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Procedia

Environmental Science, Engineering and Management

**27th International Trade Fair of Material & Energy Recovery and Sustainable Development, ECOMONDO, 5th-8th November, 2024
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Selected papers

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GUEST EDITOR

Fabio Fava, born in 1963, is Full Professor of "Industrial & Environmental Biotechnology" at the School of Engineering of University of Bologna since 2005. He published about 250 scientific papers, 220 of which on medium/high IF peer-review international journals of industrial and environmental biotechnology and circular bioeconomy. He has more than 12000 citations, a H-index of 62 and an i10 index of 150 (Google Scholar) along with 220 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.

Fabio 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), Copenhagen, 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 (2021-);

• 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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IDENTIFICATION AND AUTOMATIC CORRECTION OF AMMONIA PROBE OFFSETS IN WASTEWATER TREATMENT PLANTS*

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Abstract

In modern wastewater treatment plants, there is an increasing use of advanced intermittent aeration process controllers, which allow significant energy savings while maintaining high discharge quality standards. The measurement of ammonia in the tank is the ideal parameter for controlling intermittent aeration, especially in plants with restrictive discharge limits for this parameter. However, ammonia measurement probes are subject to frequent calibration losses, known as "offsets", which require urgent calibration to ensure representative measurements and correct operation of the process controller. The real-time identification of these offset events and the automatic implementation of effective countermeasures represent a significant challenge due to the complexity of the process and the interactions between measurements, controllers, and biological processes. This study presents an innovative system that uses a machine learning algorithm to identify offset events and distinguish them from other anomalies, such as high input loads. The system then automatically verifies the extent of the probe offset using the process controller and corrects the measurement autonomously, thus ensuring that representative data can be used for aeration calculations. The algorithm was trained on a dataset from 17 plants and then refined through an active learning approach on two test plants, on which it was put into operation. In the first three months of operation, the system achieved a recall of 77% and a precision of 100%, correctly identifying ten offset events and automatically correcting measurements within 24 hours. These results demonstrate the effectiveness of the proposed system in improving plant management, offering a promising solution to the challenges of probe calibration, reducing the need for manual intervention, and optimizing aeration control.

Keywords: automatic management, fault detection, intermittent aeration, process control, wastewater

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1. Introduction

In modern wastewater treatment plants (WWTPs), the implementation of advanced intermittent aeration process controllers has led to notable energy savings while ensuring high discharge quality standards (Guglielmi and Andreottola, 2011; Miao et al., 2022). Ammonia measurement in the tank serves as a crucial parameter for controlling intermittent aeration, especially in plants with stringent discharge limits. The proper functionality of these sensors is particularly critical, but it is not always guaranteed due to sensor fouling, incorrect calibration, or signal transmission problems. Furthermore, due to the strong interconnection between measurements, controllers and the biological process, it is difficult to distinguish an erroneous measurement from other plant issues. It is also challenging to determine, in case of discrepancies between measured ammonia and oxygen levels, which of the two probes is faulty without additional information.

The ammonia probe calibration drift known as "offset" refers to the gradual drift in the accuracy of the probe readings over time. The probe usually read a value higher than the real ammonia value. The offset or drift occurs particularly in ion-selective (ISE) probes and it is generally caused by membrane fouling, which occurs due to biofilm accumulation and microbial growth on the membrane surface or to chemical deposits of inorganic substances on the membrane, obstructing the passage of ammonia ions. Another cause of drift or offset is electrolyte degradation, which is time-related or contaminants-related (exposure to contaminants from the wastewater can alter the electrolyte composition, affecting the probe's sensitivity). Moreover, sensor aging (the electrodes inside the probe can wear out or corrode over time) and repeated exposure to harsh environmental conditions can cause diminished performance and drifting signals. Finally, fluctuations in temperature or pH can affect the probe's response, leading to offsetting issues; most ISE probes have automatic pH and temperature correction, but this correction has to be calibrated, and the correlation can change over time.

An offset on the ammonia measurements can lead to suboptimal control of the nitrification and denitrification processes, reducing the treatment plant's overall efficiency. Inaccurate data can also result in the plant failing to meet regulatory standards for total nitrogen discharge because the controller will tend to aerate more due to the higher ammonia reading, detracting time from denitrification and increasing nitrates in the effluent. To counteract offset issues, probes need more frequent cleaning and calibration (Papias et al. (2018) suggest a cleaning every two weeks and observed drifts which require calibration after 30 days of monitoring), which increases maintenance costs. For these reasons, implementing software algorithms that can detect and correct an offset in the probe readings will improve data reliability and reduce maintenance costs.

Various studies have explored the potential of artificial intelligence to identify and correct sensor errors (Corominas et al., 2018, Newhart et al., 2019). However, although anomaly detection and time series prediction have been studied in various applications for many years, their use in real-time problems such as wastewater treatment is challenging because of the complex and interdependent mechanisms that govern biological treatment processes.

In addressing ammonia probes drift or offset, Papias et al. (2018) developed a protocol in which probes were regularly immersed in a drift control solution for NH_4-N measurement. Assuming a linear drift over time, they estimated that NH4-N concentrations increased by 0.03 mgN/L every day. Therefore, the raw NH_4-N signal was corrected by subtracting 0.03 mgN/L/day. This method is very labor-intensive as it requires periodic testing with standard solutions. Moreover, it is not guaranteed that the drift will remain constant over time.

Wang et al. (2021) tackle the problem by developing a denoising data processing algorithm (DDPA) for a solid-state ion-selective membrane sensor. However, the study's constraints include its short-term scope (25 days) and its application specifically in combination with a PTFE-loaded sensor, restricting its generalizability to all ammonia probe types. Cecconi and Rosso (2020) worked on detecting faults in ammonium measurements using an artificial neural network (ANN) model. They gathered data from five sensors (inlet NH4, pH, ORP, DO, TSS) to predict ammonium levels and utilized the residuals in a fault-detection mechanism based on principal component analysis (PCA) and Shewhart monitoring charts. Once a fault is detected, the model prediction is used in place of the sensor for process control. The limitations of this approach include the need for many sensors for prediction, especially the inlet ammonia sensor. Additionally, the model may identify treatment process anomalies without distinguishing them from sensor anomalies. For instance, it is difficult to distinguish process inhibition (due to inadequate temperature or TSS concentration, or the ingress of inhibiting substances) from high ammonia drift, as both can result in high ammonia, high oxygen, and extended aeration phases.

To the best of our knowledge, no intermittent aeration process controller currently available in the market possesses the capability to autonomously rectify its operation in response to malfunctions in measurement probes or the underlying process. While certain fault detection algorithms are integrated into the probes themselves, these algorithms primarily rely on the trajectory of individual measurements to discern potential errors. Such an approach fails to discriminate specific errors necessitating a comparative analysis of both oxygen and ammonia levels. For instance, elevated ammonia levels may stem from either heightened inlet loads or offset/drift phenomena. In the former scenario, oxygen concentration is typically low, while in the latter, oxygen levels tend to remain elevated. In contrast, the controller proposed in this study, leveraging a multivariate methodology, facilitates nuanced distinctions of this nature.

This study introduces an innovative system employing a machine learning algorithm to identify offset events and distinguish them from other anomalies such as high input loads or process inhibition, with the aim of improving the reliability of ammonia measurements used by intermittent aeration process controllers. After the event recognition, the system autonomously verifies the extent of the probe offset using the process controller and corrects the measurement in real time, thereby ensuring that representative data is utilized for intermittent aeration calculations.

The system is embedded in the process controller and uses only measurements of ammonia and oxygen, along with the controller's parameters: an ammonia value is not considered valid on its own but is instead assessed in comparison with the oxygen trend, the aeration phase, and the current controller's settings.

This work is divided in three main parts:

- data collection and labeling of 17 wastewater treatment plants, that allowed to develop a machine learning algorithm to be used to classify anomaly events in intermittent aeration process or instrumentation; the data and process are described in 4.1, while the machine learning model is described in 4.3.
- implementation on two plants (described in 4.2) of the machine learning classifier, together with specific process controller logic that automatically reacts to events; the controller logic is described in the final paragraphs of 4.3.
- analysis of results and improvement obtained with active learning in paragraph 5.

2. Materials and methods

The system is based on an anomaly classification algorithm described in Bellamoli et al. (2023) and further improved after that through the collection of additional data.

The dataset used for the algorithm development comes from 51 trains of 17 wastewater treatment plants in Northern Italy, containing minute-by-minute measurements of oxygen and ammonia levels in activated sludge tanks with intermittent aeration. Additionally, the aeration state is recorded every minute, indicating whether the system is in an aerated phase for nitrification or a non-aerated phase for denitrification. The duration of data collection ranges from 6 months for certain plants to 2 years for others.

2.1. Measurements and events

The algorithm relies on measurements of ammonia and oxygen as these instruments are standard in all intermittent aeration systems based on ammonia. These measurements are aggregated over the intermittent aeration cycle (lasting one to eight hours) to calculate various features, such as the anoxic fraction and the slopes of ammonia levels, which are indicative of process state and anomalies. The calculated features are then used as input to a gradient boosting model, which classifies each aeration cycle into one of the following classes: no anomaly, low ammonia probe drift, oxygen probe fouling, offset of the ammonia probe, inhibition of the biological process, and high drift of the ammonia probe.

An "offset" occurs when there is a shift in the readings of the ammonia probe. This means that when the ammonia concentration is supposed to be zero, the probe measures a value significantly different from zero, causing a malfunction in the process controller. This can lead to extended aeration and unnecessary energy waste. The difference between an offset event and a high ammonia drift is that, in the case of an offset, there is simply an upward shift in the measurement compared to reality, of a fixed amount. In the case of drift, on the other hand, the measurements are much higher than the actual values, and this difference is not consistent across all measurement ranges. Additionally, high drift usually occurs suddenly or very quickly and usually requires the replacement of the probe electrode or a two-points calibration. For offset, a one-point calibration or software error correction is generally sufficient, and this is the reason why we focused on this anomaly for the development of an automatic correction. On the other hand, as the offset occurs and grows very slowly, it is difficult to recognize it automatically before it causes a malfunction of the process controller.

In Fig. 1, an example of ammonia and oxygen trends during an offset event is shown. The ammonia decreases slowly during the aerated phases, as it was near zero, but the measured value is much higher than zero. The oxygen, in contrast, rises much higher than the oxygen setpoint, which is usually set to 1.5 -2 mg/L.

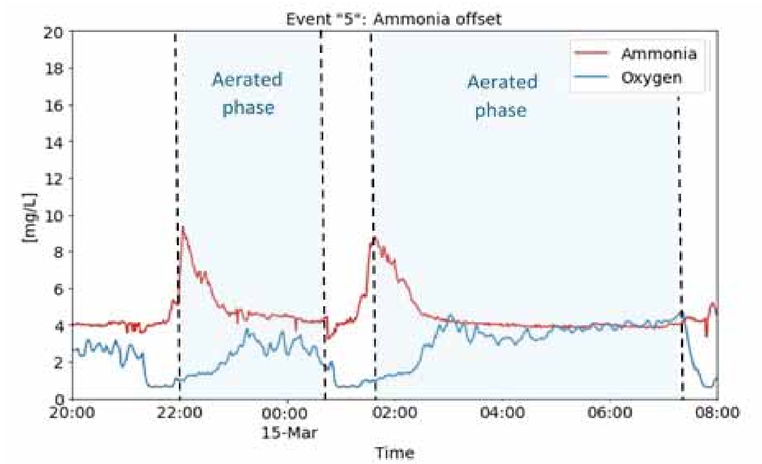


Fig. 1. Example of ammonia and oxygen trends during an offset event

In intermittent aeration processes, the trends in oxygen, ammonia and power are related to each other both by the biological processes taking place in the tank and by the action of the controller itself. Incorrect measurement of ammonia or oxygen probes affects the action of the controller, which in turn changes the actual ammonia and oxygen in the tank, thus making the correct identification of anomalies very difficult, even for an experienced technician.

There is also a certain variability between different plants regarding the type and degree of possible regulation: some plants have fixed oxygen setpoint, others dynamic, some have the possibility to regulate the power of the blowers, and others operate at fixed power, some use mixers and others use pulsed-air to mix the sludge during non-aerated phases.

From these two points, it is easy to understand the challenge of adapting a trained model to a new plant with different characteristics, even though it still falls under the category of intermittent-aeration activated-sludge systems. Additionally, the difficulty of collecting data for the new plant and the time required for the data-labeling process are very high.

2.2. Plants

In light of these challenges, a different approach was necessary. Rather than training a machine learning model for each WWTP, we opted to train a model using data from various plants, with careful attention to data normalization. Subsequently, we developed Active Learning algorithms to adapt the general model to a new plant without extensive data labeling (Tuia et al., 2016). The active learning procedure was tested on four plants, two of which included a process controller with automatic offset correction for offset events.

The procedure is as follows:

- A first model was trained on a dataset from 17 plants.
- Additional data (about 6 months) were collected for the two test plants.
- Samples from these data were selected with active learning procedure and were labeled by expert technicians.
- For each plants, the labeled samples were added to the initial dataset and the model was re-trained.

The characteristics of the chosen plants are the following (in this paper we anonymize the plants for privacy reasons):

- **Castiglione Torinese WWTP, SMAT S.p.A.**: the biggest WWTP in Italy, it treats 3'800'000 population equivalent and is divided into four sub-plants and made up of 24 trains in parallel. In this work we have data of 18 trains, 10 of which were active during the test period. The process controller installed in Castiglione Torinese has advanced intermittent aeration logic which comprehend dynamic oxygen setpoint (related to ammonia measurements) and a minimum number of aerated trains in order to never switch off the blowers (the aeration of each train is regulated by modulating valves).
- **Settala WWTP, CAP Holding S.p.A.**: 58'000 population equivalent, divided into two biological trains. A modulating valve regulates the aeration of each train, but the intermittent aeration controller is simpler than that in Castiglione Torinese one (it has a static setpoint during aerated phases and each train is independent).

Both these plants have a biological section based on an intermittent aeration process, which uses one ammonia and one oxygen measurement for each train. The trains operate in parallel and are independent from an aeration point of view but can be considered part of a single plant (domain) from the model training point of view.

2.3. Machine learning model and process controller

Using the active learning procedure, two LightGBM models were trained, one for each plant, they were installed on the plant, and they were used in real time to identify anomalies and send them to the process controller, which acts accordingly. The LightGBM is an ensemble gradient boosting method that constructs a sequence of decision trees by trying, at each iteration, to reduce the errors of the previous ensemble model: each new tree is trained on the residuals of the predictions of the previous model and the predictions of each tree are added sequentially and can be weighted using a learning rate to make the algorithm learn slower and more accurately (Ke et al. 2017).

The models detect all the anomalies mentioned in the previous paragraphs. However, for the purpose of this article, only the ammonia probe offset events will be analyzed and discussed. This focus is due to their frequency of occurrence and to the potential for effective software correction.

The LGBM model is embedded as part of a sophisticated preprocessing structure (which excludes gross events such as controller disablement or machine breakdown) and a highly articulated post-processing: it is necessary, in fact, to avoid intermittent or too short alarms or the alternation of different anomaly reports in a short time.

The controller contains logic to automatically adjust its parameters based on the classifier's output. When the controller receives a non-zero input from the classifier, it implements specific logic for each event. For an ammonia offset alarm, a nighttime test is conducted to confirm or deny the offset and calculate its exact value. The measurement is corrected once the event is confirmed and the offset is calculated. If the estimated offset is higher than a set threshold, the probe's measurement is considered invalid, and an alert is sent to the operator to recommend a calibration.

The process controller is installed on-site on an industrial PC connected to the plant's PLC. The controller gathers measurements of ammonia and oxygen through the PLC and sends them to a computing center (in the cloud) for processing. The computing center then calculates the features and applies a classifier. Initially, classification is performed using a pre-trained LGBM model (trained on an initial fixed dataset).

The classification results are sent back to the field PC, which uses them as input for the controller logic described above. The scheme of the interaction between classifier and process controller is shown in Fig. 2.

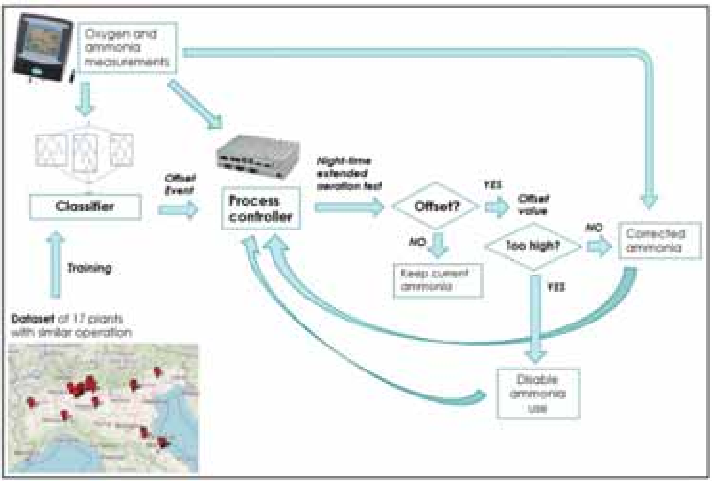


Fig. 2. Scheme of the interaction between classifier and process controller for offset event handling

During the initial months of the controller's usage, the ammonia and oxygen data are saved in a database, and an indication of which periods should be considered for retraining is saved by the classifier. An expert operator labels the data from these periods (reviewing and confirming or denying the classification made by the model), and then the LGBM model is retrained on a dataset consisting of the initial set plus the newly labeled data. This results in a new, more accurate model that is specific to the plant, and this new model replaces the previous one.

3. Results and discussion

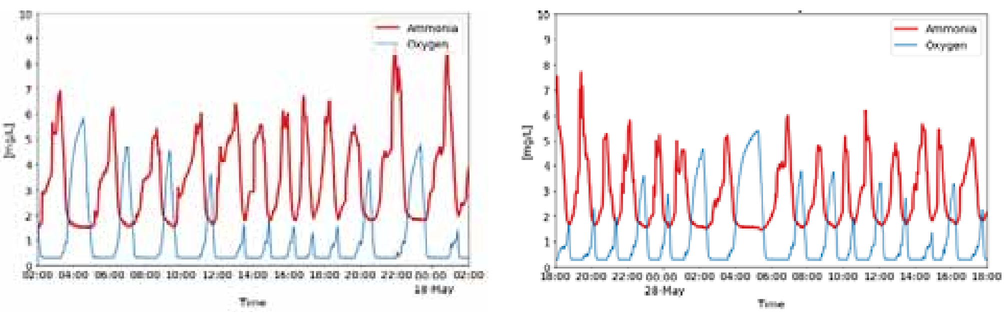
The test period runs from the beginning of April 2024 until the end of June 2024. There was a total of 12 active trains in the two plants (10 for Castiglione Torinese and 2 for Settala). As reported in Table 1, throughout this period, a total of 13 offset events occurred, 10 of which were successfully identified and corrected by the algorithm.

Table 1. Performances of the anomaly detection algorithm for ammonia offset events

	Castiglione Torinese	*Settala*	*Total*
True positives	6	4	**10**
False positives	0	0	**0**
False negatives	3	0	**3**
Precision	100%	100%	**100%**
Recall	60%	100%	**77%**

Two of the unidentified events (shown in Fig. 3) had relatively small offsets (1.5 mg/L), which the operator was able to identify due to the particular aeration logic implemented in Castiglione Torinese. This logic requires at least two trains to be kept aerated, which can result in prolonged aeration during low-load periods. Typically, the threshold for ammonia levels at this plant is set between 3-4 mg/L, making it challenging to detect small offsets unless there is a prolonged aeration phase during the night. However, these cycles are short compared to the average length, and the algorithm fails to classify them as offsets.

Figure 4 shows some examples of the offset events correctly identified by the algorithm. Notice the significant differences in the trends of ammonia and oxygen during different events, even within the same plant. For instance, in the summer period, with higher tank temperatures, the increase in oxygen is less compared to the spring season.



(a) (b)

Fig. 3. Examples of small offset events (Castiglione Torinese, train 4) not detected by the algorithm. Ammonia thresholds in this plant are usually set to 3-4 mg/L, so it is not easy to highlight small offsets except during a prolonged aeration phase during the night.

In Settala, in addition, there are significant fluctuations in the summer period due to a sub-optimal setting of the PID controller for oxygen setpoint, leading to ammonia fluctuations that do not follow the typical smoothing pattern during the aerated phase. Furthermore, variations in input load also result in different behaviors, with higher load in train 3 of Castiglione Torinese compared to train 6. However, the algorithm can recognize the events regardless of all these variations in trends.

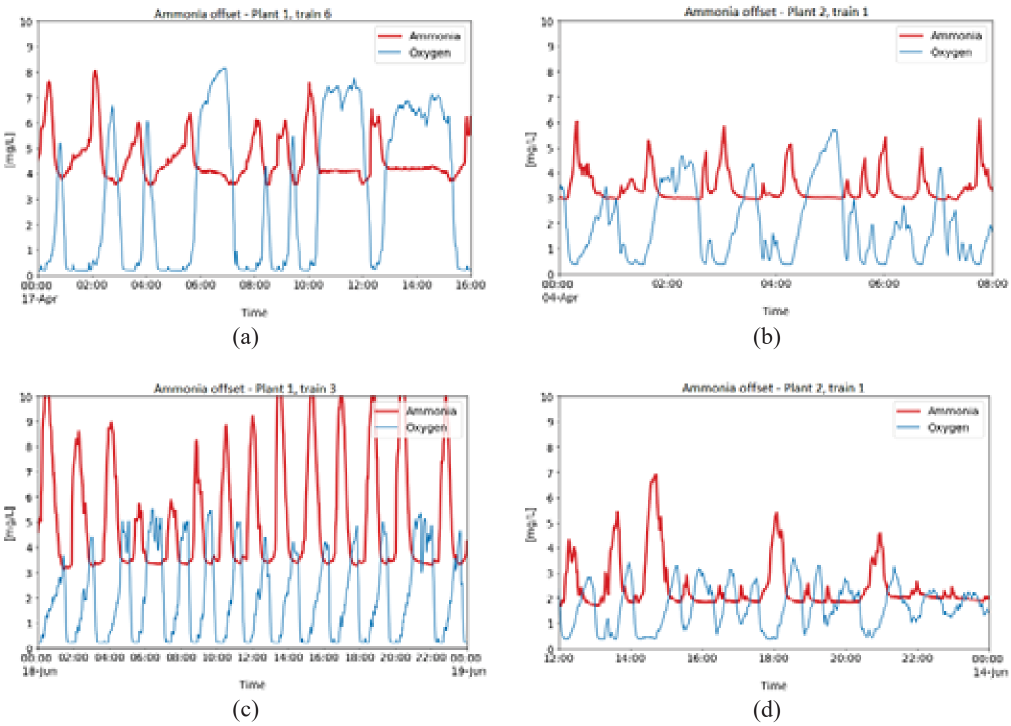


Fig. 4. Example of offset events detected by the algorithm in Castiglione and Settala

After identifying a possible offset, the process controller schedules a test for the following night at a time set by the operator (based on the plant's minimum-load time). During this test, the train is aerated with maximum airflow for a set minimum time and a maximum time determined by the slope of the ammonia curve: once a plateau is reached, the test stops, and the offset is calculated based on the average of the last measured ammonia values. The test is considered valid only if oxygen exceeds a minimum threshold and if the ammonia reaches a sufficiently low slope. Under these conditions, it is assumed that during a period of low load, the nitrification reaction may have consumed all the ammonia, and the correct measurement is close to 0 mg/L.

The offset value calculated in this way is then subtracted from the probe measurement, as can be seen in Fig. 5. This correction allows, in subsequent cycles, a more correct adjustment of the length of the aerated and non-aerated phase, based on a better estimate of the actual ammonia concentration in the tank.

The algorithm underwent a final test using again active learning to re-train it. This involved the labeling of only a few cycles selected by the algorithm from data of the first 40 days (April 1st – May 10th). The re-trained algorithm was then tested on the period from May 11th to June 30th.

As a result, one of the two previously unrecognized offset events was correctly identified, increasing the recall from 71% to 86%. The final F1 score improved to 92%, as reported in Table 2.

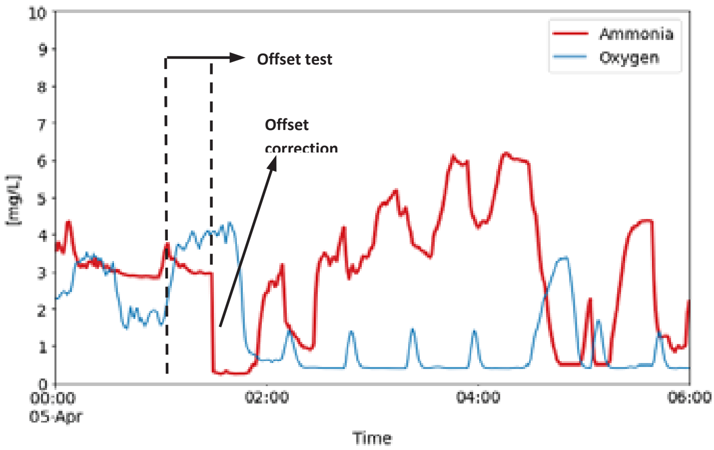


Fig. 5. Example of offset test and correction, Settala, train 1

Table 2. Performances of the anomaly detection algorithm for ammonia offset events on the test set before and after the active learning re-training using data from 01/04/2024 to 10/05/2024

	11/05 – 30/06 Pre-trained model	***11/05 – 30/06 After re-training***
True positives	5	6
False positives	0	0
False negatives	2	1
Precision	100%	100%
Recall	71%	86%
F1-score	83%	92%

Finally, we report in Table 3 the calculation times required for the different steps performed by the classifier, each of them including reading and writing on the database.

Table 3. Classifier calculation times

	Average	**Standard deviation**
	s	*s*
Cycle calculation	9.512	4.166
Model running	15.923	8.716
Post-processing	4.937	2.647
Total	**30.171**	**12.724**

The classifier runs every 10 minutes for each train of each plant.

6. Concluding remarks

This study demonstrates the successful implementation of an advanced machine-learning system for the real-time identification and correction of ammonia probe offsets in two wastewater treatment plants. The innovative approach, combining a machine-learning algorithm with an active learning strategy, effectively distinguishes true offset events from other anomalies, such as high inlet loads.

By automating the identification and correction of these offsets, the system ensures reliable measurements, which are crucial for optimizing intermittent aeration processes. Unlike conventional alert or decision support systems, this system's automatic correction feature eliminates the need for manual intervention, making it particularly advantageous for unmonitored plants. Through the execution of specific automatic tests to confirm or reject identified anomalies, the controller ensures operational safety and significantly mitigates the incidence of false positives.

Furthermore, the model's ability to adapt to specific plants through active learning within a short period allows for a much more precise response close to the needs of the specific plant without requiring protracted data collection periods.

The system's performance, with a recall of 77% and a precision of 100% during the initial three months of operation, demonstrates its reliability and potential for significant improvements in plant management. This reduces the need for manual calibration interventions and maintains high discharge quality standards, ultimately leading to energy savings and better compliance with stringent discharge limits.

Future work may focus on further refining the system's performance and exploring its application to other types of sensors and processes in wastewater treatment plants.

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DECARBONIZATION OF THE TARANTO STEELMAKING AREA: REDUCTION OF ENVIRONMENTAL AND CLIMATE IMPACTS*

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Abstract

Strict decarbonisation guidelines represent a major challenge for steel industries. The steel production sector is responsible for a large amount of CO_2 emissions, equal to up to 9% of global emissions, as well as significant environmental contamination from persistent toxic pollutants, such as polycyclic aromatic hydrocarbons, dioxins and chlorinated furans. According to European policy, the goal of zero net carbon emissions should be achieved by 2050 but traditional steel industries, such as that of the former ILVA in Taranto, still work with technologies based on the carbothermal reduction of iron minerals. These industries represent one of the protagonists in leading the challenge towards decarbonization, thanks to the necessary modification of current industrial plants. The strong point of the steel sector is the "circularity" of steel, a 100% recyclable material. Steel production is therefore in an excellent position to seize the opportunities that arise from the affirmation of a development model based on the circular economy and thus contribute to the decoupling between economic growth, resource consumption and waste production. Specifically, the process of evolution of the Taranto steelworks is based on the abandonment of the integral cycle production system and the adoption of new technologies with electric furnaces powered by pre-reduced iron (DRI: Direct Reduced Iron), produced through the reduction of iron with carbon monoxide and/or hydrogen. The elimination of coke and the transition to new industrial systems would also allow the recovery of the CO_2 produced in the various processes and an effective reduction of greenhouse gases. The production of green hydrogen as a reducing gas through renewable sources, the use of bio coal in the synthesis of steel and the development of processes for the electrochemical reduction of iron oxides open up new perspectives to guarantee the steel sector the sustainability necessary for new environmental challenges.

Keywords: carbothermal reduction decarbonization, Direct Reduced Iron (DRI), green hydrogen, steel production

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1. Introduction

Climate change and pollution reduction are one of the challenges of the 21st century. A major source of greenhouse gas (GHG) emissions is the steel industry. The 2018 IPCC (Intergovernmental Panel on Climate Change) report set targets to limit global warming to 1.5 °C by 2050 (Chen et al, 2018). To achieve these targets, "rapid transitions" are needed in both energy production and the steel industry, which is expected to grow by 25-30 % until 2050. Today, steel production with the blast furnaces is an energy-intensive process, with a high consumption of fossil fuels. The steel sector is responsible for about 7% of all anthropogenic CO_2 emissions: global emissions are currently 1.8 t CO_2/t of steel produced. Therefore, to achieve the targets set for 2050, emissions should decrease significantly. In this regard, several research and development programs have been launched in recent years that include improving energy efficiency, modernizing plants and adopting the best available technologies in all production phases (Holappa, 2020).

Current challenges concern the modification of the steel production process, through the elimination of polluting plants, such as the coke and the sintering plant. The “green” transition towards clean energy production and decarbonization to reduce greenhouse gas emissions is one of the hottest topics in heavy industry. In this direction, several technologies have been developed to reduce the environmental impact such as gas recovery (CO_2 and CO) and the direct use of coal for the reduction of iron ores (Corex® and Finex® technologies). The use of natural gas (methane) to produce reducing gases (Midrex® process) has proven effective in reducing CO_2 and pollutant emissions (Midrex®, 2013). Replacing carbon (from natural gas or coke) with hydrogen as a reducing agent for iron could further reduce the impact on CO_2 emissions. Direct Reduced Iron (DRI) processes and the possibility of carbon capture or storage (CCS) have recently become popular: by modifying production plants and energy systems and adopting new pioneering methods, the level of 0.4-0.5 t CO_2/t of steel produced could be reached, reducing current annual emissions by two-thirds (Bataille et al., 2018).

But it is "green steel", produced with the use of hydrogen from renewable sources, that represents the future, also for the historic Taranto steelworks: hydrogen, in fact, can be used as an auxiliary reducing agent or as the sole reducing agent in a process known as "direct iron reduction". The use of renewable energy combined with electrolysis processes could be the priority way to produce “green hydrogen” for the steel industry (Hybrit Project-Pilot, 2020). In this paper, current strategies for the decarbonization of the steel industry are discussed. The main objective of this study is to analyze the environmental sustainability of the current steel production system and evaluate the different alternatives to production through integrated cycle plants based on blast furnaces such as the one in Taranto. In this context, alternative technologies are illustrated, which offer guarantees not only for the reduction of environmental impact, but also for the production of high-quality steel.

The main objective of this study is to analyze the environmental sustainability of the current steel production system and evaluate the different alternatives to production through an integral cycle with a view to reducing atmospheric emissions, especially greenhouse gases. In this context, alternative technologies are illustrated, which offer guarantees not only for the reduction of the environmental impact but also for the production of high-quality steel.

2. Methodology

Starting from the analysis of emissions from the Taranto (Apulia, Southern Italy) integrated steel plant (Galise et al., 2019), alternative processes for reducing iron without the use of coke have been identified. Steel is ultimately one of the candidates to lead the challenge towards decarbonisation. The strength of the steel sector is the “circularity” of steel, a 100% recyclable material. Steel production is therefore in an excellent position to seize the opportunities that arise from the affirmation of a development model based on the circular economy and contribute to the decoupling between economic growth, resource consumption and waste production.

The evolution process of the Taranto steel plant is therefore based on the abandonment of the current integrated production system and the adoption of new technologies based on the use of electric furnaces fed with pre-reduced iron (DRI) produced by the reduction of iron oxides with carbon monoxide and/or hydrogen. The elimination of coke and the transition to these new production systems would also allow the recovery of CO_2 produced in the various processes, with an effective reduction of greenhouse gas emissions.

3. Results and discussion

3.1. The integral cycle steel plant of Taranto

Among the contaminated sites of national interest, the Taranto area is particularly important due to the type of industrial settlements and the high environmental contamination. The intense industrialization process that has seen the city as a protagonist since 1960 has meant that Taranto was included in the first fifteen areas classified as "high risk of environmental crisis" (Italian Ministry of the Environment, 2020). In this area, the largest industrial settlement is represented by the steel plant of "Acciaierie d'Italia", the largest integrated cycle plant in Europe (Fig. 1). In this plant, the production of steel from iron ore is based on indirect reduction with carbon coke produced by the coke plant. A sintering plant is also necessary because the iron ore, coming from the mines, is largely made up of very fine particles, incompatible with the feeding of the blast furnaces. The sinter plant and the coke oven are the two most polluting plants, responsible for emissions of dioxins and chlorinated furans and polycyclic aromatic hydrocarbons (Cardellicchio, 2020). At present, steel production in Taranto is less than 3 million t/year, and only one of the five blast furnaces is active. In recent years, the adoption of various plant solutions (covering of mineral parks and conveyor belts, reduction of emissions from the agglomeration plant and the coke oven, the blast furnaces and the converters) has made it possible to improve the environmental impact. However, the challenge of the European Green Deal (Fetting, 2020) pushes towards ambitious climate neutrality objectives by 2050; this means for the steel sector and, in particular, for the Taranto steelworks, a significant decarbonization as required by Europe.

The steel mill currently produces about 2 million tons of CO_2 for every million tons of steel produced, and from 2029-2030 it will have to pay high costs for this production as established by the European Community. It is likely that from 2030-2031 CO_2 emissions will have to be drastically reduced, so the only future possibility for the steel sector is the use of pre-reduced iron (DRI = Direct Reduced Iron) as a raw material, obtained by reducing iron oxides (Fe_2O_3) with CO and H_2 (derived from methane and/or bio-methane) or with green H_2 (obtained by electrolysis of water and renewable energy). Based on these considerations, it appears that DRI technology is currently the solution that allows to achieve the decarbonization of the primary steel production process in the long term. However, the reconversion of the Taranto plant from coal-fired blast furnaces to DRI requires an estimated investment of 2.5 billion euros, assuming a plant configuration that allows the production of 8 million tons of steel per year.

3.2. Decarbonization strategies of the steel industry

In the steel industry, carbon compounds are the raw material used both as a reducing agent and for generating energy. To reduce atmospheric emissions of CO_2 and of other pollutants, decarbonization strategies should be adopted following the directives of the Paris Climate Change Conference of December 2015 (Kinley, 2017)). For this purpose, it is often necessary to completely or partially modify the steel production process. Second, production can be decarbonized by increasing iron scrap usage and “carbon-free” electricity.

Fig. 1. A blast furnace of the Taranto steel plant

A blast furnace uses coal to chemically reduce iron ore, which is then further processed into steel. This process releases a large amount of greenhouse gases (CO and CO_2) in the atmosphere. In Europe, some steelmakers capture these by-product gases, transforming them into electricity and useful heat. That makes integrated steel plants a key area for decarbonization. Different projects being tested involve the capture of CO and CO_2 emitted from the blast furnaces and their transformation into ethanol, through a “gas fermentation process” that uses microorganisms (Carbalyst® project, 2015). This technology was developed by the US firm Lanza Tech in collaboration with ArcelorMittal. With the post-combustion capture of greenhouse gas it is possible to reduce both combustion and process emissions without modifying existing industrial plants.

Decarbonization in integral cycle steel production can take place by drastically modifying the production process. Today, iron ores are smelted and converted into iron in the blast furnace (which uses coke as a fuel and reducing agent). The blast furnace could be eliminated using a direct reduction of iron (DRI) process where methane (DRI-CH_4) or hydrogen (DRI-H_2) can be used as reducing agents. In this case, the subsequent transformation of iron into steel can take place in electric arc furnaces. The DRI-H_2 process, with subsequent electric furnaces is now an option for the complete decarbonization of steel production. In recent years, various technologies have been adopted to eliminate polluting plants such as the coking plant and the sintering plant.

Particularly:

- Direct reduction processes (Midrex®, HYL® or Finmet® processes that use methane or hydrogen as a reducing agent of iron minerals (Babich et al., 2008);
- Corex® and Finex® technologies (Hasanbeigi et al., 2014) in which coal is still used as a reducing agent, but the agglomeration plant and coking plant are eliminated and therefore most of the polluting emissions;
- Electric ovens, with elimination of the whole hot area; however, this solution requires to be competitive large quantities of iron scrap as raw material and low-cost electricity.

The Midrex® process uses as a reducing gas a mixture of CO and H_2 which are produced by reacting natural gas (methane) with carbon dioxide from recovery gas (Eq. 1):

$$CH_4 + CO_2 \rightarrow 2\ CO + 2\ H_2 \quad (1)$$

Today there are more than 60 plants that use the Midrex® process with a total production of 500 million tons (approximately 76% of the world production of pre-reduced iron obtained from natural gas). Countries with large natural gas reserves such as Saudi Arabia, Qatar, USA and Iran have implemented this technology for steel production (Midrex®, 2013; Sarkar et al. 2018). In the HyL® process (Hojalata y Lamina, Monterrey, Mexico), the reduction of iron is achieved by gas resulting from the steam reforming of methane with water (Eq. 2).

$$CH_4 + H_2O = CO + 3\ H_2 \quad (2)$$

The Corex® and Finex® technologies do not use the coke oven and the iron ore sintering plant. The difference between the two technologies Corex® and Finex® is that the first one uses iron oxide pellets, while the second one uses fine powder (Ziebik et al., 2008; Yi et al., 2019). The Corex® process is based on the use of hard coal (instead of coke) and iron ore. This technology no longer requires the passage of coal in the coke oven and iron ore in the sintering plant. The cost reduction is 20% and the environmental benefit with the reduction of CO_2 emissions is significant. Finex® technology uses iron ore in the form of fine powder and coal dust. Thanks to the recovery and reuse of the substances formed during the process, Finex® technology, compared to the traditional blast furnace, reduces pollution (90% less toxic-harmful substances and 98% less water contamination), energy consumption and production costs (15% less). Furthermore, CO_2 and carbon monoxide emissions are significantly reduced.

Most of the CO_2 emissions from steel plants are also due to purchased energy (electricity) which is largely based on the use of coal. The switch to cleaner fuels such as natural gas has a favorable impact on CO_2 emissions. Natural gas use, however, due to its limited availability, cannot be considered a long-term solution so the switch to DRI technology would allow an immediate environmental benefit, without the deteriorating the quality of the final product.

Hydrogen is an alternative to fossil fuels for the reduction of iron oxides and, in combination with electricity generated from renewable resources, could offer a long-term option for a drastic reduction of emissions. At the moment and in the foreseeable future, industrial production of H_2 without CO_2 emissions can only be done by electrolysis, with quite high costs. These costs could limit the use of H_2 in steel mills for some years, i.e., until cheaper power generation sources are commercialized.

3.3. Electric oven technology

Steel production can be achieved with electric furnaces (Fig. 2) that use electric arc technology (the most widely used) or induction technology (Hongming et al., 2021. These technologies use iron scrap as raw material with small additions of coal or cast iron to provide the carbon necessary to produce steel, but they could also use pre-reduced iron, coming from other processes. Oxygen also enters the electric oven to oxidize nitrogen and phosphorus and thus facilitate their separation. The electric arc provides the energy to bring the iron to a liquid state at 2000 °C. The possible use of pre-reduced iron instead of scrap as a raw material has the advantage of obtaining cleaner steel.

