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Detritus - Multidisciplinary Journal for Waste Resources and Residues - is aimed at extending the "waste" concept by opening up the field to other waste-related disciplines (e.g. earth science, applied microbiology, environmental science, architecture, art, law, etc.) welcoming strategic, review and opinion papers. **Detritus is indexed in Emerging Sources Citation Index (ESCI) Web of Science, Scopus, Elsevier and Google Scholar**. Detritus is an official journal of IRACE / International Research Association on Circular Economy (www.irace.eco) and IWWG / International Waste Working Group (www.iwwg.eu).

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Editorial

CIRCULAR ECONOMY ACROSS STAKEHOLDERS: OBJECTIVES, CHALLENGES AND FUTURE PERSPECTIVES

Introduction

The overarching objective of the Circular Economy is to decouple economic development from resource depletion and environmental degradation by transforming waste into valuable resources.

Achieving this objective requires balancing economic growth, environmental protection, public health, and social well-being in accordance with the United Nations Sustainable Development Goals (SDGs).

Consequently, the Circular Economy should be viewed not merely as a waste management strategy but as a complex socio-technical system involving multiple stakeholders whose mutual interactions (schematically represented in Figure 1) strongly influence the effectiveness of the adopted strategies and the outcomes achieved. The different political, economic, and cultural influence exerted by the various actors can either facilitate or hinder the achievement of sustainability goals.

The Role of Key Stakeholders

Politicians

Within the Circular Economy framework, political representatives are called upon to establish objectives, priorities, and regulatory instruments capable of promoting the transition toward more sustainable production and consumption models. They must also foster awareness among citizens and businesses while maintaining continuous dialogue with the scientific community so that decisions are supported by the best available knowledge.

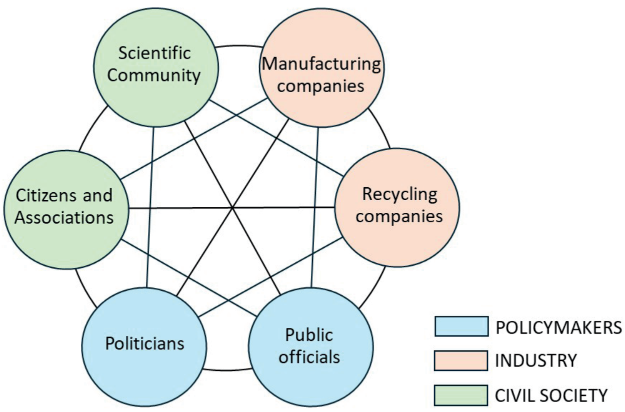

FIGURE 1: Schematic representation of the interrelationships among the main Circular Economy stakeholders.

Public Officials

Officials working within European, national, and local institutions play a central role in translating political decisions into practical actions. They develop technical and administrative regulations, manage programs and funding schemes, oversee regulatory compliance, and coordinate services and projects.

Citizens and Associations

Citizens and civil associations contribute to the Circular Economy through responsible consumption patterns and sustainable behaviors, including waste prevention, conscious purchasing decisions, product life extension, participation in sharing economy initiatives, and proper waste separation practices.

Scientific Community

Beyond supporting technological innovation, the scientific community plays a crucial role in providing objective evidence to policymakers, citizens and companies. By identifying emerging environmental and health concerns, evaluating risks, and proposing technically sound solutions, research helps ensure that circularity strategies remain scientifically robust and socially beneficial.

Industry and Business Sector

The business sector drives the Circular Economy. Companies create societal and economic value, but ultimately focus on profitability, continuity, and competitiveness. The circular landscape relies on two primary groups:

- *Manufacturing companies*: tasked with redesigning lifecycles to use fewer virgin materials, improve repairability, incorporate recycled content, and minimize production waste.
- *Recovery and recycling companies*: responsible for turning waste into secondary resources and ensuring the environmentally safe disposal of final residues.

Governance Failures and Stakeholder Distortions

Many of the shortcomings observed in current circular economy systems originate from distortions in stakeholder roles, responsibilities, and interactions:

- political decisions influenced by vested interests, demagoguery, short-term electoral considerations or ideological biases, (as exemplified by persistent opposition to certain waste-treatment technologies);
- insufficient technical and scientific updating among

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parts of the public administration, whose participation in scientific forums has become increasingly limited;
- citizens' vulnerability to misinformation and fake news, particularly through social media;
- difficulties within the scientific community in providing clear, consistent, and widely shared information, sometimes yielding to pressures associated with industrial lobbying;
- industrial strategies focused primarily on profit maximization through planned obsolescence, fast-fashion business models, and proliferation of disposable products;
- inadequate communication between manufacturers and recycling operators regarding changes in product composition and design;
- reluctance among some industrial operators of the environmental and health risks associated with products and or specific recycling pathways.

Persistent Systemic Challenges

In addition to stakeholder-specific weaknesses, several systemic challenges continue to hinder the effective implementation of circular economy strategies, such as:

- insufficient prevention of disposable products generation;
- overly optimistic narratives that underestimate the technical and economic complexities of circular transitions;
- instability & volatility in secondary raw material markets;
- bureaucratic and regulatory barriers affecting End-of-Waste implementation;
- limited adoption of Extended Producer Responsibility schemes aimed at combating planned obsolescence and ensuring proper end-of-life management, especially for products that are difficult to recycle (e.g., textiles containing elastane);
- the transfer of environmental burdens associated with recycling activities to developing countries;
- the absence of an integrated strategy capable of effectively coordinating all stakeholders throughout the value chain.

Strategic Priorities for the Future

The transition toward a truly sustainable Circular Economy requires the adoption of a comprehensive strategy based on several key principles, (Fraeyman et al., 2026):

- comprehensive monitoring and control of material flows;
- ensuring the sustainable closure of mass balances;
- managing non-recyclable residues in a technically & environmentally sound manner, free from ideological biases;
- integration of prevention, reuse, recycling, energy recovery, and final disposal within a coherent system in which all components contribute to overall performance, much like gears within a complex mechanical system (Figure 2);
- strengthening the role of independent scientific research in policymaking processes;
- contrasting the distorting influence of lobbying activities on regulatory decisions;
- combating planned obsolescence and the production and widespread use of disposable products;

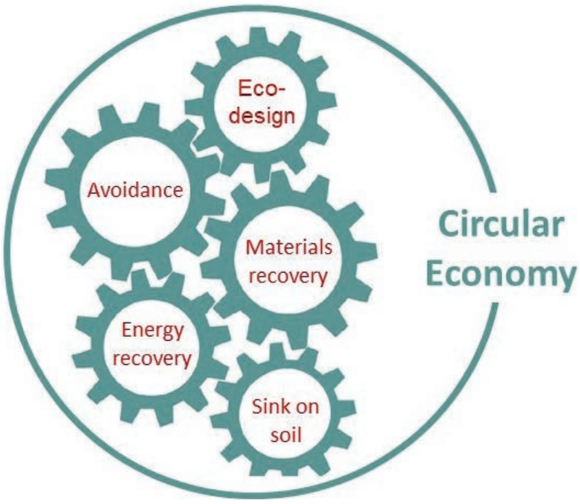

FIGURE 2: Graphical representation of the integrated management of products and waste from a sustainability perspective, supporting the objectives of the Circular Economy (Cossu, Ferrante, 2026).

