute the final product, identifying them as a source of income and not as a cost that must be incurred for their disposal. In this context, an important role is played by technological and process innovation, through the adoption of new technologies applicable to residues for their enhancement. The creation of cooperatives or districts of IS can further favour the reuse of resources in new processes. Therefore, the involvement of all stakeholders, such as research and development institutes, industry associations and government bodies, as well as companies, is primary to create favourable conditions for the development of new business ideas.

2.1. Circularity in the olive oil and wine processing sectors

Lombardy constitutes the most important agricultural region in Italy. In absolute values, the Lombard agricultural sector involves 41,116 companies, with an extension of the Utilised Agricultural Area (UAA) equal to 958,378 ha. Overall, there are 56,000 production facilities operating in the agri-food sector (agricultural production, related activities and food processing), which involve about 200,000 workers, of whom 143,000 are permanently employed, equal to 3% of the Lombard total (Data in ISMEA 2020).

With a sales volume of 3 billion euros (ISTAT data in ISMEA 2018), the olive oil supply chain represents 2% of the total turnover of the agri-food industry. Italy ranks second among the olive oil producing countries in the world.

Olive pomace (exhausted pulp, stone and seeds) and OMWW are significant by-products in Lombardy with a high environmental impact when not properly treated. However, at the same time these by-products are also rich in high-value compounds, which can be used directly after extraction, or enhanced as ingredients for other industrial sectors: food industry, feed industry, the nutraceutical and cosmetic sectors. Grapes represent one of the largest fruit productions globally, an amount of 60-70 million tons are produced every year; 60% of the grapes produced are used as “pressed grapes”, for the production of wine or grape juice (Gómez-Brandón et al., 2019; Muhlack et al., 2018). In particular, the European Union is the largest wine producer, accounting for 65% of global production; in 2018 in Italy more than 8.6 tons of grapes were harvested, and in Lombardy alone in 2019 wine production reached 130 million litres (Chebbi et al., 2021). During the wine production process, the pressing of the grapes generates solid residues (pomace), consisting of stalks, skins, seeds and water, which represent about 25% of the grape mass; for the production of 6L of wine is estimated to produce about 1 kg of pomace leftover, for a total of 10.5-13.1 million tons of pomace per year (Gómez-Brandón et al., 2019; Muhlack et al., 2018). Given the high quantities of pomace produced annually by wineries, the sector is under pressure to implement plans for an adequate and sustainable disposal of this biomass: the pomace, in fact, is characterized by high COD and BOD (Chemical/ Biochemical Oxygen) values, which makes disposal an important and costly environmental problem (Campanella et al., 2017).

There are multiple possibilities for valorizing residues and processing by-products of these two production chains, some of which are traditional and consolidated practices, others more innovative and under development. The current principal valorization processes for olive pomace, OMWW and grape marc are shown in Table 1.

Table 1. Strengths and limitations of olive oil and wine processing chain residues valorizing methods

Resource	***Technology***	***Strengths***	***Limitations***	***Reference***
Olive pomace	Pyrolysis	The valorizations of organic wastes through fast pyrolysis appears to be a highly promising option for decreasing pollutants and reducing consumption of natural resources	Developing a novel cost-effective and environment-friendly process	Dorado et al., 2021
	Bioconversion	Exhausted olive pomace (EOP) represents a potential candidate stream to be utilized in biotechnological processes	EOP composition includes significant amounts of extractives and pectin, which are both usually discarded and are not utilized in the valorization process	Paz et al., 2020
	Anaerobic digestion			Elalami et al., 2020
	Bioremediation			Flores-Céspedes et al., 2020
	Animal feed	Reduce adverse environmental effects of this by-product and to enhance the quality of products of animal origin	Maintenance of the products quality	Chiofalo et al., 2020
Olive mill wastewater (OMWW)	Purification through membranes	High content of molecules was isolated		Tundis et al., 2020
	Hydrothermal carbonization	Promising technique for wastes conversion into carbon rich materials		Azzaz et al., 2020
	Animal feed	Reduce adverse environmental effects of this by-product and to enhance the quality of products of animal origin		Branciari et al., 2020
	Bioconversion	The process was successfully validated on an industrial scale		Ramires et al., 2020
Grape marcs	Extraction of useful molecules	The technology already exists	Seasonality of raw materials	Brazinha et al., 2014
	Pyrolysis	Process applied as pre-treatment step for grape marc within energy generation	A crucial first step in developing a novel cost-effective and environment-friendly process	Marculescu and Ciuta, 2013
	Bioconversion	High by-product valorisation process	Technology improvement	Campanella et al., 2017
	Animal feed		The nutritive value of grape pomace varies depending on the proportion of seeds and pulp	Guerra-Rivas et al., 2017
	Bio remediation			Chebbi et al., 2021

2.2. The potential of circular economy in metallurgical industry

The metallurgical sector, known also as metal industry, plays an important role in Lombardy's regional industry. The number of industries in this sector is 1446 of which 406 located in the province of Brescia as the focus area (ISTAT, 2019). Meanwhile this sector is one of the main producers of industrial waste in the region with the total production of 8,290,853 tons in 2018, which formed 34.6 % of the total production industrial waste in the manufacturing sector in Lombardy region. From this number a quantity equal to 1.704.058,6 tons were produced only in the province of Brescia (ARPA Lombardia, 2019). Almost 45% of the industrial waste produced by the metal industry in Lombardy region comes from EAF slag, which corresponds to 72% of the total production of EAF slags at the national territory (Lombardy Region, 2021). As a non-hazardous waste it can be treated by the companies specialized in treating waste (ATECO code 38.21).

In addition, the companies specialized in manufacture of other non-metallic mineral products (ATECO code 23) can recover these wastes in a symbiotic way as a raw material in their production processes. The number of these types of firms is 2400 in the Lombardy region from which 420 companies are located in the province of Brescia (ISTAT, 2019). Therefore, a considerable potential exists for avoiding the disposal of this material, which made it necessary for searching new IS pathways.

2.3. Circularity in steel industry: EAF slag valorization

Steel sector is regarded as an energy intensive sector. Meanwhile, it also possesses a productive cycle with a high amount of wasted material compared to the unit of final product. Considering the different technologies for steel production, Italy is the first rank among EU (27 countries) for EAF steel production (Piemonti et al., 2021). In Italy, about 80% of the steel comes from the EAF. The steel production plants in the province of Brescia are almost exclusively equipped with EAFs, accompanied by second metallurgy processes in ladle furnaces. The main residues derived from steel production by EAF are listed in the Table 2 (Remus et al., 2013).

A high percentage of the total waste generated in steel mills belong to slags. Based on the estimations provided by the local steelmakers in Lombardy region, the total generation of slags may be reach up to 20 % of the total weight of the final steel products (Comune di Brescia, 2021; Feralpi Group, 2018). From this amount, almost one-third belongs to white slag. The generated slags stand for almost 70 % of the total waste generated in each steel company. The rest consists of less than 20 % hazardous wastes and almost 10 % non-hazardous wastes. At present, the management of white slag (LF) and black slag (EAF slag) are considerably different. Most of the white slags are also sent to landfill, even if many research initiatives have been already initiated about the possible solutions for their valorisation.

One of the most promising options is the usage of white slag as an alternative material for cement in construction application (Aponte et al., 2020; Santamaría et al., 2020). On the other hand, the situation for black slag is more complex (Piemonti et al., 2021). At this moment, different pathways are being followed by the local enterprises for their reuse. Recycling is one of the options, in which the companies send their slags as waste to other plants which have the authorization of transforming the slags to new inert products to be used in civil engineering works and as a primer for road paving.

However, some of the companies have initiated recently to take a further step in the hierarchy by developing specific plants inside their own establishment for transforming the black slag to a by-product. This type of material sometimes known as synthetic aggregate or synthetic stone is no longer considered as waste and therefore from the legislative point of view requires less sensitivity in transportation and it can be sold in the market as a new product of the company. The strength and limitations of recycling the EAF slag for innovative applications could be summarized as per presented in Table 3.

Table 2. Kind and specific quantity of solid wastes/by-products from EAF steelmaking (source: Remus et al., 2013)

Solid waste/by-product		***Specific quantity (range) (kg/t LS)***
Slags from carbon steel/low alloyed steel production:	Slag from EAF	100 – 150 10 – 30
	Slag from ladle	
Slags from high alloyed steel production:	Slag from EAF	100 – 135
	Slag from ladle	30 – 40
	AOD slag	Approximately 160
Dusts from carbon steel/low alloyed/high alloyed steel production		10 – 46
Refractory material		2 – 25
NB: LS = Liquid steel. AOD = Argon Oxygen Decarburization		

Table 3. Strengths and limitations of the incorporation of EAF slag for different applications

Application	***Strengths***	***Limitations***	***References***
Internal reuse as alloying agent in the metallurgical process	Slag can be valorised for partial replacement of lime, alloying agents and slag formers in the melt shop Potential recovery of valuable metals from slugs	Degradation of the material properties over time and efficiency loss in the steel making process. Long term monitoring and characterization of slags content are needed.	De Colle et al., 2019 Menad et al., 2021
Production of rubber and other polymeric	Slag as a filler increases the composites' hardness and elastic modulus at the expense of toughness	The leaching of hazardous elements out of the polymeric matrix The mechanical performance of the product is less than other conventional fillers	Gobetti et al., 2021
Production of stone wool thermal insulation	The production process results in a higher value-added product and also minor amount of iron as by-product	EAF slag can only partially substitute raw material The process needs energy consumption and further emissions	Paroc, 2019
Aggregates for construction industry	Concrete with EAF slag has 11% higher attenuation coefficient Bitumen mixture with EAF slag aggregates is more durable Resilient modulus and dynamic creep modulus values of EAF slag can be increased through aging process Compressive strength and elastic modulus of concrete with EAF slag aggregates are comparable to the commercially available concrete, but is cheaper to produce	Concrete with EAF slag has volume instability and durability issues under extreme conditions and is vulnerable to repeated cycles of wetting and drying EAF slag is generally more porous and have higher water absorption than conventional road pavement materials	EUROSLAG and EUROFER, 2012; Teo et al., 2020
Filter or adsorbent in wastewater treatment plant	EAF slag can: - effectively remove phosphorus from effluent - be processed to improve its adsorption capacity - be used to reduce the acidity of wastewater	EAF slag has limited adsorption capacity for long term usage Using EAF slag to treat acidic wastewater may produce unwanted precipitates that need to be disposed of separately	Teo et al., 2020
Fertiliser for agriculture industry	EAF slag: - contains Fe, K, Mn, and P that could sustain plant growth - can be processed into higher added value phosphorus fertiliser - have the potential to reduce toxic elements uptakes of agricultural plants	EAF slag also contains low amount of harmful elements such as Cd and Pb Remediation procedures might be needed to reduce harmful elements	Teo et al., 2020
Partial replacement for cement	The reuse as partial replacement of the cement is possible if combined, for example, with small percentages of gypsum or steel sludge	Increase in setting times Less initial strength development Slightly greater autogenous shrinkage compared to the standard concrete	Piemonti et al., 2021
Raw material for ceramic building materials	In terms of chemical composition, slag is similar to raw materials used for the production of ceramic tiles. Leaching test revealed that the concentrations of the heavy metals leached in both tap water and rainwater conditions were low	Optimal EAF slag wt.% varies based on its composition from different sources Monitoring of the risk from harmful elements that emits from the products are within safe level	Teo et al., 2014 Teo et al., 2016

3. Materials and methods

The methodology, developed by ENEA, is the result of consolidated experience on IS (Cutaia et al., 2015). It is based on three basic pillars:

1) Language of symbiosis: a shared language that is expressed in the formats for collecting information (personal data and relating to input and output resources);

2) Communication with companies: continuous throughout the whole symbiosis implementation process;

3) Knowledge and experience: this aspect concerns the knowledge base that allows ENEA to support collaboration between enterprises and resources exchange as prerequisite for the implementation of IS paths (Fig. 1). According to the methodology, activities related to the implementation of IS followed

these operational phases:

Step 1_ Identification of stakeholders in the Lombardy region: preparation of company's database, selection of enterprises to be involved including business associations and local authorities;

Step 2_Preparatory activity for the OM: Invitation of companies; registration; preliminary data collection;

Step 3_OM with companies: sharing of resources, finding synergies and help companies identify matches;

Step 4_Identification of significant resource flows and potential synergies: data analysis of shared resources, in-depth study of the potential synergies that emerged during the OM and identification of new potential synergies, summary report elaboration;

Step 5_ Study of synergies in collaboration with companies: study of technical feasibility and environmental aspects through LCA, assessment of economic impacts, study of legislation and technical standards;

Step 6_ Drafting of the technical handbooks;

For the CREIAMO project, the ENEA methodology has been adapted to be carried out in telematics mode, due to the pandemic situation. Therefore, both OM and information exchanges with the enterprises and stakeholder involved took place remotely.