The reasons for the use of electric furnaces for the production of steel as opposed to blast furnaces derive not only from the reduction of polluting emissions, but also from the lower investment costs and flexibility of the plants. Electric arc technology has lower CO_2 emissions, and if electricity were produced from renewable sources, it could be considered a technology in complete line with COP21 indications, with a view to decarbonizing the planet.

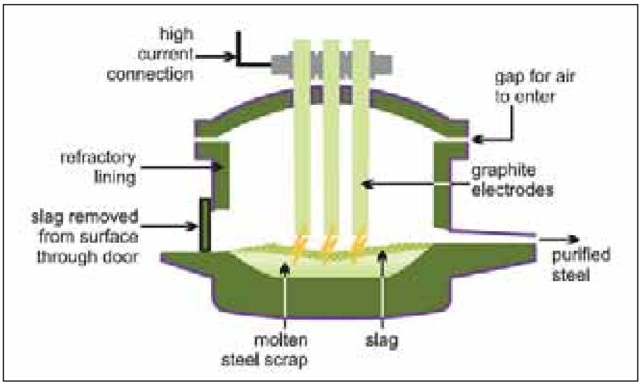

Fig. 2. Diagram of an electric arc furnace

3.4. Options for decarbonization: the use of hydrogen

For the purpose of reducing CO_2 emissions by 2050, one of the fundamental actions is the switch from fossil fuels to renewable fuels such as hydrogen, bioenergy and synthetic fuels. On the basis of these prospects, the consumption of fossil fuels in the industrial sector could decrease by 50-60 %, depending on the technologies adopted in some production sectors, starting with the steel industry. In particular, hydrogen is, in perspective, the alternative energy vector for the production of steel. In the event that a complete replacement of the integrated cycle steel plants with pre-reduced iron with hydrogen (DRI-H_2) is considered, this would also allow the elimination of CO_2 capture and storage plants. Hydrogen is therefore a valid alternative for replacing natural gas. To date, however, replacing coal with hydrogen would raise the price of a ton of steel by about a third. This gap is likely to narrow in the next few years, both because coal prices could rise and because the costs of hydrogen production could become competitive.

Most hydrogen is currently produced by steam reforming, a process that uses natural gas and emits CO_2 as a by-product. Hydrogen can also be produced through water electrolysis: this allows the production of “green” hydrogen not from carbon (Hybrit Project, 2020).

DRI technology is already a reality in several parts of the world such as India (28 million tonnes / year of DRI capacity) and Iran (26 Mt/year of DRI capacity). In Europe, new plants are under construction in several countries. There are already four European examples that can be inspired: 1) Sweden with the HYBRIT model which, thanks to a green hydrogen DRI plant, aims to produce 1.3 Mt per year of clean steel from 2026, to reach 2.7 Mt in 2030; 2) “H_2 Green Steel” which instead aims to produce 5 Mt of green steel in Boden (production start expected by the end of 2025); 3) Finland where Blastr Green Steel wants to invest 4 billion euros to produce 2.5 million tonnes (Mt) of low carbon steel from 2026 using green hydrogen; 4) Germany, which aims to produce 100,000 tons of steel per year using grey hydrogen obtained from gas, and then move on to green hydrogen, through a project launched in 2019 by Arcelor-Mittal that involves an investment of 65 million euros to experiment with the production of green steel in Hamburg; 5) finally Austria, which with the H_2FUTURE project, funded by the European Union, has built in Linz what is currently the largest pilot plant for the production of hydrogen for the steel industry.

6. Concluding remarks

The necessity of reducing of CO_2 emissions in the steel industry will result a real revolution in production processes in the next few years, with an increasing use of green hydrogen produced by renewable energy. At least in the first phase, however, the capture of CO2 and its storage will be essential to achieving the reduction objectives in the short term.

The use of hydrogen, together with the use of renewable energy, could further reduce CO_2 emissions. The option available for the Taranto steel plant, which is currently the only integral cycle steel production hub in Italy, is undoubtedly the replacement of all production based on blast furnaces with production based on electric furnaces and pre-reduced iron (DRI).

In this process, the reduction of production capacity and the simultaneous replacement of blast furnaces with furnaces fueled by DRI would certainly facilitate the achievement of the 2030/35 objectives and those of 2050 with the replacement of natural gas with hydrogen. The central problem of this option, in addition to the reduction in employment, remains the high production cost due to the cost of natural gas and electricity that would drive the produced steel out of the market.

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EIP GOVERNANCE FOR LOCAL SYMBIOSIS AND CIRCULAR ECONOMY KNOWLEDGE TRANSFER*

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Abstract

This paper has been elaborated on the evidence drawn from the Ecole – Interreg Alpine Space project. This project focuses on defining Action Plans for sustainable and circular economy transformation of ten Industrial Parks based in the Alpine Space.
One of the most important issues of the project is to consider the Governance of each Industrial Park to better understand how this is applied in different situations and verify the efficacy in reaching circular economy and industrial symbiosis targets. Based on the information gathered and categorization of the Governance system applied, it has emerged that there are substantial differences between them and low to medium attention to reach circular economy targets trough ad hoc strategies and plans. The main recommendation to suggest is to focus more attention to this issue by enforcing functions and activities of such park management bodies.

Keywords: circular economy, eco-industrial parks, governance, industrial symbiosis

1. Introduction

Industrial parks play a crucial role in the green perspective to support industrial symbiosis projects and circular actions. These spaces, designed to accommodate companies from different sectors, offer a number of significant advantages in terms of sustainability and resource management. Here are some key points that underline the importance of industrial parks in this context:

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Resource optimization: industrial parks allow you to create networks of companies that share resources, energy, and materials. This approach reduces waste and improves overall resource efficiency.

Reduced environmental impact: the proximity of companies within an industrial park facilitates the coordinated management of waste and emissions, reducing the overall environmental impact.

Promotion of industrial symbiosis: industrial symbiosis involves cooperation between companies to make the most of resource flows. In industrial parks, this cooperation is facilitated by physical proximity and the presence of common infrastructure, such as waste management systems and energy networks.

Supporting the circular economy: industrial parks can serve as hubs for the circular economy, where materials and products are continuously reused, repaired and recycled. This economic model reduces dependence on virgin resources and minimizes waste.

Sustainable infrastructure: the design of modern industrial parks often includes sustainable infrastructure, such as renewable energy plants, stormwater management systems, and green buildings. These characteristics help to reduce the ecological footprint of industrial activities.

Innovation and competitiveness: the presence of numerous companies in the same industrial park favors the sharing of knowledge and innovative technologies. This environment stimulates the research and development of sustainable solutions, increasing the competitiveness of companies globally.

Economic and social benefits: in addition to environmental benefits, industrial parks can generate significant economic benefits, such as job creation and local economic development. In addition, by promoting sustainable practices, they improve the quality of life of the surrounding communities.

Regulation and governance: The coordinated management of industrial parks facilitates the implementation of environmental regulations and sustainability standards. Local authorities can work directly with companies to ensure compliance with regulations and promote sustainable practices.

The focus of this paper is to highlight how essential it is to have a well-structured **Governance** for industrial parks to ensure their long-term success and sustainability. Effective governance offers numerous benefits that can improve management, collaboration and innovation within the industrial park: to facilitate the coordinated management of common resources; to encourage communication and collaboration between the different companies present in the industrial park; to ensure compliance with environmental regulations and the adoption of sustainable practices; to manage and maintain infrastructure; to increase the attractiveness of investors; to promote innovation through the creation of joint research and development programmes and the facilitation of knowledge sharing; to make the industrial park more resilient to economic, environmental and social changes; to ensure that local communities are involved in and benefit from the activities of the industrial park; to define roles and responsibilities, improving accountability and transparency in the operations of the industrial park. The above considerations will be presented based on the governance solutions adopted in the industrial parks participating in the ECOLE-Interreg project (https://www.alpine-space.eu/project/ecole/), which have allowed the analysis and comparison between realities belonging to the Alpine Space, subject to the funding.

The overall aim of the ECOLE project is to assist project partners and their stakeholders with the practical implementation of the eco-industrial park (EIP) concept into existing industrial parks (brownfield investment) and new industrial parks (greenfield investment). The ten industrial parks involved have all different situations in terms of tenants, activities, relationships with stakeholders and governance. They are also driven by different regulations and policies depending on their geographic location that lead them to have different sustainable goals at stake with various actual and potential actions to be pursued.

The objective of this presentation at ECOMONDO focuses on the Governance structure of the industrial parks, with particular attention to benchmarking the different approaches on the field. This in order to be informative for them and to better understand the possible scope of actions, to conceive roadmaps for actions, and to define the overall scope of interventions that can contribute to improve the overall management of the industrial park towards circular economy targets.

This work is divided into three main parts:

1. Circular Economy Principles and their relevance for the development of Industrial Parks (IP);
2. Industrial symbiosis as key driver for EIP and the importance of Governance on the guiding the process;
3. Different models of Governance for IPs participating in the ECOLE project, analysis of their performances, drawing conclusions and formulation of recommendations for policy and decision makers in the sector.

2. Circular Economy principles and their relevance for the development of Industrial Parks (IP)

A circular economy represents an industrial model designed to be inherently restorative and regenerative. This approach offers a systemic framework aimed at tackling major global issues, including climate change, biodiversity degradation, pollution, and waste generation. By shifting away from the traditional “take-make-dispose” linear model, the circular economy is founded on three core principles: minimizing waste and pollution, extending the lifecycle of products and materials, and revitalizing natural ecosystems (Ellen MacArthur Foundation, 2013; Preston, 2012).

Adopting circular economy practices fosters a transformative shift by decoupling economic development from environmental degradation and dependence on carbon- and resource-intensive processes. Key practices include eco-design to enhance product longevity, reusability, upgradability, and repairability; reducing hazardous substances; and improving resource and energy efficiency. These efforts prioritize the reuse of components and materials, promote repair, refurbishment, and remanufacturing, support recycling to reclaim valuable materials, and enable energy recovery from non-recyclable waste (World Bank, 2021).

Applying circular economy principles to industrial parks is crucial for ensuring the sustainable management of resources. Key focus areas include efficient water use and discharge control, sustainable energy sourcing with an emphasis on renewables, waste reduction, and effective waste management (UNIDO, 2011). To successfully implement circular strategies in enterprises and industrial parks, innovative methods must be adopted, integrating advanced technologies and redefined business models.The sustainable path of an industrial park requires a series of useful strategies to develop the circular economy that not only relate with material and productive part of industrial processes. Such strategies should apply a systemic approach that also takes into account relevant relationships with all stakeholders in the area. It is by considering such relationships that circularity is promoted and enforced on the territory.

The principles of circularity, according to literature, cover, in several ways, all possible implementable strategies. Starting from these principles, and for each strategy, it will be possible to identify indicators for measuring the circularity performance of a company or group of companies. They must also make it possible to trace the development trajectory towards improvement of circularity performance on the basis of reference benchmarks or objectives that the organization aims to achieve.

3. Industrial symbiosis as key driver for EIP and the importance of Governance on the guiding the process

The concept of the circular economy is intrinsically linked to industrial ecology and industrial symbiosis. Industrial symbiosis involves the collaboration of traditionally independent entities to gain a competitive edge through the exchange of materials, energy, water, and by-products. This type of symbiosis primarily takes place at the inter-company level, leveraging geographic proximity to foster synergies and shared benefits (Chertow, 2000). Beyond inter-company interactions, industrial symbiosis can also extend to include various stakeholders, such as municipalities and other actors influencing or impacted by industrial park activities in the surrounding areas.

Through coordinated efforts, businesses collectively achieve greater advantages than they would independently, promoting stronger social ties among participants. These relationships often extend beyond the industrial zones to neighboring communities. The synergies established can take various forms, including supply chain integration (e.g., raw material suppliers, manufacturers, and end-users), utility sharing (e.g., energy co-generation and water recovery), service cooperation (e.g., shared training programs and maintenance services), by-product reuse, and waste exchanges. Additionally, collaboration may give rise to innovative sectors and new business activities driven by the exchange of ideas.

According to Morales and Diemer (2019), the process of industrial symbiosis is guided by two main mechanisms that support the sustainable transformation of industry. The first mechanism involves an internal assessment of firms' production processes, seeking an optimal balance between cost reduction through efficiency gains and the added value derived from by-product utilization. Economic viability is crucial, as any reduction in profitability could disrupt symbiotic interactions or cause a firm to exit the network. The second mechanism focuses on broader societal dynamics, emphasizing stakeholder coordination and the enhancement of social benefits relative to social costs at local and regional levels.

For industrial symbiosis to succeed, it must generate not only environmental benefits but also measurable social advantages. Crucially, the effectiveness of industrial symbiosis hinges on a well-structured governance framework that ensures consistent and productive collaboration among firms, industrial park management, and external stakeholders, including local communities.

4. Results and discussion: Governance in practice within the Ecole Project

An eco-industrial park is a community of businesses and organizations located within a common property whose members seek enhanced environmental, economic, and social performance through collaboration in managing environmental and resource issues. **Governance** is at the heart of any successful enterprise, especially in the field of EIPs, where the convergence of sustainability, industry, and community underscores the critical role of effective management structures. At its core, governance within EIPs encapsulates the mechanisms, policies, and frameworks that guide decision-making, operations, and collaborations among stakeholders. Governance basically refers to the system of decision-making, coordination, and management that ensures the effective and sustainable operation of the park. It involves the development and implementation of policies, regulations, and collaborative processes that guide the interactions among various stakeholders, such as businesses, government bodies, local communities, and environmental organizations.

Through an extensive and detailed research, a partial goal of ECOLE project is to emphasize the intrinsic link between sound governance models and the overall development and performance of EIPs by analyzing the Governance models of the ten industrial parks of the project. It highlights the critical role that Governance plays in promoting sustainable practices, fostering innovation, mitigating environmental impact, and driving economic growth within these specialized industrial ecosystems. It also identifies the various Governance models tailored to meet the different needs and objectives of diverse EIPs.

The significance of a robust governance framework in industrial parks is multifaceted:

- **Administrative Support and Stakeholder Coordination:** A governing entity plays a crucial role in handling administrative tasks and facilitating development processes. It ensures streamlined coordination when multiple stakeholders—such as government agencies, municipalities, local authorities, investors, development organizations, and NGOs—interact with firms within the industrial park. Having a centralized governing body serves as a single point of contact, which is essential for efficiently managing various interests and ensuring cohesive oversight.
- **Integrated Development Planning and Financial Management:** A dedicated governing body is vital for devising and executing a comprehensive development plan, which encompasses activities such as land preparation (in the case of greenfield sites), infrastructure development, and utility provision. This body also acts as a master planner, coordinating the phased implementation of different projects. Additionally, it handles the procurement and allocation of financial resources needed for infrastructure and facility development. With sound governance, there is also potential for focused marketing and promotional strategies aimed at attracting investors and boosting the industrial park's growth.
- **Sustainability and Circular Economy Implementation:** Effective governance is key to ensuring the sustainable transformation of industrial parks. Implementing circular economy principles, such as industrial symbiosis, requires well-orchestrated efforts, alignment of stakeholder interests, information sharing, and coordinated actions. Without a committed governance structure, the transition toward circularity and sustainability remains fragmented and limited in impact.

Governance structures for industrial parks can vary significantly based on global practices. Four common governance models include:

1. **No formal governance:** This is the most widespread scenario, where public entities play a minimal role, typically limited to territorial planning for brownfield redevelopment or greenfield industrial site preparation. In such cases, local authorities or regional development agencies are involved in land-use planning but do not oversee the operations of individual firms or set circular economy goals for the industrial site.
2. **Statutory body:** In this model, a governing entity is established through legislative action at the national or regional level, with clearly defined responsibilities and powers. The statutory body is mandated to manage and oversee the park's development and administration.
3. **Corporation:** This model involves the creation of a profit-oriented entity tasked with developing and managing the industrial park. The corporation is established under corporate law and operates with a commercial focus.
4. **Hybrid model (Statutory body and corporation):** This approach combines a statutory body with a corporate entity. Public stakeholders, such as local authorities, municipalities, and development agencies, are represented in the statutory body, which is responsible for park administration and safeguarding public interests. Meanwhile, the corporate entity focuses on land development, investor attraction, and tenant management. Ownership of the land may vary - municipalities or local authorities may retain ownership, individual tenants may purchase plots, or the corporation may own and manage the land.

This diversity in governance structures underscores the importance of tailoring the framework to the specific needs and context of the industrial park, ensuring a balance between public oversight and private sector-driven development.

According to the general concept related to Governance in the IPs, it becomes necessary to assess in which way the single Ecole IPs differ from each other and evaluate such differences. To do that, we have developed a comprehensive list of key performance indicators (KPIs), relaying mainly on the performance indicators of UNIDO's International Framework for Eco-Industrial Parks. We selected indicators that can cover the full spectrum of industrial parks covered by the ECOLE project and, in consultations with the project partners (following a series of workshops), we adapted the measurement and formulation of the indicators such that they can capture the state of development and implementation across industrial parks. Figure 1 below reflects the full list of indicators grouped in three main categories: park management services, monitoring and risk management, and planning and park design.

Park Management Services	Park Management Entity	A well-defined park management entity exists?
		Involvement of local public authorities in the governance structure of the IP
		Degree of decision making influence on the governance by local authorities
		Degree of representation of all the tenants in the IP governance structure, committee, or existing organization structure of companies/tenants
		Number of meetings to present IP's strategies with all the tenants in a year
		Number of meetings within the ECOLE project related to stakeholders engagement and park management
		Board member numbers
		Extent of board member expertise in circularity/sustainability
		Diversity of board directors in terms of background, sector, gender, etc
	Park property, common infrastructure, and services	The park management entity manages the land use of the IP, including plot allotments and re-allotments
		If the answer above is "No", is the local authority or the municipality in charge of land management?
		Waste collection areas and services, and utilities are available for tenants
		Presence of security and emergency response services and facilities
		Presence of capacity building and knowledge exchange activities and services (e.g. networking, training courses, educational opportunities also related to sustainability)

Monitoring and risk management	Monitoring performance and risks	Critical risks are identified and defined in a list
		Monitoring performance of the critical risks is done every 6 months
		All tenant firms are aware of the critical risks within the park and the monitoring process
	Climate risk assessment	Climate change risks are identified and defined in a list
		Monitoring procedures for prevention and disaster preparedness are established
		Monitoring performance of the climate change risks is done every 6 months
		Mitigation strategies are identified and shared with tenant firms
	Information on applicable regulations	Local and national regulations and standards related to sustainability/circularity are integrated in the Master Plan of the IP and communicated to the tenant firms
		Monitoring procedures are established to evaluate the compliance of the regulations and standards

Planning and park design	Master plan development	Presence of a strategic plan for circularity and sustainability

Fig. 1. KPIs used to evaluate the governance of the 10 Industrial Parks

The first step is to assess the management structure of the park and services provided to all tenants within the IP. The most important is to assess whether a park management body exists and whether there is involvement of local public authorities and main stakeholders gravitate around the IP. Then, the analysis needs to evaluate the degree of representation and direct involvement of all tenants in the IP's governance structure. Park management shall also be considered from its ability to plan and designing activities in the IP setting circularity and more general sustainable goals. The latter represents a crucial issue if the goal of setting and attaining sustainable goals shall be considered for all relevant stakeholder gravitating around an IP.

The Park property and infrastructure management is another aspect to be considered on the role the park management assume to provide certain services to all tenants in the IP, including utilities and provision of capacity building and knowledge exchange withing the boundaries of the industrial settlement. Finally, the presence of a managing body shall introduce monitoring and risks management also from a climate point of view in order to adapt and increase resilience to all potential impacts.

5. Concluding remarks

The paper we have analyzed here has taken into consideration the theme of industrial parks and their transformation according to sustainable and circular economy perspectives. Based on this objective, the ECOLE project, Interreg Alpin Space co-funded by the European Union, has deepened the importance of the governance of an industrial park as a crucial element to set sustainable goals and ensure that companies and all the main stakeholders that gravitate around it can effectively focus their efforts on achieving them effectively.

The analysis of the literature shows how, in fact, many industrial parks taken into consideration at international level meet the requirement of having effective governance, which often translates into a management board representative of all the interests at stake, both those of tenants, workers and in general of the communities that revolve around the activities of the industrial park.

The comparative analysis between the different experiences of Ecole's industrial parks shows, on the other hand, situations where the management board is absent or plays a generic role of planner to welcome new companies by giving initial support for the provision of public utility services, but without a well-defined and structured governance structure. In only two cases, on the other hand, the board has a statutory nature with a defined level of structuring and composition of the individual members who represent the main stakeholders of the reference territory and who are focused on more general actions of economic development of the reference areas, in general, areas that were degraded and underdeveloped in the past.

In none of the cases considered were strategic plans for sustainable development detected with possible actions to synergistically strengthen the industrial activities present in the industrial park with a view to industrial symbiosis, nor plans that contained operational indications for developing circular economy actions aimed at improving the efficiency of water consumption, the development of forms of renewable energy, the reuse of waste material in production processes. These initiatives are certainly developed individually by some of the companies, but there is no strategic park approach that can consider, according to a holistic vision, all the possible efficiencies that can be obtained from a broader perspective of the territory.

We therefore believe that the considerations highlighted above show the need to take into consideration the importance of governance of industrial parks also with a view to greater attractiveness of the same by those companies that are looking for strategic positions to establish and develop their business.

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SUSTAINABLE WATER MANAGEMENT IN ITALIAN OIL REFINERIES RELATED TO CLIMATE CHANGE[*]

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Abstract

This study is focused on the impact of climate change and extreme weather events in the refinery sector, as one of the most important industrial activities in Italy. The spatial analysis of the refineries in relation to the potential natural hazards and their potential impacts on the environment allowed a first assessment of their exposition to the risk of flooding events, tsunami, heavy rains and sea level rise.
In order to evaluate the actions implemented to address water-related risks, a selection of case studies has been carried out taking into account the specific characteristics of the area where they are located, particularly in relation to hydraulic risk. From the results obtained, it is clear that the implementation of sustainable water management practices is an essential tool to provide protection against climate hazards.

Keywords: climate hazards, extreme weather, flooding, hydraulic risk, refinery

1. Introduction

Oil refineries in Italy play a crucial role in the country's energy industry, processing crude oil into petroleum products such as gasoline, diesel and other derivatives. Refineries are crucial for meeting Italy's energy demands, ensuring a steady supply of fuel for transportation, heating and industrial use. Climate change and extreme weather events represent a real

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physical threat to the refinery sector. In fact, industrial activities using processes and substances classified as hazardous or polluting, in case of damage following extreme events, could pose significant negative impacts on health and the environment, especially on the water matrix. In Italy, the National plan for adaptation to climate change (PNACC, 2023) has the main objective of indicating actions to reduce the risks arising from climate change, improve the adaptive capacity of socio-economic and natural systems and exploit the opportunities that may arise with the new climatic conditions.

Spatial environmental risk analysis for refineries is a key process for assessing and mitigating the potential environmental impacts these facilities may have on the surrounding area. Spatial analysis helps to identify the areas potentially most exposed to risks associated with pollutant emissions and releases, identifies vulnerable areas (populated, ecologically sensitive or economically significant) potentially affected by accidents, and provides valuable support in planning risk mitigation and emergency management.

Climate change contributes to an increase in the frequency and intensity of a range of natural hazards such as extreme temperatures, sea level rise, heavy rainfall, flooding, coastal and riverbank erosion, storms, lightning, drought and forest fires. Industrial activities that are already exposed to hydro-meteorological events may be the most vulnerable to extreme rainfall and flooding, namely oil and gas infrastructures that are in low-lying lands and along the coast. The most significant impacts on hazardous activities to be expected in our country will therefore be determined by changes in the rainfall regime, especially in some areas of the national territory, such as the Pre-Alps, the Po Valley, the upper Adriatic and the coastal areas of central-southern Italy, Sardinia and Sicily, where most of the installations are located. This will entail greater risks of flooding and landslides, negatively affecting the stability of the land and consequently of the infrastructures and main components of industrial activities (tanks, process equipment, piping, etc.) located in unstable or otherwise vulnerable sites (PNACC, 2023). Rising sea levels in the Mediterranean Sea, due to global warming, pose a serious threat to Italy's coastal areas.

According to projections by ENEA (National Agency for New Technologies, Energy and Sustainable Economic Development), vast coastal areas of Italy could be submerged by 2100 in the absence of effective mitigation and adaptation measures. Estimates of sea level rise vary depending on the model used and the least conservative forecast estimates range from 1.31 to 1.45 meters (Sannino et al., 2022).

In Italy in the last 20 years there have been at least 20 critical events that have affected refineries, chemical and petrochemical industries and gas pipelines (PNACC, 2023) and it is becoming common to assess the effects of climate change on infrastructures and hazardous industrial activities. It is necessary to increase the production of spatial impact scenarios, risk analyses and systematize information on implemented good practices. The refinery sector needs to take climate change seriously, assess its own vulnerability and take appropriate measures to prevent or mitigate any potentially negative effects. In particular, the implementation of improved and sustainable water management practices is essential for providing protection against climate hazards, minimizing the environmental impact of refineries and also ensuring the long-term viability of water resources in Italy (United Nations World Water Assessment Programme, 2021).

The primary objective of this study is to highlight the potential risks, induced by natural phenomena and intensified by climate change, involving refineries in Italy. Through the proposed real case studies, an analysis of the different criticalities is shown and lessons learned are shared, by providing a comprehensive overview of sustainable water management actions implemented or planned in the Italian refining sector, to address water-related risks in the refinery sector.

This work is divided into four main parts:

- spatial analysis of refineries in Italy in relation to the potential natural hazards they face and their potential impacts on the surrounding environment.
- selection of real case studies and collection of data on extreme weather events occurred.
- evaluation of the measures implemented in the selected refineries to mitigate the impact of extreme weather events linked to climate change with a comparison of the outcomes in terms of environmental impact categories and scale; assessment of best management scenarios for extreme weather events also considering the specific characteristics of the area, particularly in relation to hydraulic risk.
- analysis of the results, followed by conclusion and the formulation of recommendations for policy and decision makers in the refinery sector.

2. Materials and methods

The spatial analysis of the refineries in Italy in relation to the potential natural hazards and their potential impacts on the surrounding environment is based on the intersection of the map identifying the refineries localization with other types of maps showing a specific hazard for the refinery or the surrounding area. The input maps refer to official information layers, such as:

- Maps of hydraulic, landslide and seismic hazard areas
- Coastline Geodatabase from ISPRA (Italian Institute for Environmental Protection and Research).
- Land cover map ISPRA (De Fioravante et al., 2021).
- Earthquake-induced tsunami inundation maps and associated warning zones that identify the Italian coastal areas potentially exposed to earthquake-induced tsunamis.
- Population map (Cimini et al., 2023)
- The map of protected areas: Natura 2000 Network, EUAP Areas (Official List of Protected Areas), Ramsar Areas (wetlands of international importance under the Ramsar Convention).

Information regarding measures in place in the refineries to mitigate the impact of extreme weather events is available in:

- plans and procedures implemented to comply with the provisions of environmental permit for each installation.
- reports developed by refineries after an accident occurred.
- safety reports required by the Seveso Directive, transposed in Italy into the Decree Law 105/2015.
- annual report provided by the operator of installation.
- annual inspection report developed by ISPRA.
- environmental declarations of each refinery draw up according to the European regulation EMAS n. 1221/2009.

3. Results and discussion

3.1. Spatial analysis

The spatial analysis was produced with QGIS software by intersecting the refinery map with the following input maps.

- Code 1. The distance to surface water bodies. The land cover map ISPRA, specifically the land cover class of the water surface, was used to calculate a buffer zone of 150 meters, referring to the buffer zone in art. 142 (a), (b), (c) of Decree Law 42/2004.
- Code 2. The coastline was used to produce a buffer area of 10 km from the coast inland, divided into three coastal bands (0-300, 300-1000, 1000-10,000 m).
- Code 3. Tsunami alert areas.
- Code 4-5-6. The hydraulic, seismic and landslide hazard areas, are derived from the new national mosaics based on the Hydrogeological Structure Plans-PAI Landslides (v.4.0-2020–2021). The hydraulic hazard maps are drawn up by the District Basin Authorities, according to the scenarios of Decree Law 49/2010, implementing the Floods Directive (2007/60/EC). For seismic hazard areas, data are integrated with the reference data of the National Institute of Geophysics and Volcanology.
- Code 7. Map of protected areas (EUAP, Natura 2000 Network, Ramsar areas) updated to 2023, Ministry of the Environment and Energy Security.
- Code 8. Population map analyzed in relation to the 2-kilometre buffer area around the refineries, according to the Decree Law 105/2015.

Table 1 shows the results of the intersections for each map.

From the spatial elaborations, referring to the water component, a strong relationship between the refineries and the proximity to water bodies and the coastline can be observed. 10 installations are located within 150 meters of a surface water body and 9 within 300 meters of the coastline. This means that the surface water reticulum with freshwater basins to the sea are systems potentially exposed to the risk of contamination caused by refineries emissions. Furthermore, the absolute proximity of the refineries to the coast means that they are in a vulnerable position to tsunami risk, with only 3 installations not falling within the tsunami warning area. 4 installations fall in hydraulic risk areas within the high-risk class and 2 border on risk areas. 4 refineries are inside the high-risk class while none is within landslide risk. 4 installations border protected areas. Finally, the number of inhabitants affected by potential impacts is over 8,000 only for 1 installation, is between 1,000 and 6,000 for 5 refineries and is less than 1,000 for 7 installations.

3.2. Real case studies

Italian refineries with environmental permit are subject to various environmental and safety requirements to mitigate risks related to extreme weather events such as flooding, heavy rains and sea level rise.

The following are the selected case studies particularly at risk due to the specific characteristics of the area where are located or where a recent accident occurred due to extreme weather events. The evaluation of the measures implemented in the selected refineries to mitigate the impact of extreme weather events is also reported.

Table 1. Spatial analysis of the 13 refineries in Italy

Name	*Code 1*	*Code 2 (m)*	*Code 3*	*Code 4*	*Code 5*	*Code 6*	*Code 7*	*Code 8*
SARPOM (Trecate)	in	1,000-10,000	out	borders	out	out	borders	323
ENI (Sannazzaro)	out	1,000-10,000	out	borders	out	out	out	735
IPLOM (Busalla)	in	1,000-10,000	out	high class	out	out	out	5,884
ENI (Venice)	in	0-300	in	out	out	out	borders	7
ALMA PETROLI (Ravenna)	in	0-300	in	high class	out	out	borders	3,178
ENI (Livorno)	in	300-1,000	out	high class	out	borders	out	4,642
ENI (Taranto)	out	0-300	in	out	out	out	out	80
SONATRACH (Augusta)	in	0-300	in	out	high class	out	out	1
ISAB (Priolo Gargallo)	in	0-300	in	out	high class	out	out	21
RAM (Milazzo)	in	0-300	in	out	high class	out	out	3,791
SARLUX (Sarroch)	out	0-300	in	out	out	out	out	1,840
API (Falconara Marittima)	in	0-300	in	high class	high class	out	out	8,212
ENI (Gela)	in	0-300	in	out	out	out	borders	7

3.2.1. ENI refinery of Venice

The Venice refinery is in an area characterized by periodic "high water" phenomena, which pose a constant threat to the infrastructure (Fig. 1). However, the refinery did not experience significant flooding during exceptional events, such as the one that occurred in November 2019, thanks to the protective measures implemented (Enilive, 2024). In fact, the operator entered into an agreement with the Ministry of the Environment and the Ministry of Infrastructure to carry out embankment and containment works on the lagoon shores of the industrial site. These works included the construction of embankments and a physical barrier (sheet piling) to prevent erosion and flooding, improving soil stability and protecting the entire industrial area. The physical barrier between the aquifer matrix and the adjacent shore soils has significantly contributed to securing the site, protecting it from water infiltration that could cause flooding. In addition to these structural interventions, the refinery has adopted planting measures to stabilize the soil and regulate groundwater, preventing possible flooding due to sudden rises in groundwater levels. These actions also improved landscape compatibility with the surrounding lagoon context.

The adopted measures demonstrate the Venice refinery's commitment to managing hydraulic risk, protecting the area from the effects of "high water" and extraordinary rainfall, and ensuring the safety of industrial operations and the surrounding environment. The refinery represents an example of excellence in the sustainable management of infrastructure in hydraulic risk areas.

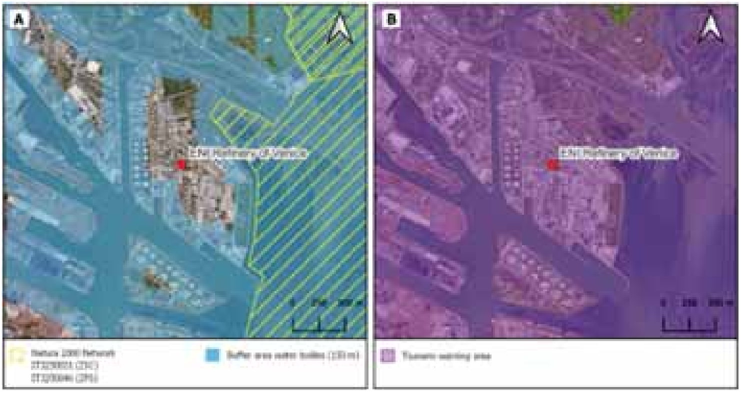

Fig. 1. Venice refinery is A) in the buffer area of the water bodies and the protected area and B) in the tsunami warning area

3.2.2. API refinery of Falconara Marittima

Since the area in which the refinery is located is subject to heavy rains, flooding and strong winds, the refinery has enhanced its emergency response plans including improved drainage systems and protective infrastructure to effectively manage stormwater (Fig. 2). Additionally, the refinery has upgraded its fire-fighting capabilities and installed systems to manage potential environmental impacts.

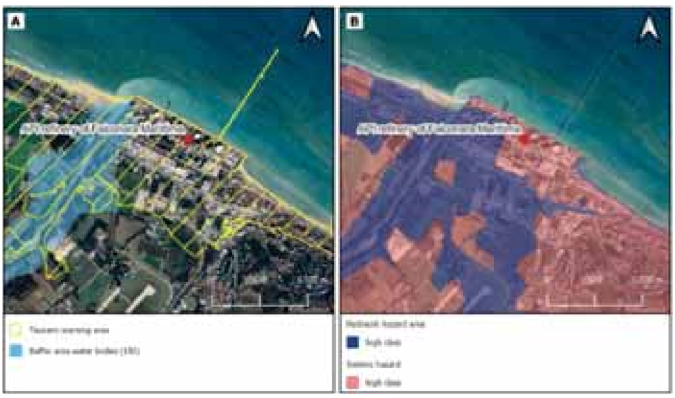

Fig. 2. Falconara Marittima refinery is A) in the water body buffer area and tsunami alert area and B) in the High hydraulic and seismic risk class

The refinery has developed a study on emergency weather event management (API, 2023) that allowed the determination of the critical event accumulation volume with a return time of 20 years. The calculation has been performed by measuring the maximum distance between the cumulative rainfall volume curve and the final storage volume emptying curve.

The emptying curve, on the other hand, in a volume - time diagram, is a linear equation representing the volume of rainwater emptied from storage volumes over time and sent to treatment. From the statistical mathematical analysis, the resulting maximum storage volume has been calculated. In addition, the analysis of the capacity of the pumps upstream the water treatment system to transfer excess drainable water to the storage tanks showed that the capacity to pump rainwater is higher than the maximum flow rates that can be conveyed to the water treatment system during rainfall events.

3.2.3. ALMA PETROLI refinery of Ravenna

The installation is located at about 2 km from the coast and is bordered by the Candiano Canal and a marshy area in direct communication with the sea. Despite what is reported, the area does not appear to belong to flood hazard areas (Fig. 3).

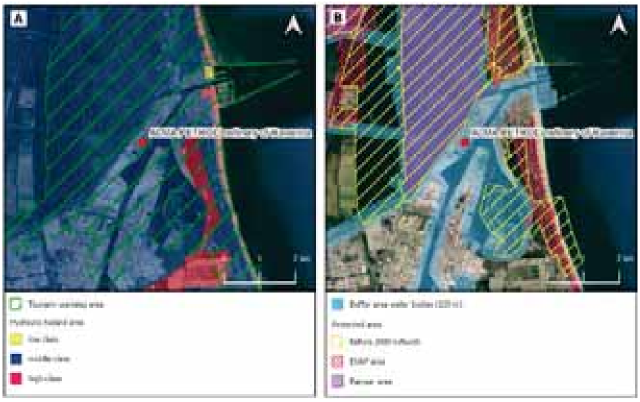

Fig. 3. Ravenna refinery is A) in the tsunami warning area and High hydraulic hazard class and B) in the water body buffer area and surrounded by protected areas

Instead, the area may be affected by high tide phenomena, in conjunction with gales produced by strong winds from the southern sectors of the upper Adriatic Sea. However, the damage recorded on such occasions mainly takes the form of beach erosion and marine ingress producing flooding of urban or non-urban areas bordering the coast. Since the plant became operational (year 1960) a significant danger hasn't occurred in none of the high tide phenomena. In addition, the Integrated Management System presents an operational instruction related to the risk of flooding where all the preventive and/or operational measures that employees must undertake to minimize risks are described. Among the issues reported within the Area event management plan (Alma Petroli, 2019) to be addressed within the refinery during extreme weather events, is the lack of utilities.

The plan indicates the measures to be implemented if power should fail both the cogeneration plant and the national grid. In case of unavailability of a single utility plant, if important adjustments for safety purposes are involved, the equipment is designed in such a way that due to lack of piloting they would be arranged in a safe condition.

3.2.4. IPLOM refinery of Busalla

The IPLOM refinery is located near the right bank of a stream, and it extends along the course of the stream for a length of about 1.5 km (Fig. 4). To carry out a hydraulic analysis on the flood profiles with return times of 50-200 and 500 years in a significant section of the receiving body, the refinery used the HEC-RAS calculation code designed to perform hydraulic calculations for natural and artificial channels (Iplom, 2010). The refinery could be affected by partial flooding, for a flow corresponding to a 200-year return time, varying from 0.00 m to about 1.10-1.20 m on the bank wall.

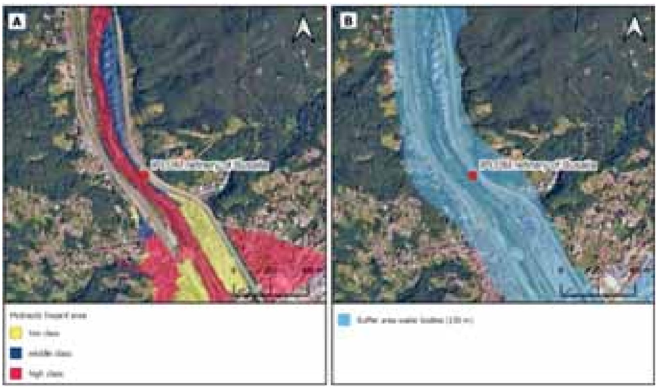

Fig. 4. Busalla refinery is A) in the Low and High hydraulic risk classes and B) in the buffer area of water bodies

The study showed that the risk in relation to the possible hydraulic hazard of the receiving body could be controlled by carrying out works mainly involving the raising of the entire existing bank wall.

3.2.5. ENI refinery of Livorno

Livorno refinery is located north of Livorno city and close to the coast at the mouth of a river (Fig. 5). Regarding the historical and analyzed flood events, according to the Provincial Territorial Coordination plan (PTC), approved in 1998, the refinery is in a low hydraulic hazard territory (not affected by flooding phenomena in the 1991-1995 years and/or having return times higher than 200 years for flooding events). However, due to the physiographic features of the whole site, the PTC foresees that in such areas further additional insights would be necessary to be carried out at site-scale, also in relation to the use of the territory that could strongly modify the hydraulic regime (ENI, 2010, 2018).