- assessing and minimizing the release of contaminants, hazardous substances, and microplastics throughout product life cycles;
- recognizing the important contribution of energy recovery from waste through scientifically validated technologies, including biofuels, biohydrogen production, chemical recycling of plastics, and thermal recovery of non-recoverable residual fractions;
- acknowledging the strategic value of controlled land deposition of residues via the "Back to Earth" framework. This entails driving EU-level policy toward sustainable engineered "sinks," rather than merely amending older directives based on unsustainable traditional landfilling.

Conclusions

The Circular Economy represents one of the most promising strategies for addressing the environmental, economic, and social challenges of the twenty-first century. However, its success cannot rely on oversimplified narratives or purely ideological visions; rather, it will depend on the ability of stakeholders to transcend sectoral interests and embrace evidence-based decision-making. This approach must effectively integrate environmental and public health protection, economic competitiveness, and collective well-being. Only under these conditions can circularity become a tangible pathway toward sustainable development, rather than a merely aspirational concept.

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HOW CONSUMERS PERCEIVE DIFFERENT MATERIALS, PACKAGING, AND WASTE: A PLASTIC-FOCUSED ANALYSIS

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ABSTRACT

Plastic pollution is a topic that increasingly concerns consumers all over the world. Policymakers and industry practitioners are also called upon to work on solutions. One strategy to fight those amounts of plastic is recycling, which can only be achieved if consumers are convinced of the value and importance of plastic. Two online questionnaires with consumers were conducted in Austria, where separate collection infrastructure is well established, but recycling targets for plastic packaging are still unsatisfactory. The perception of the material itself, the material as waste, and the material as packaging was investigated. Results show that plastic is perceived as significantly worse than other materials (i.e. glass, paper, and metal) in various dimensions (perception as valuable, good, important, and natural). However, when asked if it is convenient, plastic comes close to the good evaluation of the other materials. The overall negative perception was also supplemented by participants' free associations, whereby an apparent dissonance between glass and plastic was identified. While plastic was associated with an overwhelming amount of waste and as "unnecessary," glass creates more ambivalent associations: although the higher weight is perceived as unfavorable, positive associations such as "recyclable" and "sustainable" predominate. Researchers, companies, and policymakers need to take this dissonance seriously and work to reconcile public perception by responsibly using and designing plastic packaging and enhance convenience during the disposal stage. This must be accompanied by clear consumer education, so that plastic is perceived as valuable material that consumers consider important to recycle.

1. INTRODUCTION

Recycling is one of the lower-rated principles in the waste hierarchy, yet it is seen as a major instrument to decrease plastic pollution and an essential step towards a circular economy which aims at reducing resource depletion and unsustainable waste management (Ellen MacArthur Foundation & McKinsey & Company, 2016). In this context, the consumer perspective is an essential component of a thriving circular economy (Kirchherr et al., 2017) since consumers not only influence which materials are consumed, but also decide how these materials are disposed-of when they become waste (Klaiman et al., 2016; Thoden van Velzen et al., 2019). However, the potential of consumers in enhancing the sustainability of the plastics value chain has not yet been fully harnessed (Johansen et al., 2022; Nemat et al., 2020).

A significant discrepancy exists between consumer perceptions of packaging sustainability and scientifically validated assessments of its environmental impact. As early as 1996, Van Dam found that glass was perceived as the most environmentally friendly material and plastic the least environmentally friendly when a particular product was presented in different packaging to randomly selected participants, despite life cycle analyses proving it different. This has been proven repeatedly in recent years through studies in which students were asked about the packaging of liquid goods (drinks, beer, oil, etc.) (Boesen et al., 2019;

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De Feo et al., 2022). Steenis et al. (2017), who used a specific product (tomato soup), even describe this discrepancy between consumer perception and the scientifically proven results of life cycle assessments (LCA) as a “threat to sustainable development” (p.294). Processed tomatoes were also used in a choice experiment study with young German consumers, confirming this discrepancy between perceived and LCA-based sustainability of packaging materials (Bock & Meyerding, 2023). Moreover, questions about food packaging, without using a specific product, revealed that Swedish (high-income) consumers tend to have a negative attitude towards plastics and rely heavily on the material itself, without considering sustainability as a combination of product and packaging, and their life stages (Lindh et al., 2016). A qualitative interview study involving participants from multiple countries confirmed that, particularly among Germans, the material composition serves as a key criterion for evaluating the environmental impact of packaging (Herbes et al., 2020). However, this material-based assessment approach was also observed among French and American participants (ibid.). Further studies show that the material is one of the most important clues for consumers to assess whether the packaging is classified as sustainable (Ketelsen et al., 2020; Magnier & Crié, 2015; Nguyen et al., 2020). While packaging is the shaped material used to contain, protect, transport, or present a product until it reaches the consumer, material refers to a substance used to make a product or a packaging (European Commission, 2025). As a result, packaging (made from a specific material) ends up in the hands of consumers, with waste being defined as something that needs to be disposed of after use (European Commission, 2018a). Therefore, assessing materials, packaging and waste is essential for understanding consumer behavior.

This insight enables more effective strategies for guiding responsible and sustainable consumer actions. As this study focuses on perceptions of materials, packaging and waste rather than on the physical or technical properties, it offers a clearer view of how consumers interpret and respond to material choices in various contexts.

1.1 Theoretical background

Regarding recycling actions, consumers are confronted with a number of barriers, which can be divided into macro-environmental factors (political, economic, sociological, technological, ecological, and legal factors), micro-environmental factors (situational factors such as perceived condition, perceived convenience, etc.), and personal factors (Ertz et al., 2023), which are interlinked and influence each other. Aligning with studies by Stoeva and Alriksson (2017) and Tonglet et al. (2004), it can be argued, however, that despite external factors like adequate waste management, as it is provided in Austria (Schuch et al., 2023), a positive intrinsic attitude towards recycling remains essential, emphasizing the importance of their personal attitudes. Generally, attitudes, subjective norms, and perceived behavioral control were found to predict intentions to perform behavior and represent the three major pillars of the TPB (theory of planned behavior) (Ajzen, 1991, 2020). The TPB is commonly used as a theoretical framework to predict recycling behavior and is extended in various forms (Botetzagias et al., 2015; Cheung et al., 1999; Khan et al., 2019; Stoeva & Alriksson, 2017; Tonglet et al., 2004; Yuriev et al., 2020). Attitude is the subjective perception or belief regarding a certain behavior. Subjective norms reflect the perceived social pressure to perform a behavior that is considered expected, whereas perceived behavioral control describes the perception of opportunities to perform the behavior, e.g., based on sufficient time, space, facilities, and convenience (Ajzen, 2020). While proper waste management is in progress in the EU (European Commission, 2023), the severe influence of subjective perceptions was shown by a study conducted in the UK by Dunant et al. (2017), where misperceptions and miscommunication contributed to increased costs and impeded recycling efforts. This underscores the need to prioritize the study of attitudes that reflect perceptions.

1.2 Focus, key contributions and relevance of the study

In its early warning assessment reports (European Commission, 2023) on the recycling targets for municipal waste and packaging waste, the European Environment Agency (EEA) found that many countries are at risk of missing the recycling rate targets as defined in the Waste Framework Directive (European Commission, 2018a) and the Packaging and Packaging Waste Directive (European Commission, 2018b). When it comes to packaging materials, plastics are considered to be the material that poses the greatest challenges in terms of achieving recycling targets, with Austria also at risk of failing to meet its targets. For instance, in Austria, only minor proportions of glass (18%) and paper (17%) packaging are not separately collected, in contrast, 47% of plastic packaging is disposed of in mixed wastes, and therefore hinders recycling (Lipp & Lederer, 2025). To get to the bottom of this challenge, attitudes towards the material itself were examined, as it was assumed that this also hinders attitudes towards recycling. This attitude is determined through two anonymous online questionnaires.