At first, ENEA drew up a specific online form that companies filled out before the OM. These forms contain company details and shared or requested resources data (type, quantity, availability, characteristics etc.). This anonymous database (the company name has been replaced by a unique code) was used as a base of information during the online operating session.

Participants anonymously expressed their preferences on the use or willingness to share involved resources, allowing an initial match identification. The IS OM was held on February 19, 2021, aimed at enterprises in the province of Brescia and neighboring provinces.

4. Results and discussion

There were 22 firms participating in the OM and they belong to very different production sectors, as it can be seen from the graph (Fig. 2). During the meeting 96 resources were shared, mostly material resources. Of these, 24 were input resources (required by companies), and 72 output resources (offered for sharing) composed of waste, by-products or surpluses (Table 4).

Overall, 102 synergies were identified, 77 synergies on output resources and 25 on input resources. To these must be added the synergies identified by ENEA downstream of the workshops, which envisaged intermediate treatments of the resources made available (Table 5).

Following the OM activity, thanks to the contribution of Confindustria Brescia, the resources database was integrated with information on companies that were registered to the event, but were unable to participate. The identification of new potential synergies and the drafting of a summary report for each company followed this phase.

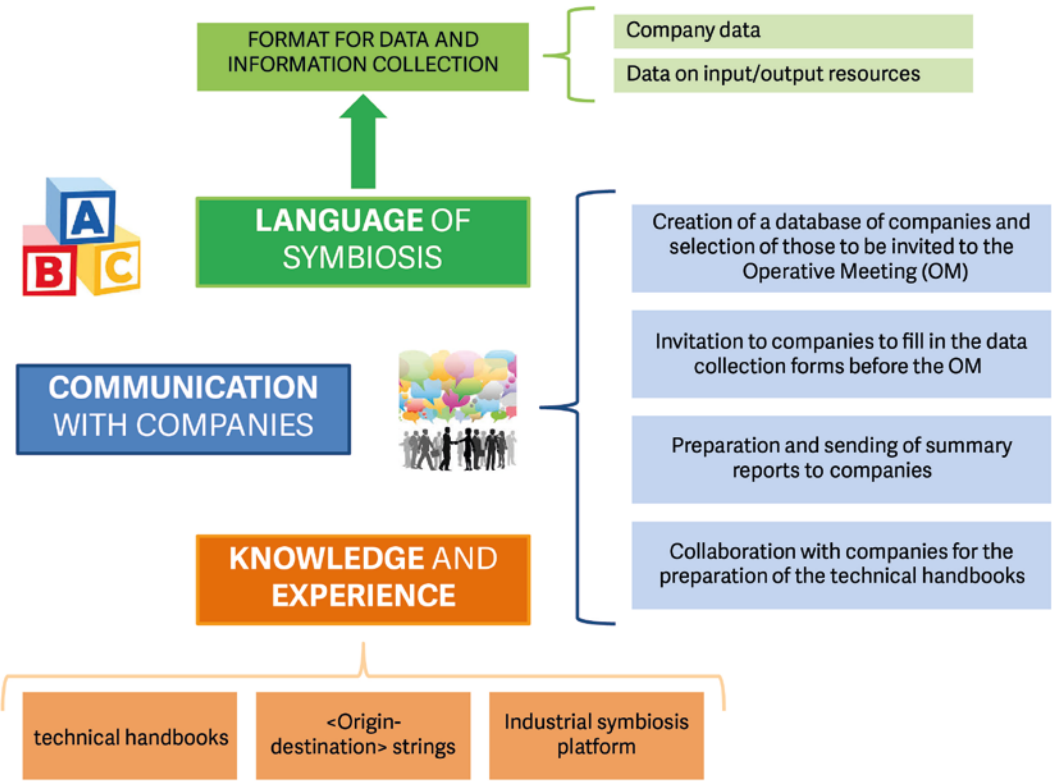

Fig. 1. The three pillars of the ENEA methodology

The document contains a summary of the shared and requested resources and a description of the potential synergies identified (Fig. 3). A further phase of investigation led to the identification of the most significant resource flows both from a quantitative and qualitative point of view. The valorizations solutions for these flows were studied in-depth in two technical handbooks: Technical handbook on the synergies identified for organic resources, i.e., waste from olive oil and wine productive process, in particular olive and grape marc and OMWW. In this handbook, three flows of organic resources have been studied starting from waste from the companies involved:

- Olive pomace, produced by three different farms with the possibility of being valorized:
  - Through the extraction of compounds with higher added value such as polyphenols or antioxidants, in turn addressed to the fishing, cosmetic or nutraceutical industry;
  - For the production of bio-oils used for combustion;
  - For the production of natural bio-surfactants.
- OMWW, produced by three different farms with the possibility of being valorized:
  - Through the extraction of compounds with higher added value such as polyphenols or antioxidants, in turn addressed to the fishing, cosmetic or nutraceutical industry;
  - For the production of natural bio-surfactants.
- Grape marc, output classified as by-products from two different farms with the possibility of being valorized:
  - Through the extraction of compounds with higher added value such as polyphenols or antioxidants, in turn addressed to the fishing, cosmetic or nutraceutical industry;
  - For the production of bio-oils used for combustion;
  - For the production of natural bio-surfactants.
  - Technical handbook on the synergies identified for inorganic resources, which investigates the potential synergies for the resources deriving from the steel sector and from industrial and post-consumer waste plastic materials. In this handbook, three streams of inorganic resources have been studied in particular, starting from waste from companies involved;

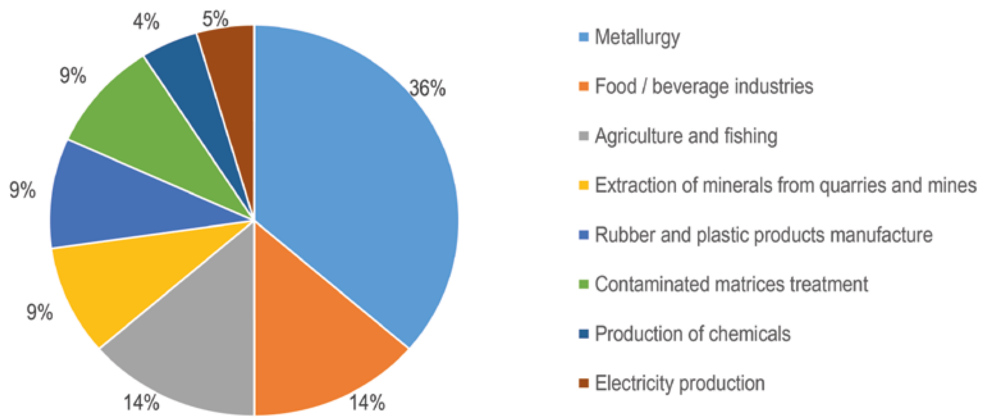

Fig. 2. Production sectors of the 22 companies that participated at the IS OM

Table 4. Shared resources during the IS OM

Resources category	*Input resources*	*Output resources*	*Total*
Material	21	64	85
Water	1	2	3
Energy	1	1	2
Competence	1	2	3
Other	0	3	3
	24	**72**	**96**

Table 5. Synergies emerged during the IS OM

	Synergies on output resources	*Synergies on input resources*	*Total*
Material	68	24	92
Energy	7	0	7
Competence	2	1	3
	77	**25**	**102**

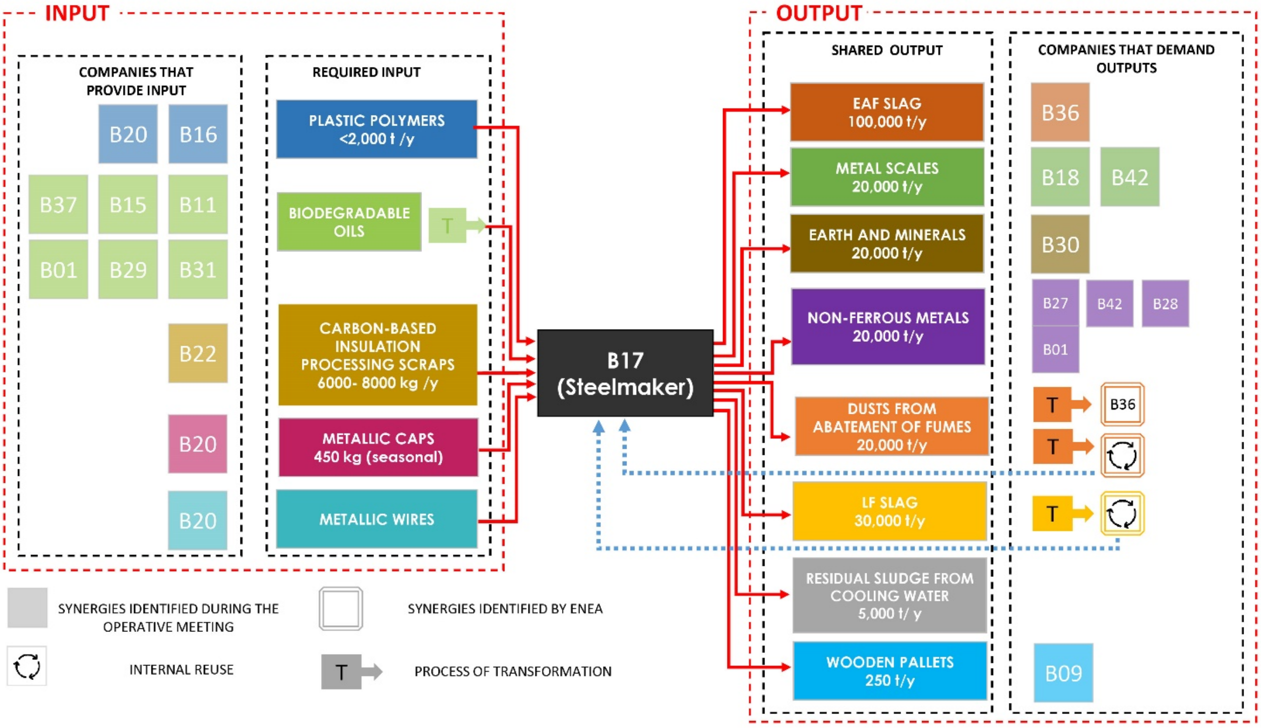

Fig. 3. Example of a summary scheme of the synergies identified as reported in the summary report

- Black slag from EAF, treated as a by-product or waste by two companies in the steel industry and intended for reuse in a company that produces cement and bituminous conglomerates;
- Plastic waste in the form of flakes and powders from a food packaging production company and intended for steel companies such as Secondary Reducing Agent (SRA) for use in blast furnaces as a reducing agent in the oxidation reactions of ferrous minerals to replace Coke.
- Post-consumer plastic waste for use in the steel industry for the same purposes.