The expected return times of 200 years were disregarded and interrupted as the site was affected by the intense meteorological event in 2017, when a maximum cumulated rainfall up to 245 mm (Consorzio LaMMA, 2017) was recorded along the coast and the river overflowed, flooding the refinery and water mixed with hydrocarbons leaked from the internal sewage system into the sea (SNPA, 2017). It must be noted that the flooding event, given its exceptional nature, completely disrupted the knowledge frameworks concerning the hydraulic hazard for the municipality of Livorno, as areas equal to about 9% of the municipal territory were flooded on that occasion. The refinery promptly carried out the progressive and complete shutdown of the production facilities and activated prevention actions mainly consisting in the reactivation of the hydraulic piezometers went out of service and the consolidation of the perimeter wall at the southern boundary of the site cracked during the event.

Following the flood event, the Italian Ministry for the Environment (MASE) revised and improved the prescriptions already issued in the permit of 2010 by introducing structural and management interventions, such as: covering of sewage and process water treatment tanks (flocculation and flotation tanks, also with treatment of conveyed emissions aimed at guaranteeing safety criteria), collection and treatment of tank vents, partial waterproofing interventions through the realization of the feasibility project aimed at paving and/or waterproofing of tank containment basins.

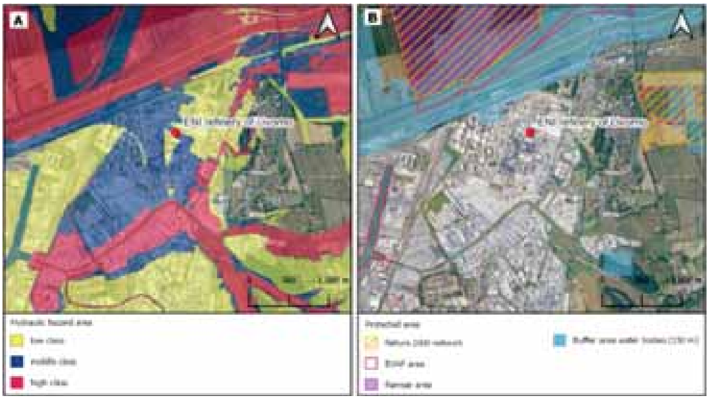

Fig. 5. Livorno refinery is A) in the Low, Middle and High hydraulic risk classes and B) in the buffer area of the water bodies and near the protected area

In the updated Safety report, the refinery identified a series of prevention and protection measures (ISPRA, 2018) both related to plant engineering and management, against possible natural climate-related risks in compliance with European Commission guidelines, including further improvements of the plant structure against flooding events. All new paved areas must be equipped with a suitable rainwater collection and sewage system, which provides the accumulation, pumping, storage and treatment phases in the existing plant. In addition, the refinery must develop additional interventions related to hydraulic risk, in compliance with the provisions of the current regulatory framework and the new Operational Plan adopted by the Municipality of Livorno in 2023.

Further actions have been implemented also by local Administrations. The Municipality of Livorno provided a thematic map of the hydraulic hazard that delimits all the areas affected by flooding, setting them in high or very high hydraulic hazard of the flood risk management plan. In September 2020, within the Sustainable Energy and Climate Action Plan, a Risk and Vulnerability Assessment (RVA) of the Municipality of Livorno with respect to climate change has been defined (Comune di Livorno, 2020), recognizing the Livorno territory as highly vulnerable to the effects of climate change (e.g. for anomalous heat waves, coastal storms). Moreover, within the Local Climate Change Adaptation Plan for Flood Risk (ADAPT) the municipality carried out additional studies related to flooding problems which could be particularly heavy for the whole territory. The outcome of the above-mentioned studies is that the refinery now is at moderate risk for climate impacts and for flooding. Based on the new assessment of the impact of climate change the identified risks related to flooding events have been classified from medium to very high, thus strongly modifying the early 1998 PTC, which reported a low hazard for the same areas.

6. Concluding remarks

Through spatial analysis the evaluation of the potential risks induced by extreme weather events involving refineries in Italy has been carried out. The selected real case studies showed how industrial infrastructure can operate in areas subject to hydraulic risk only if effective measures to manage and mitigate the risks associated with floods and extraordinary rainfall events should be adopted. A case of accident related to a flooding event highlighted critical management operational issues and consequently the need for new prevention measures and the revision of the permit. These examples also provide the opportunity to reflect on best practices against the influence of ongoing climate change, the effectiveness of current European and National environmental regulations, as well as on actions that can be implemented to improve sustainable water management in the refinery sector.

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RESTORATION OF URBAN SEALED SOIL, CONTAMINATION ANALYSIS AND EVALUATION OF CROP POLLUTION: THE REUSES PROJECT*

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Abstract

Urbanization continuously consumes land resources. Soil sealing disrupts carbon fixation, water cycles, and air flows, threatening ecosystems. To preserve and restore ecological soil functions, the European Union aims to achieve 'no-net-land take by 2050', supporting the de-sealing of unused urban areas. The project REUSES (Restore Urban Sealed Soil for Alternative Ecosystem Services) mainly aims to restore the soil functionality of case study areas that have been sealed for a long time by impermeable materials, such as concrete and asphalt, and to establish green spaces for citizens in the form of community gardens. The first step implied de-sealing selected areas in Ancona, precisely two abandoned parking lots. Afterwards, the soil's biochemical and physical parameters will be evaluated before and after the interventions. The presence of contaminants, including heavy metals and hydrocarbons, will also be assessed. Then, the soil will be ploughed and hoed to reduce its compaction and amended with suitable compost in different concentrations to promote plant growth. Afterwards, two crop cycles of seasonable vegetables will be planted. The impact of soil de-sealing on crop production will be assessed by analysing the change in soil characteristics and the edible parts of the selected vegetables. The presence of heavy metals and other contaminants in the edible parts of the plants will be evaluated for food safety. Moreover,

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the REUSES project also aims to assess citizens' perceptions and interests in urban gardens and determine what is necessary to involve them by conducting a local survey. The insights gained from this project can serve as a basis for broader initiatives and projects aimed at urban restoration, generating best practices protocols for soil restoration.

Keywords: green recycling, soil de-sealing, soil re/storation, urban/community garden, soil contaminant

1. Introduction

Soil plays a vital role in maintaining environmental and ecosystem equilibrium, and it is considered as non-renewable resource within a human lifetime. The increase in urban development caused by population growth and economic development drives ever-growing land consumption at the expense of natural and semi-natural land (European Environment Agency, 2021; Marquard et al., 2020). Land take causes several harmful effects, as confirmed by various studies, from the loss of natural habitats and biodiversity to the increased risk of floods and pollution (Gregory et al., 2015; Scalenghe and Marsan, 2009).

The Environmental European Agency reported a higher increase (+0.15%) between 2006 and 2012 in the average soil sealing index in the Mediterranean countries in comparison with the rest of Europe (Ferreira et al., 2022), especially in the coastal areas (Munafò et al., 2013). One of the most detrimental types of land take is soil sealing with asphalt or concrete. Being covered with impermeable materials makes the soil unreachable from water and air, causing the progressive degradation of its properties. Soil's nutrients and biological activity become depleted, the ecosystems are severely impaired due to the lack of water and gas exchange, and the available organic carbon decreases considerably (European Environment Agency, 2022).

To limit the progression of land take and to preserve and restore ecological soil function, the Council and the European Parliament defined the goal of "no-net-land take by 2050" within the 7th Environment Action Program and the European Union Roadmap to a Resource-Efficient Europe (Build Europe, 2022). To achieve this goal, artificialized land must be recycled in three main ways (Fig. 1): urban densification (new buildings between already existing constructions to increase populations' density), grey recycling (constructions of buildings on a land already developed, reuse and requalification of already existing buildings), and green recycling (development of green urban areas and land re-naturalization).

Developing green areas in an urban context significantly impacts citizens' quality of life (Addas, 2023) and urban climate (Heidt and Neef, 2008). Furthermore, urban gardens serve as gathering places where community members can connect and engage in collaborative activities that promote physical and mental well-being, helping to reduce the risk of exclusion (Kim et al., 2014). The type of green areas that are developed bring different benefits. Parterres, ornamental flowers and tree areas provide a safe place for social and recreational purposes; kitchen gardens can also offer zero-mile fruit and vegetables.

2. The REUSES project

The possibility of restoration of sealed soil is often underinvestigated. The common perception is that once the soil is sealed for a long time, its functionalities and productivity are lost forever. Moreover, if the urban land is abandoned, it loses its intended social function while adversely affecting the environment. The REstore Urban Sealed soil for alternative Ecosystem Services (REUSES) project finds the perfect collocation in this context. REUSES has been funded by the European Union-Next Generation EU–PNRR (Mission 4 • Component 2 • Investment 1.1 PRIN 2022–Project code: P2022M3ENS, CUP: I53D23007390001).

Fig. 1. Land recycling possibilities. Urban densification requires the optimisation of land use by increasing population density; grey recycling includes all the necessary measures for the retrieval of existing urban areas, with the optimisation and adaptation of already in-place buildings; green recycling aims to restore and implement green urban areas and to re-naturalise exploited lands

The REUSES project aims to retrieve abandoned sealed soils and reuse them as community gardens (CG); therefore, three prominent aspects will be considered and developed. First, sealed soil will be revitalised to restore its essential ecosystem functions, such as productivity, carbon sequestration, water and air storage and exchange, and fostering the development of new habitats. Second, the feasibility and safety of food production on the selected land will be evaluated and demonstrated. Third, restoring an abandoned area will yield significant social benefits, especially if the community actively participates. Hence, REUSES is a pilot study that aims to understand better what steps are necessary to retrieve abandoned and asphyxiated land, to make it productive again, and possibly set "best practice guidelines" for managing the restoration of sealed soil in an urban-social context.

Two institutions, the Polytechnic University of Marche (UNIVPM) and the National Research Council of Italy (CNR), are involved in the REUSES project. The variety and complementarity of expertise enable a comprehensive investigation into the requalification of abandoned sealed soil, the development of urban gardens, and the citizen's perception and interest in participating in similar future initiatives.

The UNIVPM participates with the Department of Agricultural, Food and Environmental Sciences and is in charge of the management and administration of the REUSES project. The UNIVPM research group has expertise in Soil Science. It has gained competencies in urban soil research thanks to its involvement in the risk assessment of pollutants in Ancona and several studies on the effect of climate change on the chemical, physical, mineralogical, and biochemical properties of soils in the central Apennines. This expertise is crucial for the evaluation of the sealed soil regeneration. In the REUSES project, the UNIVPM group is responsible for the study site preparation (asphalt and roadbed removal), sample taking, and soil morphological and physicochemical characterisation. The team will also overview the field operations, such as soil preparation, compost distribution, and crop sowing/harvesting.

The CNR participates in the project with two institutes, the Research Institute on Terrestrial Ecosystems (IRET) and the Institute of Sciences and Technologies for Sustainable Energy and Mobility (STEMS).

The IRET group's research focuses on the dynamics and interactions among soil/substrates, organisms (mainly plants), and atmosphere, as well as the effects and impact of contaminants and climate change on plant and soil characteristics. The group's expertise ranges from soil physics and chemistry, even in extreme environments, to the use of biotechnologies to optimise soil resources and improve soil fertility. Within the REUSES project, IRET is responsible for analysing soil, compost, and plant samples and evaluating data. Moreover, it collaborates with UNIVPM in the project management.

The area of expertise of the STEMS group ranges from applying new technologies in agricultural machinery for improving sustainability and efficiency to studying the environmental impact of agro-industrial activities. The research also focuses on the sustainable management of municipal solid waste organic fraction and agro-industrial waste and the limitations of greenhouse gas emission from the composting process. Moreover, STEMS group developed a solid knowledge in investigating final user attitudes toward sustainable innovations. Within the REUSES project, STEMS is responsible for selecting and analysing the compost, evaluating data, drafting the survey, and engaging Ancona's citizens to assess opinions and interest in community gardens.

Figure 2 summarizes the main phases of the REUSES project.

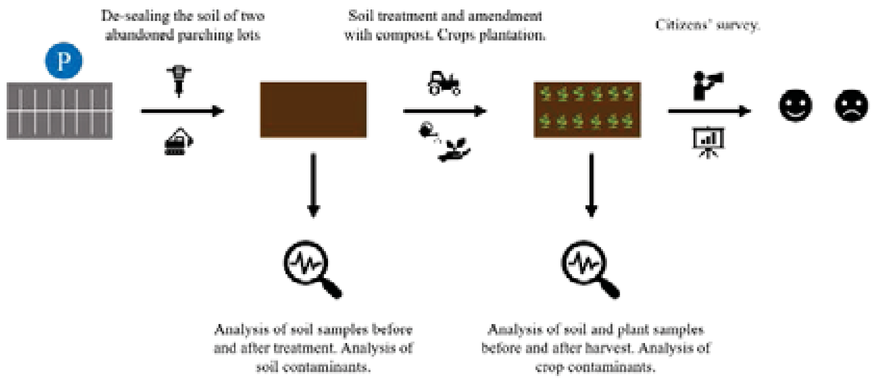

Fig. 2. REUSES project main phases

3. Materials and methods

Two locations have been selected in Ancona, a medium-sized city with 100,500 inhabitants, in central Italy along the Adriatic coast. The municipality granted two abandoned parking slots of ca. 100 m^2 each, as shown in Figures 3A and 3B, on loan for free use. One of the two locations was sealed with a compact and undamaged asphalt layer, not allowing any aeration or water penetration (Fig. 3A). The other slot was covered with deteriorated asphalt with an exchange of water, even if very limited (Fig. 3B). This disparity gives the possibility to evaluate different stages of soil-sealing.

3.1. Experimental design and physicochemical analysis

With the assistance of the Municipality of Ancona, both asphalt and roadbed have been removed to reach the soil level. Thus, three soil trenches have been excavated in each lot to study the pedological variability. Soil profiles were morphologically described, and soil samples were collected according to the genetic horizons for analysis (Schoeneberger et al., 2012). The soil's physicochemical (e.g. texture, pH, total organic carbon, total nitrogen, available phosphorous) and biological (e.g. basal respiration, microbial biomass) properties will be evaluated in the following months. Since the final purpose of the project is to grow an urban garden, the presence of harmful pollutants will be studied, among others, the presence of heavy metals (e.g., arsenic (As), mercury (Hg), lead (Pb)), hydrocarbons, and oils. Before sowing, the ground was ploughed and hoed to loosen the soil compaction and allow the air and water to be exchanged.

Fig. 3. Abandoned parking lots granted from the municipality of Ancona. Fig. 3A: First lot covered with a compact and undamaged asphalt layer; Fig. 3B: Second lot covered with deteriorated asphalt

Each area will be divided into nine randomly distributed plots of ~ 8.5 m^2 (Tahiri et al., 2022). Plots will be divided into two sub-plots for planting two seasonable vegetables under different conditions: *i*) control soil without amendment, ii) compost dose 1, and iii) compost dose 2 (double dose 1). Every treatment and crop condition will be done in three replicates for statistical data treatment.

Compost derived from urban tree mowing was selected to promote soil restoration and plant growth. Compost characterization will include the analysis of pH, electrical conductivity, total organic carbon, organic, total nitrogen, C/N ratio, and heavy metals. The dose of compost to add will be determined according to compost and soil properties. To simulate the cultivation succession, two crop cycles will be carried out accordingly with the alternation of the seasons. The selected vegetables will be salad and fennels for the autumn/winter, while potatoes and tomatoes will take over during spring/summer. The chosen vegetables have different edible parts (leaves, fruits, bulbs, tubers). Each part of the plants will be analyzed to evaluate the potential presence and/or accumulation of toxic contaminants to ensure food safety. Figure 4 summarizes the experimental design.

3.2. Citizens engagement

Within the REUSES project, a survey will be administered locally to estimate the potential community desire for involvement and evaluate the public's perception and interest in CGs. To develop the proper questionnaire to engage the citizens of Ancona, bibliographic research was conducted with various keyword combinations and synonyms: questionnaire/survey, urban/community garden, food safety, CG benefits, and CG risks. Different typologies of surveys have been considered, including in-person, online, multiple-choice, and open questions. To obtain the best comparability between in-person and online data, the easiness of administration, and the correct classification of respondents' answers (Patten, 2014; Schuman and Presser, 1979), a multiple-/scale-responses questionnaire in person and online has been chosen.

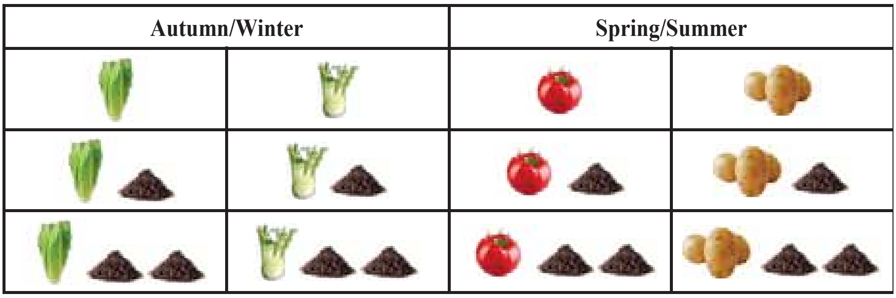

Fig. 4. Experimental design for the crop cycles of salad and fennels in autumn/winter and potatoes and tomatoes in spring/summer. Each vegetable will be cultivated in three conditions: without compost and with the addition of two different amounts of compost. Each condition will have three replicates

4. Preliminary results and discussion

4.1. Morphological properties of de-sealed soils

Figure 5 shows soils after the de-sealing. The first location presented a cover of asphalt and roadbed of 40 cm depth and homogeneous soil morphological properties. The representative soil profile consisted of a series of C horizons, marked by a massive structure with no visible roots and skeleton content < 2%. The upper horizons showed signs of prolonged asphyxia as suggested by gleyic colors (e.g., dark greenish grey), absent in the below layers. On the contrary, the second location had a less thick layer of coverage, with impermeability somewhere compromised. The de-sealed area is characterized by higher pedodiversity, likely due to the preparatory operations for the construction of the parking lot, which involved the addition of terrigenous fill material in a non-uniform manner.

The variability in the morphological properties among the three excavated profiles can be summarized by the presence of BC genetic horizons, with differences in structural development ranging from strongly to weakly developed. Some profiles clearly show evidence of pedogenetic processes, such as accumulating secondary calcium carbonates in the lower layers (indicated by the BCk horizon). Additionally, the presence of roots with a wide range of sizes (from very fine to coarse) suggests that the soil cover still allows for gas and water exchange, even if minimal.

4.2 Questionnaire

The other crucial aspect is the social impact of the project. Remediation from harmful pollutants must be left to experts and professionals. Still, communities can and should be involved in the green recycling of abandoned urban areas for the sustainability and success of the project. In perspective, in fact, locals are those responsible for maintaining a requalified green urban space and are those who will benefit in the first place.

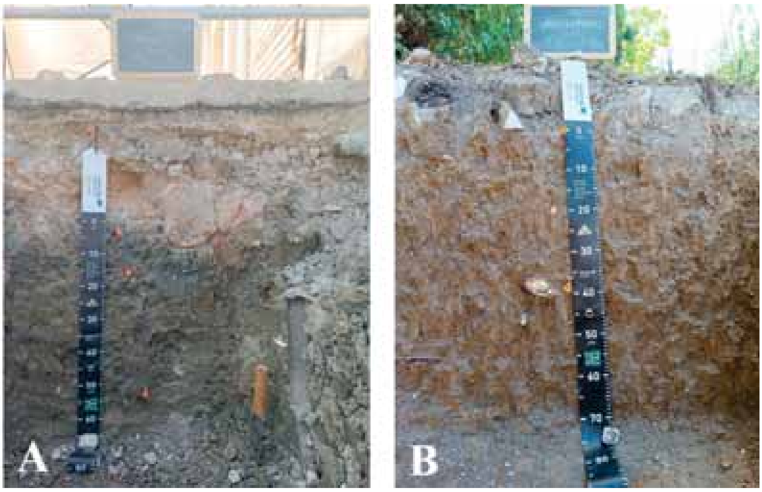

Fig. 5. The two study areas after the removal of the asphalt and the roadbed. Fig. 5A: First lot, previously covered with a compact and undamaged asphalt layer; Fig. 5B: Second lot, previously covered with deteriorated asphalt

A questionnaire was developed to engage the citizens of Ancona, both in person and online mode. The survey is articulated in two blocks of questions: 1) nine multiple-/scale-response questions about community gardens and 2) ten socio-demographic questions (e.g., gender, age, degree, family status). The first block of nine questions covers several aspects of the CG topic. It starts by assessing citizens' civic sense, especially in the context of environmental respect and participation in the maintenance of common spaces, then focuses on general knowledge about community/urban gardens and different sources of information on the topic. Then, the survey evaluates the interviewees' interest in urban gardens and willingness to take over their management. The questionnaire concludes by asking about the main factors that could incentivize the citizens to participate in CGs, their knowledge of contaminants, their perception and concerns about food safety for urban gardens' products, and the perceived benefits of such initiatives. The survey will be administered in the next months in person and online mode, allowing the evaluation of the long-term feasibility and criticality of urban green recycling projects.

5. Concluding remarks

The REUSES project aims to enhance our understanding of sealed soils in the context of developing community gardens in urban areas. It will provide crucial insights into the soil's physicochemical and biological conditions of soil resulting from asphalt sealing, as well as outline the essential steps needed to restore its functionality. Thanks to detailed analysis, the presence of contaminants that could be relocated in the vegetables will be investigated into the soil and, after the harvest, in all the edible plant parts to evaluate and guarantee food safety. To complete the framework, the output obtained at the end of the project could guide and encourage municipalities to safely rehabilitate abandoned urban spaces, transforming them into green areas and community gardens.

This approach will revitalize the ecological functions of long-time sealed soils and requalify abandoned places. The spreading of CGs in urban areas will promote a more sustainable lifestyle, with the production of zero-mile fruit and vegetables. Moreover, CGs will serve as gathering centers and promote collaboration and civic sense while also encouraging physical activity.

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ENHANCING SAFETY IN GREEN JOBS: THE SOHS PROJECT FOR EFFECTIVE SAFETY TRAINING IN WASTE MANAGEMENT PLANTS*

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Abstract

Occupational Safety and Health (OSH) has a remarkable impact on the productivity of companies, as well as on their environmental and social responsibilities. The combination of “safe” and “green” becomes particularly challenging when we consider municipal solid waste management (MSWM). Workers in this sector engage in tasks that promote resources sustainability and the preservation of the planet, but these activities are often “Dirty, Dangerous and Demeaning” and the combined exposure to multiple hazards (chemical, biological, biomechanical and psychosocial) and unpredictable waste materials in plants represents an emerging risk. Safety training is crucial for accident prevention and the evolution of training through the integration of digital technologies becomes essential to improve its effectiveness. The SOHS (Sustainable Occupational Health and Safety) project addresses these challenges through a human-centered ergonomic approach. Four Italian academic partners collaborate to create a prototype of a gamified training solution based on a multidimensional occupational risks

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assessment in two waste management plants. The multi-method risk assessment relies on both objective and subjective data. The case studies treat different materials (plastic, paper and cardboard), process similar quantities of materials and are similar in the level of mechanization of their activity. The first phase of the risk assessment included the administration of a questionnaire to 31 workers and observation of working postures of 12 workers from the two plants. The results pointed out specific needs in the two plants for workstation re-design to improve workers' posture and workload, based on their anthropometric and behavioral variability. Participants declared to be familiar with digital devices but their potential as safety training tools has to be further explored. Objective and subjective data will be integrated and used to create game scenarios with rewards and penalties in the prototype of the innovative training tool with potential for industry-wide adoption in the waste management sector.

Keywords: digital innovation, gamified training, occupational safety, waste management

1. Introduction

The rate of waste generation is greatly increasing and it represents a big issue all over the world (Kaza et al., 2018). The world generates 2.01 billion tons of municipal solid waste annually and this is expected to increase further, reaching 3.40 billion tons per year by 2050, unless we take significant and effective action (ibidem). Recycling waste is synonymous with sustainability to create a more balanced world system, which is in line with the Circular Economy principle. As a result, the Municipal Solid Waste Management (MSWM) industry is rapidly expanding with an increase in waste sorting and recovery facilities as well as waste management workforce (Song et al., 2022; Szulc et al., 2022). This industry is linked to sustainability, environmentally sound management and resource efficiency (Gregson et al., 2016).

However, MSWM workers often do not operate under sustainable conditions. Working in the resource recovery industry involves tasks such as separating, sorting and segregating discarded materials or waste (Gregson et al., 2016), which can be Dirty, Dangerous and Demeaning (DDD). The job is often monotonous and physically demanding and this sector is highly hazardous due to the combination of chemical, biological, biomechanical and psychosocial factors (EU-OSHA, 2009). In addition, new risks may emerge when handling unpredictable waste materials, asking for much empirical evidence on the Occupational Safety and Health (OSH) issues to which workers are exposed (EU-OSHA, 2019). In Italy, in 2018, 151 thousand people worked in the MSWM (INAIL, 2021) and of these, from 2014 to 2018, 36 thousand were involved in work-related injuries (ibidem). How can occupational hazards related to MSWM be prevented, thereby protecting workers?

The scientific literature showed the relevance of occupational safety training in promoting safer work environments and demonstrated that engaging training methods (for example hands-on demonstrations) can promote safe work practices, reduce stress, and enhance safety commitment (Ricci et al., 2016). In this sense, the emergence of new technologies presents promising methods. Gamification, namely using game-like elements in training, offers a cost-effective and flexible approach that can provide realistic simulations and promote learner- and user- centered education (Brahm et al., 2016; Mohd et al., 2019; Vigoroso et al., 2021). Game-based safety training activities proved to be effective in reducing workers' risk exposure in many industries (Vigoroso et al., 2021) but the potential of these training methods is still unexplored in the area of waste treatment.

2. The SOHS project

Within the abovementioned context and to provide a contribution for a safer and more sustainable workplace in the waste management sector, the Sustainable Occupational Health and Safety (SOHS) project has been developed. Four Italian academic partners collaborate in the project to create a prototype of a gamified training solution through a human-centered ergonomic approach based on a multidimensional occupational risks assessment (including biomechanical, chemical, biological and psychosocial risk factors) in two waste management plants. The multi-method risk assessment relies on both objective and subjective data, which will be integrated to identify the most critical risk scenarios in the analyzed plants. These will be translated into digital scenarios enriched by the game elements, to train operators in identifying hazards in the plant and in performing correct and safe behaviors. A prototype of the gamified training solution will be developed and its usability will be tested with different groups of workers from the two plants, representing the extremes of human variability (in terms of age, gender, cultural differences and level of work experience).

The SOHS project consists of seven main phases, represented in Fig. 1. All the phases are developed adopting an ergonomic Human Centered Design (HCD) approach (ISO 9241-210:2019). It refers to the focus always being on the user-worker, who is involved in every phase of the design of the gamified training tool as well as his or her physical and cognitive diversity in interactions with tasks, machines, the environment, and other workers. This multi-dimensional perspective is favored by the diverse nature of the scientific and academic partners participating in the project, with many different and well-integrated competencies.

The aim of the present paper is to report the first results of the field analysis and risk assessment phase. Data collection is ongoing, but useful insights are already emerging to address the objectives outlined above.

Fig. 1. The SOHS project seven main phases.

3. Materials and methods

3.1. Context of the study

The SOHS project focuses on two case study plants. Both have been identified as representatives of most of the processes and working procedures related to the MSWM, are in Northern Italy and have some common characteristics. The case studies treat different materials (plastic, paper and cardboard), process similar quantities of materials and are similar for the level of mechanization of their activity. Henceforth within this paper, we will identify with "A" the plant that mainly deals with plastic recycling and with "B" the one that mainly deals with paper and cardboard recycling.

Plant A is a social cooperative established to combine social and environmental actions. The activities and services offered in the environmental sector allow both the reduction of waste and consumption and support paths of innovation and cooperation for creative recovery and enhancement of human and natural resources.

Plant B is managed by a leading company in the recovery of recyclable materials. Thanks to the experience acquired in more than 50 years of activity, the company can provide a complete service to find the best solution to waste management, providing the most technologically advanced and suitable equipment for the customers' needs.

About the quantity of waste, that entering plant A in the year 2022 was about 55 thousand tones and that in plant B in the same year was about 46 thousand tones. The amount of recovered waste leaving plant A in the same year is about 53 thousand tones and that from plant B is about 45 thousand tones. Fig. 2a and 2b show the floor plans photo of the two plants.

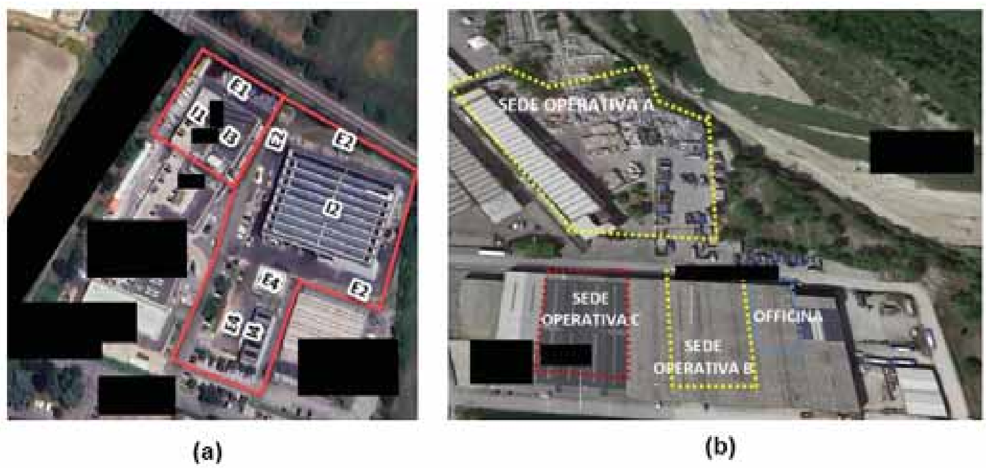


Fig. 2. Floor plan of Plant A (a) and Plant B (b)

The level of mechanization of the two plants is also similar. The waste is collected from the producers, usually using unloadable containers or compactors provided by the case study companies themselves as part of the service. The incoming material must be separated and isolated from foreign substances and is sorted by material type into different subcategories (e.g. hard/soft plastics, colored/white paper, cardboard, cellophane etc.). Sorting is partly done automatically, but mainly by manual sorting and this is the main activity of the operators involved in the study. The workers at the plants' operating sites mainly perform the tasks of waste sorting operator and trolley driver. The different types of waste are handled in dedicated areas that form the heart of the firm's activities. The work areas are distributed in different sheds as well as in open areas, where all operational phases take place: waste unloading, mechanical and manual sorting, shredding of paper documents, pressing of papers or plastics, storage and dispatch, in addition to the handling of goods from one area to another. Fig. 3a, 3b and 3c represent some typical workstations in the two plants.

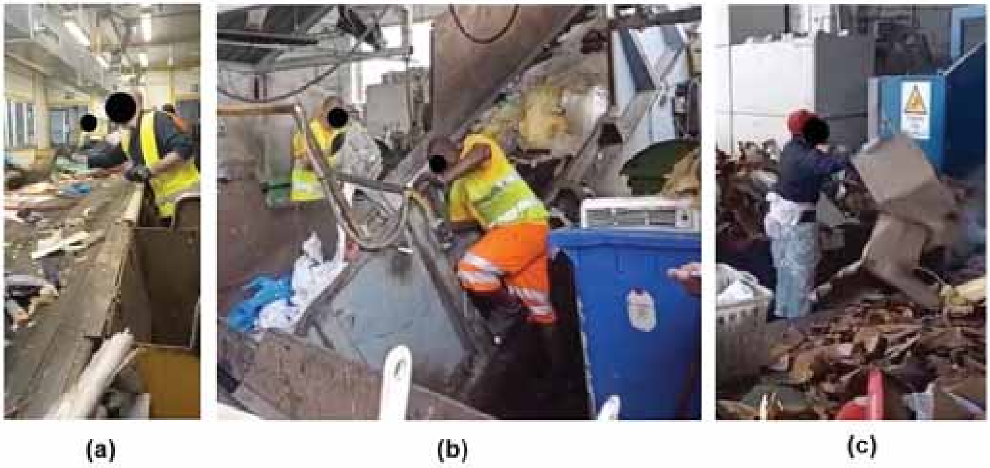


Fig. 3. Workers engaged in manual sorting by conveyor belt placed horizontally (a), by conveyor belt placed obliquely (b) and on the ground (c)

3.2. Data collection and risk assessment methods in case study companies

To conduct the risk assessment, the research team collected data on the actual activities carried out in the two case study companies, involving both the workers and the managers of the two plants. In the meetings with the management, the work organization within the plant was discussed, as well as the mandatory risk assessment document (Documento di Valutazione dei Rischi, DVR), the training activity and the safety culture of the plants.

For the risk assessment with workers, three instruments were used: the Rapid Upper Limb Assessment (RULA, McAtamney and Corlett, 1993), Corlett's postural discomfort evaluation form (Corlett, 1995) and an ad-hoc psycho-social questionnaire.

The RULA is a postural targeting method for estimating the risks of work-related upper limb disorders. The RULA gives a quick and systematic assessment of the postural risk for a worker through the direct observation of workers during their daily work tasks. Seven levels of injury risk and four action levels are provided, based on the results of the assessment (Fig. 4). The tasks observed were ground-based manual sorting, in-cab horizontal and oblique non-in-cab manual conveyor belt sorting, and table-based random sorting, with time intervals of about 5 minutes for each worker observed.

The postural discomfort assessment form (Corlett, 1995) allows the worker to indicate in which of the 27 marked body areas he/she perceives discomfort at the end of the work shift, on a scale from "mild" to "unbearable" (Fig. 5). Its completion took about 10 minutes. The RULA is therefore based on data observed by the research team, while the body discomfort map collects data self-reported by the worker.

Action level	RULA score	Interpretation
1	1-2	The person is working in the best posture with no risk of injury from their work posture.
2	3-4	The person is working in a posture that could present some risk of injury from their work posture, and this score most likely is the result of one part of the body being in a deviated and awkward position, so this should be investigated and corrected.
3	5-6	The person is working in a poor posture with a risk of injury from their work posture, and the reasons for this need to be investigated and changed in the near future to prevent an injury.
4	7+	The person is working in the worst posture with an immediate risk of injury from their work posture, and the reasons for this need to be investigated and changed immediately to prevent an injury.

Fig. 4. The four RULA action levels, score and interpretations.

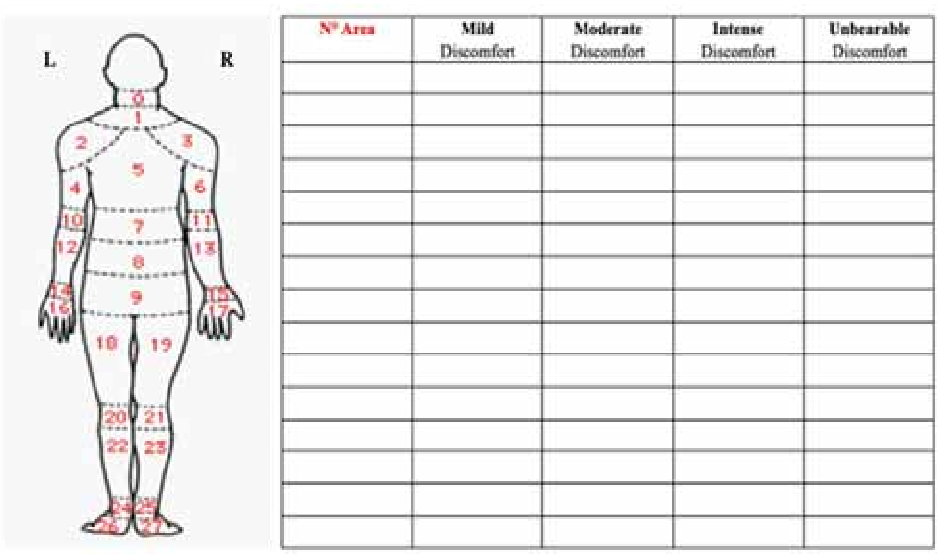


Fig. 5. Corlett's postural discomfort assessment form (Corlett, 1995)

As for the psycho-social questionnaire, it was based on previous instruments used in other work sectors (Caffaro et al., 2017; Vigoroso et al., 2024) and then adapted to this study context by the research team. The questionnaire was composed of 15 items divided into two sections entitled "Work and Safety" and "Use and Familiarity with Digital Devices" (in addition to the final section devoted to socio-demographic information). In the first section, aspects related to working conditions and safety climate were addressed on a 4-point rating scale, whereas the second section assessed the adoption/intention to adopt digital devices for both leisure and training objectives (4- and 5-point rating scale). Four open-ended questions addressed workers' perception of risk in the workplace, the games they prefer to play, and what types of risks they would like to address in gamified training activities. The questionnaire took about 10 minutes to be filled in.

Workers completed both the posture discomfort evaluation form and the questionnaire on paper. Completion took place in a silent setting (the offices of the two case study companies) in which workers had the opportunity to clarify any doubts regarding the meaning of the questions and/or answers directly with the researchers. Before the completion of any of the three instruments, the workers who participated in the study signed an informed consent. The project and the related data collection activities were approved by the ethical committee of the University of Torino on 30/04/2024 (Prot. n. 0250477).

4. Results and discussion

So far, 31 workers from the two case study plants have participated in the data collection activities. Fifteen workers belonged to company A and sixteen to company B. These included workers mainly engaged in manual sorting on the ground, manual sorting by conveyor belt placed both horizontally and obliquely, manual sample sorting on a table and forklift operators. Twelve workers at the extremes of height and weight variability, in the present sample, were observed with the RULA during their daily work activities. Thirty-one workers completed the postural discomfort assessment form and the psycho-social questionnaire. Their main socio-demographic characteristics are listed in Table 1.

Table 1. Participants' socio-demographic characteristics

Variable		*N*	*Percentage, %*
Gender	**Males**	17	54.84
	Females	12	38.71
Education	**Primary school**	5	13.89
	Middle school	12	33.33
	High school	13	36.11
	Missing	1	2.78
Training courses attended	**0**	2	6.45
	1	5	16.13
	More than 1	24	77.42
		Mean	**Standard deviation**
Age		44.24	10.47
Work experiences (yrs)		7.52	5.03

Regarding safety training, during the meetings the managers of the two plants pointed out the complexity and importance of the regulations governing waste management, as well as the significant degree of risk that some operators face in different tasks, making it necessary for all operational personnel in the sector to participate in various specific trainings. Plant B in particular reported being involved in many projects regarding work safety.

Figures 6 and 7 report the results of the observed postural risks assessment and the perceived postural discomfort assessment form, respectively.

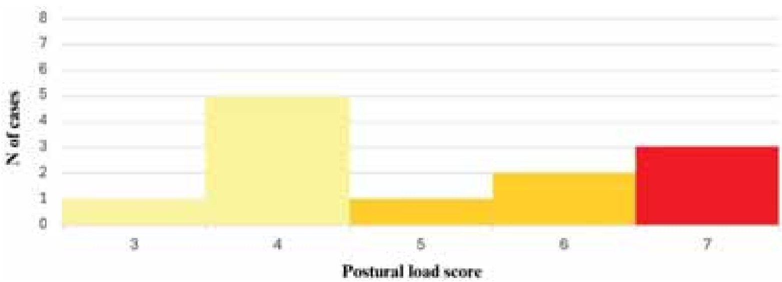
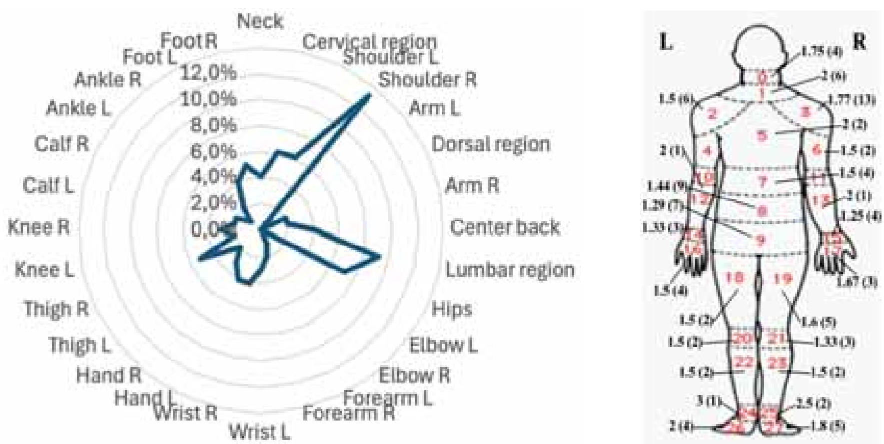


Fig. 6. Observed postural load in twelve workers with the RULA

As it can be seen from Fig. 6, the postures adopted during work were found to be critical according to the risk assessment method adopted, with high scores on the RULA scale for half of the workers observed (6 out of 12): in three cases they assumed postures and body angles for which investigations and changes were needed soon (scores 5 and 6) but in three cases the modification intervention was urgent or even immediate (score 7+). It was also observed that postural overload depends on workers' anthropometric differences and the way in which workers carry out their activities. Therefore, not only small adjustments to workstations are recommended, but also training in correct postures and movements for primary prevention.