Considering the vast impact of consumer perceptions on recycling and the limited attention given to the consumer perspective, it is critical to positively steer those perceptions. Hence, to effectively influence consumer perceptions, it is essential to first thoroughly understand and investigate them. Thus far, research has primarily focused on the perception of a material within the context of its application in packaging. However, the perception of a particular packaging material can be product-specific (Schifferstein, 2009). Along with the fact that the materials used in packaging are also evaluated for their environmental impact, it is crucial to thoroughly investigate this issue. Further, as the material is such an essential part of the packaging, producers, designers, and recyclers should all be able to relate to it. Therefore, the urgency arises in assessing the perception. Comparing common packaging materials is of substantial interest to gain a comprehensive understanding of how consumers perceive the material itself and what differences arise between plastic and alternative materials in terms of the attributes assigned to them.

Additionally, to draw conclusions on the disposal step also the state as "waste" is of interest. Especially in regard to plastic associations with "plastic food packaging" in the product stage show that it is already then considered as "waste" (Koenig-Lewis et al., 2022), which leads to the vital question of how materials and waste change in perception, which, to our knowledge, has not been investigated to date, as it is aimed for in this article.

Therefore, this study aims to investigate consumer perceptions of the material itself, the material as waste, and as packaging, using the case study of Austria to answer the question: Do materials retain value after becoming waste? In contrast to previous studies, a representative sample of the Austrian population in terms of gender and age, with a well-distributed proportion of different levels of education, was used. In addition, by utilizing a within-subject and an in-between subject design, findings are validated.

Two online surveys were conducted: The first, carried out as within-subject design in 2021, assessed the perception of paper, glass, plastic, and metal across five dimensions (valuable, convenient, good, important, and natural). This was followed by the second survey which was conceptualized as a between-subject design to compare plastic and glass using the same dimensions in 2022. The results are discussed in comparison to scientific literature in order to draw comprehensive conclusions for the scientific community, producers and designers of packaging materials, policymakers, and society.

2. METHODS

2.1 General study design

In the following, two surveys are presented. In Survey 1, an anonymous online questionnaire with a within-subject design was applied. A within-subject design uses multiple stimuli, equal for all participants. In this case, the participants were presented with the most important materials, which are also used in packaging (plastic, glass, metal, and paper). Survey 2 used an anonymous experimental online questionnaire with a between-subject design, meaning the participants (155 each) were randomly exposed to one of the two between-subject conditions, namely either glass or plastic. This allows a comparison between the different stimuli (either plastic or glass). The focus was on glass in comparison to plastic, as both are used for similar packaging applications due to their barrier properties suitable for liquid (Deshwal et al., 2019). Additionally, glass was the dominant material for such food packaging until plastic partly replaced it (Bolanča et al., 2018), and according to recent results, glass is preferred over plastic due to a higher perceived sustainability (Hallez et al., 2024).

The two different survey designs were chosen to increase the statistical power and validity, and to reduce the potential for unfavorable response effects (Charness et al., 2012). In addition, an attention check was performed in both surveys to ensure data quality, with the aim of reducing the error variance and increasing statistical significance (Oppenheimer et al., 2009). The attention checks instructed participants to ignore the displayed question and instead select a specific response option. The instruction read: "We are interested in your honest opinion and therefore ask you to read our questions carefully. Otherwise, some of your responses may be unusable for us. To verify your attention, please ignore the question shown below and instead click on the answer option 'Stowe/Kaiserschmarrn.' Thank you very much!" Participants who failed this check were shown the item again, up to two additional times, accompanied by a note reminding them to read the instructions carefully. If the check was not passed on the third attempt, the survey ended automatically. No further exclusions were made.

Participants for both studies were recruited via a market research agency, a common practice in consumer research (c.f. Geissmar et al., 2023; Hofstetter et al., 2024; Sokolova et al., 2023). It was asked to recruit a representative sample of Austrian citizens through its online panel, and the questionnaire was distributed via an online link and included sociodemographic questions to identify the characteristics of the sample (Table 1).

The characteristics of both samples correspond well with the 2021 overall population of Austria in terms of gender and age (M_{age}= 43.2, 50.7% female) according to the Austrian census (Statistics Austria, 2024b). The educational background also matches the Austrian population in 2021 very well, with the largest proportion (32.6%) of the Austrian population having completed vocational training.

TABLE 1: Procedural and sociodemographic characteristics.

Characteristics	Survey 1	Survey 2
Research Design	Within-subject	Between-subject
Data collection period	01/2021	01/2022
Attention check passed	81.87%	92.96%
N	316	310
Mean Age	M_{age} = 41.73 years SD_{age} = 13.77	M_{age} = 42.46 years SD_{age} = 13.06
Gender	49.69% female, no one diverse	48.39% female, one person diverse (0.32%)
Education	Vocational training: 42.72% Secondary school: 16.14% Higher education entrance qualification: 16.14% Academic degree: 16.14% Compulsory school: 8.86%	Vocational training: 47.10% Secondary school: 15.16% Higher education entrance qualification: 14.84% Academic degree: 17.10% Compulsory school: 5.81%

Secondary school and higher education entrance qualifications are counted together and account for 30.4%, while 19.7% have completed higher education and 17.3% have compulsory schooling as their highest level of completed education (Statistics Austria, 2024a). No post-stratification weighting was applied.

2.2 Survey 1: Within-subject design

Consumers' perceptions were examined with semantic differentials to measure meaning (Osgood, 1952). For this purpose, participants were asked to evaluate (1) different materials (plastic, paper, glass, metal) and (2) the corresponding waste (plastic waste, paper waste, glass waste, metal waste). The question was formulated as follows: "Plastic/ Paper/ Glass/ Metal as a material is for me …" The participants could then choose answers on a 5-point Likert scale with semantic differentials (valuable – valueless, convenient – inconvenient, good – bad, important – unimportant, natural – unnatural). This was followed by similarly worded questions on the topic of waste: "Plastic/ Paper/ Glass/ Metal waste is for me …" using the plural of waste in German and the same semantic differentials as before with a 5-point Likert scale. Further variables were assessed as well as the original expressions can be found in Section S1 of the Supplementary material. However, since this article focuses on evaluating the materials and the corresponding waste, the results of questions like for example on waste separation are not presented.

2.3 Survey 2: Between-subject design

Survey 2 was built on the results of Survey 1 in January 2022. Free associations to plastic/glass packaging were assessed at the beginning of the questionnaire with the question: "What comes to your mind spontaneously on the subject of 'plastic/glass food packaging'?". Followed again by a 5-point Likert scale with the same semantic differentials (valuable – valueless, convenient – inconvenient, good – bad, important – unimportant, natural – unnatural) as in Survey 1, to ask about the opinion on plastic or glass, respectively. Further variables which were assessed but are not presented in this study can be found in Section S2 of the Supplementary material.

After data collection, the free associations were rated as positive, negative, or neutral by two authors of the article applying qualitative content analysis (Mayring, 2010; Schreier, 2012). The entire answer was rated, such that if a participant mentioned a positive and a negative association, both associations were considered. Additionally, any reasons provided for their associations were systematically coded into categories. Finally, the ratings were compared. Disagreement between the two raters was not systematic, and the raters subsequently discussed each statement until an agreement was reached.