4.1. Scenario for the enhancement of wine and olive oil waste: Extraction of high added value molecules

Biomasses are renewable energy sources that are distinguished from other renewable sources (such as wind, solar, geothermal) as the available energy is stored in the chemical bonds present in the various molecules that compose it. This means that they are a source of energy, but also of basic chemical compounds or high added value and biomaterials (Torres et al., 2020). The extraction of chemical compounds with high added value from biomass already represents an important market in the pharmaceutical (chitosan), cosmetics (chitosan and extracts polyphenols), nutraceutical (dyes derived from biomass, texture modifiers and food supplements) and agricultural (pyrethrum-based insecticides); so the extraction processes can be defined as sustainable, it is important to use technologies with high energy efficiency and which are based on low environmental impact solvents obtained preferably from renewable sources (Herrero and Ibañez 2018).

Olive pomace, OMWW and grape marc represent a very varied source of bioactive compounds that could have potential applications in various markets as mentioned before. Real cases have been identified during the OM (Fig. 4). Among the companies involved, two of them (indicated with the code B03, B16) requested as input molecules with high added value such as antioxidants and polyphenols, intended for the fishing industry, to increase the quality of feed, or for the creation of plastics for food packaging, to increase the freshness and shelf life of packaged foods. Among the companies present none was able to share directly these types of molecules but five of them (B11, B15, B37, B29, B31) shared olive pomace, OMWW and grape marc for a total of 1040 m^3/y, 1300 m^3/y e 100 tons/y respectively. In literature there is much research aimed at extracting these products from pomace, OMWW and pomace as they are present at high titers (Table 1). The extraction of these high added value molecules is now carried out on an industrial scale starting from edible plants and crops.

Therefore, a possible strategy to valorise these by-products could be the implementation of these extraction processes, which already exist, using the resources examined in this work as starting biomass. Fig. 4 shows, more in detail, the case study developed by ENEA; the green and purple arrows highlight the distance of olive pomace, OMWW and grape marc respectively from the companies that supply these outputs to the different processing firms identified by ENEA in the Lombardy region. Furthermore, the grey arrows highlight the distances between the processing companies identified and the ones that require polyphenols and antioxidants as input.

In the arrows (Fig. 4) a range of distances is shown from the smallest to the largest between the various companies taken in consideration. These values can therefore undergo changes since the intermediate extraction process, which must be done on the resources, is carried out on site by the companies in question or by third-part companies. The distances between firms are one of the factors that has the greatest impact on economic costs but also on the environmental impact. For this reason, one of the foundations of IS is the closeness between companies and for this reason in this work the distances between them have been analyzed in detail. In general, it has been observed that the distances between the companies that provide resources (B11, B15, B37, B29, B31) and those that receive them for treatment (A, B, C, D, E) lie in a range of distance that goes from 13 to 191 km, while between the "T" companies and those that use the final resource (B03, B16) they are found in a range that goes from 29 to 100 km. It is possible to observe in detail the specific ranges for each company in the synergy diagram (Fig. 4).

4.2. Scenario for the enhancement of steel mill waste: the use of black slag as an artificial inert

The diagram (Fig. 5) outlines the synergy between three steel companies and a firm that produces cement and bituminous conglomerates using black steel mill slag as an artificial aggregate for alloyed and unalloyed uses (alloyed uses refers to the use for cements, concretes or bituminous conglomerates; unalloyed uses refer to the use for the construction of embankments and road foundations, landfill "capping" etc.).

Among the enterprises involved, three of them belonging to the steel sector (indicated with the code B26, B17, B04) indicated the black slag from an electric furnace steel mill (EAF) as a resource to be shared. Only two (B17 and B04) made by-products available, while only one (B26) shared the resource as waste, preliminarily subjected to a process of separation and recovery of steel fragments. The total quantity of black slag amounts to 270,000 tons per year, of which 200,000 are certified by-products according to the UNI EN 13242 (2013) standard, used as fillings in civil engineering works, as drainage layers for covering or layers of capillary rupture for landfills. The remaining quantity (70,000 t / year) is waste and is sent to authorized and specialized platforms for reuse in road foundations and in cement and bituminous conglomerates. The transport phase of the aforementioned resources from the company that supplies them and the one that uses them takes place for an average distance of about 25 km.

5. Conclusions

The IS activities carried out in the CREIAMO project have aroused interest among the companies who actively participated in synergies implementation, confirming environmental, social and economic advantages deriving from resources exchange between enterprises.

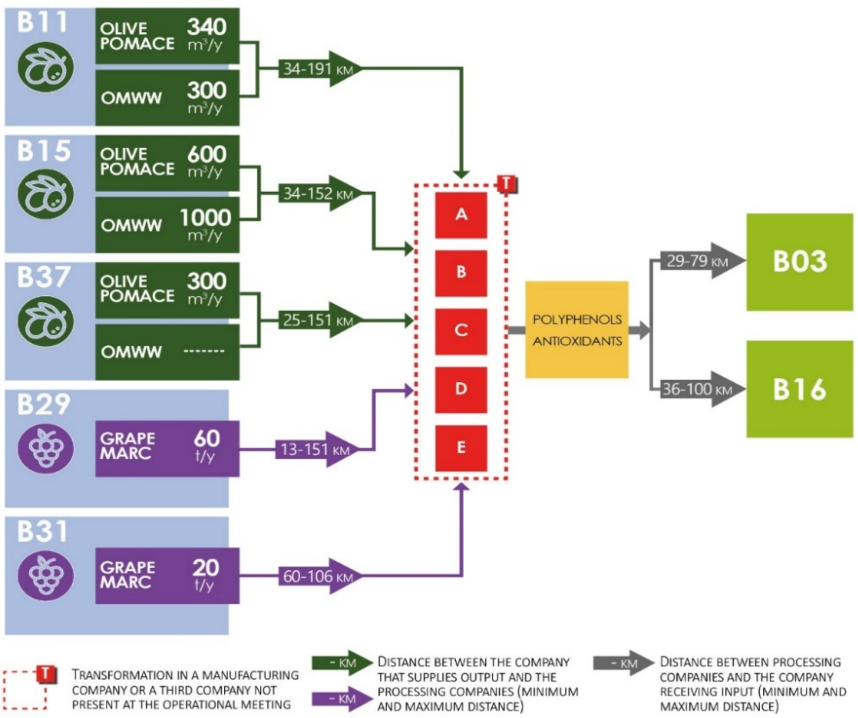

Fig. 4. Enhancement scenario of olive pomace, grape marc and OMWW for the extraction of high added value molecules

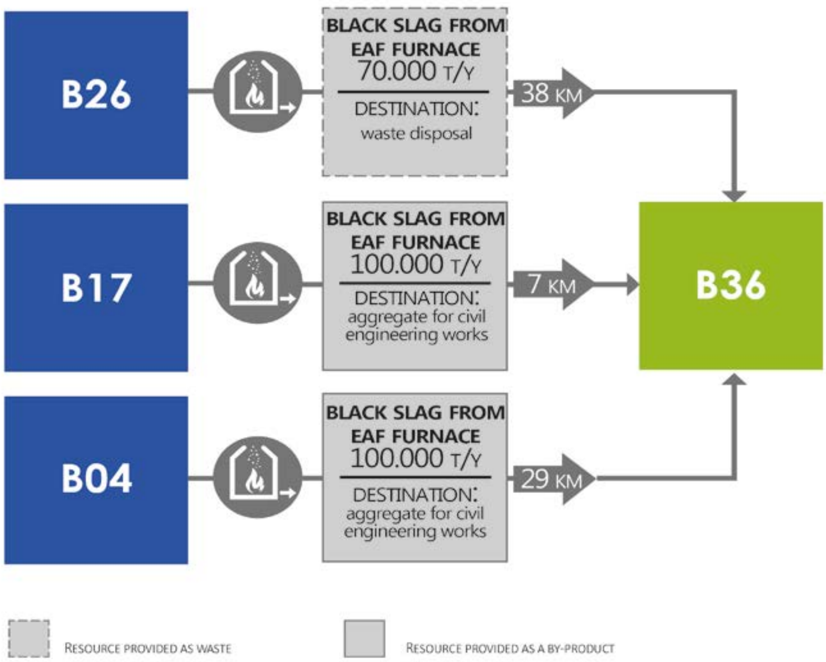

Fig. 5. Synergy diagram for black slag from EAF

In fact, the development paths outlined, such as the extraction of high added value molecules from oil and wine production waste and the use of black slag as an artificial inert from steel mill waste, can be taken as a pilot case for the development of analogous synergies in territories where there is a productive fabric that produces the same kind of resources.

The feedback effects mainly materialize in economic and environmental advantages, as in the case of the production of antioxidants and polyphenols, where the use of agro-industrial by products determines a reduction in production costs, an increase in value chains and a closure of production cycles with the relative reduction of environmental impacts. Analogous effects affect the valorisation of EAF slag with both purely environmental advantages (reduction of the exploitation of natural resources, reduction of the impact on the landscape, reduction of soil consumption etc.), but also involve characteristic aspects of the circular economy (use of otherwise destined for landfill), as well as technical performance.

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A TOOLKIT TO MONITOR MARINE LITTER AND PLASTIC POLLUTION ON COASTAL TOURISM SITES

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Abstract

Mismanaged waste at sea poses a great challenge to local marine systems. Plastic waste is considered the most abundant litter type in coastal tourism areas; yet, observational data fail to capture the full extent of plastic pollution on tourism beaches and its main drivers. This study aims to advance knowledge of marine litter and plastic pollution (ML&PP) sources, pathways, and drivers on tourism coastal sites. The research involves a 7-step toolkit to comprehensively assess marine pollution, by also engaging citizens in data collection. The toolkit provides a set of guidelines to identify, map, and quantify ML&PP, thereby supplementing to the current paucity of synoptic global analyses on marine pollution.

Key words: citizen science, coastal tourism sites, marine litter, plastic pollution, toolkit

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1. Introduction

Marine litter is among the greatest global challenges of the 21st century (Bettencourt et al., 2021). Marine litter is described as "*any persistent, manufactured, or processed solid material discarded, disposed of or abandoned in the marine and coastal environment*" (UNEP, 2009). It is estimated that nearly 80% of all marine litter found from the sea surface to the sea depths is made of plastic (IUCN, 2021), and the volume of ocean plastic is expected to increase further without action (SYSTEMIQ, 2020; WEF et al., 2016), with disastrous consequences for marine ecosystems (Derraik, 2002). Hence, studying the extent and distribution of ocean plastic pollution is of utmost importance to preserve the health and substance of the planet's seas. On the regulatory front, several measures to tackle marine litter and plastic pollution (hereinafter ML&PP) have been implemented. For example, EU member states have adopted the "Marine Strategy Framework Directive" to protect the marine environment across Europe's seas (EC, 2008; Galgani et al., 2013a), and "A European Strategy for Plastics in a Circular Economy", specifically aimed at reducing the plastic footprint (EC, 2018), among others. At the global level, the United Nations promoted measures for the containment of plastic losses and microplastics from land-based sources into the marine environment (UNEP, 2018, 2019a, 2019b), as well as the "Sustainable Ocean Principles" on retention of land-based and sea-based anthropogenic pollution (4.1: End plastic waste entering the ocean) (UNGC, 2020).