Figures 7a and b report the frequency and intensity of body discomfort for the 27 areas of the Corlett assessment form (1995). Only two workers declared no discomfort at all it, while six indicated it in only one body area and the remaining twenty-four from two to ten body areas. In decreasing order of frequency, discomfort was reported on: right shoulder and lumbar region and hips; cervical region and left shoulder, right foot and right tight (Fig. 7a). Workers reported frequent and middle/high discomfort in the areas of right shoulder, cervical and lumbar region while they declared moderate discomfort in left shoulder and hips; in the case of ankles, feet and neck the frequency was limited to a few subjects but the intensity was high (Fig. 7b).



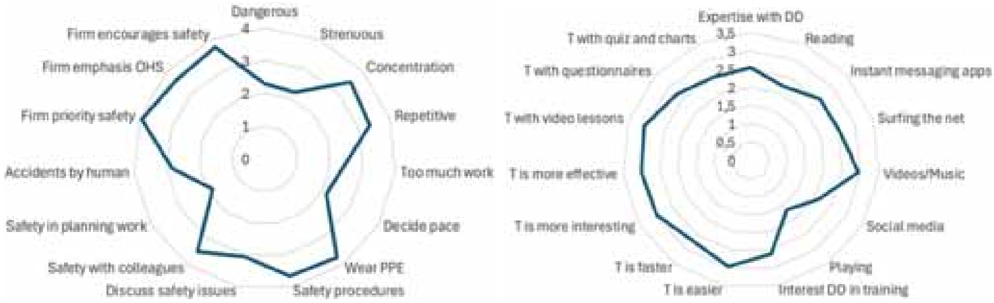
(a) (b)

Fig. 7. Perceived discomfort (N=31 workers) in the 27 body areas of the Corlett assessment form (1995): by frequency (a) and by average intensity for each area (b). The number of workers who reported the discomfort is in brackets.

From these first results, some ameliorative changes in the workstations and work processes can be proposed to the case study companies, such as:

- Place stools/seats to alternate position.
- Adopt arm clamps for picking/pre-selection and to reduce bending.
- Adopt increased use of PPE (e.g. earplugs/headphones and cut-resistant gloves).
- Install washable rubber/plastic guards where not present.
- Relocate some waste containers (closer and lower to the operators' position).
- Uniform the heights of the containers where necessary.
- Install removable lifting platforms where necessary.
- Include specific cleaning times at mid/end of shift.

Regarding the psycho-social questionnaire, the results are shown in Fig. 8.



(a) (b)

Fig. 8. Results from the questionnaire administered: Perceived working conditions and safety climate (a); Self-reported use and familiarity with digital device and predisposition to training with digital devices (b). *Note.* DD = Digital Device, T = Training

If we compare the RULA results with those from the perceived postural discomfort form and the psycho-social questionnaire, it may be noted that in both case study plants, workers who were observed to have a 5+ upper limb load are on average taller and perceived discomfort in fewer areas of the body. The same workers also reported that they perceive their work as less dangerous, strenuous and repetitive on average than those who were observed to have a 5- upper limb load. These discrepancies between observed and self-reported data stress the importance of a multi-method risk assessment, to be able to identify the gaps between objective and subjective criticalities and develop targeted interventions (Zare et al., 2021).

As it can be seen from Fig. 8a, workers considered their work dangerous and strenuous slightly above the average. Workers also perceived their work as requiring great concentration and attention, as well as being very repetitive. The repetitive movements are consistent with workers' self-reported levels of discomfort on the Corlett scale and the positions observed with 5+ values with the RULA. Furthermore, workers perceived the company as attentive to safety and health at work and declared they were compliant with the use of PPE and safety procedures. Despite this, they seemed to lack safety citizenship behaviors (Didla et al., 2009), since they reported to consider little safety aspects when planning their daily work and not often discuss safety issues with colleagues. These results seem to show that other initiatives are needed at organizational level to promote a safety culture which can become part of workers' routine and integrated in their everyday work behaviors, in line with previous results in other industries (Caffaro et al., 2017).

Regarding familiarity with and perception of digital devices (Fig. 8b) workers considered themselves experts with digital devices above the average. Workers said they were familiar with digital devices, but they also stated that they use them little to play games. The SOHS project, which has as one of its main goals to use gamification in training activities, will have to answer the question of how to be able to combine these different workers' statements. This could be fostered by workers' stated good predisposition to training through digital devices (easier, faster, more interesting and more effective with use of video lessons with questionnaires, quizzes and charts to carry out training activities) and by the large number of activities they declared to perform on digital devices (reading, using instant messaging apps, surfing the net, listening to music/watching videos, using social media).

5. Concluding remarks

The initial findings of the SOHS project demonstrate significant discrepancies between observed and self-reported work conditions and behaviors among workers in the waste management sector. The multi-method risk assessment revealed critical postural risks, with half of the workers observed showing high RULA scores, underscoring the urgent need for workstation adjustments and targeted ergonomic interventions. Notably, workers' perceptions of discomfort varied, with frequent complaints about shoulders, lumbar regions, and hips.

Despite workers acknowledging the hazardous and strenuous nature of their tasks, the study highlighted a lack of proactive safety engagement. Although the workers reported compliance with PPE usage and safety procedures, the absence of safety citizenship behaviors suggests a need for organizational measures to enhance safety culture and integrate it into daily routines.

The results also indicate a positive attitude toward digital training, despite limited engagement with game-based tools. This presents an opportunity for the SOHS project to develop an engaging gamified training tool tailored to the workforce's needs and preferences. The planned game scenarios, incorporating realistic work conditions with a system of levels, rewards, and penalties, aim to bridge the gap between observed and perceived risks, promoting safer work practices through interactive learning.

These preliminary conclusions highlight the potential for innovative, technology-driven training solutions to enhance occupational safety in hazardous sectors like waste management. Further research and validation of the gamified training prototype will determine its effectiveness and scalability for broader industry application.

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ENHANCED INSTRUMENT TO DETECT MICROPLASTICS IN WATER*

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Abstract

This study presents the development and investigation of a continuous measurement instrument concept designed to detect and classify individual microplastics in water. The instrument utilizes optical UV–Vis–NIR spectroscopy, offering a non-invasive and real-time solution to identify the type and amount of microplastics present in runoff water. Given the environmental and health concerns associated with microplastics, this approach aims to bridge the gap in existing monitoring methods, which are typically labor-intensive and time-delayed. The instrument setup integrates multiple light sources, including a laser diode, halogen lamp, xenon flash lamp, and LED, with optical fibers transmitting light to a glass cuvette through which the water-microplastic mixture flows. Advanced data acquisition and processing systems controlled via LabVIEW allow automated measurement sequences and data transfer to a server for archiving and analysis. Spectral data was analyzed using Principal Component Analysis (PCA) for dimensionality reduction and clustering, while classification validation was performed using Support Vector Machine Discriminant Analysis (SVMDA). The tested microplastics included polyethylene (PE), polyvinyl chloride (PVC), polyamide (PA), polycarbonate (PC), polypropylene (PP), polyurethane (PU), and rubber (RM). Preliminary results demonstrated the instrument's ability to distinguish among different microplastic types, achieving an improved signal-to-noise ratio compared to earlier versions. Notably, the instrument also detected rubber particles, broadening its applicability.
Challenges and potential enhancements in opto-mechanical design were identified, particularly in ensuring stability and robustness under varying environmental conditions. Future improvements will focus on modularity, enhanced optical transmission, and adaptation for field deployment. The study highlights the potential of this innovative instrument to support continuous environmental monitoring, contributing to sustainable water management solutions.

Keywords: microplastics, optical spectroscopy, principal component analysis, support vector machine, water

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1. Introduction

Plastics have been produced worldwide due to their wide usability, durability, and ease of manufacture (Kutz, 2011). Plastics are also an environmental problem (Andrady, 2017; Vethaak, 2021), since once released into environment, plastics typically just break down into smaller pieces. The harmfulness of microplastics is partly due from the used chemicals in the manufacturing process of plastics that enhance their properties like softness, UV resistance, flame retardancy, etc. Microplastics can also act as carrier for a wide range of other substances like other chemicals, hormones, and microbes. Microplastics are generated from plastic products, packaging material, car tires, and fabric fibers. Over time, microplastics end up everywhere – including in water bodies (Hänninen et al., 2021).

Traditionally in environmental science, microplastic samples are collected from a place of interest in a form of a measurement campaign, post processed and analyzed in a laboratory, which can provide results perhaps after several weeks. In contrast, in water utilities, runoff water monitoring, and industry, there is a need for continuous and even real-time monitoring of microplastics to optimize the process, energy efficiency, and the amount of chemicals used, and monitoring in general. There is a need to develop a practical method and a device for various applications since adequate equipment for this purpose is not available. Recently an initial concept has been presented (Hietanen et al. 2023).

Here a continuous measurement instrument concept for detecting the type and amount of individual microplastics in water was investigated. In the instrument concept microplastic sample materials were passing through the cuvette tube with water. The combination of optical UV–Vis–NIR spectroscopy was applied. Data analysis of spectra was performed using the Principal Component Analysis (PCA) and the received result was validated by Support Vector Machine Discriminant Analysis (SVMDA) technique. The tested plastics were PA, PC, PE-HD, PE-LD, PP, PU, PVC, and a rubber type. The focus of the instrument is to monitor runoff water.

2. Measurement setup

The measurement concept was designed to study the optical UV–Vis–NIR spectral responses of microplastics in water. The optical setup was built around a glass cuvette in which the microplastics traveled with water. The water flow was produced by a pump. Four light sources were used. The laser diode of 405 nm was used to detect individual microplastic particles. Once the particle was detected, the broadband Halogen lamp and Xenon flash lamp as well as LED were used to illuminate the target particle from different directions for spectral analysis. Each light source had a separate optical path. They all were focused on the expected location of a microplastic under study. Data acquisition of all spectra received was performed using the LabVIEW controlled computer system.

2.1. Setup

Figure 1 presents the optical measurement system in more detail. On the left A–A diagram of Figure 1, the light of the Avantes Halogen lamp (HGL, 350–4000 nm) was guided via the shutter (SH), the bifurcated optical fiber bundle (OF1) and the fiber port 1 (FP1) to illuminate the cuvette perpendicularly (Y axis). The shutter was applied to enable fast illumination cycles of the halogen lamp. Similarly, the light of the Hamamatsu Xenon flash lamp (XFL, 190–1100 nm) was guided via the bifurcated optical fiber bundle at UV-band (OF2) and the fiber port 2 (FP2) to illuminate the cuvette perpendicularly from opposite direction. Another end of the OF1 was connected to reference detector (Ref-1) to monitor applied optical power, and respectively another end of the OF2 was connected to the Ref-2. The variable speed pump sucked up water-microplastics-mixture from a glass bowl via the silicone tube (not present in Fig. 1). In the middle of the silicone tube, the 120 mm long glass cuvette (OD 5,2 mm / ID 1,2 mm) was installed (X axis). These axes formed the horizontal X-Y plane that was 100 mm above the aluminum plate.

On the right B–B diagram of the Fig. 1, the light of the Thorlabs collimated laser diode (LD) of 405 nm and the Thorlabs light emitted diode (LED) of 365 nm was guided via the bifurcated optical fiber bundle (OF3) and the fiber port 3 (FP3) to illuminate the cuvette perpendicularly through the aluminum plate (Z axis). All receivers were located on the top side of the cuvette on the X-Z plane. On the opposite side of the cuvette was the collimator lens (CL), optical fiber 6 (OF6), and the Thorlabs Si amplified detector the blocker detector.

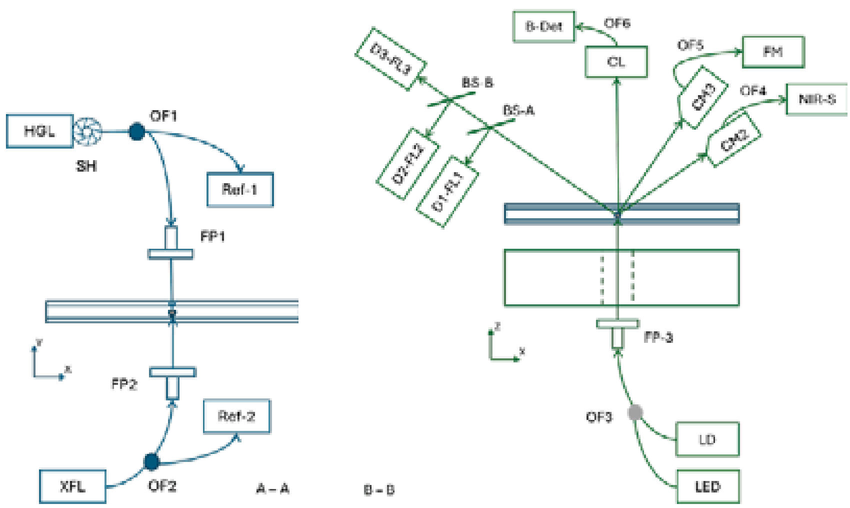

Fig. 1. The A–A diagram of the optical measurement setup from top (horizontal). The B–B diagram of the optical measurement setup from side (vertical)

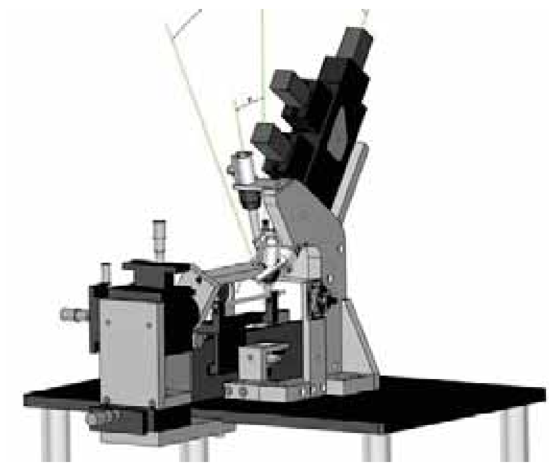

Fig. 2. The modelled alignment mechanics of the instrument concept. Fine mechanics based on machined components and precise mechanics applied commercial fiber ports

(B-Det) of 340–1100 nm to detect laser-illuminated particles at the cuvette measurement point. Next on the right side from the blocker detector there was the collimator mirror 3 (CM3), optical fiber 5 (OF5), and the Avantes spectrometer (FM) to observe the wavelengths to observe the wavelengths of 350–1100. Further on right there was the collimator mirror 2 (CM2), the optical fiber 4 (OF4), and the Ocean NIR spectrometer (NIR-S) to observe the wavelengths of 900–1700 nm. Left on the blocker detector there were three Hamamatsu photomultiplier tube module detectors (D1-FL1, D2-FL2, D3-FL3) with the associated beam splitters (BS-A, BS-B) and lenses to produce optical bands for wavelengths of < 567 nm, < 638 nm, and > 638 nm. Figure 2 shows the mechanics of the instrument concept where the fine mechanics are based on machined aluminum components while the precise mechanics applied commercial fiber ports.

For the experiments, microplastics were produced by milling high quality engineering bulk plastics on an automatic milling machine. The produced plastic chips were sorted mechanically with metal meshes. The types of plastic milled were polyamide (PA), polycarbonate (PC), polyethylene (PE-HD, PE-LD), polypropylene (PP), polyurethane (PU), polyvinylchloride (PVC), and rubber (RM). In the visible light range, the microplastics used were translucent or colored. The microplastics were mixed with de-ionized water. To minimize particle clustering, the water-microplastic mixture was continuously stirred during the measurement. This also assisted the microplastics lighter or heavier than water to mix throughout the liquid volume and to enter the sampling system.

2.2. Control system

Once a particle was observed and placed on the right location at the cuvette, all light sources and receivers were executed in the preselected sequence to receive the scattered light with various optical bands from microplastics illuminated. To perform the requested measurement sequence automatically, the instrument is computer controlled using the LabView software. The computer is connected via a 4G router to transfer measurement and associated meta data to the dedicated server using the ThingsBoard SW for archiving and visualization purposes. Further, there is a remote access for data sharing via internet for selected clients. Figure 3 presents the data transmission.

The modules that produce analog voltage signals, like Thorlabs Si amplified detectors, Photomultiplier tube module detectors, Xenon flash lamp, etc. are connected to the control computer via the National Instrument I/O board. The modules equipped with the USB port, such as spectrometers and the shutter of the halogen lamp, are connected directly to the control computer. The instrument has also the analog level trigger utilizing the wideband AD8561 comparator circuit, several voltage sources, adjustable reference voltage and gain circuits for the photomultiplier tubes. Figure 3 presents also the block diagram.

Data flow considerations are essential to achieve functional detection and classification system. The received raw measurement and meta data is collected and enhanced in the instrument control computer using the LabVIEW software. Then data is transferred to the ThingsBoard server for archive and visualization purposes. To study received data at spectral domain in general or for the microplastics classification modeling, the data is transferred to MATLAB either via internet or via a memory used in the Python docker. To classify an individual particle in to modelled microplastic category, the measured data of the associated microplastic particle will be transferred from ThingsBoard to the Python server for the classification after which the classification is returned to the ThingsBoard. A client can be provided with access to the ThingsBoard. Figure 4 presents the interaction between software programs.

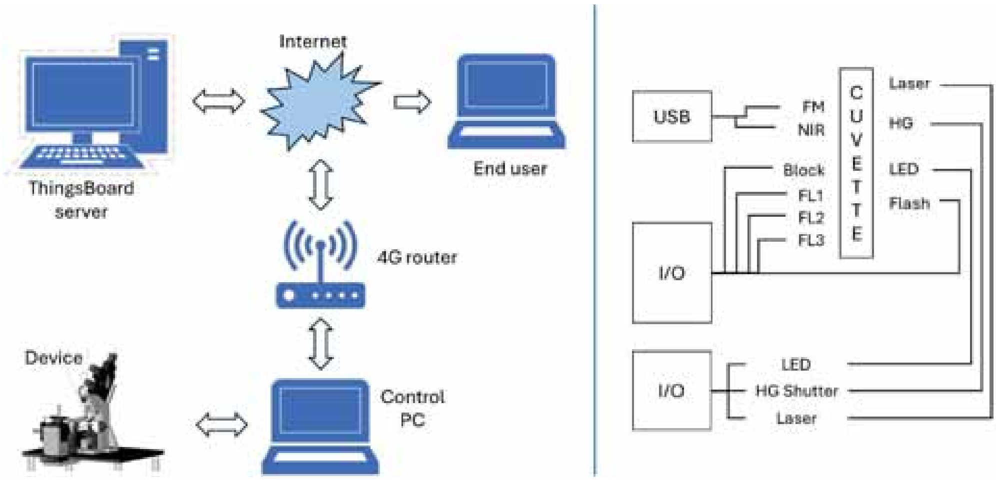

Fig. 3. On the left, the overall data transmission between the system components: instrument, control PC, router, ThingsBoard, and data sharing for end users.
On the right, the block diagram of the sensing modules

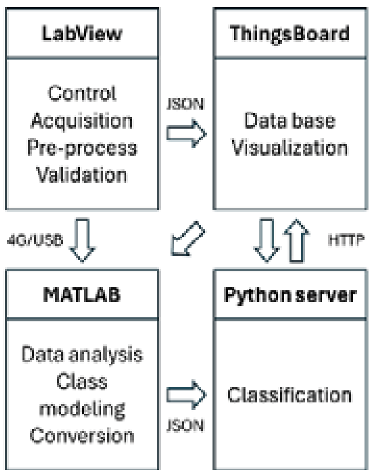

Fig. 4. The data flow utilizes the LabVIEW, ThingsBoard, MATLAB, and Python SWs and modules.

3. Results

The microplastics in water were measured in the glass cuvette tube. The enhanced instrument was tested with several microplastic types that were PE, PVC, PA, PC, PP, PU and RM. Microplastics were classified based on their spectral data. In this preliminary study, all measured raw reflectance spectral data at the was analyzed with the principal component analysis method (PCA). PCA projects spectra into a multidimensional principal component space, where the clustering of samples can be observed in a 3D principal component space (PCS). Figure 5 presents three (3) principal components of the PCA. In this analysis the PC-1 predicts 81 %, PC-2 predicts 14 %, and PC-3 predicts 3 % of the grouping. It can be easily seen in this figure that all PU samples are in one clear group. Also, the RM samples separated well into their own group, even if two RM samples overlap slightly perhaps due contamination. With this presentation PA and PP seem to overlap partly.

The performed PCA analysis above was compared with the support vector machine discriminant analysis (SVMDA) in the MATLAB software. SVMDA with PCA data reduction as pretreatment produced separation on different plastic samples in distinct manner even samples that overlap in principal component space. Thus, this validated the preliminary PCA analysis. The implementation of the applied SVM model was accomplished in the MATLAB by the PLS toolbox of Eigenvector Research, Inc.

Based on the conducted measurements, the generated data sets, and the performed PCA and SVM tests, it can be concluded that the signal-to-noise-ratio (SNR) was improved with this enhanced instrument compared to the previous device version. Further, this instrument detected the rubbers (RM), which are one subcategory of the microplastics.

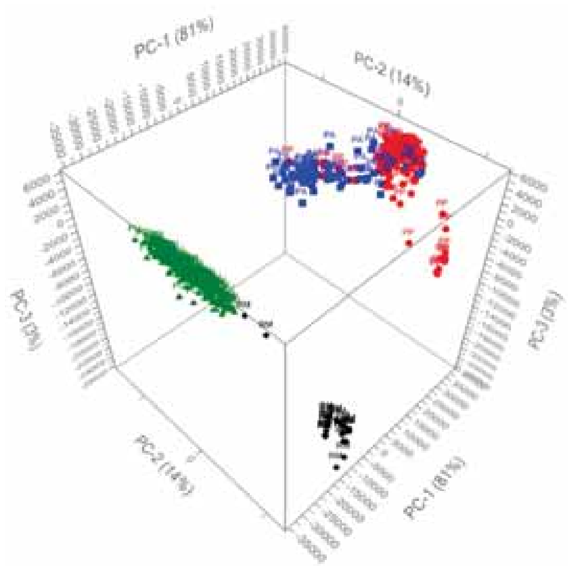

Fig. 5. The PCA score plot using raw data. The PP, PA, and PU microplastics and RM rubber already group well in the preliminary analysis

Further it can be noted that the autofluorescence of the PU samples activated the photomultiplier tubes. With the received results, the amplification levels of the autofluorescence channels can be tuned. Regarding spectral data treatment practices each wavelength band can be tuned separately, which optimize UV signal and NIR signals.

4. Discussion

Continuous measurement requires a stable measuring instrument and a capable data analysis model. The implemented measuring instrument has some development needs, which have been identified during the development of the instrument. From a spectroscopic point of view, the key issue is the best possible SNR over a wide range of wavelengths. The implemented multiple light sources work well. The wavelength-specific optical transmission paths consist of optical fibers, lenses and a cuvette-tube in which the sample particles move with the water.

The Cuvette tube material was quartz glass BK7, with a defined wavelength range of 300-2500 nm. As a material, BK7 also transmits UV wavelengths < 300 nm, but with significant attenuation of the light intensity. An alternative material would be Suprasil 130 or 310, this UV quartz has a wavelength range of 180-2500 nm. Suprasil 130 or 310 cuvette tube material was not readily available in stock during instrument construction.

The signal from the xenon flash lamp was routed via fiber port 2 to the cuvette tube. The optimal wavelength range of the current standard lens is 1050-1620 nm, while the wavelength range of the flash lamp is 190-1100 nm. The fiber port lens could be replaced with more suitable antireflective coatings, although lens replacement is a risky operation. The risk is related to the insertion of the magnetic holder of the new lens. This improvement is planned for a later stage.

This is a sensitive optical measuring instrument. When the instrument is moved from one place to another, it is also subject to small mechanical shocks and vibrations. For this reason, vibration absorbers were designed into the instrument housing between the instrument housing and the optical plate, to eliminate the sharpest shocks.

All physical measuring instruments are to some extent functions of temperature. The field instrument is subject to challenging outdoor conditions, as both outdoor temperature and solar radiation have a significant effect on the internal temperature of the instrument housing. The instrument consists of two parts: the measuring device and the voltage source unit. In this structure, a significant amount of heat and electromagnetic interference is isolated from the instrument unit itself. Direct solar radiation will be reduced by a separate radiation shield, which will be placed on top of the instrumentation unit and will also act as a rain shield.

The overall design of the instrument is good and functional and relatively easy to adjust. In further development, attention can also be paid to modularity. Runoff water sampling is challenging due to the presence of both soil solids, minerals, plant and animal biological matter and other particulate particles. Therefore, some form of runoff water pre-filtration is necessary.

5. Conclusions

An instrumentation concept has been developed to measure microplastics in runoff water. The measurement principle was based on the UV-Vis-NIR light spectroscopic response of microplastic particles in water. Here the focus is on the opto-mechanical implementation of the concept. In the design of the module assembly utilizing optical ports, the essential aspect was to separate fine and precise mechanics and this way to enable control of mechanical tolerances.

The implementation used optical fibers as the transmission pathways from the light sources to the fibre ports and from there to the cuvette tube. The light sources used were a continuous wave halogen lamp, a xenon flash lamp, a laser diode, and a LED. In turn, the light received was guided by lenses or mirrors through optical fibers to the detector. The detectors used were a NIR spectrometer, a UV-Vis spectrometer, a Si detector, and three PTM fluorescence channels.

Based on preliminary measurements and PCA and SVM tests of the measurement raw data, it was found that the signal-to-noise ratio (SNR) was improved. Further, it was found that the device could detect at least one type of rubber in addition to microplastics, which were PE, PVC, PA, PC, PP, PU and RM. In this respect, the key opto-mechanical device development objectives were met.

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MEASURING THE STATE OF ADVANCEMENT OF CIRCULAR ECONOMY GOOD PRACTICES IN AGRI-FOOD SECTOR*

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Abstract

This study explores the adoption of sustainability and Circular Economy (CE) practices within the agri-food sector, focusing on their potential to mitigate crisis effects and enhance resource efficiency. The research leverages the Technology Readiness Levels (TRLs) framework, adapted to assess the advancement stages of CE good practices (GPs), particularly those registered in the Italian Circular Economy Stakeholder Platform (ICESP). Analyzing 44 agri-food GPs across various regions and sectors in Italy, the study identifies significant disparities in TRL stages, with regions like Emilia Romagna and Piemonte exhibiting a higher concentration of advanced practices. The results reveal that agricultural GPs generally exhibit a lower stage of advancement, while Food and Beverage (FandB) practices are more prevalent in later stages, particularly during market introduction and expansion. These findings underscore the need for tailored strategies to support CE adoption, address sector-specific barriers, and promote the scalability of innovative practices. The study concludes that a structured TRL framework is essential for advancing sustainability in the agri-food sector, offering insights that can guide future research and policy interventions aimed at fostering a more widespread and effective transition to a circular economy.

Keywords: agri-food sector, circular economy, good practices, sustainability, technology readiness levels,

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1. Introduction

Adopting sustainability and circular economy (CE) practices may lead organizations to mitigate crise effects by reducing risk exposure, efficiently managing costs and resources and avoiding supply interruptions, because of a reduction on physical exchange between economic systems and the environment ((Carmack et al., 2017; Lopes and Farinha, 2019). Whereas 114 definitions exist for the CE (Kirchherr et al., 2017), they all share a common starting point of reducing the strain on natural resources and encouraging the efficient utilization of mineral resources, fossil fuels, and forests for overarching the objective of sustainable development (Matarazzo et al., 2021). CE, therefore, provides the economic system with an alternative flow model, one that is cyclical (Boulding, 1966). As outlined in the report "Growth within: a circular economy vision for a competitive Europe," this circular model, characterized by continuous resource reuse and minimal waste, could lead to substantial cost and resource savings of €1.8 billion per year by 2030. Consequently, this shift would contribute to GDP growth and generate higher levels of employment (The Ellen MacArthur Foundation, 2015). However, the Circularity Gap Report of 2022 states that global circularity decreased from 9.1% to 8.6% in the last few years due to the limited capacity of recycling materials at an equal level around the world. Several agri-food sector organizations are experimenting innovative circular economy good practices (GPs) to implement and consolidate within different business areas (Arfò et al., 2022; Hallstedt and Pigosso, 2017).

The National Agency for New Technologies, Energy, and Sustainable Economic Development (ENEA) has created the Italian Circular Economy Stakeholder Platform (ICESP, 2022) to collect and promote innovative good practices. So far, ICESP has collected about 242 GPs from diverse sectors and business areas to quantify the environmental, social, and economic impact and evaluate their replicability, to encourage good practices adoption by other companies (Matarazzo et al., 2024). Although 44 GPs derive from agri-food organizations, their degree of sharing is limited due to the peculiarities of the sector itself (e.g., using another company's waste as input in a food production process is often questionable).

To support food organizations reducing their uncertainty and reluctance to encompass these innovative GPs within their business, it is necessary a model capable to efficiently measure the advancement stage of such practices (Ingenito et al., 2024). Technology Readiness Level (TRL), developed originally by NASA, is a structured measurement framework utilized to evaluate the advancement stage of a specific technology, facilitating the comparison of readiness levels across diverse technological domains (Mankins, 1995). Maturity is defined as the condition of being mature, where "mature" denotes reaching a conclusive or preferred stage. Readiness, on the other hand, refers to being prepared for a specific purpose. While maturity can be viewed as a binary state, readiness introduces the notion of progression or advancement (Buchner et al., 2019).

The present study aims to develop a methodological framework to assess the advancement stage of new GPs and link them to adequate TRLs. The research objective is twofold: first, supporting companies, interested in becoming more sustainable, in the adoption of new circular economy approaches; second, to back test current circular economy practices registered in ICESP to provide in a clear view on the advancement stage of those innovative practices around Italy within the agri-food sector.

2. Material and methods

The study is conducted using the data provided by ICESP to test the model and analysis the readiness level of GPs with respect to five areas of application (i.e., production, consumption, waste management, row material procurement, and innovation and investment).

To do that, the authors consulted a private ICESP database explaining each good practice in terms of objective, description and results obtained from the GP implementation. In case of a lack of data or unclear information, the GP corresponding person was directly contacted to properly gauge the information needed by the model.

The key variables taken into consideration are the following: GP description, qualitative and quantitative result from the GP implementation, sector (i.e., food and beverage or agriculture), geography, barrier encountered in the implementation, financing need, current investment. The agri-food GPs assessed are 44 out of a total set of GPs amounting to 242 (which includes different sectors) as of the first of May 2024 in the ICESP database.

This study proposes a TRL framework adapted to the nature of circular economy GPs, which encompasses non-technological aspects. Similarly to Buchner G. A., et al. (2019), to identify stages of advancement, the model distinguishes Working Flow (WF) and Tangible Result (TR) for each TRL (Table 1). TRLs corresponds to EARTO clusters including the following main stages: invention, concept validation, prototyping and incubation, pilot production and demonstration, initial market introduction, and market expansion (EARTO, 2014).

Table 1. Descriptive Technology Readiness Level (TRL) model adapted to circular economy good practices (GPs)

EARTO maturity model	***Invention***		***Concept validation***		***Prototyping and incubation***	***Pilot production and demonstration***		***Initial market introduction***	***Market expansion***
TRL	**TRL1**	**TRL2**	**TRL3**	**TRL4**	**TRL5**	**TRL6**	**TRL7**	**TRL8**	**TRL9**
Definition	**Idea**	**Concept**	**Proof of concept**	**Preliminary process development**	**Detailed process development**	**Pilot trials**	**Full-scale demonstration**	**Commissioning**	**Production**
Working flow (WF)	general research (literature, existing practices, survey)	Initial practice concept formulation	practice concept validation / economic and or legal assessment	practice development / validation / scale-up preparation	properties and functionality detailing / simulation of practice using bench scale information	practice properties and functionality finalization	testing in relevant working environmental (industrial or retail)	Final practice generation / testing the market acceptance	Full scale practice properly working / final integration of GP into the business culture
Tangible result (TR)	idea / rough concept / vision	effective concept / list of solutions / RandD plan	MVP / proof of concept in laboratory or office	MVP validated / experimental results	detailed practice model found / Beta practice ready	working pilot practice / practice model finalized	optimized pilot practice / sample production or process / finalized and qualified system	full scale practice constructed / initial market test	Practice ready to scale in the market / practice operated over the full expected condition

Source: authors' elaboration

By evaluating the current WF from the description of GPs and assessing the current TR attained from the key variables provided by ICESP, the model allows to track the positioning of GPs with the appropriate advancement stage of a circular economy GP. (Sauser B., et al., 2006). This study, through such a descriptive model, assess all 44 agri-food practices registered in the ICESP database around Italy and not only, as of the first May 2024.

3. Results and discussion

The outcome of the adapted TRL model allows to assess the readiness level of circular economy GPs, emphasizing differences among practices of different geographies, sectors and areas of application. Figure 1 illustrates the number of GPs labeled in TRL per Italian region. It is evident that Emilia Romagna and Piemonte are the regions with the greatest number of GPs, while Campania and Friuli Venezia Giulia report only one GP per region. By contrast, several Italian regions do not register any GP. At the same time, GPs with the highest TRL

(TRL8 and TRL9) are represented by Emilia Romagna, Basilicata and Calabria as well as two GPs at national level. There are not GPs with TRL1 and TRL2 and three of them are not identified due to the poor level of description of the practice itself. Although Piemonte reports six agri-food GPs, most of them have an advancement level lower of TRL7.

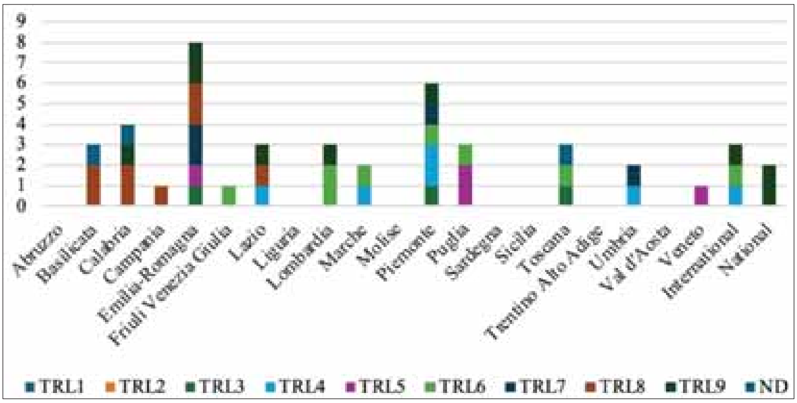

Fig. 1. Readiness Level of ICESP GPs per Italian Region (05/2024)
(Source: authors' elaboration)

Figure 2 shows a comparison on advancement levels of GPs distinguishing agriculture from Food and Beverage (FandB). In between concept validate and incubation stage, i.e., TRLs 3, 4 and 5, the presence of agriculture GPs is by far greater compared to FandB. Within the middle TRL groups, circular economy GPs are equally distributed, i.e., four GPs in TRL6 and two GPs in TRL7. In the initial market introduction phase (i.e., TRL8) there are six FandB good practices against four in the agriculture sector. Finally, GPs in the market expansion phase (TRL9) amount totally to seven with agriculture having one GP more of FandB.

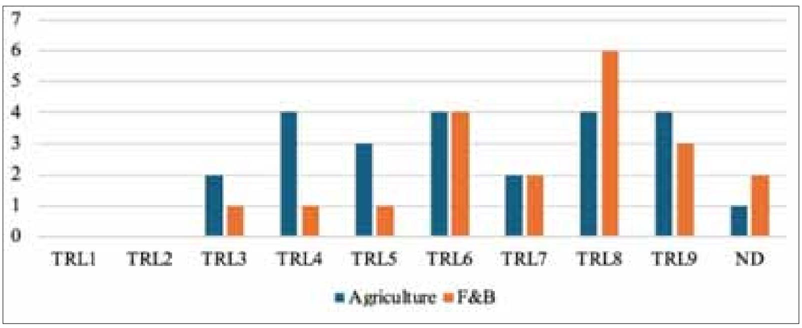

Fig. 2. Readiness Level of ICESP GPs in Agriculture and FandB (05/2024).
(Source: authors' elaboration)

Figure 3 depicts the advancement stages of GPs with respect to areas of application within agri-food business processes. Circular practices on production are present at all levels of TRL with a greater presence in TRL8 and TRL9 (i.e., 6 out of 12 production GPs). Whereas many consumption practices are in the initial market introduction stage (e.g., TRL8), those on raw material procurement have not been introduced into the market, having a TRL lower or equal to 7. Waste management and innovation and investment practices are nearly equally distributed around the different stage of advancement.

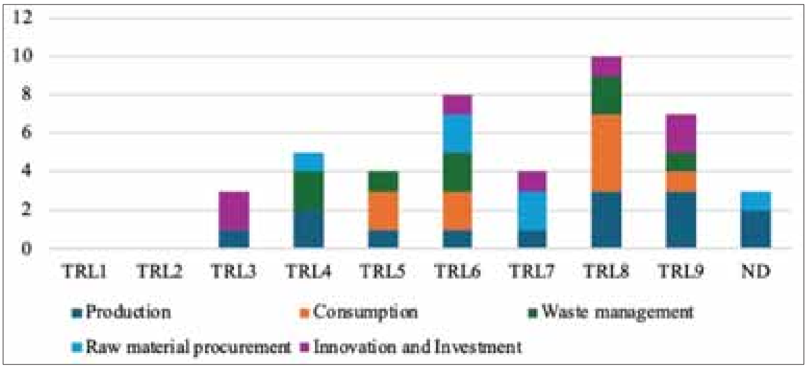

Fig. 3. Readiness Level of ICESP GPs per Area of Application (05/2024)
(Source: authors' elaboration)

4. Conclusions

The findings of this study highlight the critical importance of adopting sustainability and circular economy (CE) practices within the agri-food sector, particularly in mitigating the effects of crises and contributing to broader environmental and economic goals. By reducing dependency on natural resources and minimizing waste, CE practices not only promote resource efficiency but also bolster organizational resilience against supply chain disruptions and economic fluctuations. This research emphasizes the necessity of developing a robust framework for assessing the readiness and maturity of CE practices, particularly in the context of agri-food businesses, which face unique challenges due to the sector's inherent characteristics.

The adaptation of the Technology Readiness Levels (TRLs) model to evaluate the advancement of CE good practices (GPs) presents a novel approach to understanding the progress and potential scalability of these practices. The results indicate significant variation in the TRL stages across different regions and sectors in Italy, with regions like Emilia Romagna and Piemonte leading in the number of advanced GPs. However, the uneven distribution of TRLs and the absence of GPs in certain regions underscore the need for targeted interventions and support to foster CE adoption across the country.

Moreover, the analysis reveals that while agricultural GPs generally exhibit higher readiness levels in the early stages of the TRL framework, Food and Beverage (FandB) practices tend to dominate the later stages, particularly in market introduction and expansion. This distinction suggests that different sectors within the agri-food industry may require tailored strategies to enhance their CE practices' readiness and integration into the market.

The implementation of CE practices, as facilitated by a structured TRL framework, holds significant promise for advancing sustainability within the agri-food sector. However, reaching this potential will require concerted efforts to address existing barriers, promote knowledge sharing, and support the development of practices across all regions and sectors.