2.4 Comparison of survey results to the separate collection rate

In order to better understand the survey results with the physical basis of a circular economy, the respective separate collection rate (SCR) is displayed for indicative comparison with the survey results, based on values from Lipp and Lederer (2025) for the year 2020. The reason for displaying the SCR and not the recycling rate is that the SCR gives information on the share of waste that is collected and disposed of separately by consumers. Thus, the SCR represents a consumer decision. Contrary to that, the recycling rate shows the share of waste actually recycled. This value differs substantially from the SCR for plastic and metal packaging. In the case of plastic packaging, the difference is due to sorting losses in sorting plants, resulting in lower recycling rates than SCRs. For metals, the recycling rate is higher than the SCR since metals recovered from mixed municipal solid waste and waste incineration bottom ashes can be added to the recycling rate according to European Commission (2019a). In both cases, the recycling rate is then not only a result of the consumer decision, but of sorting technology. For a comparison, the recycling rates of packaging wastes in Austria shown in the Eurostat data in the year 2020 were 80% for paper, 25% for plastics, 66% for metals, and 82% for glass, whereas the SCR were in the same year 83% for paper, 53% for plastic, 55% for metals, and 82% for glass (Lipp and Lederer, 2025; Eurostat, 2024a). The metal SCR is calculated based on the mass-weighted quantities SCR of iron and aluminum packaging in combination (Lipp & Lederer, 2025).

3. RESULTS

3.1 Survey 1: How do consumers perceive different materials?

The perceptions of plastics as material are clearly the worst compared to all the materials questioned in our study. A repeated multivariate analysis of variance (MANOVA) showed significant results comparing the consumers' perception of the different materials (plastic, paper, glass, and metal) on the respective dimensions (valuable, convenient, good, important, natural) Pillai´s Trace=0.681, $F(15,3774)=73.92$, $p<0.001$ (Section S3, Supplementary material).

As shown in Figure 1, plastic consistently achieves the lowest mean values of the dimensions if compared to the other materials. The only exception was convenience. Mean values and standard deviations can be found in Section S4 of the Supplementary material.

The analysis revealed a significant difference in how valuable the materials were perceived, $F(3,313)=177.78$, $p<0.001$, $\eta_p^2=0.630$. The remaining materials seem to be perceived as very valuable as the mean of paper, glass, and metal were all above 4 on the 5-Point Likert scale.

Likewise, in the case of convenience a significant difference is shown $F(3,313)=39.35$, $p<0.001$, $\eta_p^2=0.274$. Furthermore, a significant difference between the materials perceived as good, $F(3,313)=252.63$, $p<0.001$, $\eta_p^2=0.708$, and important is found $F(3,313)=102.61$, $p<0.001$, $\eta_p^2=0.496$. Finally, a significant difference was found between the materials in terms of whether they were perceived as natural or unnatural $F(3,313)= 466.38$, $p<0.001$, $\eta_p^2=0.817$ by Austrian consumers. The Bonferroni-adjusted post hoc tests confirmed a significant difference between plastic and the respective materials, except for metal in the dimension of

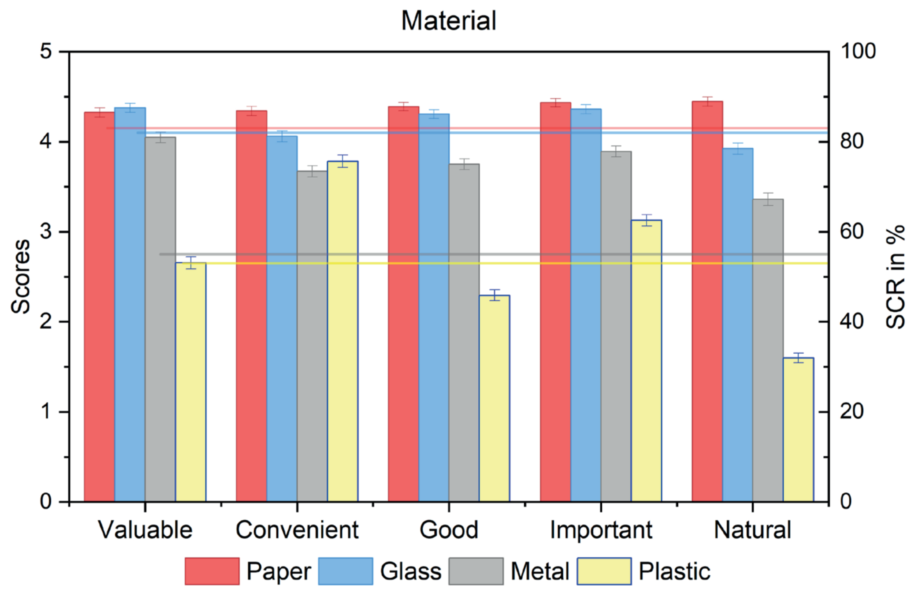

FIGURE 1: Mean and standard errors of the perception of the different materials (paper, glass, metal, and plastic) in the dimensions valuable, convenient, good, important, and natural (N = 316). The respective Austrian separate collection rate (SCR) is displayed for information purposes as a line (right axis) containing the same colors and starting at the bar regarding the material.

convenience, see Section S4 of the Supplementary material.

To sum up, except for convenience, plastic is significantly less positively perceived than paper, glass, or metal. It is perceived as the least valuable, good, important, and natural material; only when asked about the convenience, it ranges closer to the others and even before metal. Paper was perceived as the most valuable and important material alongside glass but more convenient and natural than glass. Additionally, the SCR (shown as light lines) were inserted into the graph to show that there is a similarity regarding the high and similar results for paper and glass, while for plastics the lowest SCR is seen. Although there is no causality this is another indication for an interaction between perception and collection intention.

3.2 Survey 1: How do consumers perceive different waste?

The perception of the waste of the material revealed a similar result as the perception of the materials, as shown in Figure 2. The relation between the dimensions is similar when asked for the material. A repeated multivariate analysis of variance (MANOVA) showed significant results com-

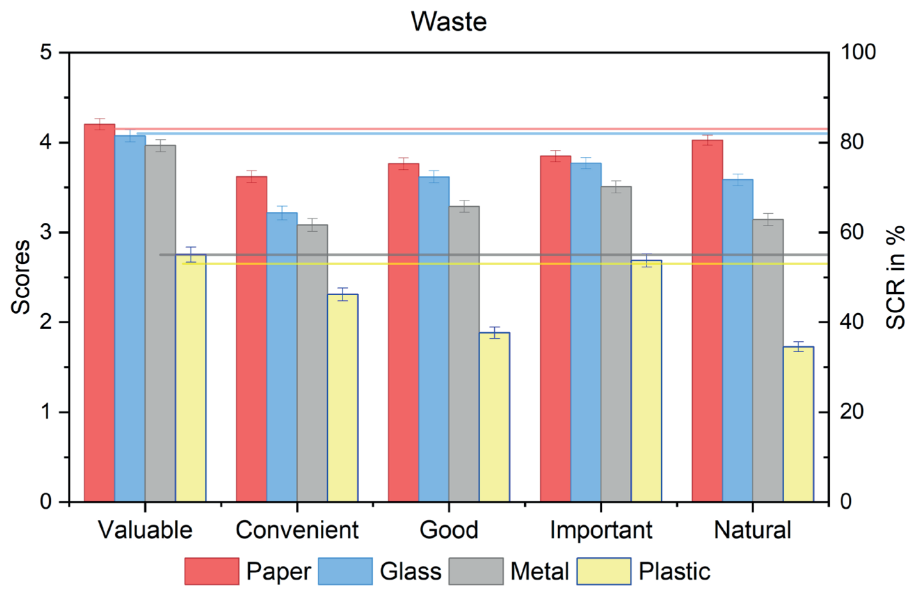

FIGURE 2: Mean and standard errors for the perception of the disposed of material (paper, glass, metal, and plastic) in the dimensions valuable, convenient, good, important, and natural (N = 316). The respective Austrian SCR is displayed for information purposes as a line (right axis) containing the same colors and starting at the bar regarding the material.

paring the consumers' perception of the different waste materials (plastic waste, paper waste, glass waste, metal waste) on the respective dimensions (valuable, convenient, good, important, natural): Pillai´s Trace=0.462, $F(15,3774)=45.75$, $p< 0.001$ (Section S3, Supplementary material).