At the same time, the industry is increasingly taking action to reduce pressure on the environment by rethinking existing production and consumption models and exploiting innovative technological solutions (UNEP, 2014, 2021). Extant literature shows initial evidence of the industrial transition to a circular economy for plastics (e.g., Dijkstra et al., 2020; Gong

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et al., 2020; Maione et al., 2022; Paletta et al., 2019), also thanks to increased consumer awareness and demand for sustainable plastics (Rhein and Schmid, 2020).

Despite initial progress in the fight against plastic pollution, plastic is a persistent pollutant (Geyer et al., 2017) and plastic waste accumulations on coastal tourism sites often result in ingestion from marine organisms (Cózar et al., 2014), degradation of fragile ecosystems (Lamb et al., 2018), and reduction of mariculture (Wang et al., 2019). Marine pollution can also severely affect local economies, causing loss of tourism incomes due to environmental deterioration (Jang et al., 2014; McIlgorm et al., 2011), and a decline of coastal recreational activities (Mohammed, 2002; Staehr et al., 2018), which account for large portions of coastal economies.

A growing body of research indicates the need to further understand the amounts, sources, and contributing factors of ML&PP (Veiga et al., 2016). Monitoring ML&PP presents numerous benefits: first, the identification and quantification of the outflows leaving the system to assess the ecological impacts (UNEP, 2018a, 2019b, 2019c). Second, pollution monitoring can enable detection of loopholes in the plastic's value chain, including material losses during plastic production, handling, sector applications, and waste management of plastic waste (Ryberg et al., 2019). Third, it can supplement the current lack of transparency and traceability of plastic flows across their entire life cycle, including information on plastic production and consumption, data on waste streams and recyclables, and plastic pollution sources and pathways (Geyer et al., 2017), which altogether make the circular economy of plastics a hard-to-reach perspective. Finally, data from ML&PP monitoring can provide industrial stakeholders and policy makers with practical implications and decisional support to strategic interventions on pollution management, as well as to evaluate their effectiveness over time (Barnardo and Ribbink, 2020).

Several protocols for monitoring ML&PP have been developed (e.g., JRC, 2013; Lippiatt et al., 2013; NOWPAP, 2007). These protocols have demonstrated remarkable success employing in situ surveys for the analysis of macro-debris at the sea surface or on beaches, and water or biota sampling for assessing micro-debris in the water column (Salgado-Hernanz et al., 2021). However, observational data still fail to capture the full extent of ML&PP and its pathways from land to sea (Van Sebille et al., 2015).

To this end, this research attempts to provide a comprehensive evaluation of ML&PP, including quantitative assessment of input waste accumulations, sources and pathways of marine pollution, and its rooting causes. The study introduces a 7-step toolkit to monitor ML&PP on coastal tourism sites. Implications from this study can advance knowledge of the hotspot of marine pollution, its main drivers, and the main challenges faced when dealing with plastic waste-free oceans.

2. Materials and methods

Identifying the origin of the different items that make up marine litter is a difficult and uncertain task. To identify the drivers and deficiencies in the production, consumption, and waste management systems that generate marine pollution, it is important to understand where, by whom, and why litter is released from these systems and how it enters the marine environment. This process is necessary to establish appropriate operational targets, as well as to design, implement, and monitor effective pollution management and mitigation measures. Identifying regional and sectoral differences for different plastic sources and emission hotspots is central to shaping actions against ML&PP. The toolkit presented in this paper is composed of seven steps (Fig. 1): (1) community involvement, (2) problem definition (spatial data), (3) SWOT analysis, (4) better monitoring for better management, (5) field data collection (observation, sampling), (6) perceptions of tourism (interviews), and (7) evaluate the outcomes.

2.1. Step 1. Community involvement

It is important at the early phases of the project to create awareness and engagement among communities regarding the problem of marine litter. This phase also helps the researchers to better understand the context together with the community of study. During this phase, preliminary interviews, common public events, exploratory meetings are essential to build the trust bridges, spread awareness about the environmental problem to the community and connect with the context (Tweddle et al., 2012; Senabre et al., 2021).

Furthermore, the proposed strategies are functional to develop and implement a stakeholder analysis in order to define targeted actions and address problems at different levels and scales.

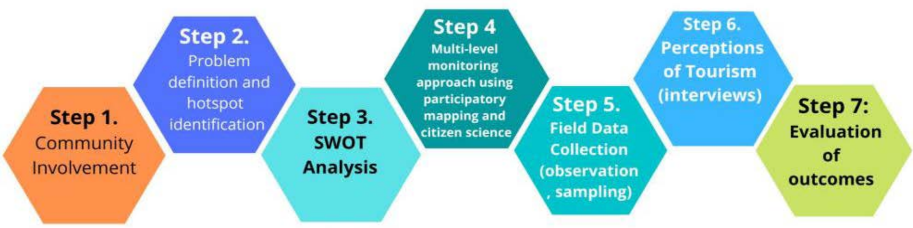

Fig. 1. The toolkit seven steps

2.2. Step 2. Problem definition and hotspot identification

Defining the problem is important to create hotspot and spatial analysis. These spatial analyses are depicted as hotspot points in a map and refer to locations of events or objects. Step 2 focuses on identifying problematic hotspot areas along shores that accumulate the most litter. This action will allow a better understanding of the distribution of plastic pollution in beaches using visualization. This information helps designate plastic beach hotspots in order to better focus on implementing coastal management efforts, in order to understand the sources of plastic pollution, and help others comprehend the vast scale of plastic pollution in the world's oceans. By collecting and visualizing plastic beach hotspots we can compare between beaches and highlight beaches that hold the highest amount of litter based on time and space (most popular tourist destinations). As a preliminary overview of the area, this step gives us a better understanding of the existing conditions of the surrounding environment.

Second, prior to conducting the plastic beach hotspots it is important to gather background information on the beach. For example any storm drains, rivers, stream, wind and wave direction, last high tide, current weather, and beach type should be described and visualized for each plastic beach identified hot spot. Third, other information to be taken into account refers to the presence of significant beach or cliff erosion in the area and the current and general beach use. If statistics on beach use are available through the city, it would be helpful to know about and visualize how many people use the beach annually, monthly, or weekly. Is it a private/public beach? Sandy or rocky beach? Nearest town and location of any outfalls? Furthermore, it is important to understand how often the beach is cleaned as some cities, counties and local environmental groups clean local beaches regularly. As a result, it is important to document as much information on cleanups as possible.

There are several marine litter monitoring programs and methods for identifying hotspots with different spatial and temporal scales, different scales for litter size, and different classification of litter, identify the beaches most likely to be affected. As noted above, in order to identify the hotspots of marine litter pollution, it is first necessary to collect data on the characteristics of the litter, including an analysis of its composition, spatial distribution and, where possible, litter sources, the hydrographic characteristics of the area. According to Guidance on Monitoring of Marine Litter in European Seas (Hanke et. al., 2013) in coastal areas the type of beach survey depends on the objectives of the assessment and the area of coastline pollution. Among the most recent tools, there is the development of numerical models that, based on the circulation of marine currents and the location of marine litter sources, track their movement. It is necessary to monitor pollution accumulations several times, as one-off monitoring is not sufficient to identify hotspots. As a result, at least two surveys per year are recommended during the high- and low-tourism season. However, due to seasonal variations, frequent surveys may be necessary to identify significant seasonal patterns to be considered when treating raw data to identify trends (EC, 2018; Galgani et al., 2013b; Petrov, 2020).

2.3. Step 3. Strengths, Weaknesses, Opportunities, and Threats (SWOT) Analysis

Performing a SWOT analysis at the city level is useful to maximize the area's strengths, minimize its weaknesses, take advantage of opportunities and limit its threats. The analysis involves specifying the objectives of the entity and identifying the internal and external factors that are favorable and unfavorable to achieve those objectives. Identification of SWOTs can help establish a framework for future planning efforts including policy development and development review. The analysis determines whether these internal and external factors may support or block the objective. The SWOT analysis can lead to a strategy or an action plan for dealing with negative factors while maximizing strengths and opportunities. For example, it is common to represent a SWOT analysis in a 2 by 2 matrix putting the categories side by side, making it easier to see the correlations among them. It is effective for analyzing and creating a simplified picture of a complex situation. To properly conduct the analysis of the efforts on marine litter Table 1 shows an example of a SWOT matrix ML&PP transformation (de Taxis du Poet and Beukering, 2018). The SWOT analysis findings show transformation/recycling can use membrane technology separately as the best technology for filtering microplastics and marine litter.

2.4. Step 4. Multi-level monitoring approach using participatory mapping and citizen science

It is important to assess a multivariate data integration matching different data sources to have an effective monitoring of ML&PP at sea and along the shores to implement circular and redesign value chains toward regenerative models. For this reason, our methodological toolkit combines satellite data with participatory mapping in order to grant comprehensive reliable information.

Tracking pollution is crucial to implement effective marine management strategies, especially along border regions where plastic debris can be transported by wind, currents, and float in transboundary waters. When tracking transboundary pollution, a major challenge pertains to the difficulty of obtaining standardized, homogenous data on pollution cycles cross-borders.

Table 1. SWOT Matrix ML&PP Transformation (Beukering, 2018)

Internal Factors	
Strengths (+) - Thermal treatment (i.e. energy recovery) may be considered a viable option for some plastic waste collected from the sea, in particular for plastic that has been in the sea for long enough to become too degraded or contaminated for material recycling - Recycling plastics cuts back on oil consumption. Helps to extend the lifespan of fossil fuel reserves. - Recycling uses energy but less than making fresh plastic - Plastic recycling is a well-established industry.	*Weaknesses* (-) - Transformation processes currently involve visible plastics, but recycling opportunities have not yet been found for microplastics.
External Factors	
Opportunities (+) -New technologies involving different inputs, outputs, scales and processes are changing the market. -Recycling plastics can be an alternative to landfill potentially causing environmental harm.	*Threats* (-) -Recycling may be seen as a disincentive for avoiding the continuous increase of plastic production. -Recycling plastics delays rather than avoids final disposal.

Issues can include limited traceability associated with different systems for material/pollution monitoring and accounting; different policies and measures to allocate resources, and keep material flows accountable; a lack of information exchange across borders; or uneven use and communication of data analytics. To address this problem, satellite imagery and aerial photos have shown initial progress in pollution monitoring as they allow real-time or nearly real-time data acquisition, wide area coverage, and high spatial resolution (Biermann et al., 2020; Topouzeli et al., 2019). Multi-data and multi-method approaches can be integrated with remote sensing, GIS technologies, satellite data and participatory GIS (Frails, 2021). The proposed toolkit aims to provide a consistent global, harmonized system for assessing particles swirling in coastal tourism sites, including abundance, distribution, and location of the sources and pathways of pollution into the marine environment. Regarding data collection the toolkit is part of a multi-level monitoring approach that combines remote sensing and proximity sensing techniques. In fact the data acquired by citizen science can be combined with open-source space-based earth observation to map pollution accumulations and create a consistent ocean particle tracking model (Figure 2). (Rummel et. al., 2016). Following, satellite imagery can be combined with high resolution spectrometric images to detect the extent of plastic accumulations that are not readily visible through satellite images (e.g., smaller plastic particles, ocean plastic flows at the water surface) (Free et al., 2014)

Second, effective ML&PP measurement should integrate available data on water quality (e.g., national statistics and accounting, environmental reports) with proximity sensing techniques (e.g., detection sensors) and in-situ observations. Furthermore, the use of the "citizen science" paradigm allows citizens to acquire litter data in a participatory way. Traditional data sources can indeed lack accessibility and spatial variations (Fritz et al., 2019).