Future research should focus on refining the TRL model further and exploring its applicability to other industries to enhance the global transition towards a circular economy.

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APPLICATION OF MULTI-CRITERIA DECISION ANALYSIS APPROACH FOR EVALUATING THE SUSTAINABILITY OF LANDFILLS WASTE IN SICILY*

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Abstract

In Sicily, the waste emergency is a major problem from both managerial and environmental point of view. Although the Sicilian region has good levels of differentiated waste collection, the landfills continue to be full. In the long run, landfills represent a significant environmental problem.
The performance of landfill management in terms of sustainability may be inherently uncertain, considering that its performance depends not only on individual site characteristics and variability, but also on integrated and potentially long-term environmental, social, economic and technical impacts.
This study proposes the use of the multicriteria decision analysis (MCDA) TOPSIS method for the management of complex environmental, economic and social decisions.
The analysis, following a critical multi-dimensional approach based on a vector of weights, shows that the sustainability performance of different sites varies widely due to differences in implemented best management practices (BMPs). The environmental dimensions in the remediation strategy and implementation processes contribute more to the overall sustainability performance when considering whole life cycle management, while the social dimensions are relatively little considered. Based on a sensitivity analysis of the TOPSIS method, random variations in the vector of weights did not lead to significant alterations in the modelled sustainability performance of the assessed sites, indicating that the method provides a relatively robust approach. The MCDA approach developed allows stakeholders to adopt best management practices to control risk and improve sustainability performance in landfill management, covering the entire life cycle of site remediation.

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Keywords: best management practices, landfills, remediation life cycle, sustainability performance, TOPSIS method, waste emergency

1. Introduction

The waste emergency represents one of the most critical and urgent challenges of our time, with significant impacts on the environment, public health and the quality of life of communities. The steady increase in waste generation, due to population growth, urbanisation and unsustainable consumption patterns, has led to a global crisis in waste management. Despite existing regulations and efforts to improve disposal practices, Sicily continues to face an emergency characterised by saturated landfills, inadequate waste management and a growing proliferation of illegal dumps. Recent studies (Di Bella et al., 2020; Esposito et al., 2018) highlight how the saturation of existing landfills, combined with insufficient infrastructure, has led to increasing environmental pressure, with negative effects on soil, water resources and air quality. The controlled landfills in Sicily, while complying with national and European regulations, are not without their criticalities. Ineffective leachate and gas management, lack of continuous monitoring and structural deficiencies have been identified as recurring problems (Ruggiero et al., 2021; Simanaviciene and Ustinovichius, 2010). This liquid can contaminate groundwater, compromising the quality of drinking water and causing damage to local ecosystems (Twardowska et al., 2006). In parallel, the spread of illegal landfills in Sicily represents a growing threat, with serious environmental and social consequences. These dumps, often located in rural or difficult-to-access areas, escape the control of the authorities and contribute to the widespread pollution of land and watercourses, endangering the biodiversity and health of local communities (Catania et al., 2020). However, despite technological and regulatory advances, many landfills continue to operate in sub-optimal conditions, exacerbating environmental and health risks (Slack et al., 2005).

In Sicily, the saturation of existing landfills and the presence of illegal dumps highlight gaps in sustainable management practices and the need for a more integrated approach. Recent studies have shown how the adoption of best management practices (BMPs) and the implementation of advanced technologies can significantly improve the sustainability of landfills while reducing environmental and health risks (Catania et al., 2020). However, the Sicilian regional context presents unique challenges, linked to both geographical and socio-economic factors, which require tailor-made solutions to improve the sustainability performance of landfills.

2. Indicators for landfill analysis

This article considers the indicators to be used for analysing landfills in Sicily, what they are and the reasons why they were chosen. They are: recycling rate, composting capacity, RDF recovery, methane emission reduction, management costs, economic benefits and land value. The recycling rate in Sicily, with particular attention to the use of this indicator on landfills, requires an analysis of the local context, environmental challenges and waste management policies in the region. It is of strategic importance as a tool to monitor and improve waste management, reducing pressure on landfills and promoting more sustainable practices (Cossu and Williams, 2015). Specifically, this indicator measures the share of waste collected separately and sent to recovery processes with respect to the total amount of waste produced and is fundamental for assessing the effectiveness of waste management policies (ISPRA, 2020). The importance of using the percentage of recycling in Sicilian landfills as an indicator lies in its ability to highlight the inefficiencies of the current system and to stimulate corrective actions. A high recycling percentage indicates not only a reduction in dependence on landfills, but also an improvement in overall waste management, from separate collection to the treatment and reuse of recovered materials (Pavone and Giacchetta, 2020). In addition, the use of this indicator can help raise awareness among the population and policy-makers about the need to reduce waste generation and improve separate collection and recycling processes.

Composting capacity refers to the maximum amount of organic waste that a waste management system can process. This parameter is essential for assessing the effectiveness and sustainability of organic waste management policies, as adequate composting capacity allows waste to be transformed into valuable resources such as compost, while reducing the volume of waste that ends up in landfills (Hogg et al., 2017). The importance of using composting capacity in Sicilian landfills lies in its ability to reduce pressure on the landfills themselves, prolonging their useful life and improving the quality of the surrounding environment. Moreover, increasing composting capacity is closely linked to the achievement of circular economy and sustainability objectives, as the compost produced can be used in agriculture, improving soil fertility and reducing dependence on chemical fertilisers (Martínez-Blanco et al., 2013). This is particularly relevant in Sicily, where the agricultural sector plays a key role in the regional economy.

Refuse-Derived Fuel (RDF), a fuel derived from waste subjected to sorting, shredding and stabilisation treatments, represents an alternative energy resource that can be used in co-firing plants, such as cement factories or thermoelectric power plants (Pires et al., 2011). This approach allows not only to reduce the volume of waste going to landfills, but also to energetically valorise materials that would otherwise contribute to waste accumulation without any added benefit (Consonni and Viganò, 2012). In Sicily, where landfills are close to saturation and waste treatment infrastructures are often lacking, RDF could play a crucial role in improving the efficiency and sustainability of the waste management system. The use of RDF in Sicilian landfills can offer numerous advantages, including reducing the mass of waste sent to landfills, decreasing greenhouse gas emissions from the anaerobic decomposition of organic waste and producing energy from alternative sources (Adani et al., 2004). Furthermore, RDF recovery can stimulate the creation of new waste treatment plants, contributing to the modernisation of existing infrastructure and creating new economic opportunities in the region (Pavone and Giacchetta, 2020). However, the successful implementation of this technology requires proper planning, significant infrastructure investments and clear policy-making at regional and national levels (Hogg et al., 2017).

Methane emissions from landfills are a major source of greenhouse gases in the solid waste management sector, contributing significantly to global warming and climate change (IPCC, 2014). Methane (CH_4) is mainly produced by the anaerobic decomposition of organic waste in landfills. In Sicily, a region characterised by a highly landfill-dependent waste management, the reduction of methane emissions is crucial not only to mitigate local environmental impacts, but also to contribute to global greenhouse gas reduction targets (ISPRA (2020)). Sicilian landfills, many of which are not equipped with advanced biogas capture and treatment systems, pose a significant environmental risk. The absence of such systems allows methane to be released directly into the atmosphere, contributing significantly to the greenhouse effect and climate change. The implementation of effective methane emission reduction strategies, such as the installation of biogas capture and combustion systems, would not only reduce the environmental impact of landfills, but could also generate economic benefits through the energy valorisation of biogas (Scheutz et al., 2019). The reduction of methane emissions in Sicilian landfills is crucial for several reasons. Firstly, it directly contributes to the reduction of air pollution and the improvement of air quality, with positive effects on public health (European Environment Agency, 2020). Secondly, the reduction of methane released from landfills can play a crucial role in aligning Sicily with the European Union's climate and energy targets, which require a significant reduction in greenhouse gas emissions by 2030 (European Commission, 2020). Finally, the promotion of biogas treatment technologies can incentivise the adoption of more sustainable and resilient waste management practices, helping the region to overcome current infrastructure deficiencies and improve overall waste management (Hogg and Favoino, 2016).

The operational costs of landfills, which include operating expenses, post-closure maintenance costs and investments in technologies to reduce environmental impact, are a critical component in the planning and sustainability of waste disposal systems (Williams, 2013). In Sicily, the problem is further exacerbated by a number of specific factors, including high waste production, limited capacity of disposal facilities and the complex economic and administrative dynamics that characterise the region (Mazzanti and Zoboli, 2008). These conditions not only contribute to rising management costs, but can also lead to significant inefficiencies, putting pressure on municipal and regional budgets (Lombardi et al., 2017). The analysis of landfill management costs is essential for several reasons. Firstly, a proper assessment of costs allows the identification of inefficiencies and waste, helping to reduce the financial burden on local governments and citizens (Bai and Sutanto, 2002). Secondly, understanding cost trends can incentivise the adoption of more sustainable technologies, such as biogas capture systems or waste pre-treatment technologies that, although initially costly, can lead to significant long-term savings (Ritzkowski and Stegmann, 2012). Finally, careful economic management of landfills can improve compliance with environmental regulations, avoiding penalties and promoting environmental protection (European Environment Agency, 2020),

The analysis of the economic benefits of efficient landfill management is essential not only to ensure environmental sustainability, but also to ensure the economic viability of public and private investments. In Sicily, the application of these financial metrics can have a significant impact on improving the economic performance of landfills. Despite the difficulties associated with inefficient management and high regulatory pressure, accurate profitability analysis can guide investment decisions towards more sustainable and profitable technologies and practices. For example, the adoption of biogas capture or material recycling plants can not only reduce environmental impacts, but also improve the economic return for local governments (Lombardi et al., 2017). In regions such as Sicily, where demographic pressure and economic activity exert a strong pressure on natural resources, the value of land becomes a key element to consider in spatial planning and waste management (Mazzanti and Zoboli, 2013). This problem is particularly serious in Sicily, where the scarcity of land suitable for landfills, together with the growing demand for soil for agriculture and urbanisation, makes prudent land management essential (Agovino et al., 2016). The correct assessment of the value of land is crucial for deciding where to locate new landfills and for implementing technologies that minimise environmental impact. Furthermore, understanding the economic value of land can guide landfill reclamation and reuse policies, fostering land redevelopment once the landfill life cycle is over (Christensen, 2010). These approaches can not only preserve land values, but also generate long-term economic and social benefits for local communities.

The main purpose of this study is to verify that the sustainability performance of different sites varies considerably due to differences in the implemented best management practices (BMPs). The TOPSIS (Technique of Order Preference Similarity to the Ideal Solution) method provides a relatively robust approach, although it assumes that preferences are monotonic for each evaluation criterion and that qualitative scales are converted to quantitative before applying the method. However, both assumptions have been widely criticised in the literature. The MCDA approach developed enables stakeholders to adopt best management practices to control risks and improve sustainability performance in landfill management. The study is complemented by a comparison with soil values to understand whether any remediation actually correlates with sustainability performance.

3. Outline of the work

This work is divided in three main parts:

- selection of case study: "Motta Sant'Anastasia" landfill and "Lentini" landfill, and data collection regarding the indicator for each landfill;
- evaluation of the current waste management systems in the selected locations; using sustainability indicators and following a critical multi-dimensional approach based on a combination of weights, this study shows that the sustainability performance of different sites varies widely due to differences in implemented best management practices (BMPs) (Arfò S., Matarazzo A.,2022).
- analysis and comparison of the results in terms of environmental impact categories and size; analysis of results, drawing conclusion and formulation of recommendations for policy and decision makers in the sector (Oliveri et al., 2023).

4. Materials and methods

4.1. "Motta Sant'Anastasia" landfill

The first solid urban waste landfill examined is the one located near the municipality of Motta S. Anastasia to the east of the Etnean capital, about 25 km from the urban centre, on the border with the municipality of Misterbianco. The landfill receives waste produced by a very large number of users; according to the latest ARPA Sicilia report, it has a number of inhabitants served of approximately 1,100,000. The area within which the landfill plant is located extends for about 35 ha; specifically, the portion of land that coincides with the landfill plant is about 35 ha. The portion of land that coincides with the landfill occupies about 29 hectares, while the remaining 6 hectares host the services. Remaining 6 ha host the support services for the management of the plant. The territory under examination constitutes part of the extreme foothill offshoot of the south-eastern Etna extending as far as Paternò, culminating at Monte Tiritì. Its territory is essentially divided into 4 large macro-areas.

Landfilling takes place close to the hills, by filling open gaps along the slopes due to calanque areas, slopes due to gully areas or tributaries. The bases of the 4 large lots are now filled with waste and therefore the deposit is only developed in height. Now, in fact, there are no plans to build new lots for the dumping of waste.

Within the area there are also: - housing modules as well as offices where employees carry out their activities; - a weighing device for incoming lorries with waste and outgoing tankers for the transport of leachate for disposal; - a meteo-climatic station to obtain information regarding rainfall atmospheric precipitation, which as we know influences leachate formation; - a GPS system to facilitate topographical surveys and to constantly monitor slopes and the general morphology of the territory; - a biogas collection plant and a biogas analysis plant; - a leachate collection basin, located in the most depressed area of the landfill at the landfill at approximately 135 m above sea level; leachate is disposed of daily by transporting it by tanker trucks to an authorised centre tankers, to an authorised centre for the purification of civil and industrial sludge in the neighbourhood of Gioia Tauro (RC).

The quantity of waste authorised by Sicily Region Decree of 09/07/1997 is approx 3.2 million m^3. The degree of compaction given to the waste being landfilled is 0.9 t/m^3, it follows that the quantity of waste authorised is approximately 2.8 million m^3.

4.2. "Lentini" landfill

The Lentini landfill, in contrada Grotte San Giorgio, is one of the largest (40 hectares in area) and most important landfills in Sicily and probably in southern Italy. It is located in the province of Syracuse, in the municipality of Lentini, in a strategic location for the placement of waste from eastern Sicily. The landfill itself was built to hold one million tons of waste per year, and renovations have been made to extend the site's capacity to four and a half million tons to prolong its life. The landfill mainly accepts rinsed solid waste, but also disposes of non-hazardous special waste; on some occasions, it has accepted waste from other regions of Italy. The landfill is currently closed for technical reasons and ongoing judicial issues. Before disposal, waste undergoes mechanical and biological treatments that reduce its volume and the cost required to dispose of it. A "biostabilization" installation treats organic material, separating it to reduce biogas production.

The infrastructure included in the plant includes containment barriers made of geo-textiles and compacted clay to prevent seepage from occurring into the soil or within the groundwater; a treatment plant for "leachate" accumulated in the village's domains; and a drainage facility that carries "leachate" released at the decomposition of organic material to a separate treatment stage. Finally, there is a biogas collection system, which is captured from the anaerobic decomposition of waste and then can be used to make energy with a gasifier. These components of site management counterbalance sociological benefits with environmental benefits and the durability of the site.

The biostabilisation plant for the wet fraction of non-hazardous urban waste, located in contrada Codavolpe-Catania, was authorised by Regional Government Decree no. 1004 of 01/10/2009, subsequently amended by Regional Government Decree no. 901 of 02/12/2011 and Regional Government Decree no. 518 of 01/06/2018, for the biological treatment of the wet fraction (sub-sieve) from the shredding and screening of undifferentiated municipal waste entering the neighbouring Mechanical Treatment Plant authorised by D.R.S. no. 248 of 26/03/2009 as amended and supplemented for a treatment period of no less than 21 days and inside AIEs (60) made of reinforced concrete with mobile roofing in breathable canvas through static heaps subjected to forced ventilation. The plant, which has a capacity of 315,000 t/year, has been authorised for the disposal operations

The quantity of waste authorised by a Sicily Region Decree is approximately 4.5 million m^3. The degree of compaction given to the waste being landfilled is 0.9 t/m^3, it follows that the quantity of waste authorised is approximately 4 million m^3. It should be noted that both landfills are currently under judicial receivership. The TOPSIS method helps to select the best option among the available alternatives by considering various criteria. In this case, in this study we use the following criteria: Percentage of Waste Recycled, Composting capacity, RDF recovery, Reduction of Methane Emissions, Operating Costs, Economic Benefits.

The basic concept of the TOPSIS method, (Hwang et al., 1981), is that the alternative to be selected must have the shortest distance from the ideal solution. Therefore, the ultimate goal of the TOPSIS method is to define the two virtual solutions (ideal and negative-ideal) and to measure, against these, the distance of each real alternative (Azar and Rajabzade, 2014). This technique is based on the concept that selected alternative should have the least distance from the ideal solution (the best possible state) and the most distance from a negative idea solution (the worst possible state) (Yoon and Hwang, 1995).

Step 1. Supposed there are n indices and m sites for evaluation, the raw indices' data constitute the initial decision matrix $A_{ij} = [a_{ij}]n \times m, (i = 1, 2, \ldots, m; j = 1, 2, \ldots, n)$. Transform decision matrix into the dimensionless matrix using Eq. (1).

$$n_{ij} = \frac{a_{ij}}{\sqrt{\sum_{j=1}^{m} a_{ij}^2}} \tag{1}$$

Step 2. Construct the Weighted Normalized Decision Matrix: the matrix is processed where d_{ij} represents the weighted value of n_{ij}, multiplying each vector of the n_{ij} by its corresponding weight vector, calculated by Eq. (2). W_{nxn} is the matrix that collects the subjective weight vectors.

$$V = N_D . W_{n\times n} = \begin{vmatrix} V_{1i},\ldots & V_{1j},\ldots & V_{1n} \\ \vdots & \vdots & \vdots \\ V_{m1},\ldots & V_{mj},\ldots & V_{mn} \end{vmatrix} \tag{2}$$

Step 3. Calculate the Ideal and Negative-Ideal solutions:

$$\begin{aligned} A^{+} &= \left\{ \left(\max_i \; v_{ij} \mid j \in j_1 \right), \left(\min_i \; v_{ij} \mid j \in j_2 \right) \mid i = 1,2,\ldots,n \right\} \\ A^{-} &= \left\{ \left(\min_i \; v_{ij} \mid j \in j_1 \right), \left(\max_i \; v_{ij} \mid j \in j_2 \right) \mid i = 1,2,\ldots,m \right\} \end{aligned} \tag{3}$$

where j_1 and j_2 are the sets of criteria with increasing or decreasing preference, respectively,

Step 4. Calculate the distances (Eq. 4).

$$\begin{aligned} d_{i^+} &= \left\{ \sum_{j=1}^{n} \left(v_{ij} - v_j^{+} \right)^2 \right\}^{1/2} \quad , \quad i = 1,2,\ldots,m \\ d_{i^-} &= \left\{ \sum_{j=1}^{n} \left(v_{ij} - v_j^{-} \right)^2 \right\}^{1/2} \quad , \quad i = 1,2,\ldots,m \end{aligned} \tag{4}$$

Step 5. Calculate the relative closeness from the ideal solution: closeness means the degree of a specific alternative complying with the ideal alternative. The alternative with higher closeness value gives the top priority for decision makers is found with Eq. (5).

$$cl_{i^+} = \frac{d_{i^-}}{\left(d_{i^+} + d_{i^-} \right)} \quad , \quad 0 \le cl_{i^+} \le 1 \quad , \quad i = 1,2,\ldots,m \tag{5}$$

Step 6. Build up the Ranking of Alternatives: The best (optimal) alternative can be decided according to the preference rank order of cl_i+ (Dodangeh, 2006).

5. Results and discussion

5.1. TOPSIS application

Step 1: We want to rank the alternatives using the criteria evaluated in Table 1.

Step 2: Data: Table 1 presents the data for the various analysis criteria.

Table 1. Data (our elaboration)

Criteria	*Lentini **	*Motta S.A. ***	*Weight*
Percentage of waste recycled (%)	25	20	0.15
Composting capacity (tonnes/year)	40,000	50,000	0.20
RDF Recovery (tonnes/year)	10,000	15,000	0.20
Methane emissions reduction (tonnes CO_2 eq/year)	16,000	15,000	0.25
Operating costs (million euro/year)	3	4	0.10
Economic benefits (million euro/year)	1.2	1.5	0.10

* https://siculatrasporti.com/ ** http://www.oikosspa.com/

Step 3: Normalization of the Decision Matrix. Table 2 presents the normalisation of the data matrix.

Table 2. Normal Matrix

Criteria	*Lentini*	*Motta S.A.*
Percentage of waste recycled (%)	0.7808688	0.62469505
Composting capacity (tonnes/year)	0.624695	0.78086881
RDF recovery (tonnes/year)	1	1
Methane emissions reduction (tonnes CO_2 eq/year)	1	1
Operating costs (million euro/year)	0.6	0.8
Economic benefits (million euro/year)	0.624695	0.78086881

Step 4: Weighted Normalized Matrix. Table 3 presents the normalised matrix multiplied by the weights.

Table 3. Weighted Normalized Matrix

Criteria	*Weight*	*Lentini*	*Motta S.A.*
Percentage of waste recycled (%)	0.15	0.11713032	0.0937043
Composting capacity (tonnes/year)	0.2	0.12493901	0.1561738
RDF Recovery (tonnes/year)	0.2	0.11094004	0.1664101
Methane emissions reduction (tonnes CO_2 eq/year)	0.25	0.1823843	0.1709853
Operating Costs (million euro/year)	0.1	0.06	0.08
Economic benefits (million euro/year)	0.1	0.0624695	0.0780869

Step 5: Computation of the ideal solution and the ideal negative solution

Ideal solution A+ = [0.1171, 0.1562, 0.1664, 0.1823, 0.06, 0.0781]

Ideal negative solution A− = [0.0937, 0.1249, 0.1109, 0.1709, 0.08, 0.0625]

Step 6: Determine the distance between each alternative from the positive and negative ideals.

d+(Lentini)= 0.0635 d+(Motta S.A.)= 0.0282
d−(Lentini)= 0.0282 d−(Motta S.A.)= 0.0635

Step 7: Determine the relative proximity of each alternative to the ideal solution and ranking the alternatives

Cl+(Lentini)= 0.307 Cl+(Motta S.A.)= 0.693

Step 8: Ranking alternatives by Table 4, which presents the sustainability level of the two analysed landfills.

Table 4. Ranking of alternatives

	Sustainability performance
Motta S.A.	0.693
Lentini	0.307

Taking into account the OMI values of the Agenzia delle Entrate's real estate market observatory (Bonifaci and Copiello, 2015), we compared the above result with the soil value in the two territories.

Table 5. OMI soil value

OMI soil value	***min m_2***	***max m_2***	***min m_2***	***max m_2***
	MOTTA S.A.		**LENTINI**	
Affordable housing	450.00 €	630.00 €	385.00 €	570.00 €
Boxes	550.00 €	780.00 €	355.00 €	510.00 €
Villas and cottages	800.00 €	1.150.00 €	660.00 €	970.00 €
Warehouses	320.00 €	520.00 €	240.00 €	355.00 €
Typical sheds, workshops	350.00 €	550.00 €	345.00 €	495.00 €
Motta S.A. TIRITI'				
Lentini Grotte S. Giorgio				

The analysis of Table 5 shows that the land value in the municipality of Motta Sant'Anastasia is always higher than the value in the municipality of Lentini. These values can also be considered as indicators of the perception of environmental sustainability performance. The sensitivity analysis, conducted using causal numbers, simulating variations in the criteria weights showed that they have minimal impact on the overall sustainability performance results. The application of the TOPSIS method provides a comprehensive and flexible approach to assessing the sustainability of landfill management practices. The results indicate that environmental factors play a crucial role in sustainability performance; The MCDA approach developed in this study helps stakeholders to make informed decisions and adopt BMPs that improve sustainability throughout the life cycle of landfills.

The Motta S.A. landfill has a better performance in terms of sustainability and reuse than Lentini, according to the criteria and data used for the analysis. This could indicate that Motta S. A. has implemented more effective management practices or has performed better with respect to the indicators considered.

6. Concluding remarks

The case study showed that intensified implementation of advanced environmental management practices improves overall sustainability performance. We underline that social aspects must also be considered in landfill management strategies in order to achieve a more balanced assessment of sustainability. The use of multi-criteria analysis can serve to conduct periodic assessments and adapt BMPs in response to changing environmental and social conditions. Considering that the data used in MCDA are commonly modifiable (e.g. depending on data availability, selection of experts for qualitative assessments, etc.), the study must be complemented by sensitivity analysis to find out how the uncertainty in the output of a model varies as the input parameters change.

This study can be integrated with the Monte Carlo method to perform sensitivity analysis on the TOPSIS model, using several iterations to randomly generate the initial weights of the indices, based on the assumption that the total sum of all weights must be equal to 1.

In future studies, we will apply the analysis using further multi-criteria methods that develop results using also qualitative data without converting them to quantitative data. We would also like to have the possibility of greater collaboration and interaction with stakeholders to ensure that different perspectives are taken into consideration in the decision-making process, improving therefore the effectiveness of landfill management practices.

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CIRCULAR ECONOMY INDICATORS APPLIED TO A WASTE MANAGEMENT TECHNIQUES BY A SICILIAN COMPANY. THE CASE STUDY TRITOR L.T.D.*

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Abstract

Tritor technology can be implemented within any type of waste treatment plant. Waste characterized by a high component of organic materials, having a low calorific value, must be separated in order not to affect the purposes of waste-to-energy, being then set aside in special containers. The machine designed by Tritor carries out its activity as a replacement for this treatment, guaranteeing a better result in considerably reduced time. More precisely, going from three weeks to a single day, to bring benefits at economic, operational and logistical level. In addition to the services offered by the machine, the operator can change the size of the outgoing waste, making it larger or smaller based on customer needs. This study applies the ISO 59020 standard to measure LC in waste management to improve transparency, accountability, and stakeholder trust, and produce results to support business decision-making regarding sustainability investments. The study is applied to the case of the Sicilian waste company Triton L.t.d. and particularly to the Tritor technology.
Therefore, qualitative, quantitative and semi-quantitative data were collected to estimate indicators related to material, energy and water resources, waste and emissions, logistics and capital policy. We use Material Circularity Indicator (MCI). The results were aggregated, providing a comprehensive set of circularity indicators to evaluate the environmental and social performance of different productivity inputs. A comparative comparison was carried out with other similar companies and with the average of companies in the sector to evaluate circularity performance.

Keywords: ISO 59020, level of circularity, TOPSIS method, waste management, waste treatment

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1. Introduction

In recent years, the energy crisis has put the entire Italian industrial system under pressure, prompting the government to look for innovative and sustainable solutions to counter rising energy costs and reduce dependence on natural gas. In this context, the introduction of Law no. 6/2023, which converts the so-called Aiuti-quater Decree, represents a decisive step towards the adoption of Solid Secondary Fuel (CSS) as a valid energy alternative. The Aiuti-quater Decree introduced paragraph 6 bis to Article 5-bis of Decree-Law No. 14 of 25 February 2022, establishing a regulatory simplification of great impact for the industrial sector. Until 31 March 2024, in fact, the substitution of natural gas with alternative fuels, including CSS, will no longer be considered a substantial modification of industrial plants (Decree 14, 2022). This regulatory innovation allows companies to retrofit their plants more quickly and less expensively, simply by notifying the competent administrative authority of authorisation exceptions and the type of alternative fuel chosen.

In practice, this means that plant operators will be able to make the necessary technical changes to replace gas with CSS without having to go through the long and complex bureaucratic process traditionally required for substantial changes. After sending the notification, the competent authority will have 30 days to express any objections. If there are no objections, companies will be able to proceed with the introduction of CSS for an initial period of six months, renewable. The adoption of CSS has numerous advantages for the industrial sector. In terms of energy, CSS, if of high quality, can provide adequate heat input to replace natural gas in many production processes, supporting to stabilize energy costs. From an economic point of view, this transition could result in significant savings for companies, reducing their exposure to fluctuations in the price of natural gas, which in recent times has reached unsustainable levels for many production facilities. In addition to the immediate benefits, the use of CSS helps closing the waste cycle, thus contributing to reducing the environmental impact of industrial production. CSS, in fact, derives from the valorisation of non-hazardous waste that, suitably treated, is transformed into fuel. This process not only reduces the amount of waste going to landfills, but also contributes to the reduction of CO_2 emissions, aligning with the European Union's environmental sustainability goals. The regulations introduced with the Aiuti-quater Decree are in continuity with a path of bureaucratic simplification started some time ago, aimed at making the Italian production system more competitive and in line with European standards. In many EU Countries, in fact, the use of CSS as an alternative to fossil fuels is already widespread, with substitution rates that reach 50% on average. With this new measure, Italy is taking a significant step towards the European model, favouring an energy transition process that, in addition to responding to the contingent needs of the energy crisis, is a long-term strategy for the sustainability of the industrial sector.

In this context, the new ISO standards for the circular economy were recently introduced. They were created to provide organizations with a common vocabulary, operational guidelines and measurement tools to effectively apply circularity principles. These standards stem from the work of the ISO/TC 323 technical committee, which published a package of ISO 59000 series standards on May 22 (these are the first four standards: 59004, 59010, 59020, 59032), developed over more than five years with input from experts from more than 100 Countries and 19 international bodies. The ISO 59000 standards are key to sharing international practices aimed at maintaining a circular flow of resources and promoting sustainable development. Other standards will soon be introduced, such as the revision of the Italian UNI/TS 11820 standard and new European standards proposed by CEN/TC 473. Specifically, ISO 59020:2024 defines a framework for measuring and evaluating circularity performance using standardized indicators, ensuring consistency and verifiability of results. It aims to standardize the method by which organizations collect and calculate data employing both mandatory and optional circularity indicators, ensuring verifiable and consistent results. ISO 59020.2024 provides guidelines for demarcating the boundaries of the system, selecting appropriate indicators and interpreting the data, thus enabling the evaluation of circularity performance on various levels, from product-specific (nano-circularity) to organizational, inter-organizational and regional.

This study applies the ISO 59020.2024 standard to measure LC (level of circularity) in waste management to improve transparency, accountability, and stakeholder trust, and produce results to support business decision-making regarding sustainability investments. The ISO 59020:2024 standard, entitled "Circular economy - Measuring and assessing circularity performance," provides guidelines for measuring and assessing the circularity performance of organizations. This standard is critical for companies that want to align with global sustainability goals by improving transparency and accountability in environmental reporting.

Main Goals of ISO 59020:

- Standardization: To provide a common framework for measuring circularity, facilitating comparison between different organizations.
- Transparency: To improve transparency in environmental reporting, allowing companies to clearly communicate their circularity performance.
- Decision Support: Helping organizations make strategic decisions based on verifiable and consistent data.
- Alignment with Sustainability Goals: Promoting sustainable practices and contributing to the transition to a circular economy.

They provide data on circularity performance to analyze the achievement of set goals, enable informed decision making and constantly monitor the performance of each production process (Oliveri et al, 2023). The indicators to be used should be chosen according to the type of organization, sector or activity to which they relate (Ninci et al., 2002). For their validity, they must meet a number of requirements: understandability; meaningfulness; demonstrability; comparability; controllability; continuity; and efficiency. In particular, we will analyse the level of circularity of the TRITOR ENERGY product.

When it comes to the design of a new circular product, the focus is on its materials used and the resources required. Regardless of the type of product, scholars identify reducing resource use by increasing efficiency, slowing resource consumption, and closing resource cycles as key principles for the transition. Practical strategies for creating circular products, such as eco-design and life extension, are based on these principles. Circularity indicators measure how much of a product's materials are reintegrated into the system, how long it lasts, its economic value at the end of its life cycle, and its social impact. This information makes it possible to assess the overall circularity of a product and identify aspects for improvement (MacArthur, 2013).

Products according to a nano-circular approach, are currently evaluated primarily through the MCI Material Circularity Indicator (MacArthur, 2015), which measures circularity, or the LCA Life Cycle Assessment (Niero and Kalbar, 2019), which evaluates sustainability. The two methods are similar but differ significantly: the MCI focuses on the resource efficiency of the product, the LCA primarily analyses the environmental impact of the product during all stages of its life cycle, including the extraction of raw materials.

The MCI and LCA are product assessment methods that therefore differ in some key features: the MCI measures resource efficiency, excluding transportation and waste, and is mainly applied to technological products, while the LCA assesses the environmental impact at all stages of a product's life cycle and is more widely applicable. The two methods use a database created with MFA. Consequently, to assess the circularity of a product in a comprehensive way, it is necessary to combine the advantages of the two methods, while also taking into account economic and social factors.

CE is a three-dimensional concept that includes environmental, social and economic aspects. Therefore, for a standard method of assessing the circularity of a product, it is necessary to combine the benefits of MCI and LCA, also introducing other important factors such as economic competitiveness and social impact (e.g., job creation). The assessment framework must also be universally applicable to products from technical and biological cycles.

2. TOPSIS technique steps

In order to analyze the level of circularity from a three-dimensional perspective, we use, also, the multicriteria method TOPSIS (Technique of Order Preference Similarity to the Ideal Solution). The basic concept of the TOPSIS method, (Hwang and Yoon, 1981), is that the alternative to be selected must have the shortest distance to the ideal solution. Therefore, the ultimate goal of the TOPSIS method is to define the two virtual solutions (ideal and negative-ideal) and to measure, against these, the distance of each real alternative real.

The TOPSIS method also starts with the prior knowledge of the decision matrix D. The steps leading to the identification of the best alternative are described below.

Step one: Formulate the data matrix based on m alternative and n index:

$$A_{ij} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \cdot & & & \cdot \\ \cdot & & & \cdot \\ \cdot & & & \cdot \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix}$$

Step two: Transform decision matrix into the dimensionless matrix using Eq. (1).

$$n_{ij} = \frac{a_{ij}}{\sqrt{\sum_{j=1}^{m} a_{ij}^2}} \tag{1}$$

Step three. Construct the Weighted Normalized Decision Matrix: the matrix is processed where d_{ij} represents the weighted value of n_{ij}, multiplying each vector of the n_{ij} by its corresponding weight vector, calculated by Eq.(2). W_{nxn} is the matrix that collects the subjective weight vectors.

$$V = N_D . W_{n\times n} = \begin{vmatrix} V_{1i},\ldots & V_{1j},\ldots. & V_{1n} \\ \vdots & \vdots & \vdots \\ V_{m1},\ldots & V_{mj},\ldots & V_{mn} \end{vmatrix} \tag{2}$$

Step four. Calculate the Ideal and Negative-Ideal solutions (Eq. 3).

$$A^{+} = \left\{ \left(\max_{i} \; v_{ij} \mid j \in j_1 \right), \left(\min_{i} \; v_{ij} \mid j \in j_2 \right) \mid i = 1,2,\ldots,n \right\}$$
$$A^{-} = \left\{ \left(\min_{i} \; v_{ij} \mid j \in j_1 \right), \left(\max_{i} \; v_{ij} \mid j \in j_2 \right) \mid i = 1,2,\ldots,m \right\} \quad (3)$$

where j_1 and j_2 are the sets of criteria with increasing or decreasing preference, respectively,

Step five. Calculate the distances (Eq. 4).

$$d_{i^+} = \left\{ \sum_{j=1}^{n} \left(v_{ij} - v_j^{+} \right)^2 \right\}^{1/2} \quad , \quad i = 1,2,\ldots,m$$
$$d_{i^-} = \left\{ \sum_{j=1}^{n} \left(v_{ij} - v_j^{-} \right)^2 \right\}^{1/2} \quad , \quad i = 1,2,\ldots,m \quad (4)$$

Step six. Calculate the Relative Closeness from the Ideal Solution: Closeness means the degree of a specific alternative complying with the ideal alternative. The alternative with higher closeness value gives the top priority for decision makers (Eq. 5).

$$cl_{i^+} = \frac{d_{i^-}}{\left(d_{i^+} + d_{i^-} \right)} \quad , \quad 0 \le cl_{i^+} \le 1 \quad , \quad i = 1,2,\ldots,m \quad (5)$$

Step seven: Ranking alternatives by quantity cl_i
The above value fluctuates between [0,1]. In this regard, $cl_i = 1$ represents the highest ranking and $cl_i = 0$ is the lowest rank (Azar and Rajabzadeh, 2014). The best (optimal) alternative can be decided according to the preference rank order of cl_i+.

The TOPSIS method assumes that preferences are monotonic for each evaluation criterion and that qualitative scales are converted to quantitative before applying the method. However, both assumptions have been discussed and criticism in the literature.

3. Materials and methods. Case studies

3.1. Tritor machinery

Growing environmental issues force companies to obtain voluntary environmental certifications and to implement measures to reduce the ecological impact at all stages of the production cycle. From the perspective of the circular economy, companies that develop technological innovations relating to waste management, with the aim of reusing materials and energy for further and different production cycles, are of particular interest, both from public and private points of view.

For these reasons, the main objective of this study is to analyse and better understand the benefits of proper waste management through the application of the ISO 59020 standard. To this end, a case study was conducted on the company Tritor Ltd., an emerging company specialised in waste treatment that has gained a significant market share. The treatment of waste, especially in Sicily, presents its greatest difficulties due to two main factors: the scarcity of waste-to-energy plants, which are practically absent throughout the country, and the complex treatment processes for differentiated product categories.

In particular, the company recognised the need to face a race against time to prevent the landfills from reaching saturation level and ceasing operation. To address this situation, the company sought a solution that would compensate for the lack of adequate infrastructure and improve the efficiency of existing landfills. Tritor developed an innovative technology for waste treatment, applicable in both public and private contexts. In Sicily several tons of municipal solid waste are delivered daily to the disposal plant by specialized collection and handling trucks. Be it, in particular, non-hazardous waste and possibly already treated at other mechanical-biological treatment (TMB) plants. The waste processing cycle within the plant, after the aforementioned delivery, begins with the depositing of the bags on top of special conveyor rollers, which have the task of handling the waste during the entire process (Cernuschi and Giugliano, 1992).

The waste once shredded, if characterized by a dynamic respiration index (IRDP) greater than 1000 mgO_2, is crammed into special cells and treated with air for a process, called aerobic digestion. The waste undergoes such treatment is the controlled decomposition of materials through the action of aerobic bacteria that require oxygen to do their work, so as to reduce odors, greenhouse gas production and accelerate decomposition. During this phase, which usually has to be implemented over a period of twenty-one days, air is fed into the cells through the use of fans or floor vents. This last stage of treatment, anaerobic decomposition, fails to act effectively, both in terms of time, as it requires more time than the usual twenty-one days, and in terms of results. Some treated waste, therefore, results in inadequate drying and volume reduction.

The TRITOR machinery devised by Tritor Ltd. performs its activity in place of such treatment, guaranteeing a better result in considerably reduced time, precisely going from three weeks to just one day, so as to bring benefits in terms of economics, operations and logistics. Specifically, the shredded waste introduced inside Tritor goes into special types of pots, more precisely four pots are arranged inside each machine. Each vat contains about two thousand five hundred chrome-plated steel marbles, which are responsible for further disintegrating the waste. The machinery, however, does not have the ability to break down hard plastics, yet this apparent disadvantage turns out to be an added value, as the plastic would make the final product more harmful due to the dioxins released, from the presence of chromium and mercury, into the environment during combustion (De Sannazzaro et al., 2014).

3.2. Tritor hospital

Proper management of biomedical waste disposal is of utmost importance; one study shows that due to improper disposal of medical waste, health care workers contracted up to 30% more hepatitis B. Such workers reported 13 percent of hepatitis C and 0.3 percent of HIV rates (Singh et al., 2020). During this pandemic of COVID 19, waste management and waste disposal in hospitals, became a particularly important issue. According to the waste management policy, each of these contaminated wastes should require proper identification, collection, separation, storage, transportation, treatment, and disposal. The contaminated material should be properly disinfected, if necessary, before disposal (Behera, 2021). Also with reference to such waste, Tritor Ltd. has patented a new machine.

Tritor Hospital Waste Station is an operational rental solution that revolutionises hospital waste management, transforming it into a valuable resource for the environment. A compact 200 or 400 litre device to simplify and optimise the medical waste disposal process. It is a station for treating and transforming medical waste into sterilised municipal waste and a station for treating and transforming sanitary waste into electrical and thermal energy that is indispensable for the hospital's energy needs.