The analysis revealed significant differences in the consumers' perception of how valuable the waste materials are, $F(3,313)=101.44$, $p<0.001$, $\eta_p^2=0.493$. Further, a significant difference between the waste materials was found for convenience $F(3,313)=75.06$, $p<0.001$, $\eta_p^2=0.418$ and the dimension good $F(3,313)=188.58$, $p<0.001$, $\eta_p^2=0.644$ and important $F(3,313)=68.78$, $p<0.001$, $\eta_p^2=0.397$. Finally, a significant difference was found between the waste materials in terms of whether they were perceived as natural or unnatural $F(3,313)=295.55$, $p<0.001$, $\eta_p^2=0.739$.

It can be seen that paper and glass waste are still regarded as valuable, good, and important, followed by metal waste. Plastic waste, on the other hand, is consistently rated significantly lower than other materials. This is also proven by the Bonferroni-adjusted post hoc tests, see Section S4 in the Supplementary material for more information. Here, too, there is no causal connection, but the comparable trend remains with paper and glass displaying high results in perception and SCR while metal follows with a still high perception followed by a significantly less positively perceived plastic, both displaying intermediate SCR.

3.3 Survey 2: How do consumers perceive packaging?

The negative perception of plastics in comparison to glass across different dimensions (valuable, convenient, good, important, natural) is also reflected in Survey 2, as shown in Figure 3. A one-way ANOVA revealed significant results using the material plastic/glass as the independent variable and the respective dimensions (valuable, convenient, good, important, natural) as dependent variables. As packaging material, glass is viewed positively - as valuable, good, important, and natural. In each of these dimensions, it receives approval ratings of at least 4 on the 5-Point Likert scale, demonstrating a clear contrast to plastic packaging. Only for the dimension convenience, no significant differences could be found $F(1,308)=0.043$, $p=0.837$, coinciding with the results from survey 1 and the SCR displayed as light lines for illustrative purposes. Mean, standard deviation, F-tests, p values, and η_p^2 for all dimensions can be found in Table 2.

The results of the free association part reveal vast differences in the perceptions of plastic and glass among participants. Plastic was mainly viewed negatively (see Section S5 in the Supplementary material), with 71% of participants expressing purely negative associations ("Too much plastic packaging. Sometimes completely unnecessary or even double and triple packaged" or "Should be abolished!") compared to only 5% who had solely positive associations ("convenient, protection from dirt" or "I think it's good") and 7% neutral ("is ok" or "bottles"). A total of 14% of participants expressed mixed sentiments about plastics, providing responses that included a combination of negative, positive, and/or neutral elements ("Makes very long-lasting, simple, but massively harms the environment" or "Convenient, protection, too much, waste in nature, microplastics"). In contrast, 36% of participants held purely positive associations for glass ("hygienic, recyclable, good for stacking in the cupboard" or "sustainable, reusable"), and 16% expressed purely negative views ("expensive, heavy, greenwashing" or "Heavy, fragile, takes up a lot of space"). In general, glass exhibited more ambivalent perceptions, with participants frequently stating conditions, e.g., glass being more sustainable only if a deposit-return system (DRS) is in place, equaling 25% of statements con-

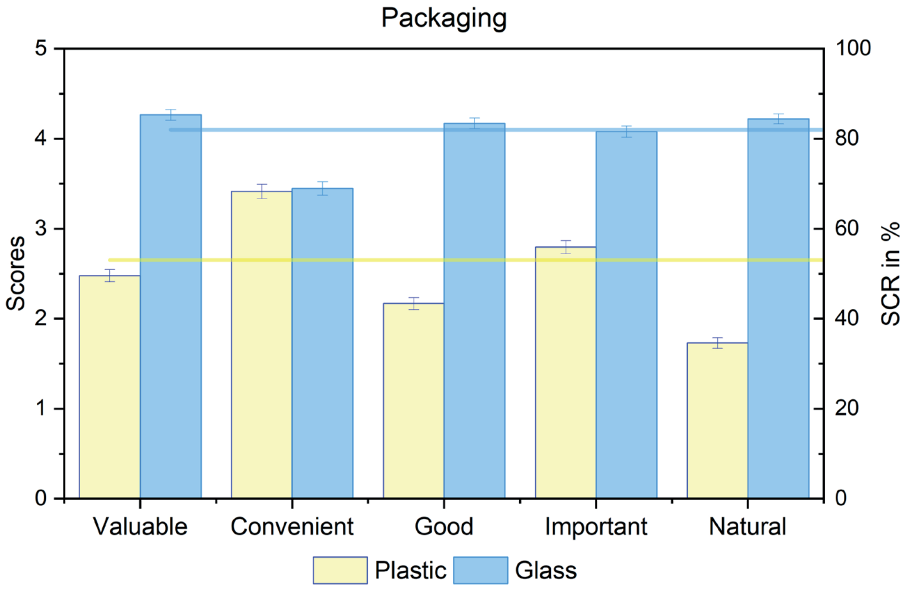

FIGURE 3: Mean and standard errors of the perception of glass and plastic packaging (between-subject design) across the dimensions valuable, convenient, good, important, and natural (N = 310). The respective Austrian SCR is displayed for information purposes as a line (right axis) containing the same colors and starting at the bar regarding the material.

TABLE 2: Mean and standard deviation for the perception of plastic and glass packaging (between-subject design) across the dimensions valuable, convenient, good, important, and natural (N=310).

Dimension	$M_{plastic}$	$SD_{plastic}$	M_{glass}	SD_{glass}	F test	p value	η_p^2
Valuable	2.48	1.20	4.26	1.04	196.1	<0.001	0.389
Convenient	3.41	1.39	3.45	1.36	0.043	0.837	0.000
Good	2.17	1.19	4.17	1.05	246.5	<0.001	0.445
Important	2.79	1.26	4.08	1.13	89.33	<0.001	0.225
Natural	1.73	1.04	4.22	0.98	472.7	<0.001	0.605

sisting of a combination of positive, negative, and neutral ("great if deposit glass otherwise useless and no better than plastic" or "basically a good idea. But if I then have to pay 20 cents more for the milk, it's a rip-off in my eyes and I'll go back to the usual tetra pack [beverage carton].")

Various categories as displayed in Figure 4 on the vertical axis, could be derived from the participants' associations, which led to one or more categories per person. A total of 269 associations were divided into 21 categories for plastics and 280 associations into 22 categories for glass. The categories were classified as positive, negative, or neutral, with a minority of cases showing multiple simultaneous classifications, e.g., a DRS for glass was considered positive as well as negative. For further information, see Section S5 in the Supplementary material.