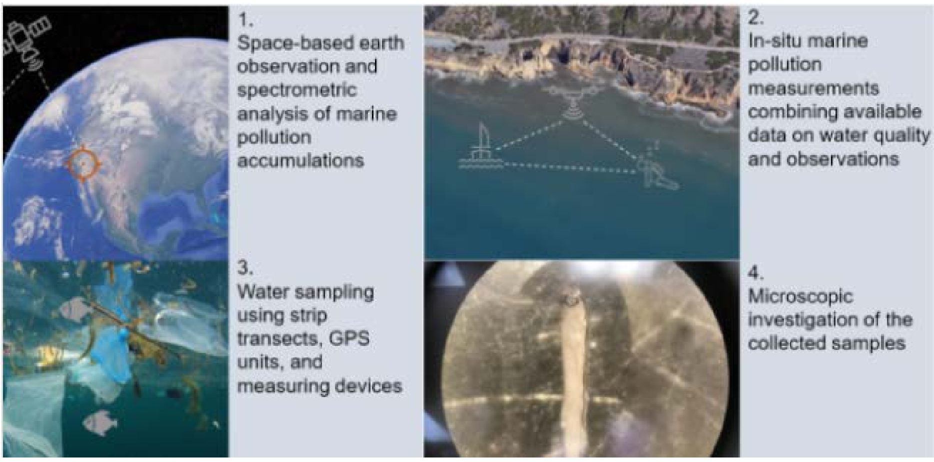

Fig. 2. Example of multi-level monitoring combining remote and proximity sensing techniques with in situ sampling

Participatory science then offers a tool to supplement satellite data to develop multilevel and multi raster maps to create "participatory maps". For this reason, not only could citizen science contribute to data collection, but it can also support monitoring and reporting, thereby enhancing timely decisions (Fraisl et al., 2020). Finally, using participatory approaches can foster community resilience contributing to a better knowledge and framing of the context, allowing to know better the boundary conditions of the environmental problems under investigation (Vito, 2019).

2.5. Step 5. Field data collection (observations and sampling)

This step is used to conduct beach litter surveys. These surveys are generally carried out to answer the following questions: (1) Where are the areas where litter is most prevalent? (2) How much litter occurs in the selected study site? (3) What is the litter composition (wet, recyclable, non-recyclable)? (4) What are the principal types of material (e.g., plastic, paper, metal etc.)? (5) What are the principal litter items? (6) Does the amount of litter vary across different transects? (7) What are possible variables that affect the input of litter at sea? To answer these questions, data should be collected at the sampling locations using the survey methodology for macro- (larger than 2.5 cm) and meso-debris (between 2.5 cm and 0.5 cm) as suggested by Lippiatt et al. (2013) and Barnardo and Ribbink (2020).

Prior to sampling, the site conditions need to be assessed by the survey supervisor(s), including the weather conditions, tide, and accessibility to the site to ensure the safety requirements during data collection. The site boundaries are then marked and the sampling area is divided into transects running perpendicular to the shoreline. The start point should identify with a permanent element, such as the edge of a seawall, sidewalk, parking lot, or a large rock. Latitude and longitude of the transects should be recorded to allow repeated measurements for future comparisons. The number and size of transects should be selected based on the dimensions, accessibility, and conditions of the sampling site. The rule of thumb is to set up an adequate number of transects to capture the diversity of the beach environment under assessment, for example, free beach, dunes, adjacent roads, waterways, polluting coastal activities (e.g., restaurants, hotels, tourism attractions, fisheries), ports, or mangrove forests etc. Table 2 summarizes the main sampling activities and materials. The surveyors collect photographic evidence and georeferenced coordinates of the assigned sampling area. For each transect, each and every piece of litter is recorded as follows: ID, date, transect n., collector, material type. Labeled litter bags can be used to collect and separate litter, for example, based on material type, to avoid material contamination. Table 3 describes the most common beach litter items by material type found in coastal areas.

Following, for each sampled transect, ML&PP is assessed based on litter item count (number), litter weight (kg), litter abundance (kg/surface), and litter coverage (estimated visual coverage, usually indicated according to four intervals: 0-25%, 25-50%, 50-75%, 75-100% of the transect surface). For a synoptic spatial evaluation of the transect, it could be useful to develop a cleanliness index that takes into account different measurements of pollution (an example of cleanliness index is offered by Alkalay et al. (2007)).

2.6. Step 6. Perceptions of tourism (Interviews)

This step investigates tourism-related perceptions via qualitative data collection. Structured interviews are conducted at each site to investigate the state and conditions of production and management of waste during the high tourism season. The interviews are to assess (1) waste facilities on tourism sites, (2) perception of tourism as a sector that generates waste, plastic materials, and (3) tourist littering practices (Table 4). To depict a more comprehensive picture of tourism-related perceptions, interview questions should target a variety of stakeholders, such as workers in the tourism and restoration sector (e.g., hotel staff, human resources coordinators, hotel managers, and restaurant owners), local operators (e.g., tour guides, drivers, and vendors), waste workers (e.g., waste pickers, street sweepers, officers from the municipal waste management services, and project managers from private waste management companies) and tourists.

Table 2. Survey activities and materials (adapted from Maione, 2021)

	Site preparation	***Litter counting***	***Litter composition analysis***
Activities	• Marking site boundaries. • Setting transects.	• Visual inspection of debris. • Litter separation by material type.	• Debris classification by material type. • Weighing of plastic debris.
Materials	• Flag markers. • 20-meter measuring tape. • Strip transect. • Digital camera. • Handheld GPS unit.	• Digital camera. • Datasheets. • Pencils. • Litter bags. • Gloves.	• Scale. • Datasheets. • Pencils.

Table 3. Categorization of common beach litter items (adapted from Fleet et al., 2021)

Category	***Items***
cloth/textile	clothing; carpet & furnishing; hessian sacks/packaging; shoes & sandals; sails & canvas; backpacks & bags; other textile; fishing net
food waste	food waste
wood	wooden corks; wooden crates/boxes; ice-cream sticks, wooden forks, chopsticks, toothpicks; wooden pallets; other wood; greens
glass & ceramics	glass bottles; jars; light bulbs; tableware (plates, cups, glasses); construction materials (bricks, tiles, cement); pieces of glass; other glass items; other ceramic/pottery items
plastics	six-pack rings; plastic shopping bags; drink bottles (< 0.5 liter); drink bottles (> 0.5 liter); cleaning products containers; cosmetics/body care containers; plastic jerry cans; plastic crates, boxes, baskets; vehicle parts; plastics caps/lids; plastic rings from bottle caps; cigarette lighters; pens; combs/hair brushes; sunglasses; chips/sweets wrappers; other wrappers; plastic cutlery (fork, spoon, knife); straws; stirrers; plastic plates, trays; plastic heavy-duty sacks; mesh bags; gloves; plastic tags; plastic sheetings; rope; fishing nets; fish boxes; fishing lines; plastic floats; plastic buoys; buckets; plastic industrial packaging; nurdles; plastic shoes; flip flops; beach toys; polystyrene pieces; styrofoam containers; CDs & DVDs; masks, fins and snorkeling equipment; syringes/needles; sanitary towels, panty liners, diapers, nappies, tampons; other personal care/hygiene products; plastic cotton bud sticks; medical/pharmaceuticals containers, tubes, packaging; plastic pipes; masks; cigarette buts
rubber	balloons; balls; rubber footwear; tires; belts; rubber sheets; tubes; rubber band; condoms
paper & cardboard	paper bags; cardboard boxes; paper packaging; cartons & tetrapack; cigarette packets; cups/drink containers; paper plates & trays; newspapers & magazines; paper fragments; other paper items; tissues
chemicals & hazardous waste	wax/paraffin; candles; medicines; batteries
metal	aerosol/spray cans; beverage cans; food cans; foil wrappers, aluminum foil; bottle caps/lids; disposable BBQs; appliances (refrigerators, washers, etc.); metal tableware & cutlery; fishing weights/sinkers; industrial scrap; barrels; paint tins; wires; vehicle parts; cables; cookware; wheel-related metal pieces; other metal items

Table 4. Examples of interview questions (adapted from Maione, 2019)

Topic	***Question example***
Waste facilities on tourism sites	Do you manage waste at work?
	Do you recycle any materials? Which ones?
	Do you store waste at work? Where?
Perception of tourism as a sector that generates waste	Do you think that tourism activities contribute to generating more waste?
	Has plastic waste increased with tourism?
Tourist littering practices	Are tourists respectful of the local environment?
	Do you think that tourists dispose of their waste into the ocean?
	Have you seen any plastic waste in the ocean?

2.7. Step 7: Evaluation

The evaluation step allows to decide whether the existing plan needs to be revised, or whether a new plan is needed to better address the problem. If you are not pleased with the outcome, return to Step 2 to select a new solution or revise the existing solution, and repeat the remaining steps. In order to integrate the evaluation step, it is important to revisit the array of considerations that need to be considered. Identifying and defining the problem, generating possible solutions, evaluating alternatives, deciding on a solution, implementing the solution and evaluation of the outcome.

3. Results and discussion

In this section we provide a case study implemented by the authors during a beach cleanup in Villapiana Scalo, Cosenza, IT, on August 22th 2022, to demonstrate the applicability of the multi-step toolkit proposed in this research.

3.1. Step 1. Community involvement

Before performing a beach cleanup, training webinars and public events have been performed to educate the volunteers and the local community on the importance of a correct management of waste on the shore and on the impacts of mismanaged waste on coastal ecosystems, as well as to train volunteers on the data collection procedure.

3.2. Step 2. Problem identification

A coastal site of 3 km along the southern end of the city was selected for analysis. This area hosts 3 bathing facilities as well 2 areas of free beaches. In particular, one of these is adjacent to a camping site with direct access to the shore, while another is peripheral and further from the main urban area, to assess how tourism specifically contributed to beach pollution.

3.3. Step 3. Strengths, Weaknesses, Opportunities, and Threats (SWOT) Analysis

Table 5 resumes a SWOT analysis applied on the selected site. The SWOT has been functional also to understand the socio-cultural context of application of the toolkit.

3.4. Step 4. Multi-level monitoring approach using technologies and citizen science

Data collection involved volunteers to record GIS position and quantity of the wastes collected. GIS positions have been taken through smartphones by volunteers thanks to the app Geopaparazzi©. GIS data have been combined also with preliminary satellite backgrounds as in Fig. 3 give an example of the spatialization of data:

The beach strip of analysis has been divided in 4 transects delimited by morphological elements, such as canals, roads, and private/public beach. The GPS coordinates of transect delimitation has been taken and indicated as blue stars in Figure 3. The red points represent the places where litter has been found and for each point a photo and an annotation on the type of litter has been done through the app. A total estimation of the waste collected per transect has been also done at the end of the collection into the transect, recording the number of waste collected and a weight when possible.

3.5. Step 5. Field data collection (observations and sampling)

Beach litter was collected over 4 consecutive transects, as shown in Fig. 3. Plastic was the most abundant type of litter on all transects. The most common plastic litter items were bottles, plastic wrapping, bottle caps, and cigarette buts. A detailed analysis of the beach litter composition is reported in Table 6. Transect C recorded the highest amount of beach litter, and specifically plastic waste. A possible reason is that the transect is adjacent to a camping site. This also explains the higher variety of litter items found. For example, we recorded a higher number of plastic/glass bottles and cans from beach bonfires.

3.6. Step 6. Perceptions of tourism (Interviews)

To assess the increased waste production during the high tourism season (June-September), the authors collected data on the management of plastic waste and marine pollution by interviewing key stakeholders from the tourism sector, waste workers, and tourists.

The majority of the study's participants reported that waste generation was greater during high tourism season, suggesting that tourism is a primary waste-generating sector on the study site. Some waste pickers indicated that, during the high tourism season, the amount of solid waste, and single-use plastics in particular, doubled on beaches.