3.3. Tritor energy

TRITOR Energy is a microcogeneration that produces electrical and thermal energy using high-quality Secondary Solid Fuel (CSS) and/or high-quality biomass. The technology developed by TRITOR allows waste to be treated efficiently, reducing weight, volume and leachate production. This process not only decreases landfill disposal costs, but also allows waste to be transformed into Secondary Solid Fuel (CSS) with high calorific value, recognized as TRITOR Energy.

TRITOR Ltd. can benefit from ISO 59020 by implementing mandatory and optional indicators to assess the circularity of its operations. This structured approach allows data to be collected and calculated in a consistent and verifiable manner, supporting strategic decisions for sustainable resource management.

To evaluate the circularity of TRITOR operations, we can use several key indicators:

Material Circularity Indicator (MCI): Measures the degree of circularity of a product considering the entire life cycle, from raw material extraction to the end-of-life.

Circular Transition Indicators (CTI): Assesses the transition to a circular economy, considering aspects such as reuse, recycling and waste reduction.

Efficiency Indicator (EI): Measures resource use efficiency by assessing the amount of materials and energy used relative to final products.

Circularity indicators specific to TRITOR Energy, such as the percentage of recycled materials, energy efficiency, waste reduction, CO_2 emissions, product lifecycle life, and material recovery, can be used to calculate the Material Circularity Indicator (MCI). These indicators reflect the efficiency and sustainability of TRITOR Energy's microgeneration system. The Material Circularity Indicator (MCI) is a tool developed to measure the degree of circularity of a product or system. This indicator considers the entire product life cycle, from raw material extraction to the end-of-life phase, and assesses how effectively materials are recycled, reused and recovered. The MCI is a value between 0 and 1, where 1 indicates a maximum level of circularity. Key Components of the MCI are: Virgin Materials (V): Amount of virgin materials used, Recycled Materials (R): Amount of recycled materials used, Reclaimed Materials (M): Amount of materials recovered at the end of the life cycle, Life Cycle Length (L): Length of the product's life cycle.

The MCI is calculated using Eq. (6) that considers the recycling rate, recovery rate and product life cycle length and is defined as follows (MacArthur Ellen Foundation, 2015):

$$\mathrm{MCI} = 1 - \left(\frac{V - R - M}{V} \times \frac{L}{L_{\mathrm{ref}}} \right) \quad (6)$$

where L_{ref} is s a reference life cycle length, which could be an industry standard or a benchmark value. This formula ensures that the MCI value ranges from 0 to 1, where 0 indicates a completely linear flow (no circularity) and 1 indicates a fully circular flow (maximum circularity). A high MCI indicates efficient use of resources and low environmental impact.

TRITOR Energy can use ISO 59020 to improve its circularity performance. By implementing indicators such as percentage of recycled materials, energy efficiency, waste reduction, CO_2 emissions, product lifecycle life, and material recovery, TRITOR Energy can calculate its MCI and compare it with industry benchmarks. The benefits of Applying ISO 59020 are: improving Environmental Performance (identify areas for improvement and implement more sustainable practices); Competitiveness (position yourself as an industry leader in sustainable waste management and energy production); Social Responsibility (demonstrate commitment to sustainability and environmental protection).

The MCI and ISO 59020 are essential tools for companies that want to improve their circularity performance and contribute to a more sustainable future. To compare TRITOR Energy's Material Circularity Indicator (MCI) with other similar companies, we can look at some key parameters and industry benchmarks. Here is a comparison based on available data and common practices in the waste management and CSS energy production industry. Table 1 presents the data for the various analysis criteria.

Table 1. Data collection

	Waste management and CSS	*Tritor**	*Green Team***	*EcoEnergy Solutions****	*Global Industry Benchmarks*****
1	Percentage of Materials Recycled, %	70	65	68	60
2	Energy Efficiency, %	85	80	82	75
3	Waste Reduction, %	90	85	88	80
4	CO_2 Emissions: Reduction, %	60	55	58	50
5	Product Lifecycle Life	10	8	9	8
6	Material Recovery, %	80	75	78	70

*https://tritor.it/ ** https://www.greenteam.srl *** https://ecoenergy-solutions.com
**** World Benchmarking Alliance (WBA), Statista, OECD Environment Statistics

3.4. Material Circularity Indicators (MCI)

For calculated Material Circularity Indicators (MCI) of the three companies we use software Python. Global Industry Benchmarks are used for normalization. The results are:

Tritor: 0.33 (or 33%)
Green Team: 0.14 (or 14%)
EcoEnergy Solutions: 0.24 (or 24%)

These MCIs reflect each company's performance in terms of material circularity relative to the industry benchmarks provided. Tritor has the highest circularity among the three, followed by EcoEnergy Solutions and then Green Team.

3.5. TOPSIS application

Step 1: Data collection: Data are shown in Table 1.

Step 2: Normalization of the Decision Matrix (Eq. 7).

Normalized Matrix:

$$\text{Normalized} = \begin{bmatrix} 0.4642 & 0.4575 & 0.4642 & 0.4456 \\ 0.5638 & 0.5631 & 0.5598 & 0.5570 \\ 0.5976 & 0.5983 & 0.6009 & 0.5947 \\ 0.3984 & 0.3870 & 0.3966 & 0.3717 \\ 0.0664 & 0.0563 & 0.0615 & 0.0593 \\ 0.5311 & 0.5285 & 0.5333 & 0.5197 \end{bmatrix} \quad (7)$$

Step 3: Calculate the Weighted Normalization Matrix (Eq. 8).

Weighted Matrix:

$$\text{Weighted} = \begin{bmatrix} 0.0774 & 0.0763 & 0.0774 & 0.0743 \\ 0.0940 & 0.0939 & 0.0933 & 0.0928 \\ 0.0996 & 0.0997 & 0.1001 & 0.0991 \\ 0.0664 & 0.0645 & 0.0661 & 0.0619 \\ 0.0111 & 0.0094 & 0.0103 & 0.0099 \\ 0.0885 & 0.0881 & 0.0889 & 0.0866 \end{bmatrix} \quad (8)$$

Step 4: Determine the ideal positive solution and the ideal negative solution:

- **Positive Ideal Solution (A*)**: The maximum value for each criterion.
- **Negative Ideal Solution (A-)**: The minimum value for each criterion.

$$A^* = [0.0996, 0.0997, 0.1001, 0.0991, 0.0111, 0.0889]$$

$$A^- = [0.0743, 0.0928, 0.0991, 0.0619, 0.0094, 0.0866]$$

Step 5: Determine the distance between each option to the positive and negative ideals.

Distances from the Positive Ideal Solution:

$$D^+ = [0.0784, 0.0914, 0.0811, 0.1016]$$

Distances from the Negative Ideal Solution:

$$D^- = [0.1347, 0.0866, 0.1130, 0.0783]$$

Step 6: Determine the relative proximity of each alternative to the ideal solution and ranking the alternatives

Similarity Coefficients:

$$C = [0.6320, 0.4869, 0.5820, 0.4355]$$

Step 7: Ranking alternatives by level of circularity: Table 4 presents the circularity evaluation level of the three analysed companies and the global industry benchmarks. The TOPSIS method, also, confirms the highest level of circularity of TRITOR.

Table 2. The final ranking of alternatives

Alternative	*Circularity evaluation*
Tritor	0.6320
EcoEnergy Solutions	0.5820
Green Team	0.4869
Global Industry Benchmarks	0.4355

4. Results and discussions

4.1 TRITOR Energy performance

TRITOR Energy demonstrates outstanding performance in key circular economy metrics, particularly in energy efficiency, waste reduction, material recovery, and CO_2

emissions reduction. The application of TRITOR's innovative technology reduces waste treatment time from the conventional 21-day period to just one day. This accelerated process enhances not only operational efficiency but also the overall sustainability of waste management operations.

Comparative analysis of TRITOR's Material Circularity Indicator (MCI) with other companies reveals its superior circularity performance. As indicated in Table 1, TRITOR achieves an MCI of 0.33, significantly surpassing the industry benchmark and other comparable companies such as Green Team and EcoEnergy Solutions. This high circularity score reflects TRITOR's efficient use of materials and its ability to reintegrate recovered resources into new production cycles.

Moreover, TRITOR's energy efficiency, measured at 85%, is notably higher than both the industry benchmark (75%) and its closest competitors. This efficiency is primarily attributed to the optimized use of high-quality Secondary Solid Fuel (CSS) and biomass in its microcogeneration system, which simultaneously produces electrical and thermal energy. Additionally, TRITOR achieves a waste reduction rate of 90% and a CO_2 emissions reduction of 60%, positioning it as a leader in environmentally sustainable practices.

4.2 Comparative Circularity Analysis

The comparative analysis, using the TOPSIS multi-criteria decision-making method, further highlights TRITOR's leading position in circularity evaluation. The TOPSIS results, as shown in Table 2, rank TRITOR highest among the three analyzed companies, with a closeness coefficient of 0.6320. This outcome underscores the company's ability to balance economic, environmental, and operational criteria effectively.

Green Team and EcoEnergy Solutions follow with closeness coefficients of 0.5820 and 0.4869, respectively, while the global industry benchmark ranks lowest at 0.4355. TRITOR's ranking reflects its consistent efforts to implement best practices in waste management and resource recovery. By excelling across multiple dimensions of circularity, TRITOR not only enhances its competitiveness but also contributes significantly to achieving broader sustainability goals.

4.3. Circularity Indicators Breakdown

To better understand TRITOR's performance, a breakdown of key circularity indicators was conducted:

- Percentage of recycled materials: TRITOR achieves a recycling rate of 70%, which is above the industry benchmark of 60%. This high percentage results from the effective sorting and processing of input waste streams.
- Material recovery rate: At 80%, TRITOR's material recovery rate ensures that a substantial portion of input materials is redirected back into productive use.
- Product lifecycle extension: TRITOR's processes contribute to a product lifecycle of 10 years, exceeding the industry average of 8 years. This extension is crucial for minimizing resource depletion and maximizing the utility of products.

4.4. Strengths and limitations of the study

One of the primary strengths of this study is the comprehensive evaluation framework that combines MCI and TOPSIS methodologies, enabling a multi-faceted assessment of circularity. This approach not only highlights TRITOR's strong performance but also provides a robust benchmark for other companies in the sector.

However, several limitations must be acknowledged. This research is based on a case study involving three companies and industry data, which may limit the generalizability of the findings. Furthermore, the use of specific MCDM techniques, while effective, could be complemented by alternative methodologies in future studies to validate and extend the results.

4. Concluding remarks

4.1. Driving sustainability through regulatory innovation and circular product design

The possibility of using Solid Secondary Fuel represents a concrete and immediate response to the challenges posed by rising energy costs and the need to reduce dependence on natural gas. Thanks to the new legislation, Italian companies will benefit from an important simplification of authorisation processes, making it easier to adopt alternative energy solutions. This measure will not only help support the competitiveness of the national production system but is also part of a broader strategy of energy transition and environmental sustainability, aligning Italy with European standards and promoting a greener and more sustainable future. In addition, the purpose of product circularity evaluation is to slowly close resource loops using strategies such as product redesign and introducing new business models (Mestre A. and Cooper T., 2017; Figge F, et Al, 2018) . Designing a circular product or transforming an existing business product into a circular product requires the implementation of multiple strategies. The multi-criteria application on the MCI index allowed us to compare the case of the TRITOR company with companies in its target market and propose a judgment on its circularity.

5.2. Future research directions

Given the promising results observed in this study, future research could explore the application of additional performance evaluation methods and other MCDM techniques. Expanding the scope of analysis to include a broader range of companies and industries would enhance the robustness and applicability of the findings. Furthermore, longitudinal studies could be conducted to track the long-term impact of circularity practices on environmental and economic outcomes.

In summary, TRITOR Energy's commitment to circular economy principles and its exemplary performance across various circularity indicators establish it as a model for sustainable waste management and energy production. The insights provided by this study can serve as a valuable reference for policymakers and industry leaders aiming to promote circular economy practices and achieve sustainability goals.

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LIFE CYCLE ASSESSMENT (LCA) OF ORGANIC FRACTION OF MUNICIPAL SOLID WASTE (OFMSW) TREATMENT PROCESSES IN AN EFFICIENT WASTE COMPOSTING PLANT*

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Abstract

Life Cycle Assessment (LCA) is a standardized methodology critical for the evaluation of environmental impacts of materials and processes, focusing on resource consumption and energy use. In the waste management sector, LCA is essential for identifying optimization strategies, both upstream (selecting recyclable or compostable materials) and downstream (improving waste management processes).
A comparative LCA was conducted and discussed in this paper: the study represents a process LCA which evaluated two scenarios for treatment of the organic fraction of municipal solid waste (namely OFMSW) to produce 1 ton of compost in an Italian composting plant.
From the life cycle analysis, the optimized scenario results in a reduction of the burdens with respect to standard configuration. Finally, a second LCA study compared the optimized composting scenario with hypothetical landfill and incineration alternatives.

Keywords: biodegradable and compostable, composting processes, environmental impacts, LCA, OFMSW

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1. Introduction

Life Cycle Assessment (LCA) methodology is a structured and internationally standardized method for the quantification of environmental impacts of product and processes along their lifetime. The study allows for the identification of the environmental footprint associated with the consumptions of resources and the related emissions during the life cycle of the considered object of the analysis. Developed during the early 70s, in view of an increasing awareness towards the environmental concerns of big scale industrialization, LCA has been applied to several and different technological fields and products, being recognized as a key-tool for the eco-design and climate change mitigation.

As known, the presence of polymers in the globalized market has revolutionized the manufacturing sector and the consequent production of products for everyday life. With low production costs, easy raw materials access and processing and versatility of application, polymers product from oil source are a constant presence in the food industry, thanks for their lightweight and compatibility with diaries. On the other hand, their massive consumption raised up concerns for their disposal fate, since recycling is not possible after food contamination, hence most of these large amounts of tableware and packaging polymer waste at its end of life is sent to landfill. The direct consequence, indeed, is the increase of the waste amount on a global scale and, in turn, the related environmental concerns. For this reason, in the last decades, new raw materials are being considered for the food industry, whose source could be both natural than industrial, but they have the intrinsic property to be reprocessed with food waste once disposed, resulting in a new product: the compost. As a final outcome, these new compostable materials have the advantage to be compatible with food, lightweight and easy processable and, in the end, to reduce the amount of waste in disposal since they could be properly treated with the organic waste in specific plants, called composting site.

Several studies over the last years focused the attention on these new materials, aiming to determine their physical properties, applications and, in particular, their life cycle impacts over the food value chain thanks to the LCA methodology.

Recent studies in the field of composting and the use of compostable tableware have highlighted the significant environmental benefits and potential of these practices. In the last years, research has focused on various aspects, including environmental impact, the efficiency of the composting process, and the role of compostable tableware in reducing waste. For example, Wagas et al. (2023) investigate conventional and emerging composting processes, highlighting mechanisms and influencing factors, emphasizing the advantages, such as reduced groundwater pollution. Similarly, Sokac et al. (2022) discuss about the efficiency of composting that depends on several factors like temperature, pH, moisture content, C/N ratio, particle size, nutrient content, and oxygen supply, and they develop a statistical optimization techniques and mathematical modelling have been developed to enhance these processes.

Azim et al. (2018) addressed the composting to restore organic matter to depleted soils, offering a sustainable fertilization alternative. This review examines the quality and stability of composts from various organic wastes, monitoring, and maturity parameters for different composting methods and raw materials.

Simultaneously, part of the research has evolved to evaluate the environmental impacts of the composting process and the importance of biodegradable and compostable materials., such as Hermann et al., (2011) estimate the carbon and energy footprints of various waste treatment options for biodegradable materials and identified the most environmentally favourable method by comparing home and industrial composting, anaerobic digestion, and incineration. Hottle et al. (2013), provided a comprehensive Life Cycle Assessment (LCA) of compostable tableware made from bio-based polymers, comparing them with conventional petroleum-based alternatives. It discussed the environmental impacts of both materials, focusing on the end-of-life composting process. The study highlighted the benefits and challenges associated with using compostable tableware, particularly in terms of reducing greenhouse gas emissions and supporting sustainable waste management practices. Also, Gisario et al., (2022) conducted a comparative LCA of biopolymer and petroleum-based plastic cups within a composting system. Their study concluded that compostable biopolymer cups have a significantly lower ecological footprint, especially when composting is carried out in optimized facilities. Moshood et al. (2022), examined the sustainability of biodegradable plastics in composting systems, demonstrating that the integration of these plastics can significantly enhance the quality of the produced compost while simultaneously reducing the negative environmental impacts associated with the management of traditional plastic waste. While Cristóbal et al. (2023) focused on practices for compostable plastic packaging waste: impacts, challenges and recommendations were among the aims of this study. In the end, the article assessed the environmental and economic impacts of different waste management schemes for Compostable Plastic Packaging (CPP) using LCA and Costing, in order to inform policy makers on the most effective practices for mitigating climate change and managing financial costs.

Opticompost project (2021-2024) is part of an Integrated Program of Facilitation (namely *Programma Integrato di Agevolazione*, PIA) funded by European Union and Regione Puglia in Italy that aims to develop innovative technological and management solutions to optimize composting processes in particular in presence of items certified according to UNI EN 13432:2002 standard

This paper presents the results of LCA study developed within an Italian regional project aimed at optimizing the composting process. The project seeks to develop innovative technological and managerial solutions for the industrial composting of materials certified according to UNI EN 13432:2002 standard, while simultaneously reducing composting times, increasing production yields, and minimizing process waste. In this context, the activities described pursue two primary goals: to analyze the environmental performance of the composting process in an optimized scenario that reduces the amount of non-compostable waste, when compared with a baseline scenario and then to evaluate the environmental benefits of decreasing non-compostable material by promoting compostable alternatives. Additionally, a further analysis was conducted to assess the environmental benefits of the new composting process compared to potential end-of-life scenarios prior to the establishment of the facility (landfill, incineration) for comparative purposes.

The article is structured to follow a logical and methodological pathway, beginning with a general overview and the objectives of the activities undertaken. This is followed by the methodology adopted for LCA. The focus then shifts to the application of LCA of the process, evaluating the environmental performance of a specific facility. Subsequently, the paper explores a comparison of different end-of-life management scenarios, highlighting the environmental implications of each alternative. Finally, the conclusions of the study are synthesized, providing a comprehensive overview of the results obtained.

2. Materials and methods

The Life Cycle Assessment (LCA) framework is the method used in this article for the evaluation of the environmental impacts, at product and process level. LCA is a standardized method used to quantify the potential environmental and human health impacts of a product or service throughout its life cycle. This includes all life cycle phases of the system, from raw material acquisition to end-of-life, (an approach known as "cradle-to-grave"). The LCA methodology is governed by the following standards as ISO 14040: 2006 and ISO 14044: 2006. The LCA methodology is divided into four phases:

1. *Goal and Scope Definition*: it establishes the purpose of the LCA study, system boundaries, and the functional unit.
2. *Life Cycle Inventory (LCI)*: it involves the data collection of all inputs and outputs of the product system throughout its life cycle. This phase includes all relevant resource use and emissions data.
3. *Life Cycle Impact Assessment (LCIA)*: it evaluates the potential environmental impacts based on the LCI data. This step involves categorizing and assessing the significance of the environmental impacts.
4. *Interpretation of results*: it involves analysing the results of the LCI and LCIA to make informed decisions and provide recommendations. This last phase also includes identifying any uncertainties and limitations in the study.

The process LCA study object of this article is applied to a composting plant sited in Erchie (Italy), aimed at producing high-quality compost for agricultural use, gardens, and green areas. The study compares two different configurations, where the amount of non-composting waste variates.

3. Case-study presentation

The LCA analysis focuses on the composting process at the Heracle facility in Erchie (Italy), aimed at producing high-quality compost for agricultural use, gardens, and green areas. The system boundaries do not include the field application of the produced compost or the associated environmental impacts and benefits, hence the approach is the so-called “cradle to gate”, considering the impacts from raw materials acquisition and processing, until the production of the final outcome of the process, i.e. the compost.

Goal and scope definition

The main goal of this analysis is to assess the environmental impacts of the new composting process at Heracle plant, located in Erchie (Italy), by comparing a baseline scenario with an optimized scenario to quantify the associated environmental benefits (Table 1).

Table 1. Two scenarios related to the LCA Analysis

Baseline scenario	***Optimized scenario***
Processing of organic fraction of MSW to produce 1 ton of compost. Non-compostable waste destined for incineration: 22.3% (based on primary data).	Processing of organic fraction of MSW to produce 1 ton of compost. Non-compostable waste destined for incineration: 7.8% (based on primary data).

Functional unit

The functional unit (FU) considered for the LCA study is **1 ton of compost** output from the composting facility.

System boundaries

The system boundaries encompass the compost manufacturing phase, starting from the extraction and processing of raw materials up to the production of compost, following a *'cradle to gate'* approach.

The analyzed system (Fig. 1) can be divided into a 'primary system' (foreground system, *dark blue*), which includes processes directly controlled by Heracle facilities, and the 'secondary system' (background system, *light blue*), which includes all upstream and downstream processes of composting, modelled based on secondary data (databases, literature, etc.).

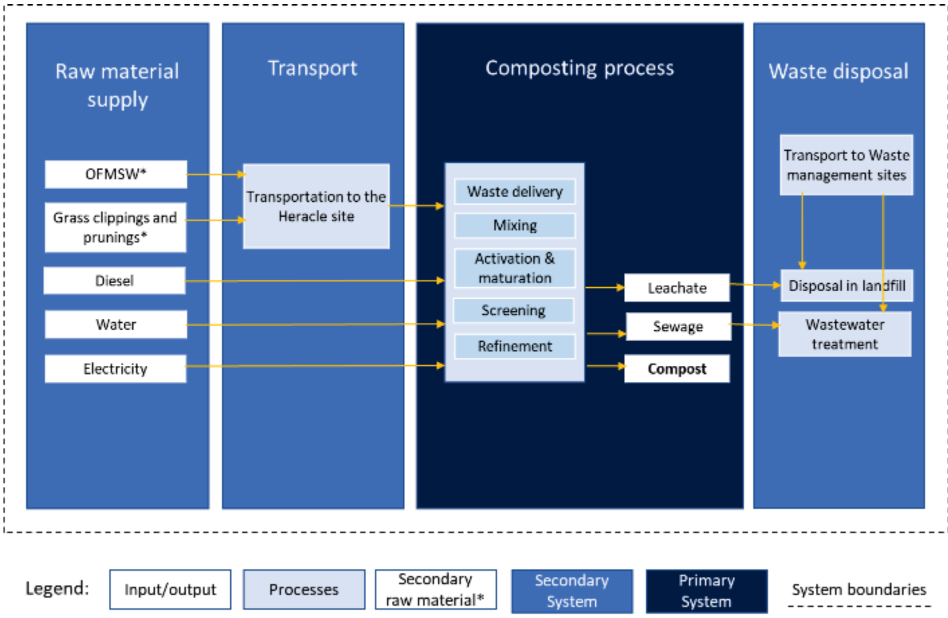

Fig. 1. System boundaries of the analysis

Assumptions and limitations

The following assumptions were made for the study:

- Only the transport of the organic fraction of municipal solid waste (OFMSW) was considered, with an average inter-provincial distance of 50 km from the Heracle site.
- Secondary raw materials used in the composting process, i.e., OFMSW (for compost production) and pruning residues (for biofilter construction), were considered to have zero impact, following the cut-off methodological approach.
- The facility is equipped with a gas effluent treatment system (wet scrubber + biofilter); consequently, gaseous emissions are considered negligible.

LCIA Method and Impact Categories

The method chosen for the environmental Life Cycle Impact Assessment (LCIA) in this analysis is the Environmental Footprint (EF 3.0) method, including 16 specific impact categories.

4. Description of the case study

4.1. Subject of Analysis: Heracle plant in Erchie (Italy)

The Heracle facility in Erchie was authorized in 2015 and built after 2016. Following regulatory adjustments, the facility was redesigned into 20 biocells to enhance the treatment process, improving internal controls and better track of product flow. The plant covers the disposal basin of the Brindisi province and the municipality of Lecce, in the southern Italy. It includes a technical area with offices, a control room and a system for stormwater and sanitary wastewater treatment. Indeed, stormwater is re-used for irrigation, while sanitary water is partially treated and reintegrated into the system process.

4.2. Process description

The composting activities in the plant object of this study are distributed as follows:

- *Reception of OFMSW*: Organic Fraction of Urban Solid Waste (OFMSW) is received at the plant, weighted and verified.
- *Unloading in the Pit:* OFMSW is onloaded into a pit with odour control.
- *Mixing:* OFMSW is shredded for uniformity.
- *Transport to Cells – Activation – Maturation:* The shredded material is transferred to one of 20 maturation biocells (45x7 meters each, 800 m^3 capacity). The process includes a 30-day activation phase and a 60-day maturation phase. Each biocell is equipped with fans to maintain proper aeration and prevent odour release. The compost is screened to remove impurities before refining.
- *Screening:* After 90 days of maturation, the compost is screened to remove impurities and refine the material.
- *Refinement:* The screened material is placed in the refining chamber. If it meets legal standards, it is packaged and sold as compost.
- *Gas Emissions Treatment:* The plant is maintained under negative pressure to prevent odours from escaping. Gas emissions are processed through wet scrubbers and a wood bark biofilter.

5. Results and discussion

5.1. LCA hotspot analysis of baseline and optimized composting scenarios

The present chapter discusses results of the LCA, comparing the two different scenarios (baseline *vs* innovative) of the composting process. Results are calculated and expressed using Environmental Footprint (EF) 3.0 impact assessment indicators. The following hotspot analysis assesses the results of the LCA study on the composting plant, covering the life cycle of 1 ton of compost (functional unit). In Fig. 2, results for the baseline scenario are evaluated.

The contribution analysis outlines a quite homogeneous distribution of the different inputs of the baseline scenario at Heracle plant; however, major contributions are remarkable. In particular, the **treatment of non-reusable waste** (whose fate here is incineration) has the major share of impacts. This parameter is one of the key-points of the implementation, so its improvement could provide important benefits to the whole environmental impact assessment of the process. In addition, also **electrical energy consumption** has a relevant share in the impacts, and it is used for the whole management and operation of the plant (i.e. equipment, services, lighting etc.), as well as fuels for the mobility inside the site (e.g. forklift).

Finally, a negative value is observed for Water use indicator, due to the **wastewater treatment**: this results, quite expected, is a benefit for the process, because the wastewater could be treated and reused inside other purposes (e.g. agriculture), reducing the need of fresh water and resulting in a resource saving.

Following Fig. 3, instead, reports the LCA hotspot analysis on the optimized scenario for the composting plant.

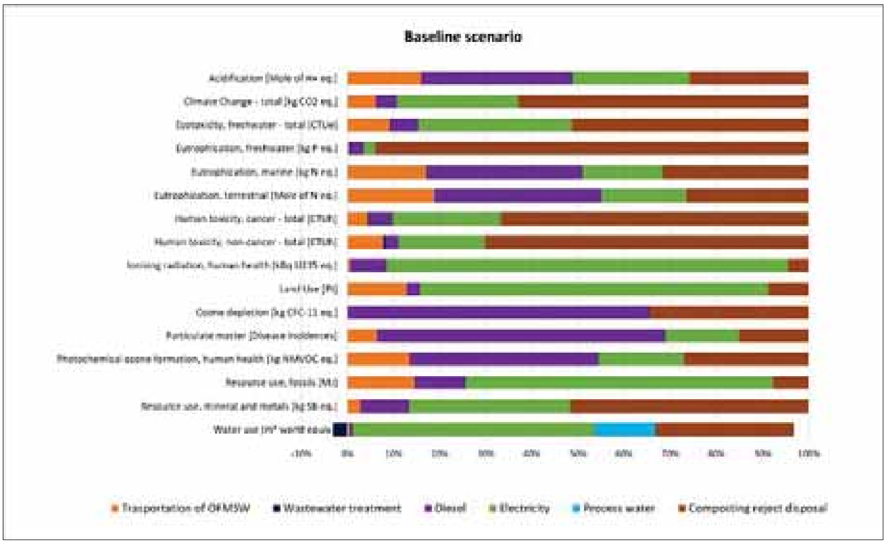

Fig. 2. Process LCA at baseline scenario: hotspot analysis

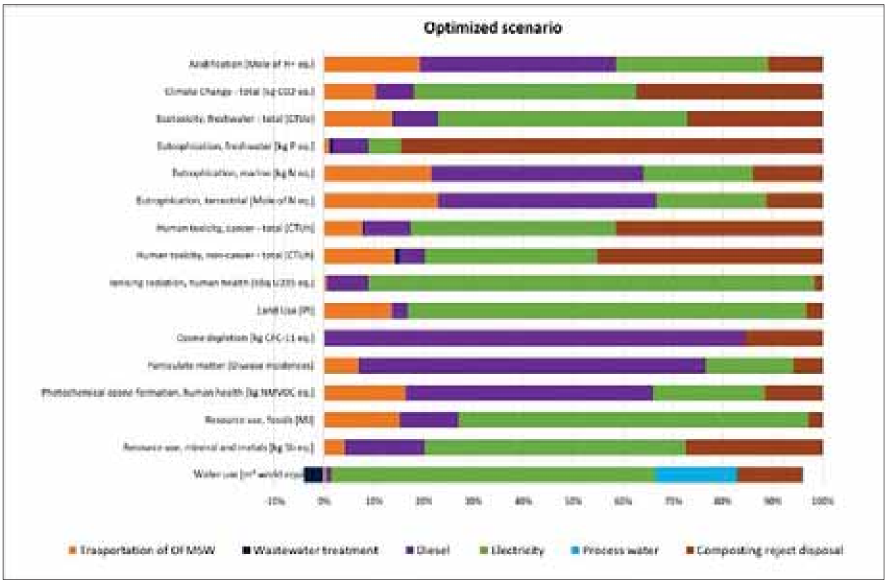

Fig. 3. Process LCA at optimized scenario: hotspot analysis

The hotspot analysis on the optimized scenario LCA results expresses again a distribution between the different contributions, but with a remarkable difference with respect to the baseline scenario. Indeed, the share regarding the **treatment of non-reusable waste** is significantly reduced with respect to baseline: this evidence is caused by a substantial decrease of the non-compostable material (up to the 7.8% of the OFMSW), thus resulting in an important reduction of the environmental impacts associated with its incineration. The other input flows, as **electricity consumption** or **diesel fuel**, are substantially the same as for the baseline scenario, since the overall management of the plant is quite unchanged. Moreover, the resource saving related to **wastewater treatment** is consolidated (about 5%), whose benefit is linked with the nature of the treated product and its possible re-use in place of the virgin source.

5.2. Scenarios comparison

The comparison assessment of the LCA results for baseline and optimized scenarios of composting process is graphically represented by Fig. 4. The selected functional unit is the same for the two LCA studies, i.e. **1 ton of compost**.

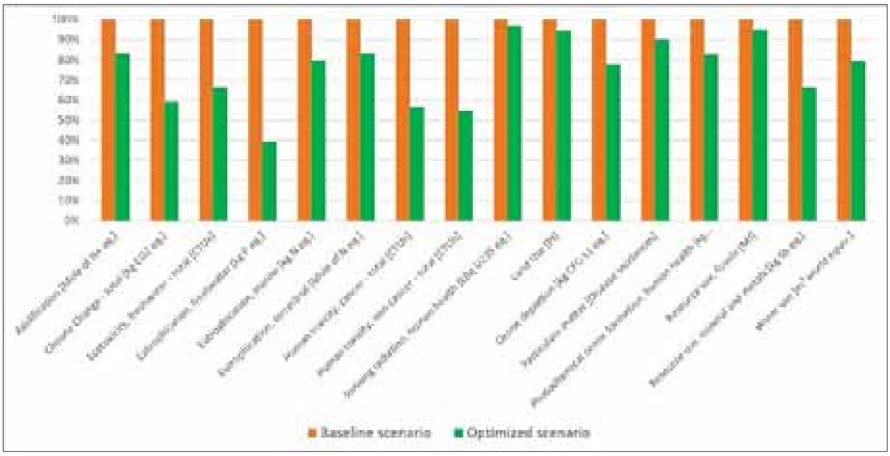

Fig. 4. Comparative assessment of LCA results for baseline and optimized scenario

Comparative assessment outlines a remarkable improvement of the environmental profile of the composting plant in the innovative scenario. Indeed, almost all the selected EF 3.0 impact indicators report an important reduction in the new configuration, with respect to the status-of-the art. This evidence is due to the decrease of the non-compostable material on the whole conveyed waste to the composting site and, thus, the amount to be sent to incineration is lower. Therefore, a global reduction of the impacts is observed for the whole optimized composting process for the selected functional unit. Hence, a better quality of the conveyed waste allows for a remarkable improvement of the environmental performances of the composting process in Heracle plant at Erchie (Italy).

In particular, *Land use* and *Resource use*, fossils could be found among the highest expressed values in the impact indicators observed for both scenarios. They are strictly correlated with the energy inputs of the processing plant (e.g. electricity, fuels etc.), which are mostly taken from the national grid mix, without the support of green sources. As a possible further improvement and suggestion, the use of renewable electricity (e.g. from a photovoltaic plant) could be a strategic action for an additional reduction of environmental indicators associated with energy consumption of the composting site.

An additional comparative LCA analysis has been conducted to evaluate the environmental profile of composting plant (in its innovative configuration) when compared to alternative waste fate available before the plant construction in the same geographical area. In absence of the composting plant, indeed, the OFMSW has two options of treatment: 1) landfill;

2) incineration. The functional unit of the LCA study is **1 ton of OFMSW**, to be treated at its end of life (EoL). Table 2 reports the different alternatives of comparison.

Table 2. Parameters for the comparative EoL LCA study

Parameter	*EoL 1) Landfill*	*EoL 2) Incineration*	*EoL 3) Composting (optimized)*
Functional Unit (FU)	1 ton of OFMSW	1 ton of OFMSW	1 ton of OFMSW
Average distance for transports	30 km (avg. in Brindisi province)	90 km (avg. Brindisi to Massafra, nearest incineration plant)	50 km (avg. Brindisi to Lecce province)

Comparative assessment of the different EoL scenarios is reported in Fig. 5, for 1 ton of OFMSW. The LCA results are calculated according to the EF 3.0 methodology.

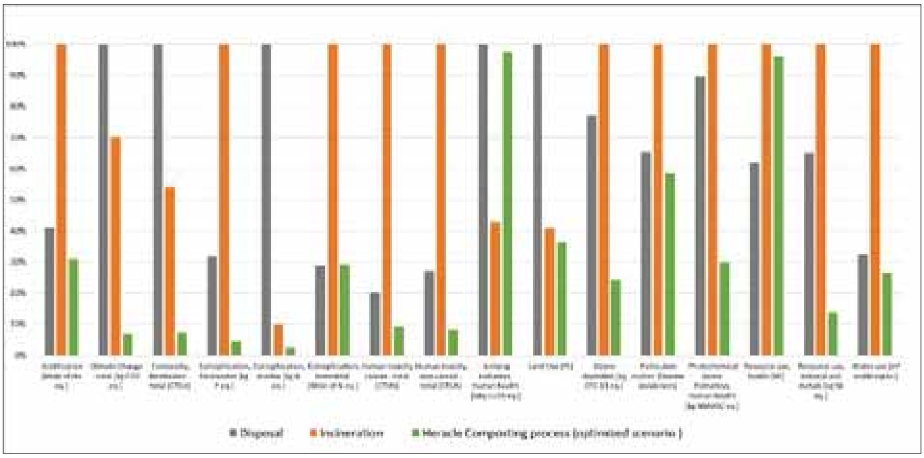

Fig. 5. Comparative LCA for different EoL scenarios

Histogram of comparison outlines the difference in terms of environmental impacts for the 3 different EoL scenarios: landfill, incineration and composting in optimized configuration. In particular, the *ex-ante* scenarios (landfill, incineration) are both highly worse with respect to the composting alternative. Considering the peculiarity of the geographical area under analysis (e.g. average distance from the disposal plants, OFMSW transports inter- or infra-cities, disposal attitudes), it is possible to observe that the composting of 1 ton of OFMSW reports a reduction (sometimes very high) of the environmental impact indicators when compared with the two other EoL alternatives.

As a consequence, this comparative LCA on the different waste fate scenarios proves that the *ex-post* presence of the composting plant in Brindisi area allows for a significant advantage in terms of environmental performance of the OFMSW disposal process with respect to the *ex-ante* alternatives (landfill, incineration), whose burdens could be remarkably higher.

6. Concluding remarks

The present paper discusses a Life Cycle Assessment (LCA) study conducted as part of the Opticompost project. The aim of the project is to develop innovative technological and managerial solutions to optimize the composting process of items certified according to UNI EN 13432:2002 standard and to improve composting times, production yields, and reduce waste.

The study reports an evaluation of environmental performance of the composting process at the Heracle facility. The results demonstrate a significant improvement in the optimized configuration, with an average reduction in environmental impacts of about 25%, and up to 61%. Further comparisons with alternative scenarios, such as landfill or incineration, show higher environmental impacts compared to composting alternative.

In summary, the study confirms that composting is a waste treatment solution with significant environmental benefits, where several variables influence the final outcome, some of which are beyond the control of facility operators. The increase in compostable materials on the market and the adoption of Directive (EU) 2019/904 is expected to further improve the composting process.

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INNOVATIVE APPROACH TO MONITOR GHG EMISSIONS FROM LANDFILLS AND BROWNFIELD SITES BY COMBINING GROUND MEASUREMENTS AND SATELLITE OBSERVATIONS*

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Abstract

Landfill and brownfield sites are major sources of pollution, particularly due to methane (CH_4) emissions, which have a global warming potential 28 times greater than carbon dioxide (CO_2). Landfills contribute 11% of global anthropogenic CH_4 emissions, exacerbating extreme weather and biodiversity loss. Brownfield sites, former industrial areas, also emit volatile organic compounds (VOC), harmful to ecosystems and human health. The ESCAPE (Environmental Sites CH_4 Assessment Platform Europe) project addresses these issues by integrating satellite-based remote sensing with mobile ground sensors for real-time methane monitoring. This cost-effective system combines the wide coverage of satellites with the precision of ground-based measurements, enhanced by machine learning algorithms for improved hotspot detection. ESCAPE combines various technologies, offering a comprehensive view of CH_4 emissions, aiding in leak identification and environmental protection. This approach supports global climate change mitigation by improving the accuracy and efficiency of GHG monitoring from landfill and brownfield sites.

Keywords: CO_2, MOX sensors, pollutant, portable toolbox, soil remediation, VOCs

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1. Introduction

Landfills and brownfield sites pose significant environmental challenges, particularly through the emission of greenhouse gases (GHGs) and volatile organic compounds (VOCs) (Vaverková, 2019). Methane (CH_4), one of the primary GHGs emitted from landfills, is of particular concern due to its relevant impact on climate change. CH_4 has a global warming potential (GWP) approximately 28 times greater than CO_2 over a 100-year period, making it a critical target for monitoring and mitigation efforts (IPCC, 2014). The increase in CH_4 emissions contributes significantly to the acceleration of global warming, intensifying environmental challenges such as extreme weather events, rising sea levels, and loss of biodiversity (UNEP, 2020). Landfill gas (LFG) consists mainly of CH_4 and CO_2, along with smaller quantities of hydrogen sulphide (H_2S) and trace amounts of VOCs (Durmusoglu et al., 2010; Siddiqua et al., 2022). These gases are released into the atmosphere as part of the waste degradation process and can escape through poorly managed or malfunctioning landfill gas extraction and collection systems (Capaccioni et al., 2011; Kaza et al., 2018; Siddiqua et al., 2022). Landfills are currently responsible for approximately 11% of global anthropogenic CH_4 emissions, contributing significantly to GHG levels (Scheehle, E et al., 2006). As global population growth continues, the amount of waste deposited in landfills is expected to increase by 70% by 2050, further exacerbating the problem (Kaza et al., 2018). In Europe alone, landfills contribute 62% of waste-related GHG emissions (EEA, 2024), making the need for more effective monitoring and management of these emissions increasingly urgent.