Several key categories reflecting participants' negative perceptions of plastic packaging were derived from their associations. Figure 4 (a) shows the general rated distribution of the association given in categories. Predominant concerns included the perceived overwhelming quantity of plastic products and waste, the environmental pollution associated with it, and the underutilized availability of alternative materials (paper, glass, no packaging at all). Moreover, plastic packaging was recurrently deemed "unnecessary," and negative emotions such as bad, terrible, deceptive, and annoying dominated. In contrast, plastic was associated with convenience and hygiene, frequently mentioned as advantages.

For glass, the categories behind negative perceptions were primarily related to its physical characteristics: participants mentioned its weight, fragility, and higher costs, see Figure 4 (b). The positive attributes associated with glass emphasized its reusability, recyclability, and perception as a sustainable and environmentally friendly option. Many participants explicitly noted that glass was viewed as superior to plastic or an unknown alternative (category called "better"), and many participants associated it with positive emotions such as good, great, or aesthetically pleasing.

4. DISCUSSION

4.1 Discussion and interpretation of consumers' perception of plastic

The negative perception of plastic has been confirmed in various studies, primarily in relation to packaging (Heidbreder et al., 2019). However, the present study demonstrates that plastic as a material itself is not perceived as valuable, important, good, nor natural. The only exception is in terms of convenience, where plastic is rated more similarly to other materials by this sample. This reflects its widespread use out of convenience, such as when consumers forget to bring their own bags (Mühlthaler & Rademacher, 2017). Furthermore, convenience is demanded of the packaging itself, for example, a possible closure for the use-phase influences the purchase (Rokka & Uusitalo, 2008) or the lightweight and transparency (Teck Kim et al., 2014) advocates for plastic and could explain the better rating for convenience as a material. However, perceived convenience also plays a crucial role in disposal. Factors, such as adequate storage space at home and a short distance to collection points, which should have a clean appearance and be strategically located (Knickmeyer, 2020), influence recycling behavior. Some packaging types, like meat trays, which might leak or develop unpleasant odors, are particularly inconvenient to store for recycling (Nemat et al., 2022).

Recycling "on the go" presents further challenges. When only mixed municipal solid waste bins are available, it is indeed inconvenient to recycle properly. Furthermore, consumers often choose them as the "safe" option as it is often unclear how and where to recycle waste properly (Hartl & Hofmann, 2024). Summarizing, since the correct disposal step requires consumers' intrinsic motivation, knowledge, feeling of easy access to infrastructure and physical action (Botetzagias et al., 2015; Tonglet et al., 2004), the desire for convenient disposal seems not to be reflected in the perception of plastic waste which is likely to hinder increasing collection rates. Nevertheless, glass proves easy access to recycling does not represent the only decisive element: it displays recycling rates around 75% in the EU (Eurostat, 2024b) although the majority of the EU Member States has a bring system implemented, which is usually less convenient for consumers (Seyring et al., 2016). In Austria, glass is collected exclusively through a bring system, while plastic is often collected more conveniently, often comingled, and as a door-to-door or bring system (Schuch et al., 2023; Seyring et al., 2016). Indeed, glass has a long reuse and recycling history (Busch, 1987), while plastic was introduced as a disposable material with little regard for recycling (Cosgrove, 2014; Meikle, 1995).

This discrepancy could be explained by a higher perceived value of glass as confirmed in this study. From Survey 1, which compared all materials within each other, it can be assumed that the value of plastic waste is perceived similarly to the material itself. This may also mean that plastic is always perceived as waste in terms of value, regardless of whether the material itself or the waste is asked about. This is supported by Survey 2, in which

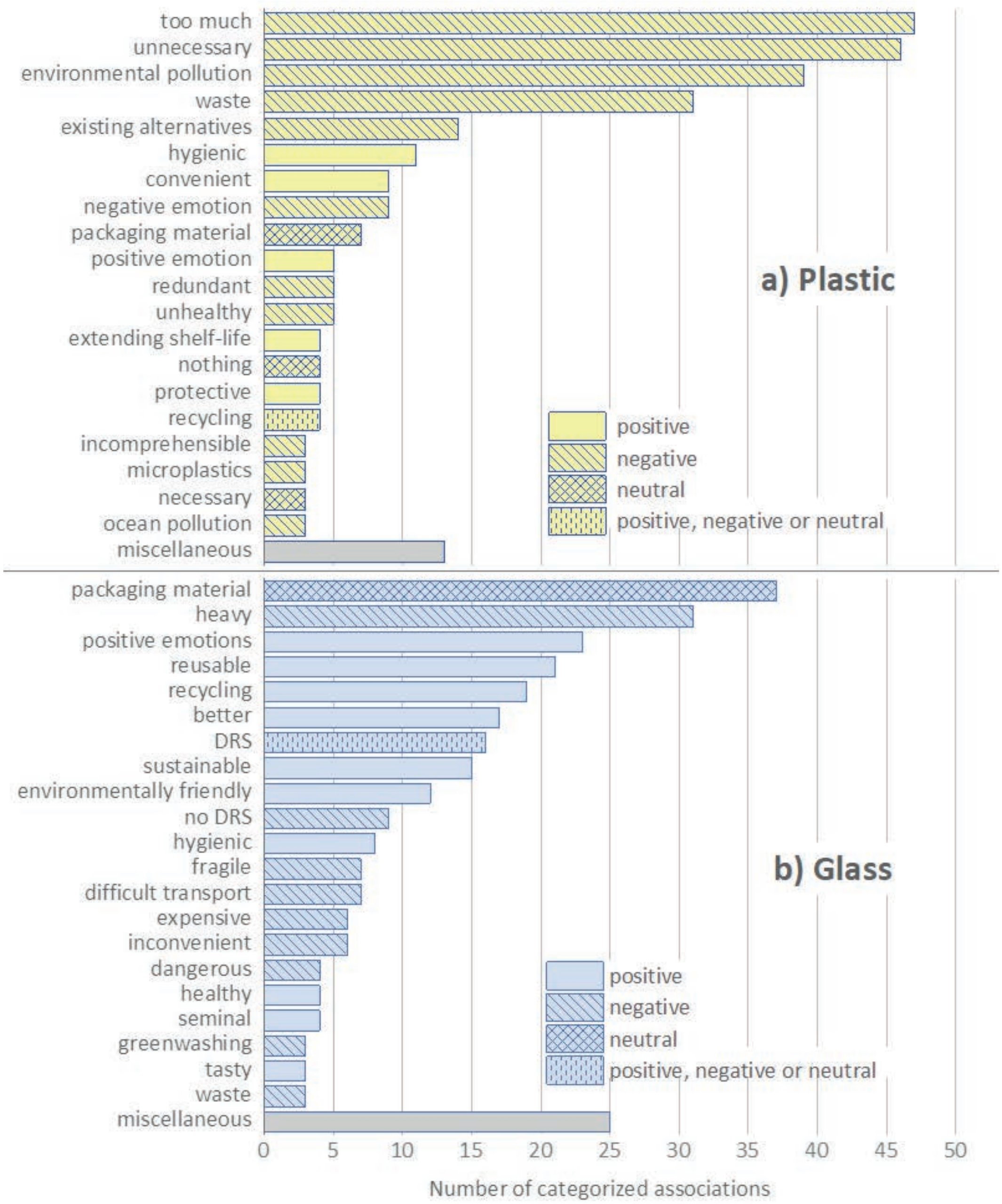

FIGURE 4: Free associations for (a) plastic and (b) glass and the corresponding categories on the left. The categories can be assigned positive (solid), negative (striped), or neutral (crossed). In two cases (deposit-return system (DRS) and recycling), the reasons matching the category were positive, negative, or neutral, so the category cannot be clearly assigned. (In between-subject design) (N=310).