Table 5. Examples of interview questions (adapted upon Maione, 2019)

Internal Factors	
Strengths (+) The selected site is a tourist site that have still margin of growth and improvement for management Local population perceive a need for change The location is a typical tourist example for south of Italy	*Weaknesses (-)* The site is very active only in summer and activity are very focused on profit on tourism Lack of proper facilities and infrastructure for a proper waste management Very traditional context quite resistant for implementing changes even if problems are perceived

External Factors	
Opportunities (+) If correctly involved citizens are very participative As classical businesses are still not hardly settled, there are margin for proposing sustainable solutions. The case study offer the possibility to scale the experience in different	*Threats (-)* As it is a very traditional context, there could also be resistance ons implementing ecosystem management activities. Skepticisms on the final results of the application of the toolkit Lack of follow up after the activities Technical problem and glitches in data acquisition due to a lack of confidence with the protocol

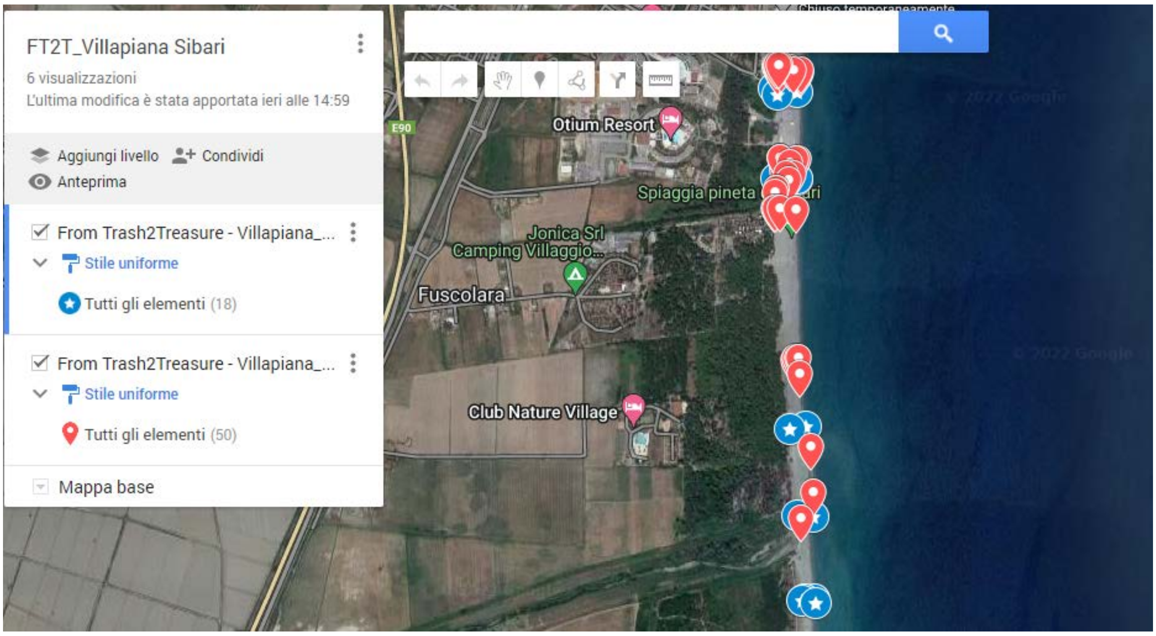

Fig. 3. Spatial representation of GIS data collected with a citizen science approach + Satellite background

Table 6. Beach litter composition analysis by transect.

ID	*Material*	*Items*	*Count (n)*	*Weight (kg)*
		Transect A		
1	Plastics	Cigarette buts	45	0.09
2	Paper & Cardboard	Paper packaging	1	0.05
3	Plastics	Mask	1	0.12
4	Plastics	Miscellaneous	1/2 bag	1.2
5	Metal	Can	1	0.03
		Transect B		
1	Plastics	Cigarette buts	23	0.05
2	Glass & Ceramics	Bottle	3	1.5
3	Plastics	Miscellaneous	1/4 bag	0.3
4	Paper & Cardboard	Paper packaging	2	0.1
5	Cloth/textile	Fishing net	1	6
6	Metal	Metal mesh	1	3
		Transect C		
1	Plastics	Miscellaneous	4 bags	10.8
2	Glass & Ceramics	Miscellaneous	16	8
3	Metal	Cans	10	0.3
4	Rubber	Tyres	4	28
5	Paper & Cardboard	Tissues	2	0.02

6	Plastics	Cigarette buts	27	0.05
7	Cloth/textile	Fishing net	1	5
8	Other	Trash deposit	7	0.5
9	Plastics	Mask	1	0.12
Transect D				
1	Plastics	Bottle	1	0.35
2	Cloth/textile	Slipper	1	0.4

Interview respondents indicated that the persistence of plastic litter was primarily driven by three factors. First, marine littering was mentioned by all respondents as a major driver of beach and coastal pollution, especially among the tourist population. A second driver of beach pollution was insufficient provision of waste management services on the beach. This was due to the inability of the municipal waste sector to provide regulations for all stakeholders (e.g., waste-generating activities such as hotels and food services, private waste management services, recycling associations) on one hand, and the absence of trash cans and official waste collection activities on the other.

Finally, the study participants mentioned that the proximity of camping sites to the beach was another main driver of beach pollution.

4. Conclusions

Social awareness is increasing but so does plastic ending into oceans. There is no one magic bullet to solve it all. What counts most is the coherence between different solutions to form a strong package of measure. This study explored the potential for monitoring ML&PP through a multi-step, multi-method toolkit to overcome some of the existing challenges to detecting sources, pathways, and rooting causes of marine pollution.

The paper presents a 7-step toolkit to assess beach litter, with a particular focus on tourism-related plastic waste. The toolkit describes simple steps which can easily be implemented by non/scientists. Another advantage of the present protocol consists of the use of low-cost tools, hence fostering the participation of citizens in scientific research. However, some limitations of this approach pertain to the integrated use of several methods, which may extend the overall duration of the data acquisition process.

Relevant implications for assessing ML&PP can be drawn from this study. Our approach supports a more detailed understanding of the main elements affecting the extent and distribution of marine pollution. The key message emerging from our research is that only a comprehensive monitoring of ML&PP, aimed at detecting pollution pathways from source to sink, can set the right path towards reducing marine pollution. Furthermore, one size does not fit all. As a result, technologies should be adapted to the social and industrial context of the point of intervention. Thus, there is a need to develop long term and short term approaches, while considering all levels, from local, to national, European, G7, or worldwide.

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CIRCULAR ECONOMY AND ZERO WASTE TARGETS IN THE TERRITORIO & RISORSE BIOMETHANE AND COMPOSTING PLANT SANTHIÀ VC – ITALIA

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Abstract

Sustainability and circular economy are the dominant themes of the moment and are totally transversal to every sector, especially in the waste treatment sector where these issues intersect with the service offered to society. Good management of municipal waste is a service to society and an opportunity for the recovery of raw materials and energy. Modern engineering produces solutions and technologies which, when integrated, achieve the goal of almost zeroing waste to be disposed in landfills and total energy recovery of the same. Technologies, good engineering practices and the process procedures make plants safe for the environment and the operators, increase recovery efficiency, allow the operator a total control of the processes, and make the plant reliable and profitable. The purpose of this paper is to describe the full-scale waste plant of Territorio e Risorse Srl (T&R) of Santhià VC and explain the operational results in this revamped plant with modern design and technology. Start-up of the new anaerobic line showed: (i) plastic over screen production less than 15 wt. % of treated OFMSW; (ii) high specific biogas and biomethane production values (190 Nm^3 dry biogas/ton of fed ingestate). These values, better than in the literature, show an efficient OFMSW valorization process and a reduction in waste produced. It is possible to make our mind on a series of important and decisive issues for the success of an AD project as well as to get some important data about plant performance which set a new benchmark or biogas and RNG production from food waste.

Key words: anaerobic digestion, composting, SRF, circular economy, zero landfill

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1. Introduction

Food waste and green waste collection in Italy has advanced significantly, a number of plants have been built and some peculiarities of the Italian waste have led to implement new technologies and solutions (Mancini et al., 2019; Scalvedi and Rossi, 2021). Making a statement regarding the performance of one of the most recently constructed plants is the goal of this study. Waste source segregation and collection for bio waste totals 7.175.000 ton/y, or 121 kg/person/year. This includes 5.230.000 ton/year of food trash and 1945000 ton/year of green waste (Centemero and Confalonieri, 2022). This quantity of waste is processed in dedicated facilities using a variety of technologies, yielding 2.200,000,000 ton/y of compost and 400.000.000 Nm3 of biogas, which are then converted into 100.000.000 m^3 of renewable natural gas that is pumped into the gas grid, as well as 440.000 MWhe of electricity and 130.000 MWht of thermal energy.

The goal for 2025 is to segregate and collect 155 kg/ab/year of biowaste, which is equivalent to 9.000.000 ton/y. This implies the construction of 52 additional biogas plants, all of which are intended to provide RNG for an additional 300.000.000 Nm^3 per year (Fig. 1) (Centemero and Confalonieri, 2022). The target for 2030 is to meet at least 10% of Italy's natural gas needs using RNG, enabling Italy to complete the cycle of biowastes.

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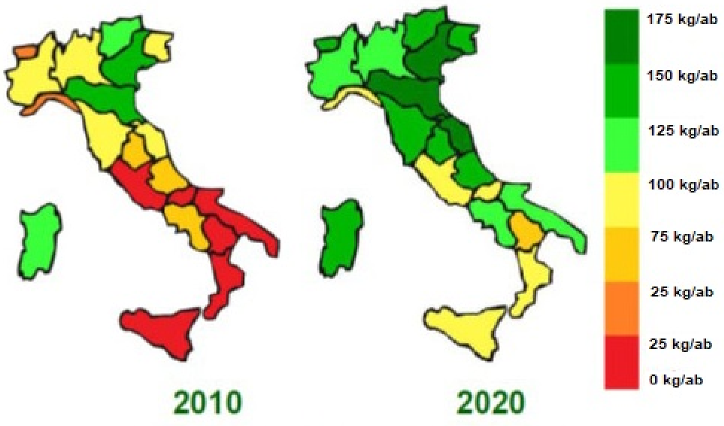

Fig. 1. Separate collection of waste in Italy

The technology created to remediate such waste streams has been fine tuned for such garbage and significantly advanced through time. This is because food waste is a heterogeneous material, and its physical and chemical characteristics depends on the definition of OFMSW is defined in different countries and other factors like weather, predominant economic activities, nutritional habits, seasonal changes and recollection system (Campuzano and González-Martínez, 2016).

Italian waste is primarily comprised of putrescible waste (vegetables), with little green waste and a 7–10% contamination rate from shopping bags, the majority of which are made of biodegradable plastic (Table 1). Anaerobic digestion (AD) plants for food waste have evolved from wet AD, where the total solid (TS) content is between 10 and 12 percent, to dry digestion, where the TS is higher at 30 percent. This allows for the largest amount of biogas to be extracted from the waste stream while also significantly reducing the amount of wastewater that must be disposed of.

Table 1. Example of OFMSW composition analysis of food waste from Northern Italy region

***Fraction** (%)*	***Value***
Putrescible organic	87.40
Cellulosic material	1.04
Plastic materials	8.70
Glass	1.77
Metals	0.55
Others	0.54

The stream may now be disposed of more easily and more affordably thanks to improvements in the removal of pollutants (mainly plastics) from the substrate and a reduction in the amount of organic fraction that must be drawn along with the contaminants. To increase the circularity of the treatment, cleaned and odorless plastic can be used as solid recovered fuel.

The plant management has been heavily automated with a totally unmanned handling of the masses throughout the process, and the final step of processing the digestate with an appropriate composting has also been enhanced to produce a superior quality compost.