Brownfield sites - previously developed land often contaminated with hazardous waste - are also significant sources of environmental pollution. These sites, which are often neglected and abandoned after industrial or commercial use, emit various pollutants, including VOCs, which pose risks to human health and the surrounding ecosystem (Cusworth et al., 2024). Revitalizing brownfield sites requires addressing their contamination issues, which are often linked to GHG emissions. As governments push for more sustainable land use practices, brownfield regeneration has become a priority, especially in urban areas where new development is limited due to the scarcity of greenfield land (NPPF, 2019). To ensure the safe redevelopment of these sites, accurate monitoring of emissions is essential, not only to prevent environmental degradation but also to safeguard public health.

Given the scale and complexity of landfill and brownfield sites, monitoring GHG emissions presents several challenges. Traditional methods for detecting methane emissions, such as flux chambers and infrared gas analysers, provide detailed measurements but are often labour-intensive, costly, and limited in spatial coverage (Mønster et al., 2019).These methods are also prone to underestimating emissions due to the high spatial and temporal variability of emissions across landfill surfaces (Huang et al., 2022; Mønster et al., 2019). Advanced techniques like Differential Absorption Lidar (DIAL) and tracer correlation methods offer greater precision but are too expensive for widespread use (EEA, 2024). As a result, there is a growing need for low-cost, scalable monitoring solutions that can provide real-time, comprehensive data across large areas.

The ESCAPE (Environmental Sites CH_4 Assessment Platform Europe) project, funded by the Eureka Eurostars Funding Framework, addresses these challenges by integrating satellite-based remote sensing with mobile ground-based sensors. This innovative approach aims to develop a low-cost, portable sensor toolbox that can be used to monitor methane emissions in real-time, providing valuable data to landfill operators, developers, and environmental authorities. The combination of satellite data with ground measurements offers a comprehensive view of emissions, allowing for better detection of hotspots and operational anomalies. Furthermore, the use of machine learning algorithms to analyse the collected data will enhance the accuracy of predictions over time, ultimately improving the management of landfills and brownfield sites. By providing a cost-effective, scalable, and accurate method for monitoring GHG emissions, the ESCAPE project represents a significant advancement in environmental monitoring technologies.

2. Available technology for methane emission detection

CH_4 emission detection technologies can be broadly categorised into three types: satellite-based remote sensing, ground-based measurements, and unmanned aerial vehicles (UAVs). Each method offers unique advantages, and combining these approaches can provide a more comprehensive picture of emissions. A schematic summary of these technologies is available at Table 1.

2.1. Satellite data

Satellite-based remote sensing provides a powerful tool for monitoring CH_4 emissions over large areas. Satellites equipped with sensors designed to detect CH_4 can provide near-global coverage, enabling the detection of emission hotspots and trends. Several satellite missions are specifically designed to monitor greenhouse gases, including methane.

Key satellites involved in methane monitoring include:

- GHGSat: This satellite is designed to detect methane emissions with a spatial resolution of 25x25 meters, allowing for detailed monitoring of individual sites like landfills. It can detect small CH_4 leaks with a minimum detection threshold of 100 kg/hr (CEOS, 2024).
- MethaneSat: launched in 2024, MethaneSat will offer a resolution of 100x400 meters and can detect CH_4 emissions as low as 500 kg/hr (EO Portal, 2024).
- Sentinel-5P: Part of the European Space Agency's Sentinel series, Sentinel-5P focuses on monitoring air quality and CH_4. Its broad spatial coverage (5500x7000 meters) is useful for identifying regional CH_4 emissions (EO Portal, 2024).

Satellite data offers several advantages, including wide-area coverage and the ability to monitor remote or inaccessible locations. Satellites can continuously track CH_4 levels over time, providing insights into long-term trends and helping identify emission sources that may otherwise go undetected. However, satellite remote sensing monitoring has limitations (Table 1). The temporal revisit time of satellites varies and the near real-time data might not always be available. Weather conditions such as cloud cover can also obstruct satellite payloads, reducing the frequency and accuracy of CH_4 detection. A recent study highlights that satellite data is most effective when used in conjunction with ground-based measurements, offering a more comprehensive approach to CH_4 emission monitoring (Cusworth et al., 2024)

2.2. Ground-based measurements

While satellites provide a broad view of CH_4 emissions, ground-based measurements offer more detailed, site-specific data. These methods are essential for accurately identifying methane leaks and understanding the localised dynamics of emissions at landfill sites.

Key ground-based measurement techniques include:

- *Flux Chambers:* flux chambers are placed over a section of the landfill surface to capture CH_4 emissions. They provide accurate, localised measurements, but their small coverage area means they cannot capture emissions across the entire landfill, leading to underestimation of total emissions (Mønster et al., 2019)

- *Flame Ionisation Detectors (FIDs):* FIDs are commonly used in walkover surveys of landfill sites, providing immediate feedback on CH_4 levels. However, they are labour-intensive and limited in spatial coverage (Babilotte et al., 2010; Cusworth et al., 2024)
- *Differential Absorption Lidar (DIAL):* DIAL uses laser technology to measure CH_4 concentrations over large areas. It provides high-precision, real-time data, but the equipment is expensive and complex to operate, making it less accessible for routine monitoring (Innocenti et al., 2017)

Ground-based sensors are increasingly being integrated with IoT technology, enabling continuous, real-time monitoring of CH_4 emissions. Low-cost sensors connected to a cloud-based system can provide valuable, localised data on emissions, complementing the broader view provided by satellite observations. These sensors are placed at multiple points across a landfill, allowing for continuous monitoring of methane concentrations and enabling operators to detect anomalies or sudden spikes in emissions.

The advantage of ground-based sensors lies in their ability to provide detailed insights into specific sources of methane emissions, helping operators identify leaks or failures in gas management systems. However, their main drawback is that they are labour-intensive and provide data from limited areas, necessitating multiple installations across a landfill site to achieve comprehensive coverage (Mønster et al., 2019) (Table 1).

2.3. Unmanned Aerial Vehicles (UAVs)

Unmanned Aerial Vehicles (UAVs), or drones, offer a flexible and efficient means of monitoring CH_4 emissions by covering large area and providing real-time CH_4 concentrations. Their ability to hover over specific areas allows for targeted monitoring, which is useful for identifying emissions from difficult-to-reach areas like slopes or closed sections of landfills.

The advantages of UAVs include:

- *Rapid deployment:* Drones can be deployed on short notice, allowing operators to quickly investigate suspected CH_4 leaks or high-emission areas (Mønster et al., 2019).
- *Safety and efficiency:* Drones reduce the need for manual inspections. By using drones, operators can collect data without putting personnel at risk of exposure to harmful gases or hazardous terrain.
- *Detailed data collection:* Drones can capture high-resolution CH_4 data over large areas, providing more comprehensive coverage than ground-based methods. UAVs can also perform repeated surveys, tracking changes in CH_4 emissions and identifying trends (Cusworth et al., 2024).
- However, drones also have limitations (Table 1). Their operations are weather-dependent, with strong winds or rain potentially grounding UAVs or affecting the accuracy of the data collected. Additionally, while drones provide excellent localised data, they require extensive post-processing and analysis, which can be time-consuming (Mønster et al., 2019).

3. The ESCAPE project: Integrating satellite and ground data

3.1. ESCAPE key components

The ESCAPE project offers an innovative approach to overcome the limitations of current methods, providing a cost-effective and scalable solution for real-time monitoring of

CH_4 emissions from landfills and brownfield sites. By combining data from satellites, ground-based sensors, and artificial intelligence (AI)-driven analytics (**Fig. 1**), ESCAPE enables more accurate and timely detection of CH_4 leaks, supporting efforts to mitigate environmental harm caused by GHG emissions.

Table 1. General summary of available solution for emission data collection

Solution type	***Data granularity***	***Temporal frequency***	***Spatial coverage***	***Limitations***
Drones, Aircraft, Plume Mappers Satellite Missions	High (Granular data)	Low (On demand)	Limited	Continuous monitoring not possible
Mobile detection sensors (FID and Flux Box)	Low	Low	Limited	Less detail, snapshots limited in time
Global Mappers Satellite Missions	Coarse	High	High	Limited spatial resolution
IoT fixed Sensors	High (Fixed points)	High	Restricted to a few sections within landfill areas	Does not detect emissions across entire sites

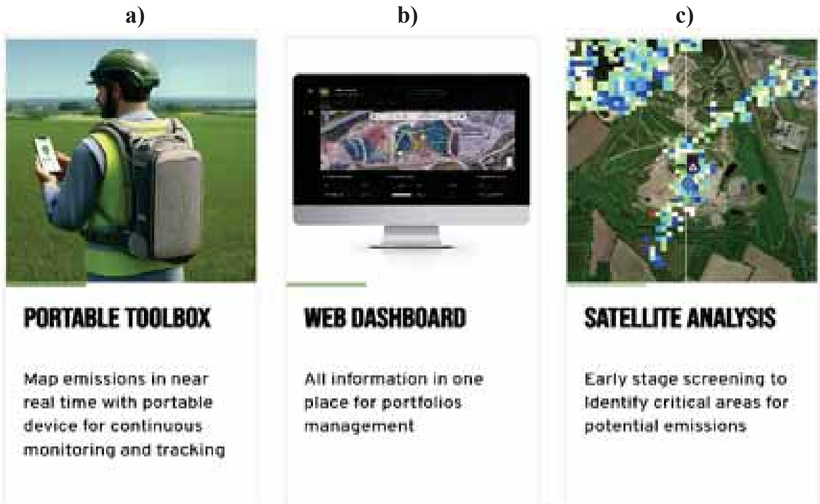

Fig. 1. a) Portable toolbox; b) Web Dashboard; c) Satellite Analysis

3.1.1. Satellite data

Satellite remote sensing plays a key role to monitor large areas and several solutions are available (Table 2). Satellites such as GHGSat and Sentinel-5P are equipped with shortwave infrared (SWIR) sensors designed to detect CH_4 emissions from space. GHGSat offers a spatial resolution of 25x25 meters, allowing to detect CH_4 plumes from specific facilities, while MethaneSat, launched in 2024, will offer alternative detection capabilities (GHGSat, 2022; Maasakkers et al., 2022).

Earth Observation Satellites provide broad-scale coverage, allowing for continuous monitoring of CH_4 emissions over time. This is especially useful for detecting large-scale emission trends or identifying hotspots in remote or inaccessible areas. However, satellite data can be affected by weather conditions like cloud cover, and its revisit times may delay real-time responses. Thus, ESCAPE complements satellite observations with ground-based measurements for more immediate and localized data (Cusworth et al., 2024).

Table 2. Summary of satellite remote sensing solutions, derived from a variety of sources

Sensor	*Launch Date*	*Spatial Resolution (m)*	*Revisit Time (days)*	*Min. Detection Threshold (kg/hr)*
GOSAT	2009	10,500 x 10,500	3	7,000
GOSAT-2	2018	9,700 x 9,700	3	4,000
Sentinel 5-P	2017	5,500 x 7,000	1	4,000
MethaneSat	2024	100 x 400	3 to 4	500
GHGSat-D	2016	50 x 50	14	1,000
GHGSat Constellation	2019	25 x 25	1	100

(Bel Hadj Ali et al., 2020; CEOS Database; EO Portal, 2024; International Energy Agency (IEA), 2024; Jacob et al., 2022).

3.1.2. Ground-based sensors

Ground-based monitoring provides granular, site-specific data. ESCAPE employs an array of low-cost, portable sensors to monitor CH_4 concentrations in real-time. The portable sensor toolbox developed allows operators to conduct walkover surveys of landfill sites, identifying areas of high CH_4 concentration quickly and efficiently. This mobility ensures that the system can adapt to changes in emission patterns and respond to emerging hotspots in real-time. The integration of IoT-enabled sensors also facilitates continuous monitoring, complementing satellite data with real-time, ground-based insights.

3.1.3. Data integration platform

The data collected by satellites and ground-based sensors is integrated into a cloud-based platform for analysis and visualisation. This platform provides a comprehensive overview of CH_4 emissions, enabling operators to track emissions trends over time, detect anomalies, and make informed decisions on emission mitigation strategies. The platform incorporates machine learning algorithms that analyse data to improve prediction accuracy over time. These algorithms can identify patterns in methane concentrations and predict future emissions, providing operators with early warnings of potential leaks or operational failures (Cusworth et al., 2024). The integration of satellite data with ground-based sensor readings offers a complete, real-time picture of CH_4 emissions, improving both the accuracy and efficiency of monitoring efforts.

3.2 Benefit of the integrated approach

The integration of satellite data, ground-based sensors, and AI analytics offers several key advantages over traditional CH_4 monitoring methods:

- Comprehensive Coverage: Satellite observations provide broad-scale monitoring, while ground sensors offer detailed, localised data. This combination ensures that both regional and site-specific CH_4 emissions are effectively tracked (GHGSat, 2022).

- Real-Time Monitoring: Ground-based sensors allow for continuous, real-time data collection, enabling operators to detect and respond to CH_4 emissions immediately. This is critical for preventing large-scale emissions from going unnoticed (Cusworth et al., 2024).
- Cost-Effectiveness: ESCAPE's use of low-cost sensors makes it an affordable solution for landfill operators, especially in regions in which traditional, high-cost monitoring systems may not be viable.
- Scalability: The ESCAPE system can be scaled to monitor CH_4 emissions across multiple sites, from landfills to broader regional areas, making it suitable for both small operators and large government monitoring programs.
- Predictive Capabilities: Machine learning algorithms enhance the system's predictive capabilities, allowing it to detect potential leaks or operational failures before they become serious environmental hazards.

4. Sensor selection and testing

The selection and testing of sensors for the ESCAPE project are critical to develop an effective CH_4 monitoring system for landfills and brownfield sites. The primary aim is to create a low-cost, portable sensor toolbox that can provide real-time, accurate CH_4 detection under variable environmental conditions.

4.1. Sensor selection criteria

The ESCAPE project identified several key criteria for selecting CH_4 sensors:

- Sensitivity to CH_4: Sensors must accurately detect CH_4 at various concentrations, from low parts per million (ppm) to higher levels indicative of significant emissions
- Cost-Effectiveness: Since the project aims to deploy sensors across multiple sites, the chosen sensors must be affordable while maintaining adequate performance
- Durability: Sensors must withstand harsh landfill environments with fluctuating temperatures, humidity, and the presence of other gases (Mønster et al., 2019)
- Selectivity: Methane-selective sensors are essential to avoid interference from other gases, such as CO_2 and VOCs, which are also common at landfill sites
- Integration: The sensors need to seamlessly integrate with the ESCAPE platform, enabling real-time data transmission and analysis

4.2. Sensors evaluated

Several sensor types were considered based on their cost, sensitivity, and performance under landfill conditions:

- Metal-Oxide Sensors (MOX): MOX sensors are widely used due to their affordability and wide detection range. However, they tend to suffer from cross-sensitivity to other gases like CO_2 and VOCs, which can complicate CH_4 detection (Mønster et al., 2019)

- Infrared (IR) Sensors: IR sensors offer high accuracy and selectivity by detecting CH_4 absorption of infrared light. Although effective, IR sensors are more expensive than MOX sensors, limiting their feasibility for large-scale deployment (GHGSat, 2022).

4.3. Selected sensors for preliminary screening

After evaluating different sensor types, the ESCAPE project selected a set of sensors to the following sensors to be preliminary tested:

- TGS2611: A MOX sensor, known for its reliability and ability to detect CH_4 concentrations as low as 500 ppm according to manufactury. In literature it's reported to be able to detect up to 10 ppm of CH4, reason for which it's been selected to be tested in this study. It strikes a balance between cost and performance making it suitable for landfill applications.
- SGP40: Primarily a VOC sensor, the SGP40 digital sensor can detect CH_4 while offering valuable data on other gases. Its multi-gas detection capability helps in identifying cross-sensitivities that may affect CH_4 readings.
- ENS160: Digital MOX sensor for VOCs detection. It has an on-chip RH compensation. Its multi-gas detection capability helps in identifying cross-sensitivities that may affect CH_4 readings.
- BME688: This sensor can detect CH_4, CO_2, and VOCs, and is equipped with built-in compensation for temperature and humidity fluctuations, ensuring stability under varying environmental conditions.
- MH-441D: While less sensitive at lower CH_4 concentrations, this optical (IR) sensor is highly selective for CH_4, minimizing interference from other gases like CO_2. It is included in the sensor toolbox to reduce false positives.

4.4. Laboratory testing

The selected sensors were subjected to rigorous laboratory testing to simulate landfill conditions and assess their performance. Testing procedures included:

- Controlled Gas Mixtures: Sensors were exposed to different concentrations of CH_4 and CO_2 (from 10 to 10,000 ppm) to evaluate their sensitivity and selectivity.
- Environmental Simulation: The sensors were tested with a setup to control humidity to simulate real-world landfill conditions (Mønster et al., 2019)
- Real-World Gas Samples: Biogas samples from a decommissioned landfill were analysed to test the sensors' performance in a mixed-gas environment, providing more practical insights into their capabilities.

4.5. Preliminary results

Laboratory testing results are reported in Fig. 2.

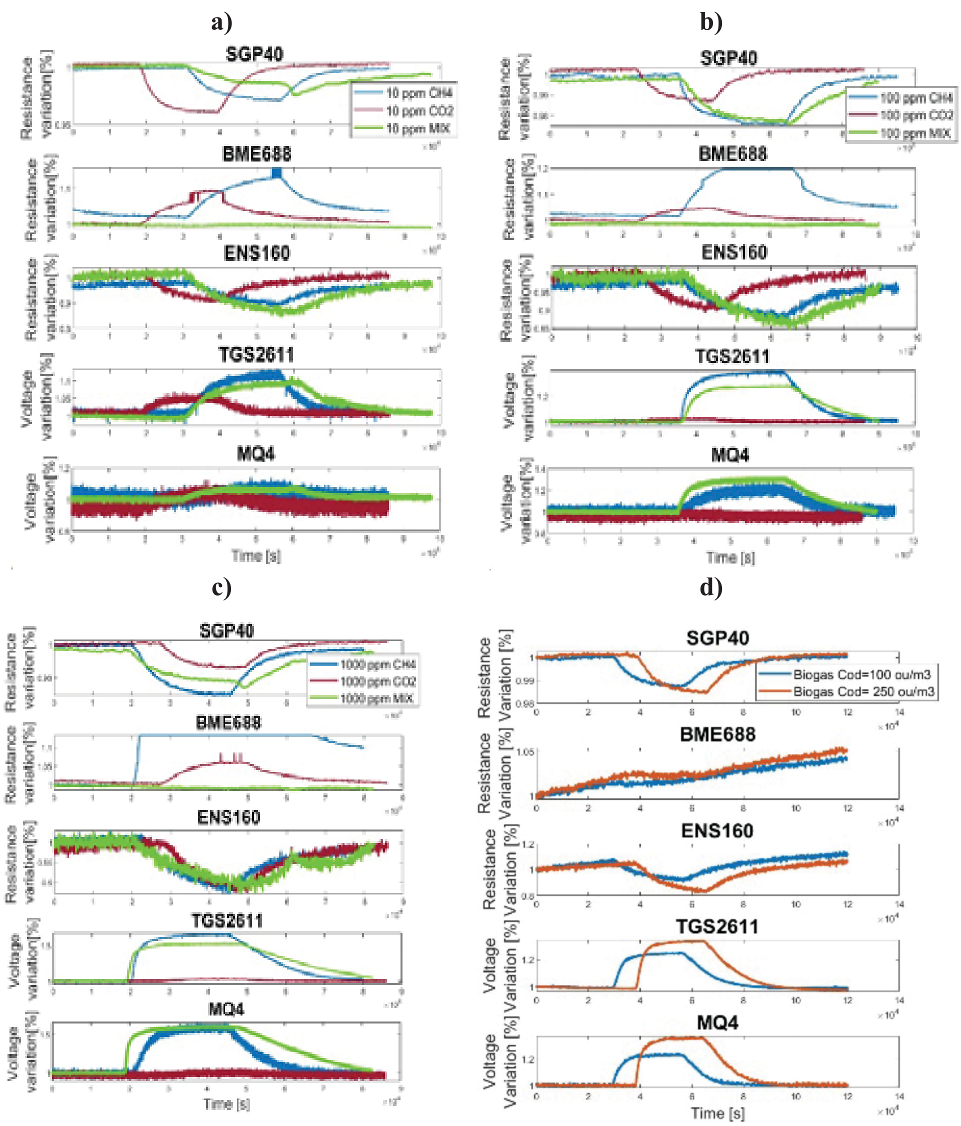

Fig. 2. Example of response curves of the 5 MOX sensors to CH_4, CO_2 and a mixture of the two at a) 10, b) 100 and c) 1'000 ppm, respectively and response curves of 2 real-world biogas samples at different dilutions d)

The testing produced the following key findings:

- Sensitivity: The TGS2611 and BME688 sensors demonstrated good sensitivity to CH_4 at concentrations as low as 10 ppm, making them well-suited for detecting small leaks.
- Cross-Sensitivity: The SGP40 and BME688 showed some cross-sensitivity to CO_2 and VOCs, but the MH-441D's strong selectivity for CH_4 minimised the risk of false positives.

- Environmental Performance: The BME688's ability to compensate for changes in humidity and temperature helped maintain consistent performance under fluctuating conditions.

5. Concluding remarks

The ESCAPE project represents a significant advancement in methane emission monitoring by integrating satellite data, affordable ground-based sensors, and AI-driven analytics into a unified, cost-effective system. This comprehensive approach addresses the inherent limitations of traditional methods by offering real-time, precise data collection and analysis of methane emissions from landfills and brownfield sites. The combination of satellite coverage, capable of detecting regional emission trends, with detailed ground-level monitoring ensures a holistic solution for tracking and mitigating CH_4 emissions.

The project's findings highlight that accurate methane detection, improved hotspot identification, and mitigation strategies are crucial for reducing greenhouse gas emissions. The system's scalability and adaptability, demonstrated through pilot implementations, suggest that it can play a pivotal role in global methane management efforts.

Furthermore, enhancing eco-efficiency in waste management and developing advanced solutions for methane reduction are critical steps in mitigating climate change. Future work will focus on refining sensor calibration, advancing machine learning algorithms for predictive capabilities, and expanding real-world applications to ensure robust and reliable environmental monitoring solutions.

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CIRCULAR LIGHTING PROJECT: LOOME THE INFINITE DESIGN*

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Abstract

Conventional economic system and industrial mass production follow a contradictory linear pro-cess that begins with the consumption of (mostly non-renewable) raw materials and ends (mostly) with the generation of non-reusable waste. The circular economy aims to disrupt this process by reintroducing as many resources into the production cycle, without wasting anything - and lighting design should be no exception. To support circular design, Hera Luce in collaboration with MATREC has developed a tool for measuring the material balance of lighting systems: in fact, while the use phase impact is strictly related with energy consumption, all other phases are associated with input/output material assessment. This tool has been certified by Bureau Veritas in 2022 and now it has become part of Hera Luce's improvement proposals dedicated to public administrations. In this article we briefly illustrate how our tool works, and we present an actual use case: the Walter Grandi garden in Imola. The garden lighting system consists only of circular components, such as lighting fixtures, that are made by recycled plastic and are 98% recyclabe. This process can set a new benchmark for lighting designs that, thanks to material balance tool, could combine energy efficiency (defined by current EuP standards) with all-around sustainability.

Keywords: sustainability, circular economy, lighting design, recyclable luminaire

1. Introduction

The introduction of LEDs has sparked debates about energy conservation and efficiency. But environmental impact and sustainability are broad issues that should include the whole lifecycle of a product, from manufacturing to disposal. This is the rationale behind

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the development of Green Public Procurement criteria, which aim to determine the best design, good, or service from an environmental perspective over its life cycle, while also taking market availability and the environmental standards established for the different stages of the procurement process into account. In Italy, GPP were adopted by Ministry of Environment in 2006. Moreover, European Energy Efficiency directive for household appliances and ISO standards (De Felice et al., 2014) are pushing manufacturers to integrate environmental concerns into the process of designing and producing goods, with the goal of promoting environmental well-being. Our planet is changing and degrading drastically due to climate change and global warming that are among the most critical and pressing issues of our time. Extreme weather events demonstrate that these phenomena can have a profound impact on human life and ecosystems around the world. Accordingly, the United Nations (UN) has outlined policies to be implemented to reduce the carbon footprint and greenhouse gases emissions (Nations, no date)(ONU, no date). This challenge requires international cooperation, sustainable policies, and individual actions and only by implementing all the three spheres of sustainability (economic, social, and environmental) a feasible circular production can be achieved, and so also designers and lighting companies need to adapt quickly and to align their practices with broader societal and environmental goals.

But how manufacturing and lighting design should change? The answer lies in appropriately combining the principles of circular economy (Rizos et al., 2017; Saidani et al., 2019) and eco-design (Calabrò and Cappellini, 2002; Capellini, 2014; Dufreneet al., 2013; Liu and Wong, 2013; Unger et al., 2008). European Parliament gives this definition of "circular economy": "a model of production and consumption, which involves sharing, leasing, reusing, repairing, re-furbishing, and recycling existing materials and products as long as possible. In this way, the life cycle of products is extended. In practice, it implies reducing waste to a minimum.

When a product reaches the end of its life, its materials are kept within the economy wherever possible. These can be productively used again and again, there-by creating further value. This is a departure from the traditional, linear economic model, which is based on a take-make-consume-throw away pattern" (Parliament, 2017). These environmental factors may cause a company's ideals to be reevaluated and to be prioritized differently during strategy conversations. This strategy must be driven by two factors that work in synergy with each other. The first concerns the flow of materials within an economy, while the latter is concerned with the economic variables that may encourage this kind of material flow (Ekins et al., 2020). The principles of circular economy can be translated to the field of lighting design through four steps: products, businesses, networks, and policies (Geng, Sarkis and Bleischwitz, 2019). Products must be designed for recyclability and reusability, employing eco-friendly supply chains and clean manufacturing processes. Second, businesses need to use cutting-edge business strategies to create value that is both public and private. Thirdly, there needs to be a connection made between networks of businesses and customers. Lastly, measures must be put into action to strengthen market support. The project that we describe in this article gives the aforementioned ideas a tangible embodiment and acts as a model for further advancements.

2. Material and methods

Hera Luce's material balance tool

As reported Di Maio et al. Study (Di Maio et al., 2017), in upcoming years we need to redefine our approach to measure resource efficiency. Life Cycle Assessment (LCA) (Deodati et al., 2022; Rivera and Lallmahomed, 2016) is a comprehensive method for evaluating the overall ecological footprint of a product or service, spanning from the initial extraction of raw materials and processing, through distribution, utilization, and eventual disposal (Fig.1). Through the conversion of input and output data into more ecologically significant insights, LCA provides insight into the environmental efficiency of products and has the potential to alleviate the ecological impacts linked to a product, process, or endeavour. Regretfully, the LCA technique lacks comparison metrics to indicate if a good is sustainable, and it is also challenging to implement. To support circular design, Hera Luce, in collaboration with a software house, developed a web-based tool to measure the material circularity of lighting systems through material balances and resource consumption assessments (Cappellini, 2017). The tool collects input data from system component manufacturers, who provide detailed material information about their products. Certified by Bureau Veritas and compliant with the UNI EN ISO 14021:2016 standard, it enables Hera Luce to communicate environmental performance and certify material circularity to Public Administrations via accurate, up-to-date documentation. This tool, the first of its kind certified nationally under the Matrec Specification, enhances resource efficiency and circular economy performance. It has resulted in an evolving database of material data for products used in lighting system redevelopment projects (Fig. 2). By analyzing this data, Hera Luce has identified less sustainable materials and initiated awareness campaigns to encourage suppliers toward eco-friendly practices.

The material balance for each system is aligned with environmental criteria (CAM) and provides a comprehensive overview of resource use throughout the lifecycle covering production, installation, maintenance, and end-of-life disposal. Though gathering data across the entire value chain from suppliers to waste collectors is time-intensive, the tool computes circularity metrics from this data. A lack of a clear regulatory framework challenges the establishment of a universal standard for measuring circularity. However, this tool streamlines data collection through a user-friendly online questionnaire and promotes transparent communication of results. This has empowered stakeholders to adopt circularity measures, such as using more recycled materials in key components. Circularity output includes both recyclable materials and those intended for energy recovery, while the recycling rate output considers only materials destined for recycling (Fig. 3).

Fig. 1. Life Cycle Assessment (LCA) pathway

Fig. 2. Through the material balance it is possible to measure the circularity of the material flow of a lighting system

Fig. 3. Material balance model

The analysis of the end-of-life materials cycle involves defining the destination of materials, which can follow one of these paths (Fig. 4):

- **Recycling**: Materials are processed and reused as raw materials or products after being removed from the waste stream.
- **Energy Recovery**: Non-recyclable waste is incinerated, and the heat generated is used to produce electricity or thermal energy.
- **Compost**: Biodegradable materials break down into a stable, humus-like substance.
- **Reuse**: Products or packaging are designed for multiple uses or cycles for the same purpose.
- **Landfill**: Waste is disposed of in designated areas, including long-term temporary storage (per Legislative Decree 13/01/2003, n. 36).

The total output of resources corresponds to the total inputs. By examining the material composition of products and their end-of-life cycle, the final destination of materials, whether recycling, energy recovery, composting, reuse, or landfill, can be accurately predicted based on the type of equipment used.

Fig. 4. The five possible destinations/paths at the end of the product's life (in this case the percentages refer to the Loome product)

3. Experimental

3.1. Loome - "the infinite street lamp"

Loome is designed for urban environments and is created thanks to Lorelux technology developed by Niteko (Deodati et al., 2022), with recycled plastic collected by Aliplast. The latter holds a significant national standing as a key player in bottle recycling. Its recycling process yields two distinct material streams: PET originating from the bottle's body and PE/PP extracted from the caps. There is also the economic factor to consider: items produced from recycled plastics can be approximately 80% more cost-effective than those manufactured from new materials, provided that expenses related to collection, sorting, and processing remain minimal (Geng et al., 2019).

The Loome is made by recovered polyethylene deriving from clean and homogeneous production waste and selected and post-consumer polyethylene. Each version of the Loome has different quantities of virgin plastic and recycled plastic. The Loome used in this project is 70% RECYCLED low density polyethylene (polyethylene from bottle caps from urban waste collection) and 30% virgin polyethylene (Fig. 5). Loome, in addition to being made of recycled and recyclable material, is also a disassembled product. This feature allows the lighting fixture to be easily repairable, counteracting planned obsolescence (Friedel, 2013; Rivera and Lallmahomed, 2016), which requires the user to make any product become waste after the end of its life. Instead, in this way, the useful life of the product and also of its parts is extended. Loome is even more innovative because is resistant to corrosion and the plastic from which it is made, unlike other types of materials, allows radio waves to pass through. It can therefore also be used to install any devices inside it to communicate data or information in real time for an increasingly smart and citizen-friendly city.

3.2. Walter Grandi garden

The Walter Grandi garden’s lighting project is an example of how we can use circular components, such as lighting fixtures, whose components are produced from recycled materials and can be recycled again. The lighting project for Walter Grandi garden in Imola was born from the perspective to do a circular project in which its components are produced from recycled materials and can in turn be recycled in total or in part. The garden lighting system consists only of circular components, such as lighting fixtures, that are made by recycled plastic and are 98% recyclabe (Fig. 6). The project is composed of 16 Loome luminaires designed by Niteko, 16 Atlantech lux plinths and 16 recycled steel poles by Imet. The core device of the project is Loome, created from recycled plastic that is collected as waste by the Hera Group and transformed by Aliplast into a polymer. This polymer is then shaped using rotational molding, a low-impact process that allows the material to be molded into virtually any form. This flexibility enables Loome to be designed with modular lines and an appealing aesthetic.

Loome is referred to as "infinite" because it is made from a recycled polymer (metal-free and resistant to corrosion) that is also fully recyclable. When a lamppost reaches the end of its life, its materials can be repurposed to begin anew. The plastic is mechanically shredded and can be used to create new lampposts indefinitely, exemplifying a perfect model of a circular economy. Loome is also a disassembled product, and this feature allows the lighting fixture to be easily repairable, counteracting planned obsolescence (Friedel, 2013; Waldman 1993) which requires the user to make any product become waste after the end of its life. Instead, in this way, the useful life of the product and also of its parts is extended. Unlike other materials, the plastic used in Loome allows radio waves to pass through, making it ideal for housing devices that communicate data or information in real time. This capability supports the development of smarter, more connected, and citizen-friendly cities.

Fig. 5. Material balance model

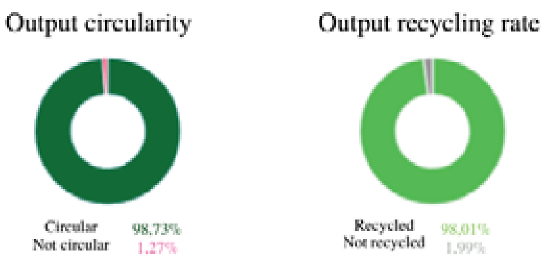

Fig. 6. Data on product circularity

Irrespective of the composition of materials used in the production process, whether they contain higher or lower percentages of recycled, by-product, renewable, or non-renewable materials, the circularity rate of the output remains constant at 99.74%. Nearly all versions of the materials are designed with recycling in mind, as they are primarily composed of easily recyclable materials. Both polyethylene and bio-polyethylene, which constitute a substantial portion of the material, are fully recyclable. A mere 0.26% of the materials are designated for landfill disposal due to their challenging recyclability, including mixed plastic and metal components and silicone, which are difficult to separate. An additional 0.35% of the components are earmarked for energy recovery, thanks to the presence of various polymers that pose recycling challenges. It's important to note that the waste-to-energy treatment of these components is considered a form of recovery rather than outright disposal, as it is transformed into fuel, serving as an alternative to other fossil sources for electricity production. This is considered a circular solution, contributing to sustainability.

Table 1. Materials of which the loome is made

Material	***Weight (kg)***	***%***
Stainless steel	0.05	0.70
Galvanized steel	1.86	25.94
Aluminum	0.15	2.09
Die-cast aluminium	1.50	20.92
WEEE complex component	0.38	5.30
NBR nitrile rubber	0.00	0.00
Mixed (Plastic, Metal)	0.02	0.28
Brass	0.01	0.14
Polyamide (PA6)	0.00	0.00
Polyamide PA66 (Nylon)	0.01	0.14
Low Density Polyethylene (LDPE)	2.50	34.87
Polymethyl methacrylate (PMMA)	0.06	0.84
Copper + Polychloroprene	0.06	0.84
Copper-Silicone	0.06	0.84
Silicone	0.02	0.28
Expanded silicone	0.01	0.14
Glass	0.48	6.69
Total	**7.17**	**100**

4. Results and discussion

The core device of the project is Loome, created from recycled plastic that is collected as waste by the Hera Group and transformed by Aliplast into a polymer. This polymer is then shaped using rotational molding, a low-impact process that allows the material to be molded into virtually any form. This flexibility enables Loome to be de-signed with modular lines and an appealing aesthetic. Projects like this, which focus entirely on material circularity, energy saving, and sustainability, can have a significant impact in terms of results and added value. The ideation and design process that leads to the development of a totally recyclable lighting system made of recycled materials help reduce waste and minimize the carbon footprint, promoting a more sustainable way of living.

This approach also encourages innovation and creativity, often leading to unique designs that enhance the aesthetic appeal of public spaces. Additionally, such projects can lower costs and create economic opportunities, all while fostering community engagement and raising awareness about the importance of sustainability. Ultimately, this process can set a new benchmark for lighting designs that, thanks to material balance tool, could combine energy efficiency (defined by current EuP standards) with all-around sustainability. This approach serves as a testament of the relief to sustainability by creatively repurposing and highlighting recycled materials in art and design. It's a powerful way to demonstrate the importance of reusing materials through different design objects.

5. Conclusion

The Gruppo Hera's exhibition space lighting design for Walter Grandi garden is a well-thought-out approach that combines sustainability, innovation, and creativity to create a unique and captivating environment. It stands as a shining example of how businesses can embrace their commitment to the environment through artistic and innovative means, setting a standard for both environmental responsibility and design excellence.

It is important to focus on environmental and circular issues from the genesis of the project. In synergy with manufacturers, engineers, and designers, one can succeed in defining a project that is totally circular and more sustainable both environmentally and economically. Remembering that in addition to the immediate economic savings, there will also be additional savings for the environment, which in any case constitutes a qualitative return for human life and welfare of the earth.

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INTEGRATING BIOFUEL AND RENEWABLE ENERGY GENERATION WITH WASTEWATER REUSE AT OLFAR S/A: AN ESG APPROACH*

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Abstract

This study aims to explore opportunities for integrating biofuel generation with renewable energy generation and the reuse of wastewater after treatment at Olfar S/A, in line with the fundamental principles of Environmental, Social and Governance (ESG). To this end, it carried out qualitative research into Olfar's 2022 Sustainability Report and interviewed the technicians responsible for implementing the wastewater plant project. As a result, the study highlights that the use of biogas as an energy source is consistent with the search for cleaner and more efficient solutions in terms of emissions (environmental ESG). Responsible waste management and the generation of energy from renewable processes highlight the company's social responsibility (social ESG), while the implementation of innovative practices shows a commitment to sustainable corporate governance (governance ESG). Finally, the company's efforts in the energy transition open doors to financial and market opportunities.

Keywords: biogas, biofuels, ESG in industry, industrial sustainability, renewable energy

1. Introduction

Renewable energies, especially biofuels, play a crucial role in the search for a sustainable energy transition. The importance of these energy sources lies not only in reducing

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greenhouse gas emissions, but also in diversifying the energy matrix, reducing dependence on non-renewable resources, and mitigating the environmental impacts associated with their extraction and burning. Biofuels, obtained from organic sources such as biomass and energy crops, are a viable alternative for the transport sector, contributing to decarbonization and promoting energy self-sufficiency (Singh, 2018). By driving innovation and investing in sustainable technologies, biofuels represent a significant step towards a greener future, where fuels and energy are generated responsibly and renewably, preserving natural resources for future generations (Fagundes et al., 2016).

In this context is Olfar S/A, one of the largest biodiesel industrial groups in Brazil, with headquarters in the north of Rio Grande do Sul and operations in the states of Rio de Janeiro, Goiás and São Paulo. Specializing in soya industrialization with vegetable oil extraction, biodiesel production and glycerine refining, it also plays an active role in grain trading, consolidating its position as one of the country's main traders, serving both the domestic and international markets comprehensively and strategically. The company is currently investing in a new industrial venture that will begin the pioneering production of ethanol from soya molasses, in parallel with the production of soya protein concentrate (SPC) for animal feed.

This study aims to explore opportunities for integrating biofuel generation with renewable energy generation and the reuse of wastewater after treatment at Olfar, in line with the fundamental principles of ESG. It also aims to present the pioneering and innovative project to install a plant to treat by-products and wastewater from the industrial process to generate energy. It should be noted that this project is directly related to the ESG principles (United Nations, 2004). This set of practices solidifies Olfar's position as an agent committed to the ESG pillars, contributing to a sustainable business model in line with the expectations of a more conscious society.

2. ESG Principles

ESG principles have a historical evolution that goes back to various initiatives and events over time. The 1990s witnessed an increase in the attention paid to environmental, social and governance factors in relation to corporate investments and responsible business practices. This was driven by events such as the Bhopal environmental disaster in 1984 and the growing awareness of social and environmental issues (Instituto de Engenharia, 2024).

The United Nations (UN) Global Compact was launched in 2000, seeking to involve companies in promoting fundamental principles in the areas of human rights, labor, the environment, and the fight against corruption (UN Global Compact, 2024). In 2004, the UN Global Compact launched the "Who Cares Wins" initiative, highlighting the connection between sustainable performance and long-term business success. This was when former UN Secretary General Kofi Annan issued a challenge to 50 presidents of the world's largest financial institutions asking for solutions to integrate social, environmental and governance factors into the capital markets by 2030. Thus, the term and acronym ESG appeared for the first time (United Nations, 2004). In 2011, the UN Human Rights Council adopted the "Guiding Principles on Business and Human Rights" (UNGP), providing a framework for the responsibility of companies to respect human rights (United Nations, 2011). Afterwards, there was a steady growth in awareness and adoption of ESG practices by companies and investors. Disclosure of information related to ESG factors has become common practice, driven by a growing demand for transparency and accountability.