associations with "waste" ultimately lead to the category with the fourth most frequent mentions and is consistent with a pilot study conducted by Koenig-Lewis et al. (2022) in which participants considered plastic food packaging as "waste". Additionally, a study by Bertling et al. (2018) came to similar conclusions, with plastics taking last place when asked about the value of materials, which was attributed to the fact that they are often used as replacements for more expensive goods such as ivory or, in the case of packaging, their primary function is to safeguard products, consequently making the plastic packaging itself appear comparatively low in value. Glass was ranked in second place after wood. This different perception, particularly between glass and plastic, could even be illustrated in a blindfold experiment with Italian students where products were judged to be better when believed to be coming from glass packaging (Balzarotti et al., 2015). This is unfortunate, as the perceived value influences perceived product quality (Magnier et al., 2016) purchasing and recycling intentions (Landaran Isfahani et al., 2023; Testa et al., 2022). While refillable and reusable functions, which are more common in glass packaging, add value, and result in increased recycling of this packaging (Langley et al., 2011; Nemat et al., 2022), distortions, such as crumpling, impair recyclability (Trudel et al., 2016). Additionally, plastic packaging often loses value as it is smaller in size, rarely reusable and frequently contaminated by greasy or sticky residues (Nemat et al., 2020, 2022). At precisely this point, the Single-Use Plastics Regulation (European Commission, 2019b) intervenes, targeting small items like cotton bud sticks, balloons, or cigarette buds and items which have lower value when being made of plastic like plates, cups, or cutlery and are therefore carelessly disposed of in the environment.

Finally, while naturalness is closely interlinked with the perception of environmental friendliness (Steenis et al., 2017), it is understandable that a synthetically produced polymer (Selke et al., 2021) is not considered natural.

In general, in Survey 1, when asked about waste, the results show a slightly lower agreement than for the material itself. This reflects the fact that waste is automatically seen as something with less value or even without any value at all (Thompson & Reno, 2017). Nevertheless, paper, glass, and metal achieve relatively high approval ratings, as all means are above 3 on a 5-point Likert scale, so materials can be seen as valuable, even when already being "waste", and those also have higher SCR than plastic. This might be one of the reasons that 47% are not considered recyclable and end up in mixed waste streams in Austria (Lipp & Lederer, 2025) which leads to considerably lower recycling quotas of plastic. With a recycling rate of 26.9% in Austria compared to 42.1% in Europe and a target of 55% by 2030, Austria, like many other Member States, still has some catching up to do in this area (Eurostat, 2024a).

Additionally, Survey 2 suggests that plastic is not perceived as recyclable, while glass is considered in the free associations as "recyclable," "reusable," "sustainable," and, in general, "environmentally friendly." In contrast, for "plastic as food packaging" associations like "too much," "waste," and "unnecessary" dominated the results. The expression "unnecessary" was also found to be mentioned in two studies in Germany (Herrmann et al., 2022; Rhein & Schmid, 2020) and two studies in Sweden, one as a focus group and the other as a consumer survey, as well as a general negative opinion (Fernqvist et al., 2015; Lindh et al., 2016). This aligns with the findings of Otto et al. (2021), in which consumers reported that too much packaging is used, especially for fresh products. This leads to consumers who wish to avoid overpackaging they perceive as unnecessary e.g., toothpaste packaged in carton (Lindh et al., 2016), and even change the previously purchased brand (Pro Carton, 2025). However, this is not only consumer perception, until 2021 increasing numbers of all packaging materials confirm this view (Eurostat, 2024b). Beyond overpackaging, the limited recyclability especially of plastics constitutes a substantial concern and is not only perception. Lipp and Lederer (2025) show that plastics have a SCR of 53%, but only a 25% recycling rate, resulting in a loss of 28%, compared to just 1–3% for paper, glass, or metals. Improvements must be made at the design stage (FH Campus Wien, 2024) and extended producer responsibility (European Commission, 2018a) must be taken seriously. An example for a possible redesign of packaging are easier separable material combinations, where necessary due to stability and barrier properties (Richter et al., 2014), or recyclable multilayer packaging which is already possible with ideal combinations (Seier et al., 2023).

Of course, one of the highest priorities for all materials in the waste management hierarchy is prevention (Potting et al., 2017).

4.1.1 Implications arising from the results and their interpretation

Compared with the other dimensions plastic performs better in terms of convenience, there it ranges closer to the other materials and does not differ significantly from metal.

However, as waste it lacks approval of being convenient. This suggests that the disposal process for plastic waste might be perceived as unclear and that further measures are needed to remedy this. Consequently, packaging-waste collection systems must be designed to be as convenient as possible for consumers. Austria recently addressed this issue by introducing a uniform nationwide collection system for all lightweight packaging (including metals) (ARA - Altstoff Recycling Austria, 2024). However, in public spaces separate collection is still lacking and could lead to further improvements (Kladnik et al. 2025). In addition, sticky or greasy residues hinder convenient collection for recycling. Highlighting the value of plastic, irrespective of cleanliness, may enhance recycling intention, and support a more efficient plastic cycle. According to the vision of Dennis (2024) (p. 6): "The future use of plastics needs to be a time when the true value of the materials is considered." Similarly, strong positive perceptions of paper and glass seem to correspond to high SCR.

Companies need to gain the trust of consumers and provide credibility through clear communication and better design for recycling (e.g. better emptying (Wohner et al., 2019)) otherwise, participation will be low (Henriksson et al., 2010). To move toward circularity, manufacturers and packaging designers must rethink their products, prioritize recyclability, and expand the use of refillable and reusable formats that can enhance the perceived value of plastic.

Policy makers can increase the value of plastic by creating incentives for recycling through various economic measures, such as setting mandatory targets for recycling rates and recycled contents, introducing a DRS, and enforcing penalties but also by unifying pictograms for recycling (European Commission, 2025; Larrain et al., 2021).

Especially in comparison to paper and glass, the current negative view of plastic is evident and is, as our results show, already associated with the material itself. This is evident from Survey 1, in which all materials were surveyed, and was confirmed in Survey 2, in which only plastic and glass were compared. In addition, the free associations of Survey 2 confirmed the discontent with the vast amounts of plastic which are perceived as too much. Combined with the literature, this underlines the need to reduce packaging where possible and avoid unnecessary combinations of packaging.

In addition to technical solutions, we suggest formulating more carefully as Ertz et al. (2016) suggest that fostering positive attitudes can promote pro-environmental behavior.

At present, however, plastic as waste is seen as neither valuable, important, convenient, good, nor natural as other materials. This negative perception poses a major challenge for plastics recycling, as plastic is much more likely to be recycled when collected separately (Plastics Europe, 2022). While a well-functioning collection system is of high significance for waste management, also the consumer is crucial and the current clearly visible negative perception of plastic as a material or waste in comparison to the other materials investigated is most likely a disadvantage.

4.1.2 Limitations

This research focused entirely on consumers' self-reported perceptions of materials, packaging, and waste, with an emphasis on plastic and glass. Since our studies capture only perceptions, further research is needed to examine how these perceptions align with actual consumer behavior. While perceived convenience is a recognized and important influencing factor for recycling behavior, its specific relationship with plastic as a material remains unclear. To the best of our knowledge, no research has directly explored this link. Additionally, the free associations of Survey 2 did not clarify what respondents specifically meant by "convenience". Further studies could investigate this aspect to gain deeper insights.