The Territorio & Risorse factory in Santhià, Italy, which is the focus of the current study, has been designed with all mentioned upgrades and now, after two years operation we are able to measure what are the real process statistic. As a result, a new benchmark for the industry has been established.

2. Case study

The Entsorga Group headquartered in Tortona Italy – over the years built more than a hundred composting, mechanical biological treatment and biogas plant in the EU, North Africa and the US by using their proprietary technologies and the 13 patents owned. The Company translates the concept of environmental sustainability with Eq. (1) showing how the human impact on the environment is the result of the product between the world population and the average individual consumption of resources, divided by the technology (www.entsorga.it).

$$Human\ Impact = \frac{Population * Consumption}{Technology} \qquad (1)$$

A challenge that Entsorga took on 20 years ago**,** was focused on the research and development of solutions with high technological value and low environmental impact. This approach leads to designing waste treatment plants where the main requirement is their environmental performance which, we believe, is clearly achieved in the plant built for the Territorio & Risorse (T&R) plant in Santhià VC – Italy.

3. Plant system analysis

3.1. The plant

The T&R plant was built in 2010 as a just composting plant for a capacity of 40.000 t/y. The plant permitted capacity was, over the years, used to get source segregated food waste which was always got a much higher gate fee if compared to other streams such as green waste. Chopped wood was bought to be used as bulking agent in the compost mixture to be made with the food waste. All the process is carried out in enclosed buildings with a continuous air extraction, such air is the then cleaned by a biofilter.

In 2018 a new permit application was submitted to expand the plant with an anaerobic digestion unit to produce renewable natural gas (bio-methane) for a total plant capacity of 50.000 t/y. The permit was granted in September 2019 (hiips://www.ibabiogas.com/case-studycomposting-and-anaerobic-digestion-plant/)

3.2. Optimizing the pre-treatment

This first requirement addresses the need of minimizing the sorted-out streams which is extremely expensive to dispose (140-180 €/t). It is very well known in the industry that food waste has a contamination of 7-10% (Italy) essentially made up of plastic bags but also metals and other materials. The sorting operation is a very sensitive issue, the usual way to do such treatment is to use a bag opener and then some sort of screening and metal removal. In doing so you may obtain an amount of sorted out materials which may go from 20 to 40% of the throughput thus resulting in having a huge quantity of sorted out material made up of plastics which is dragging a lot of organic waste thus resulting in unaffordable disposal cost and in loosing precious methanogenic materials.

By using the proper pre-treatment line, the amount of sorted out materials is reduced to 14-15% only. On top of it by using squeezers rather than screener, the exposure of the biogenic particles to the process is increased and a faster start-up of the biogas generation process is obtained. Finally squeezers have a much lower maintenance requirement than screeners. A further advantage generated by such pre-treatment is the possibility to use piston pump and a pipeline to feed the digester preventing material leaks and clogging and reducing maintenance of the feeding line to a minimum.

3.3. Minimizing water treatment requirement

By using a plug flow semi dry digester capable of having a total solid of 28-32 wt.% rather than the 10-12 wt. % of a wet digester helps a lot in this respect as you are reducing the water to 1/3 of the water you may have in a wet digester with 10-12% of TS (APAT, 2005). On top of it, a semi dry plug flow digester due to the agitator and the suspension capacity generated by the high solid in the ingestate allow us to avoid the know problems of sinking inert materials and floating materials creating a hard cap affecting wet digesters. Both issues are important as they require to be fixed to put the digester down and clean the tank, a very time demanding an expensive maintenance.

3.4. Maximizing the biogas production

In order to feed the digester 24/7 pre-treatment is made using maximum automation possible. Minimize the downtime of the plant which may happen for minimal malfunction or power supply instability which put the plant down and may keep the plant down for an entire night or weekend. The remote control of the plant enables the operators to intervene remotely.

3.5. Digester heating

The last requirement to meet is to improve the digester heating in order to save energy but also to have a tighter control over the project. Then the choice was to use a steam heating system which has the advantage to be extremely effective in distributing heat inside the processed material and in the position where such heating is more required, the inlet of the feedstock. On top of such benefit the system has no heat exchanger or pipe inside the digester thus avoiding corrosion of the pipes, leaks of the heating fluid or deposit of materials over such pipes and minimize the thermal stress in the digester concrete structure.

3.6. Biogas upgrading system

The upgrading system combines a number of filtering stages a water washing to clean the biogas from NH_3 and other soluble VOC, a chiller to reduce the gas temperature, a first activated carbon filter to specifically remove H_2S, a second activated carbon filter to remove VOC and, a membrane system to filter the CO_2.

3.6. Plant commissioning

The first filling of the digester was made by using digestate from several other plants with a mix shownin Table 2.

Table 2. Composition of the mix in digester

Inoculum matrices	***Volume, m³***	***%***
Digestate o animal manure (cows) from wet AD	1740	87
Digestate from semi-dry process of food waste	240	12
Ingestate deriving from food waste pre-treatment prepared in the plant	20	1
Total volume of the digester	**2000**	**100**

Before starting the plant commissioning, the inoculum was tested by using the COW-LAB, a pilot digester in scale 1/12 which reproduces the much bigger digester and allowed to fine tune the inoculum composition and to schedule the increase of pre-treated food waste to be fed to the digester (Fig. 2).

3.7. Daily analysis

By running in parallel the Cow-Lab and the digester full scale, the full-scale digester performance and the biogas production can be predicted. .

This activity was supported by a strict daily analysis schedule, on both system:

- biogas production
- biogas composition
- temperature
- pH
- FOS/TAC
- Total Solids TS
- Total Volatile Solids TVS

Periodic analysis has also been scheduled supported by a certified laboratory:

- organic substance
- TKN total Kjeldhal nitrogen
- Weender analysis
- micro-nutrients
- food waste composition

The result of 15 weeks ramp-up schedule summarized in Fig. 3, which correlates the increasing amount of ingestate (food waste) fed to the plant during the plant ramp up and the amount of biogas produced. The first point to consider is the production of biogas vs. throughput now stable at 190 Nm^3 dry biogas/$t_{ingestate}$ (considering a biogas moisture content equal to 10 v,v %) which is exceeding the expectations originally set at 150 $Nm^3/t_{ingestate}$ found in a similar plant in Netherlands (de Laclos et al., 1997).

Fig. 1. Image of the Cow-Lab (www.entsorga.it)

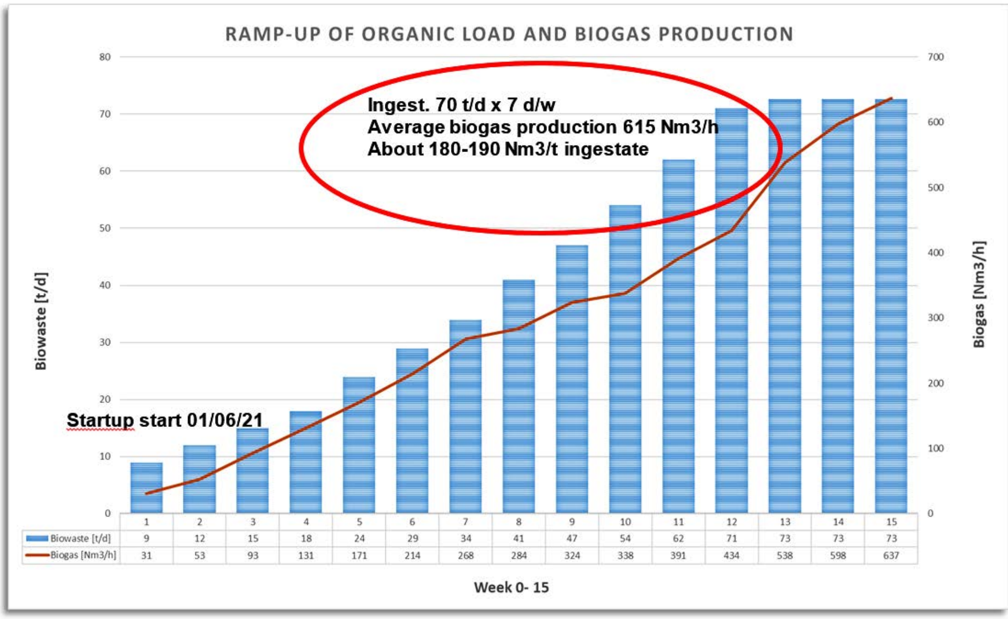

Fig. 2. Ramp up: feeding ratio vs. biogas production

In Tilburg plant the pre-treatment line is composed of a rotating screen, a magnetic separator and a shredder that crush the waste and reduce the particle size below 80 mm (de Laclos et al., 1997). The specific biogas production found in Santhià is close to Biomethane potential (BMP) found in literature by Campuzano et al. for the Italian OFSMW from 7 different cities, equal to 213.06 Nm^3 /$t_{ingestate}$ (Campuzano and González-Martínez, 2016). While some increase of biogas production may be explained by the efficiency of the pre-treatment and with the quality of the process discussed in previous chapters.

Another interesting issue is shown in Table 4: a decrease in feeding the digester of 50% during weekend leads to a considerable decrease in biogas production. During Saturday, Sunday and Monday, approximately 30, 30 and 12 tonnes respectively were loaded to the digester. Biogas production remained approximately constant between Friday and Saturday, but dropped on Sunday, from around 11000 Nm^3/d to 8353 Nm^3/d. Production rose again, restoring the load to 70 ton/d with a production around 13000 Nm^3/d of wet biogas per ton of ingestate. This testifies to a fast degradation kinetics of anaerobic microorganisms. Campuzano et al. in their research discuss the physical, chemical and bromatological characteristics of food waste from different countries and cities. They searched a correlation between these properties and the biomethane potential (BMP).

Table 5 shows an elaboration of the data presented in the paper. As shown in Table 5 the average BMP of OFMSW in Italy from 7 cities is 213,06 Nm^3 biogas per ton of ingestate. The variability of BMP depends on the variability of OFMSW which depends on weather, predominant economic activities, nutritional habits, seasonal changes and recollection system. (Campuzano and González-Martínez, 2016). Compared to BMP, which is the maximum amount of biomethane and biogas that can be produced from one tonne of feedstock, some full-scale plants show lower values depending on the efficiency of converting biomass into biogas.

Table 3. Biogas production sensitivity related to feeding

Date	*Ingestate [ton/d]*	*Biogas [Nm^3/d]*
04/10/2021	59.86	5.434.0
05/10/2021	60.00	10.353.0
06/10/2021	59.57	11.150.0
07/10/2021	44.97	10.613.0
08/10/2021	60.00	11.250.0
(Saturday) 09/10/2021	30.01	11.051.0
(Sunday) 10/10/2021	30.00	8.353.0
(Monday) 11/10/2021	12.02	6.264.0
12/10/2021	70.00	8.938.0
13/10/2021	70.00	12.727.0
14/10/2021	70.00	11.615.0
15/10/2021	70.00	14.345.0
16/10/2021	50.00	13.052.0
17/10/2021	50.00	11.487.0
18/10/2021	69.22	11.356.0
Total	**805.65**	**157988.0**

Table 5. The average BMP of OFMSW in Italy from 7 cities (adapted upon Campuzano and González-Martínez, 2016). For each country, it is reported the mean value found for different cities divided by country. For the average of Spain, the values reported for the city of Cadiz were excluded; It is considered unrepresentative. BMP (Nm^3 biogas /ton) was calculated considering a methane percentage in biogas of 58 %.