ESG principles refer to environmental, social and governance criteria that companies and investors consider in their practices and decisions. These principles aim to promote sustainability, social, responsibility, and effective management, reflecting the recognition that considerations beyond simple financial performance are crucial to assessing a company's long-term value and viability (Gary, 2019; Sideri, 2021). ESG has become a widely used set of metrics, involving the analysis of environmental, social and governance factors when determining which programs, funds, and companies to invest in (Rodin and Madsbjerg, 2021). Fig. 1 shows the three pillars of ESG.

Environmental	**Social**	**Governance**
Renewable fuels	Health and safety	Ethical standards
Greenhouse gas (GHG) emissions	Working conditions	Board diversity and governance
Energy efficiency	Employee benefits	Stakeholder engagement
Climate risk	Diversity and inclusion	Shareholder rights
Water management	Human rights	Play for performance
Recycling processes	Impact on local communities	
Emergency preparedness		

Fig. 1. The three pillars of ESG (Rodin and Madsbjerg, 2021)

The environmental pillar addresses issues related to the environmental impact of a company's operations. This pillar aims to prioritize the use of renewable energy sources, such as solar and wind, to reduce dependence on fossil fuels and mitigate the associated environmental impacts (Fitts et al., 2022); monitor, reduce and report greenhouse gas emissions, such as carbon dioxide and methane, as part of the commitment to climate change mitigation (Gull, 2023); implement practices and technologies to optimize energy use, reducing operating costs and the carbon footprint (Barykin et al., 2022); assess and manage the risks associated with climate change, including extreme weather events, to strengthen operational resilience (Erhemjamts et al., 2023); adopt sustainable practices for water use, ensuring its efficient management and contributing to the preservation of water resources (ANDRADES, 2023); implement effective recycling systems to minimize waste and promote the circular economy, contributing to responsible resource management (Kvashaet al., 2023); and, develop emergency response plans and measures to deal with unexpected events, minimizing environmental damage and protecting the safety of employees and communities (Doni and Johannsdottir, 2020).

The social pillar focuses on aspects related to social practices and the company's impact on people and communities. This pillar aims to: prioritize employee health and safety, implementing measures to prevent accidents, occupational diseases and ensure safe working environments (Kotsantonis and Serafeim, 2019); provide fair working conditions, promoting respect for workers' rights, such as adequate working hours, fair wages and an environment free from discrimination (Jain et al., 2024); offer benefits that promote employee well-being, such as health plans, wellness programs and professional development opportunities (Stan et al., 2023); promoting a diverse and inclusive work environment, recognizing and valuing the diversity of skills, experiences and backgrounds among employees; respecting and promoting human rights in all operations, avoiding practices that could contribute to violations of fundamental rights (Suciu et al., 2020); and contributing positively to the local communities where the company operates, getting involved in social initiatives, supporting education, health and other programs that benefit the community (Murawska, 2021).

The governance pillar concerns the company's management structure, transparency, and accountability. This pillar aims to: adopt rigorous ethical standards in all business practices, promoting integrity, honesty and transparency (Ratigan, 2022); establish a diverse and inclusive board of directors, with representation of gender, ethnicity and varied backgrounds, to ensure broad perspectives and equitable decisions (Ligård and Jørgensen, 2022); include stakeholders, such as employees, customers and communities, in corporate decisions to ensure that relevant voices are heard and considered (Bonetti et al., 2024); respect and protect the rights of shareholders, guaranteeing transparency in communication, promoting fairness in voting and facilitating the active participation of shareholders in company decisions (Ruhwedel, 2023); establish remuneration practices linked to performance, aligning the interests of executives with the long-term objectives of the company and avoiding inappropriate incentives (Shen et al., 2022).

This study will use "The Three Pillars of ESG" model proposed by Rodin and Madsbjerg (2021) as a framework to explore strategic opportunities at Olfar, focusing on the integration of biofuel generation with renewable energy production and the reuse of wastewater after treatment. The environmental pillar will be central to the analysis, assessing how the company can adopt renewable energy sources, reduce greenhouse gas emissions associated with biofuel production and implement effective water management practices. The social pillar will be considered when examining the impacts on local communities and employees, while the governance pillar will be key to ensuring transparency and integrity in strategic decisions. This holistic approach will make it possible to identify synergies between the different aspects of sustainability, promoting innovation and contributing to Olfar's leading position on the corporate responsibility scene.

4. Materials and methods

This research is a qualitative case study and will use Olfar's 2022 Annual Sustainability Report (Sustentabilidade Olfar, 2022) to analyze it. Increasingly widespread in the corporate sphere, sustainability reports, previously focused mainly on measuring environmental metrics, have evolved to become a crucial indicator of ESG practices in contemporary organizations.

Companies of various sizes have incorporated the annual disclosure of these practices, demonstrating an effective commitment to the sustainable agenda. Two technicians from Clean Water Technology, Inc. (CWT-Global, 2024) and two technicians from Olfar, responsible for the design and installation of the wastewater treatment plant at Olfar's biodiesel and ethanol plants, were also interviewed. The technique of analyzing the content of the interviews and the report was used to detail the process of generating renewable energy from biofuel production wastewater and the initiatives undertaken by Olfar in 2022 to strengthen its commitment to environmental, social and governance practices.

5. Results and discussion

5.1. Process for generating renewable energy using wastewater from biofuel production

Olfar has plants dedicated to the production of biofuels, with a production capacity of 2,000 tonnes per day (TPD) for the extraction of soya oil. The extracted oil is used to make biodiesel, a biofuel derived from renewable sources such as soya, corn, canola, and palm vegetable oils, which can be blended with animal fats such as tallow and waste oil (Balat, 2011).

The soya oil extraction process generates Hypro 46% bran, which is destined for protein concentration (SPC 65% protein). This procedure includes the use of ethanol solvent to extract molasses (sugars) from soya meal, generating soya molasses and the new product

SPC meal with a high protein concentration (65% meal), ready for commercialization and use in high-yield animal feed. The molasses removed from the 46% bran in the previous process is used to produce soya lecithin, a product intended for commercialization in the pharmaceutical and food industries. The residual molasses from the previous process is sent for fermentation, generating a new product, Ethanol, derived from the fermentation of soya molasses that generates vinasse as one of the final residues of this complex biofuel production process such as biodiesel and ethanol from the extraction of soya oil.

In 2022, Olfar began installing a plant to treat the by-products and wastewater from its industrial process to generate energy. The industrial processes of making biodiesel, ethanol and animal protein will generate wastewater that will be destined for specific treatments for sustainable energy generation and reuse water that returns to Olfar's industrial process. Wastewater from the production of biofuels at Olfar plays an important role in generating sustainable energy because it contains an organic load made up mainly of glycerine, lysogoma, COD, BOD and other contaminant parameters that need to be purified in advanced anaerobic processes that use microorganisms in the absence of oxygen under ideal temperature conditions, degrade the organic matter present in the wastewater that will be converted into biogas, made up of 65% methane that will be purified and transformed into a valuable source of renewable energy at the plant used to power the boilers and generate steam. The digestate resulting from the purification will be sent for further wastewater treatment to obtain quality water for reuse in the factory, making it possible to reduce dependence on fossil fuels and at the same time mitigate the environmental impacts associated with the generation of waste in the industrial process.

In the anaerobic biodigestion process, the generation of 129,715 m³/day of biogas, with a calorific value of 5,931.60 kcal/m³ (65% methane), results in an energy equivalent of 769,416,881 Kcal/day, 127,218,400 BTU/hour, 23,082,506 Mcal/month or 96,642 joules/month. Compared to natural gas, which has a calorific value of 7,562.70 Kcal/m³, the equivalent of biogas generated in natural gas is 101,738 m³/day or 4,239 m³/hour.

Based on this potential and the technologies that will be used to purify the biogas, Olfar will have to define the most efficient use or the one that best meets its needs for utilizing the biogas and, as a result, it will be able to replace a large part of the volume of chips it uses or reduce its electricity consumption, thus contributing to a more sustainable and economical approach in its operations, as well as reducing its dependence on the electricity supply from the energy concessionaires. The expectation is to generate biogas at Olfar from 2025 onwards to feed the boilers responsible for generating steam. The venture is part of a project approved with funds subsidized by Finep, with an innovation seal.

5.2. Opportunities for sustainable energy transition aligned with ESG

The energy transition is emerging as a crucial opportunity for companies committed to the ESG pillars. According to Olfar's Sustainability Report (Sustentabilidade Olfar, 2022), the company is committed to the transition to cleaner and more sustainable energy sources. Significant investments in renewable technologies have led to a reduction in the company's carbon emissions, in line with its environmental objectives. The report also highlights the company's initiative to promote diversity and inclusion in its workforce, demonstrating its social commitment. The emphasis on transparency and corporate responsibility, highlighted in the governance pillar, further strengthens the company's position as a leader in the search for opportunities in the sustainable energy transition. Below are the initiatives that Olfar has undertaken to reinforce its environmental and social commitment and governance practices during 2022.

Environmental Initiatives - Launch of the Green Code with the aim of raising awareness and informing stakeholders; through the Agrochemical Packaging Collection Programme, the volume of packaging collected was greater than that sold; ISO 14. 001 certification; energy and steam generation, 100% from biomass; in water treatment, it works with a reverse osmosis system. 001 certification; construction of the SPC bran plant, 100% circular economy; dissemination and supply of biological inputs; generation of energy and steam, 100% from biomass; water treatment using a reverse osmosis system; for waste, energy recovery and composting, re-refining and reuse; installation of an effluent station for future biogas production; the "Sou Olfar, Sou Sustentável" (I'm Olfar, I'm Sustainable) programme raises awareness of environmental sustainability; and the promotion of forestry to encourage the cultivation of eucalyptus to produce energy from the biomass of reforested wood chips.

Social Initiatives - Start of the Organisational Climate survey using the GPTW (Great Place to Work) methodology; training in risk management, relationships and commercial negotiation; launch of the Olfar Corporate University; Gerar people management and development programme; review of the job and salary policy; implementation of the online education platform; Gerar Ideas programme for suggestions of innovations by employees; improving initiatives to promote equal opportunities; investments in ergonomics reports and in a diagnosis of employee profiles; and, through Brazilian inventive laws, the allocation of part of the Tax on the Circulation of Goods and Provision of Services (ICMS) to the Rio Grande do Sul State Public Security Equipment Programme (PISEG-RS).

Governance initiatives - creation of the "Talk to Olfar" internal and external communication channel; creation of the compliance programme; progress in grain traceability processes; increase in performance indicators compared to the previous year, net revenue of 27.8%, CAGR (compound annual growth rate) of 35%, EBITDA of 8.23% and net income at levels of 6%; preparation of the company's stakeholder risk matrix, broken down into actions and measurement indicators; and, revision and publication of the new code of ethics.

Olfar's sustainability report thus not only highlights past achievements, but also outlines a promising future, where the energy transition becomes a driving force for sustainable success in globalised and environmentally conscious markets.

6. Conclusions

For Olfar, the focus on ESG principles, not only minimizes the environmental impact of wastewater, but also transforms waste into resources, aligning with sustainability and the circular economy. In addition, the use of biogas as an energy source is consistent with the search for cleaner and more efficient solutions in terms of emissions (environmental ESG). Responsible waste management and the generation of energy from renewable processes underscore the company's commitment to social responsibility (social ESG), while the implementation of innovative practices shows a commitment to sustainable corporate governance (governance ESG).

The company's efforts in the energy transition also open doors to financial and market opportunities. Expanding renewable energy generation capacity not only reduces operating costs in the long term, but also positions the company through innovation and pioneering in an increasingly sustainability-oriented sector. The emphasis on effective governance and ethical practices reinforces investor and stakeholder confidence, consolidating the company's position as an attractive choice for those seeking to align their investments with ESG principles.

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A CONCEPTUAL FRAMEWORK OF MATCHMAKING SYSTEM DEVELOPMENT FOR FEEDSTOCK ADAPTATION IN INDUSTRY*

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Abstract

The rapid depletion of raw materials and the growing problem of waste accumulation necessitate stakeholders to transition from linear business models towards circular ones by implementing new and innovative strategies. This study introduces a matchmaking framework for feedstock adaptation in energy-intensive industries such as glass, copper, and aluminum. This framework aims to enhance collaboration between feedstock suppliers and industries to close the material loop by finding the best available match based on four key criteria: environmental, material flows, social, and economic. The environmental criterion focuses on geographic proximity of matchmakers to reduce greenhouse gas emissions, while the material flows criterion promotes the use of ready-to-use materials. The social criterion prioritizes partnerships with socially responsible companies, and the economic criterion encourages also pre-treated materials and localized collaborations. The framework supports the development of the feedstock adaptation tool that will be part of a multi-agent decision support system to be developed within the TRINEFLEX project. The final score indicates the potential for circular cooperation between stakeholders, allowing them to prioritize criteria based on their preferences and goals. The applicability of the framework was demonstrated through three hypothetical case studies, highlighting the importance of the proximity of the supplier-industry and pre-treated materials that potentially could enhance circularity and reducing costs. For future research, the framework should be extended to different industry sectors including also water and energy exchanges between the matchmakers.

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1. Introduction

A key application of the Circular Economy (CE) is Industrial Symbiosis (IS), which entails a mutually beneficial collaboration between industries. Adaptable industrial processes allow alternative raw materials usage as flexible feedstock for various applications. Matchmaking tools could enhance collaborations among industrial actors including feedstock producers, suppliers or distributors, logistics providers e.g. transport services by efficiently connecting industries to facilitate decision-making with tailored recommendations based on specific criteria (Alpar, 2010; Łękawska-Andrinopoulou et al., 2021). Matchmaking is the process of searching possible matches between demand and supplies of market participants (Alpar, 2010). IS in combination with matchmaking tools could enhance company partnerships by efficiently connecting industries that can mutually benefit from sharing resources, by-products, waste and services.

The matchmaking process can also facilitate decision-making by providing tailored recommendations based on specific criteria. By analyzing both input data from the user and literature, matchmaking systems can identify suitable matches, helping decision-makers find the most relevant partners based on their preferences. Making decisions is intricate due to the complexity of problems, which can involve various alternative solutions and criteria to be investigated. Decision support tools facilitate multi-criteria decision-making by presenting and analyzing the results via numerical data and/or visual graphical aids.

This paper presents a matchmaking framework for feedstock adaptation in energy-intensive industries (EIIs) specifically glass, copper, and aluminum producers. The framework supports development of a feedstock adaptation agent: a decision-making tool to enable cooperation among feedstock suppliers and industries, aiming to close material loops with optimal matches in terms of circularity. The feedstock adaptation agent aims to facilitate decision-making, assuring increased feedstock sourcing flexibility and reducing the raw materials dependency of involved actors (AIMEN, 2023). The feedstock adaptation agent is a digital facilitation tool to be developed within the TRINEFLEX project. TRINEFLEX is an innovation action project, funded by the European Commission through the Horizon Europe programme, aimed at supporting the transformation of energy-intensive industrial processes through the integration of energy flexibility and the supply of raw materials (AIMEN, 2023). One of the aspects TRINEFLEX is focusing on, is feedstock flexibility in glass, copper, and aluminum industries located in Italy, Greece, and Spain, respectively. In this context, a concept behind a feedstock adaptation agent, that is being developed to contribute to this facet is presented.

The proposed framework builds on CE matchmaking framework (Łękawska - Andrinopoulou et al., 2021) and the IS marketplace concept (Akrivou et al., 2022). It employs multiple criteria for matching feedstock suppliers and industries, with aspects like greenhouse gas emissions (GHG), material flows, loop tightness, compliance of involved actors with CE/IS principles and simplified cost analysis. The final score indicates the potential for circular cooperation between stakeholders, allowing them to prioritize criteria based on their preferences and goals.

2. Methodology

First of all, a comprehensive literature review was conducted, towards to forms the theoretical background for the criteria selection. This groundwork then informed the methodology of the matchmaking framework for feedstock adaptation in industry. To obtain a frame of reference for the specific research context special focus was given to the following topics: (i) circular cooperation among different actors, (ii) relevant criteria, (iii) methodologies used for scoring the final solutions.

As next steps, the framework was applied to theoretical case studies and conclusions were drawn. Additionally, further research recommendations were identified for the matchmaking framework development. The conceptual steps used for the matchmaking framework design is presented in Fig. 1.

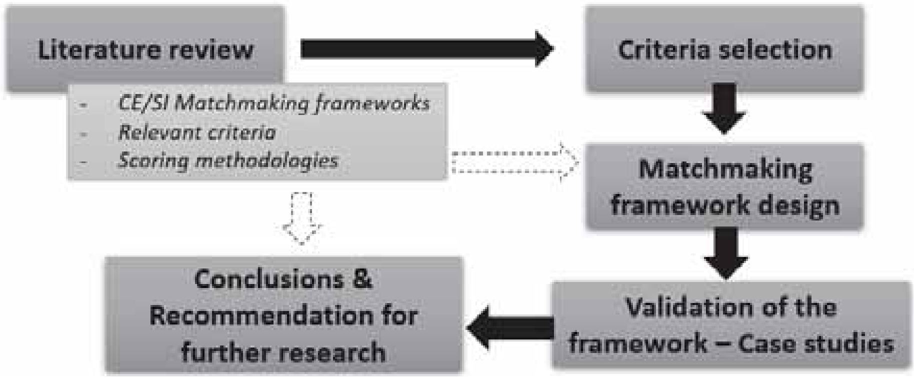

Fig. 1. Conceptual graph of the matchmaking framework design.

3. State of the art of matchmaking frameworks

This subchapter reports relevant matchmaking framework enhancing IS opportunities among stakeholders. Łekawska-Andrinopoulou et al. (2021) developed a CE matchmaking framework to enable cooperation between stakeholders by expanding offer (supply chain actors) and demand (industry) identification at the secondary raw material markets through inclusion of specific criteria in the matchmaking process. The criteria were: (i) the compliance with CE principles, (ii) the material flows analysis focusing to the loop tightness (referred to the type of collaboration e.g. reuse recycling, anaerobic digestion/energy production) and matches directness (i.e. when material from one marketplace user matches the needs of another stakeholder directly), (iii) the GHG emissions from transport between the stakeholders' warehouses. Based on those criteria a Total Relevance Score between the stakeholders is calculated, indicating the possibility for successful circular cooperation between two partners.

Varvaringos et al. (2023) elaborated a profile matching algorithm based on weighted variables in a sum model that is used by the AgriPLaCE Synergies tool. Five indexes are used to rank potential collaboration among the users, which receive the value 1 if two users have the same value and the value 0 if the value differs. The indexes are (1) the type of fruit or vegetable by categorizing waste streams based on the number of fruit/vegetable parts, (2) the waste type by specifying the part of fruit/vegetable plant e.g. peels, kernels, twigs, and (3) the location of the user specifying the region, regional unit, and municipality. The weight of each index is assigned based on its importance to the matching process. Specifically, indexes 1 and 2 are considered the most important to create synergy and receive the value 0.35. The indexes 3, 4, and 5 that are related to the location receive the value 0.1. A priority calculation matrix is used resulting in two lists with the suppliers and the demanders of the biowaste.

Capelleveen et al. (2021) designed and evaluated a recommender system prototype that supports sector-based identification of industrial symbiosis through circular supply chain management activities. The recommender system aims to support industries producing waste and therefore searching for potential waste receivers on which type of industries may absorb their particular wastes. The potential users are the waste providing and receiving industries. This system uses two datasets: (i) the waste profile data base extracted from a data set composed of waste statistics i.e., the statistical proportion of various wastes produced by an industry sector with which an end-user organization may identify itself, (ii) the recommender knowledge base consisted of a set of symbiotic implementations specifying the waste items, classified by EWC (European Waste Catalogue), and the industry sector, classified by NACE (Statistical Classification of Economic Activities in the European Community), that consider these items for developing into a potential industrial symbiosis. The set of recommendations are generated using a prediction algorithm and uses four weighting factors.

Capelleveen et al. (2018) designed a model that utilizes environmental data to make IS recommendations and to develop an instantiation of this model to identify IS opportunities. The data used for IS initiatives among industries was acquired from IS workshops and includes the type of industry, the waste item and the EWC code. Additional data was acquired from an LCI (life cycle inventory) database - named EcoInvent – and includes examples of manufacturing processes of goods (or services), the input/output associated with those production process and the produced amounts per the production of one functional unit.

A research gap in matchmaking algorithms is reveled concerning the EII sectors that are willing to use alternative materials into their process and the consideration of challenging aspects within the supply chain of these materials for instance the transportation and pre-treatment cost of materials as well as season fluctuation of production/ supplying. To address this gap, the research focused on selecting relevant criteria for a CE-based matchmaking framework.

4. Matchmaking framework design and overview

This section provides a comprehensive overview of the matchmaking framework design for feedstock adaptation in industry, along with the methodology underlying each component of the framework. The matchmaking framework is a part of the feedstock adaptation tool being developed within the TRINEFLEX project. The research goals addressed in this section are to identify the criteria for successful cooperation among feedstock suppliers with industry, and design the matchmaking framework by incorporating these criteria into the framework.

4.1 Framework context and layout

The envisaged users of the feedstock adaptation agent are feedstock producers, feedstock suppliers and industries. The user is asked to define the industry sector i.e. glass, copper, aluminum, the location where feedstock material is collected or produced, and specific quality characteristics; indicatively (i) the type of feedstock (resource, waste, by-product), (ii) composition of feedstock materials i.e. alternative raw materials that could replace the conventional ones for each process sector, (iii) the total mass, in kg or tons per year, in order to define the quantity of the feedstock material required, (iv) quality indicators (e.g. chemical composition, moisture content) of the feedstock defined for each industry sector, (v) seasonality in order to determine any season fluctuation of production/ supplying.

The matchmaking framework is focused on CE and IS related criteria for matching feedstock suppliers and industries in the context of a marketplace. This research work is an expansion of the CE matchmaking framework proposed by Łękawska-Andrinopoulou et al. (2021) to IS and the IS marketplace concept proposed by Akrivou et al. (2022) to feedstock adaptation in glass, copper and aluminium sectors (Łękawska-Andrinopoulou et al., 2021; Akrivou et al., 2022) (Fig. 2).

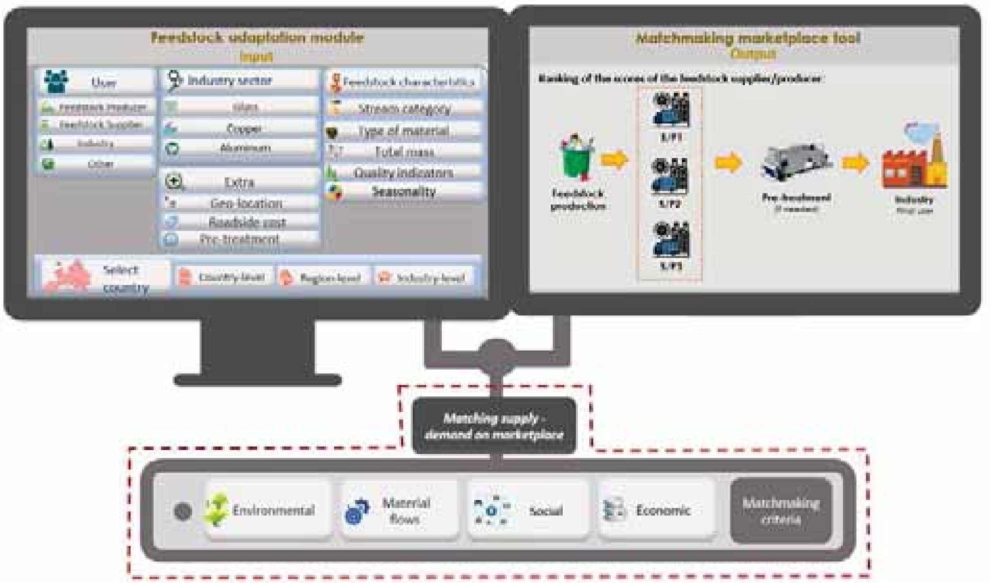

Fig. 2. Concept design of feedstock adaptation agent.

4.2 Criteria selection and implementation in framework

This subsection presents the approach for the criteria definition, that are needed for the circular cooperation matching of feedstock suppliers with industry in the context of a marketplace. A strategy was implemented based on the following criteria in accordance to Fig. 3:

Environmental (A) the GHG emissions from the transportation of the feedstocks considering the transport distance between the matchmakers and an emission factor of the feedstock vehicles;

Material flow (B) the material flow based on the direct or indirect matches by considering, if feedstock pre-treatment is needed, the definition of seasonality of material produced/supplied and demanded and the quantification of the materials that are defined from both the supplier and the industry in order to define the need of intermediate actors within the supply chain of the materials;

Social (C) the compliance of matchmakers with the CE principles based on a questionnaire related to the social aspects of the sustainable development;

Economic (D) a simplified cost analysis of the alternative feedstock materials transportation between the matchmakers and the additional pre-treatment cost if needed (Akrivou et al., 2022).

The selected criteria are used for the calculation of the total relevance score introduced by Łękawska-Andrinopoulou et al. (2021) between the marketplace users for successful circular cooperation between two stakeholders who are willing to close their loops with the best possible match. The relevance score indicates the possibility for successful circular cooperation between two users and the approach is described below.

Fig. 3. Graph presenting criteria for matching feedstock supplier-industry

- ***Criteria A**: Environmental impact*

This criterion seeks to assess the proximity of potential partners and to strengthen collaboration between the nearest locations. Thus, the GHG emissions from the transportation of feedstock from the collection/ production point to the plant gate are considered. According to the selected country, the system boundaries of the investigated area (i.e. country-level, industry-level or region-level) are determined and different range of the transported distance is assumed. The sub-score values are concluded when the GHG emissions from transportation are calculated. For the transport of solid materials, the common means of road transportation is a 40 tons truck with container use diesel as fuel (Edwards et al., 2019).

To measure the specific criterion the transport distance of the feedstock material is compared with the average distance goods for each country where the industries are located i.e. Italy, Spain and Greece. Table 1 illustrates data for the aforementioned countries. Specifically, according to the Eurostat the average distance that goods were carried in Spain, Greece and Italy was equal to 150 km, 120 km and 140 km respectively in 2022 (Eurostat, 2024).

Table 1. Distance intervals and corresponding relevance Sub-score A values

Distance interval	***Sub-score A***	***Distance (km)***		
		Greece	***Italy***	***Spain***
Up to 0.5 average	1	<60	<70	<75
0.5 average–average	0.8	60-120	70-140	75-140
Average–1.5 average	0.5	120-180	140-210	140-225
>1.5 average	0.2	>180	>210	>225

Sources: (Eurostat, 2024; Łękawska-Andrinopoulou et al., 2021)

- ***Criteria B**: Material flow*

Based on Łękawska-Andrinopoulou et al. (2021) approach, as direct match is defined the case of the outflow from one marketplace user matches the needs of another stakeholder and can be directly used as input. On the other hand, indirect match is when an intermediate stakeholder is needed to close the loop and material repurposing takes place. To measure the specific criterion, the feedstock supplier should define if the material flow needs pre-treatment or not (e.g. separation, cleaning, removal of harmful materials etc.). If yes, an intermediate stakeholder is required for the pre-treatment of the material; that is an indirect match.

Moreover, to evaluate the embedded value of material use, including the time and energy invested in making it, the level of pre-treatment requirements is considered based on the technical cycle including the stages of (i) Reusing in which materials have not been significantly modified (sub-score=1); this case is considered as direct match, (ii) Remanufacturing in which more intensive work is needed in order the materials could be used again (sub-score=0.6), (iii) Recycling where material could not be used in another way and the embedded value of the material is lost, but the value of the materials is retained (sub-score=0.3). This criterion aims to enhance the ready-to-use materials by industries.

In addition, as direct match is considered the case where the seasonality of supply-demand is matched as well as the amount of the material demanded from the industry is equal to the supplying from the supplier company (sub-score=1). In other cases, the match is considered as indirect match (sub-score=0.5).

- ***Criteria C**: Social aspect*

As part of the EU Green Deal (EC, 2019), the Corporate Sustainability Reporting Directive (CSRD) entered into force in 2023. The CSRD requires companies to report their impact on people and the environment (EC Directive, 2022; EC, 2023). Therefore, this criterion aims to evaluate the social aspect of each user by reflecting the compliance of each supplier company with the CE principles. The outranking relations between the users are quantified with a questionnaire that consists of a set of questions related to the company's circular actions by using the ELECTRE method (Hatami-Marbini and Tavana, 2011; Komsiyah et al., 2019). The form of the questionnaire is based on modified questions from Łękawska-Andrinopoulou et al. (2023) and is presented below in Table 2:

Table 2. The set of questions to the supplier companies

Category	***No.***	***Question***
Legislation		To what extent you are familiar with the CE and Corporate Social Responsibility (CSR) principles?
		To what extent does your company promote zero waste initiatives?
		To what extent do you implement and evaluate gender equality policies in your company to improve gender balance ration and increase women participation in managerial positions?
Ethics		To what extent does your company expect a matching supply and demand collaboration will create new job opportunities?
		To what extent do you foster a culture of adult learning and include training programs to low-skilled workers in your activities?
		To what extent does your company conduct CE innovation meetings/ workshops/brainstorming for innovation development?
		To what extent do you implement charitable actions in your company?
		To what extent does your company offer a healthy and safe environment to its workers?

Source: Łękawska-Andrinopoulou et al., 2023

To solve the problem of multiple attributes that are used for the decision-making of the social aspect of each company ELECTRE method is to be used. The ELECTRE method is a widely used outranking method in multi-criteria decision analysis (MCDA) problems that address conflicting systems of criteria. This is achieved by using measurements of the performance ratings and criteria weights.

A key advantage of the ELECTRE methods is their ability to consider ordinal scales without converting them into abstract scales with an arbitrarily imposed range, all while preserving the original verbal meanings. Additionally, this method accounts for the uncertain, imprecise, and linguistic assessments provided by decision-makers (Hatami-Marbini and Tavana, 2011). By using this method, linguistic preferences can easily be converted to variables. Then, these variables are compared and an outranking list of the companies is concluded (Hatami-Marbini and Tavana, 2011; Komsiyah et al., 2019). To achieve this, each supplier company should rank each question in accordance with the Table 3.

Table 3. The linguistic variables for evaluating "to what extent" questions of Table 2

Linguistic variable	Number
Very small (VS)	1
Small (S)	2
Moderate (M)	3
Large (L)	4
Very large (VL)	5

Source: Hatami-Marbini and Tavana, 2011

- ***Criteria D**: Economic aspect*

This criterion aims to enhance the use of pre-treated materials that are produced/collected in proximity to the final user. For the economic evaluation of decision-making process, the transportation and pre-treatment costs of materials are taken into consideration.

To calculate the specific criterion the transport distance of the feedstock material with the average distance goods for each country (Table 1) as well as the average transport cost of materials by truck in Europe that ranges from 0.05 to €0.10 € per tonne-kilometer (Persyn et al., 2019; Upply, 2022) are considered. To evaluate the additive cost of pre-treatment the respective sub-score used in the material flow criterion is used considering that the more intensive pre-treatment required the higher the cost; specifically, in the case of reusing, remanufacturing and recycling the sub-score is equal to 1, 0.6 and 0.3 respectively.

4.3. TRS calculation

According to these criteria, a Total Relevance Score (TRS) between the supplier company and industry is calculated suggesting potential circular cooperation between two stakeholders who seek to close the loops with the best possible match. This methodology has been proposed by (Łękawska-Andrinopoulou et al., 2021). The weighing factors of each criterion to the decision-making process are defined by the industry. This means that the stakeholder could give more importance to some criteria than others, depending on their preferences and goals. In this section, the relevance scoring between the potential feedstock suppliers and industry in case of feedstock adaptation agent is presented taking into account the investigated criteria at each level of the analysis. The sub-scores from all the levels are combined into a Total Relevance Score (TRS) that reflects the ranking score of feedstock suppliers.

At every level of the investigated criteria, relevance sub-scores (A, B, C, D) are obtained in accordance with each criterion (environmental, material flow, social and economic) presented in Fig. 3. The TRS is calculated by Eq. (1).

$$TRS(\%)=(\alpha\times A+\beta\times B+\gamma\times C+\delta\times D)\times 100\% \quad (1)$$

Each sub-score A, B, C, D describes the investigated criteria for each case and takes on decimal values between, 0 and 1 inclusive. The metrics α, β, γ, δ are used to differentiate the importance of the levels and the corresponding sub-scores A, B, C, D and could be chosen by the users. In this way the user could give more importance to some criteria than others, depending on their preferences and goals. They take on decimal values between, 0 and 1 as well, while the total should be equal to 1. An overview of the score calculation methodology is presented in Table 4.

Table 4. Overview of methodology

Sub-score	*Criterion*	*Values*	*Definition*	*Goal*
A	Enviro-nmental	1	Based on the transport distance between feedstock supplier and industry and an environmental factor (Table 1)	To strengthen collaboration between stakeholders located within the nearest distance.
		0.8		
		0.5		
		0.2		
B	Material flow[1]	1	Based on the level of pre-treatment the feedstock needs.	To enhance the pre-treated materials by industries.
		0.6		
		0.3		
		1	In accordance with the seasonality and the amount of supply/demand material from both the supplier and industry	To enhance the better cooperation for both supplier company and industry
		0.5		
C	Social	*Quantify based on the ranking list of users and the number of them.*	In accordance with the questionnaire results by using the ELECTRE method.	To evaluate the social responsibility of the supplier companies.
D[2]	Economic	1	Based on the transport distance between feedstock supplier and industry and an economic factor (Table 1).	To enhance the use of ready-to-use materials that are produced/collected in proximity to the industry.
		0.8		
		0.5		
		0.2		
		1	Based on the level of pre-treatment the feedstock is needed.	
		0.6		
		0.3		

[1] Sub-score B consists of three sub-scores B1, B2 and B3 and is calculated as: $B = (B1 + B2 + B3)/3$

[2] Sub-score D consists of two sub-scores D1 and D2 and is calculated as: $D = (D1 + D2)/2$.

The final output list is based on the TRS of the potential feedstock suppliers following the thought process that the higher the TRS, the better matching is achieved between the supplier - industry in terms of environmental, material flow, social and economic terms.

5. Validation of the framework – Case studies

This section illustrates the implementation of the framework to different case studies of an EII. Thus, four hypothetical case studies are presented for a glass industry in Italy that demands 2 tonnes of cullet to use as alternative feedstock within the process of glass bottle production for the spring and summer seasons. These cases are designed to illustrate how the logic of the matchmaking framework is applied in real-life settings with glass industry being potential stakeholder.

The cases describe hypothetical suppliers and a possible solution in the context of the matchmaking framework. Case 1 is an example of an indirect match and pre-treated materials that are produced/collected in proximity to the industry. Case 2 emphasizes direct matches and high social responsibility. Case 3 presents a situation where pre-treatment is required and the distance between stakeholders is significant. Case 4 presents an intermediate state where a direct match is achieved, not ready-to-use material is supplied and the social responsibility is low. The attributes for each case are presented in Table 5.

Table 5. Attributes of each supplier company and sub-score values corresponding to each case

Supplier / *Criterion*	**Distance (km)** *[A, D]*	**Pre-treatment requirements** *[B]*	**Amount (tn)** *[A, B, D]*	**Seasonality** *[B]*	**Social Responsibility** *[C]*
1	65 (1)	Reusing (1)	3 (0.5)	Spring, Summer, Winter (0.5)	Moderate (0.6)
2	150 (0.5)	Remanufacturing (0.6)	2 (1)	Spring, Summer (1)	High (1)
3	220 (0.2)	Recycling (0.3)	4 (0.5)	Spring, Summer, Fall (0.5)	Low (0.2)
4	100 (0.8)	Recycling (0.3)	2 (1)	Spring, Summer (1)	Low (0.2)

Based on the above attributes given for each supplier company, the following sub-scores are calculated. In this theoretical example, the glass industry gives more attention to the economic and social aspects than the environmental impact and the material flow. According to this assumption, the weighting factors used to calculate the TRS according to Equation 1 are tentatively set to the following values: α, β to 0.2 and γ, δ to 0.3. These values are presented in Table 6 and the ranking results are calculated showing that the first supplier company could achieve the best match. This could be explained due to the feedstock does not required any additional pre-treatment step as well as that the company is located near the glass industry.

Table 6. TRS calculation

Supplier	***α***	***A***	***β***	***B***	***γ***	***C***	***δ***	***D***	***TRS (%)***
1	0.2	1	0.2	0.67	0.3	0.6	0.3	1	**81.4**
2		0.5		0.86		1		0.55	73.7
3		0.2		0.43		0.2		0.25	26.1
4		0.8		0.76		0.2		0.55	53.7

6. Discussion

This research focused on criteria selection for a matchmaking framework design for feedstock adaptation in EIIs. The framework is part of a decision support tool and is based on a relevance scoring between feedstock suppliers and industry considering (i) the GHG emissions from the transportation of the feedstocks, (ii) the feedstock pre-treatment requirements, (iii) the seasonality of material produced/supplied and demanded by the industry, (iv) the quantification of the materials that are defined from both the supplier and the industry, (v) the compliance of matchmakers with the CE principles (vi) the feedstock transportation cost between the matchmakers and (vii) the pre-treatment cost if required. The output of the decision facilitation tool is to provide a ranking inventory list with potential feedstock suppliers showing the possibility of feedstock suppliers and industry to collaborate successfully based on relevance scoring results. In addition, users could choose the weighting factors of the criteria by giving more importance to some criteria than others, depending on their preferences and goals. Potential challenges that are related to methodology include: (1) limitations of data or biased data, (2) conflicting priorities among matchmakers (3) use of data from different sources (i.e. literature, datasets, industry). These challenges could be eliminated when the framework is included in the decision support tool and more participants would use it in real-life conditions. Then, the feedback from these stakeholders could be considered for improvements to the methodology.

Promising areas for future research could be the extension to water and energy exchanges between the matchmakers investigating also other industry sectors as well as the expansion of the system boundaries to the entire industrial process by including criteria related to changes to energy consumption due to feedstock adaptation. Additional, for evaluating the environmental impact of each case, emissions factors for other transport mode (e.g. ship, train) could be included as well as emissions savings achieved from raw material replacement with alternative ones. Last but not least, the cost savings from the replacement of raw materials with alternative (waste or by-products) could be considered as well. Furthermore, ideas from different industry sectors could be proposed when applying the presented framework based on the challenges they face e.g. condition of storage requirements in case of a water industry.

6. Conclusions

To sum up, this research illustrates a comprehensive matchmaking framework for optimizing collaboration between industry and feedstock suppliers. The framework leverages qualitative characteristics of feedstock materials and integrates environmental, material flow, economic, and social criteria. By fostering feedstock sourcing flexibility, resource conservation, and reduced dependency on virgin raw materials, this approach supports the development of sustainable industrial ecosystems and circular economy initiatives.

The proposed framework not only enhances the efficiency of resource utilization but also promotes innovation in supply chain management by enabling industries to access diversified and high-quality feedstock. It emphasizes the significance of proximity-based collaborations, which minimize transportation costs, reduce greenhouse gas emissions, and strengthen local supply chains. These factors contribute to improved environmental performance and economic feasibility for participating stakeholders.

Furthermore, the demonstration of the framework underscores the importance of readiness in adopting new symbiotic partnerships. By encouraging industries to utilize pre-processed, ready-to-use materials from suppliers, the framework facilitates faster integration of secondary resources into production processes, thereby supporting waste valorization and reducing the environmental footprint of manufacturing activities.

Future research could explore the dynamic adaptation of the framework in various industrial sectors and geographic regions, incorporating advanced digital tools and real-time data analytics for continuous improvement. Additionally, expanding the criteria set to include emerging sustainability metrics could further refine matchmaking accuracy and foster more resilient industrial symbiosis networks.

In conclusion, this matchmaking framework represents a significant step toward holistic and collaborative resource management, offering a scalable solution to support sustainable production and resource efficiency on a broader scale.

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