Country	*TS*	*TVS / TS*	*BMP (Nm^3 CH_4/tonTVS)*	*BMP (Nm^3 biogas /ton ingestate)*
Belgium	25.50	94.12	319.00	132.00
China	27.45	85.66	319.00	128.43
Colombia	16.00	94.38	297.00	77.32
Denmark	29.10	84.44	509.13	215.69
Germany	25.50	88.24	528.00	204.83
Ireland	29.40	95.24	529.00	255.38
Italy	27.28	87.79	522.04	213.06
Lebanon	18.60.	92.47	350.00	103.79
Mexico	29.70	75.08	545.00	209.54
South korea	21.10	82.46	502.00	150.60
Spain	25.13	72.41	221.50	69.51
United Kindom	26.67	91.25	402.00	168.66
United States	32.10	79.23.	306.00	134.18

An example is the full-scale plant in Tilburg (Netherlands), operating with Organic Fraction of Municipal Solid Waste (OFMSW) in a semi-continuous, high solid, one step, plug-flow type process with biogas yields from 90 m^3/ton fresh garden waste to 150 m^3/ton fresh food waste (de Laclos et al., 1997). Biogas production depends on several factors:

- Size resulting from the pre-treatment;
- Residence time of the biomass inside the reactor;
- Biological stability.

In the Santhià plant after an adaptation time, a specific biogas production of 200 Nm^3 wet biogas per ton of ingestate was reached with an average methane content of 58 %, and a sulphide hydrogen concentration of 500 ppm. This first results id deviating from the data in bibliography and set a new benchmark for the sector also by considering the profitability impact of this kind of infrastructure.

The reason for such performance resides in the pre-treatment exposing the material to a quick degradation, the solid digestion and the heating system and in the working HRT of 28 days. The specific electricity consumption recorded in the pre-treatment section and the digester are respectively 6.6 kWh/t food waste and digester 1.5 kWh/$t_{ingestate}$.

3.8. The Zero Waste and circularity targets

As said, the plant has the ambition to go close as zero waste as possible thus meaning the possibility to divert the total inlet waste from landfill and turn as much waste is possible into energy (Renewable Natural Gas) and reuse all other remaining fraction. To do so as already explained the plant aims to maximize the biogas production, but there are other two targets to consider:

- Minimize the wastewater to be sent to cleaning plant.
- Reuse the plastics rejects to produce a solid recovered fuel (SRF).

The plant is made up by 3 lines (Fig. 4): food waste is delivered to the anaerobic digestion plant which produces biogas and has as reject the sorted-out plastics and the digestate.

The digestate with a TS of 20-22% is suitable to be composted by mixing it with the bulking agent (chopped wood) without undergoing previous water solid split (such separation may be necessary during plant start-up when TS is lower). The composting process harnesses the High Efficiency Biological Treatment technology (HEBioT is a patented Entsorga process) and has a very high evaporation capacity thus allowing the plant to get rid of most of the water. Eventually additional leachates in the plant may be sprayed over the masses in aerobic fermentation an the evaporated as well, only 4 wt.% of the waste throughput is disposed as leachate to cleaning plant. The compost process lasts 30 days and produces a quality compost sold to farmers and mainly use in rice crops. Plastic rejects are extremely expensive if disposed to Energy from Waste plants then it was mandatory to minimize their disposal. The solution is to further aerobically bio-dry such plastic and then mechanically refine the product to get to a high quality SRF in form of a fluff suitable to replace coal in cement kilns.

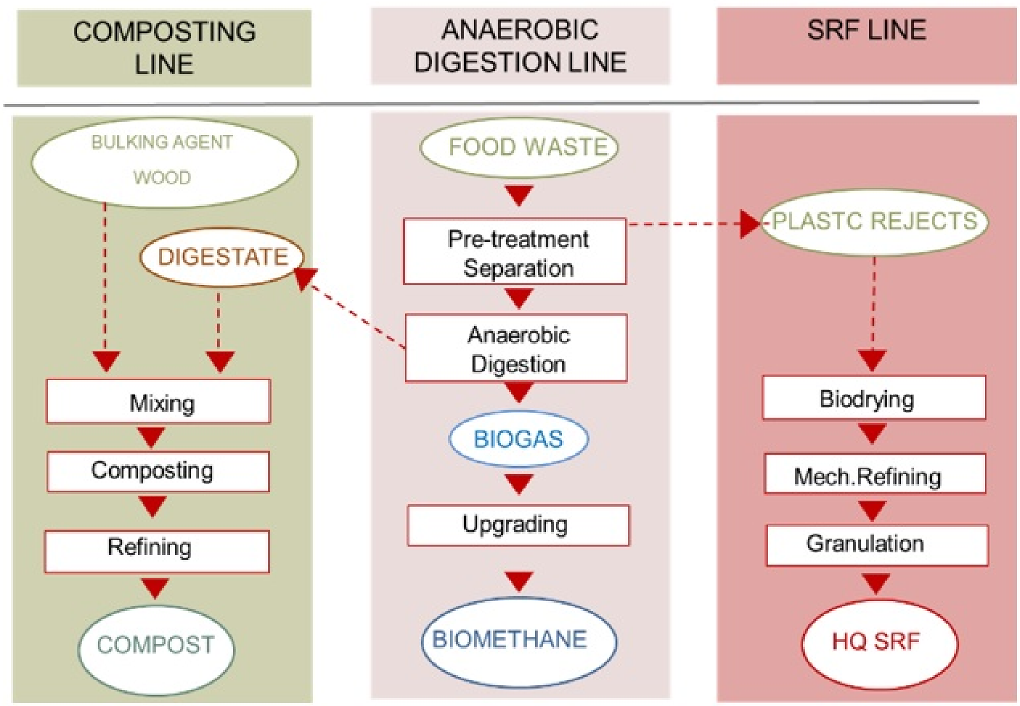

Fig. 3. Block flow diagram

Such SRF 3 wt.% of the throughput, which because of its quality 16-19 MJ/kg and a moisture content of 15-19% can be considered a commodity (according to EN 15359), it has a market value, and its use is very well consolidated in Europe and meets the European environmental policies by triggering a number of environmental benefits. The main benefit is that due to the biogenic content of SRF such fuel can be considered a renewable fuel and every ton of fuel used in replacement of coal triggers about 50% in weigh of CO_2 equivalent diversion, according to IPPC calculation methods (Entsorga Report, 2017).

4. Mass balance

4.1. Quantitative block diagram

In the end, the resulting plant mass balance is the one reported below and shows a minimal amount of rejects to be disposed in landfill or requiring further treatment thus positioning the plant among the ones with highest landfill diversion and maximum gas production.

4.2. Operational data – pretreatment

Plastics output from pre-treatment is around 15 wt. % of treated OFMSW, therefore after leachate realise, with an organic matter dragging of 7 wt. % and a moisture content of 65 wt. %.
The pre-treatment doesn't need water for working but it was possible to feed leachate from the receiving pits into the digester. After an adaptation time, a specific biogas production of 200 Nm^3 wet biogas per ton of ingestate was reached with an average methane content of 58 %, and a sulphide hydrogen concentration of 500 ppm.

4.3. Operational data anaerobic digestion

After an adaptation time, a specific biogas production of 200 Nm^3 wet biogas per ton of ingestate was reached with an average methane content of 58 %, and a sulphide hydrogen concentration of 500 ppm. The working HRT is 28 days. The specific electricity consumption recorded in the pre-treatment section and the digester are respectively 6.6 kWh/t food waste and digester 1.5 kWh/t$_{ingestate}$.

4.4. Environmental Key Performance Index

The reduced amount of leachate sent for external disposal and solids to be sent to landfill by 1 % and 3 % respectively; the latter result achieved through the recovery of the plastic fraction as SRF representing 10 wt. % of the starting waste.

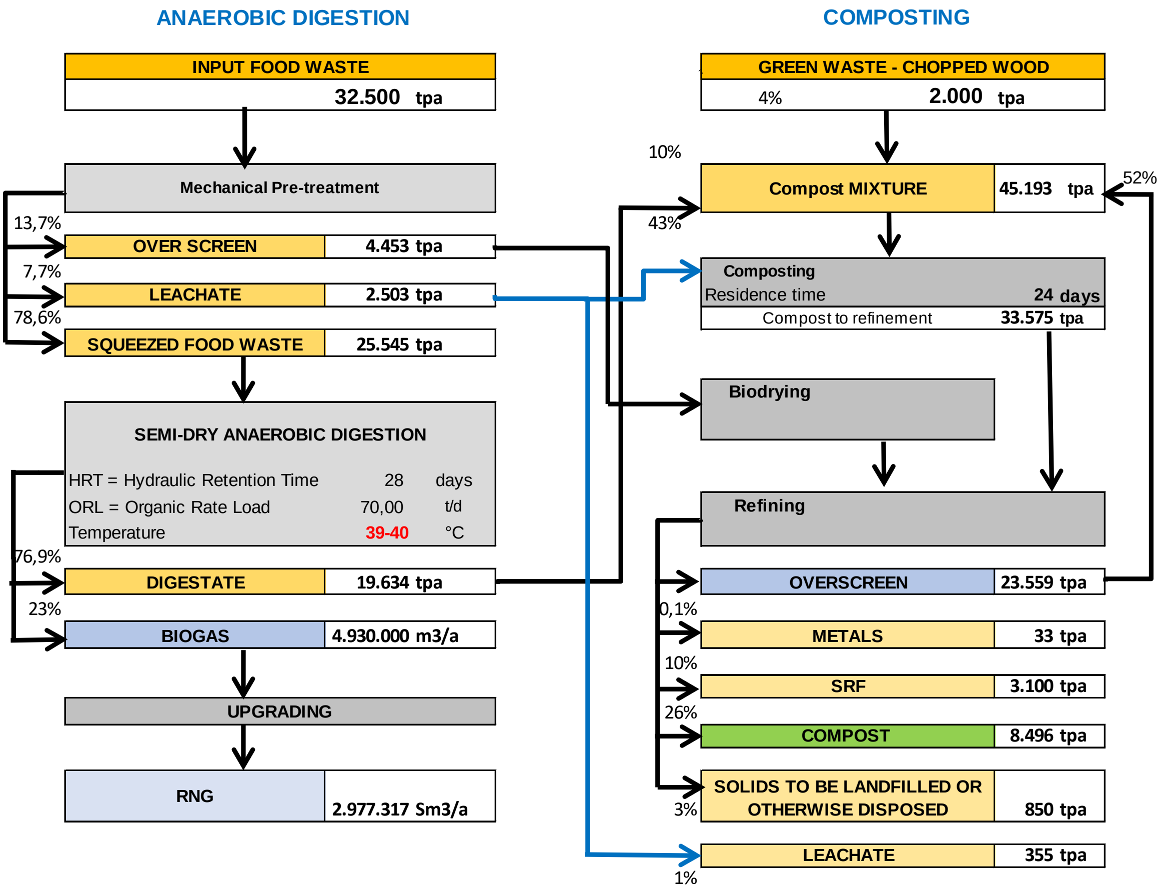

Fig. 4. Block diagram of plant mass balance

5. Conclusions

Every waste treatment plant has its own context and waste. Waste is non-homogeneous, and it is influenced by many variables such as the season, consumption habits, collection methods and policies etc.

Although there are some technical principles and practices which, if correctly applied, can lead to a high-performing plant maximizing energy production, circularity and landfill diversion. Far from having the ambition of being a scientific paper the present document re-set some key performance index with data measured in the field which likely will make the investment in AD plants more appealing from both the environmental and economic point of view. Several of the findings in this research seem to be establishing new standards for anaerobic digestion.

In particular, biogas production of 200 $Nm^3/t_{ingestate}$ may seem particularly significant because, while on the one hand, the designer must take into account different sizing for the gas units in the plant (upgrading, compressors, meters), on the other hand, it produces greater profitability and faster payback.

The achievement of a waste diversion rate of 91% shows how advantageous a plant like this is for the environment and shows how this kind of plant is a key option for the transition from fossil fuels to renewable energy.

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