A further limitation of the study is that the sample was recruited from an online panel of a market research agency rather than through random probabilistic sampling. Although the samples´ sociodemographic characteristics closely resembled those of the Austrian population and panel-based research is common in research on consumer perception (c.f. Geissmar et al., 2023; Hofstetter et al., 2024; Sokolova et al., 2023), panel-based samples might still differ in unobserved ways from the general population. Therefore, caution is important when generalizing the findings beyond the study sample.

Furthermore, regarding Austrian policy regulations over the past two decades, various measures have been evaluated and implemented to improve recycling plastic packaging, with a special focus on Vienna, where the positive effects of a combined collection system and technical improvements for plastics and metals have been confirmed (Gritsch & Lederer, 2023; Schuch et al., 2023). As a member of the European Union, Austria follows the EU Commission's regulations, including the recently updated Packaging Regulation (European Commission, 2025). This regulation sets a target of recycling 50% of plastic packaging by the end of 2025, a significant increase from the 22.5% target set in 2008 (European Commission, 2004) which was met without difficulty (Van Eygen et al., 2018). However, the very high new recycling target, as well as a revised calculation method introduced in 2019 (European Commission, 2019a) for better comparability among member states, led to lower reported recycling rates and set Austria under pressure. Therefore, the most recent step in Austria's waste management reforms is the implementation of a DRS in 2025, alongside the full unification of the collection system across the country with the aim to fulfill the targets (ARA - Altstoff Recycling Austria, 2024). The scheme ensures recycling of collected plastic bottles and metal cans while continuing to cover reusable plastic and glass bottles and containers (ARA - Altstoff Recycling Austria, 2024). Given the recent changes, it will be very interesting to observe if, with the DRS, the value of plastic packaging, in general, can improve or if only bottles will increase in perceived value, assuming that no further actions will be taken, although we would encourage additional measures. The study data displayed, however, pictures the perception before those changes.

5. CONCLUSIONS

Returning to the initial question, the study clearly demonstrated that materials such as paper and glass retain a high perceived value even when considered waste. This, however, does not apply to plastic, which is perceived far more negatively than other materials. This was confirmed through two different surveys with representative samples of Austria. Both an in-between-subject design and a within-subject design showed that plastic is rated significantly lower in the dimensions valuable, good, important, and natural. The only dimension in which plastic was not viewed as the worst material was convenience, but even with the free associations, it was not possible to undoubtedly explain what the perception of plastic as convenient was based on, which could be investigated in further detail.

The findings for plastics were largely anticipated. However, the evidence that other materials retain value, and that this might be reflected in higher SCR, reveals an untapped lever for improving recycling rates.

Consumers need to be made aware of the importance of collecting plastic waste as it is a valuable resource for new recycled plastics, especially given its prevalence in society. This complex challenge must be addressed with various measures like recycling targets, recycled contents, economic incentives in various forms, and improved product design to enhance recyclability. So that plastic will also be associated with positive aspects of sustainability in the future, as is currently only the case with glass, as seen by the participants' free associations in Survey 2.

While producers use the convenience factor to increase purchase intentions, they must be held responsible for the fact that this, in turn, requires a convenient collection system for a functioning recycling loop. This responsibility must not be shifted and should be tackled through consultation with recyclers to achieve the best possible solutions, and a clear communication strategy with the consumer, like proposed by the EU, with unified symbols (European Commission, 2025).

To sum up, improving the public perception of plastic (waste) requires clear communication, better design, and stronger circular systems.

First, products must be designed to be more durable, reusable, and easy to recycle, helping consumers see plastic as valuable materials rather than disposable items.

Second, the benefits of plastics, such as low weight, longevity and resource efficiency need to be communicated more effectively.

Third, well-functioning collection and recycling systems, along with visible use of high-quality recyclates, can strengthen the idea of plastics as a resource. Meanwhile, raising awareness about proper disposal and highlighting innovations in recycling and circular design can further shift perceptions toward plastics as part of a sustainable material cycle.

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INNOVATION IN THE PATH OF CLEANER PRODUCTION AUDIT MECHANISM FROM THE PERSPECTIVE OF CIRCULAR ECONOMY IN WASTE MANAGEMENT

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ABSTRACT

Facing climate change and resource constraints, cleaner production (CP) and the circular economy (CE) are essential for achieving China's "dual carbon" goals. While CP and CE form a mutually reinforcing coupling through material flow synergy and waste management synergy, conventional cleaner production audits (CPA) remain limited to enterprise-level scope with fragmented waste management, failing to capture systemic resource circulation opportunities. To address this gap, the research proposes an innovative CPA mechanism integrating CE principles for enhanced waste management. The mechanism introduces three innovative pathways: (1) methodological transformation from enterprise-level to industry/park-level overall audit; (2) process optimization through refined waste and material flow management; and (3) evaluation criterion reconstruction integrating waste management and resource recovery indicators. This approach provides theoretical foundations and practical pathways for implementing CE-oriented waste management, contributing to SDG 12 (Responsible Consumption and Production), SDG 9 (Sustainable Industrial Development), SDG 13 (Climate Action), and China's "Dual Carbon" objectives. While empirical validation through case studies remains a priority for future research, the proposed framework establishes a comprehensive methodological foundation for transforming conventional CPA practices toward circular economy principles.

1. INTRODUCTION

In the context of global climate change and increasingly prominent resource and environmental constraints, improving waste management efficiency and promoting resource recovery have become key tasks for countries to achieve sustainable development (Geng et al., 2019; Varsha et al., 2025). The global economy currently consumes approximately 100 billion tonnes of raw materials annually, with less than 6.9% being recycled and reused (Circle Economy, Circularity Gap Report 2025). Consequently, this linear economic model not only exacerbates resource depletion but also poses serious threats to ecosystems. China, as the world's largest developing country, has clearly put forward the dual carbon goals (carbon peak and carbon neutrality), which require a fundamental transformation from the traditional linear economic model to a circular model centered on waste reduction, reuse, and recycling (Jiang, 2025). The transition to a circular economy (CE) is estimated to have the potential to reduce global greenhouse gas emissions by 25 billion tonnes by 2030 and significantly alleviate resource pressure (Circle Economy, Circularity Gap Report 2025).

Cleaner production (CP), as a crucial means of pollution prevention and resource conservation, has been promoted in China for over two decades. Since the enactment of the CP Promotion Law in 2002, remarkable accomplishments have been made in energy conservation and emission reduction across the country (Chen et al., 2023; Zhang et al., 2023). Since 2016, over 40,000 enterprises nationwide have conducted mandatory cleaner production audits (CPA), with total investment in CP transformation exceeding RMB 270 billion and more than 610,000 CP schemes proposed. Moreover, remarkable achievements have been made in pollution reduction and carbon emission mitigation. According to available statistics, the implementation of CP transformations has resulted in the reduction of approximately 5.16 billion tons of wastewater, 370,000 tons of chemical oxygen demand (COD), 51,000 tons of ammonia nitrogen, 688,000 tons of sulfur dioxide (SO_2), and 567,000 tons of nitrogen oxides (NO_2). Additionally, through the conservation of electricity, coal, natural

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gas, and other energy sources, the cumulative reduction in carbon dioxide (CO_2) emissions has reached approximately 4.37 billion tons (Ministry of Ecology and Environment, 2022). Nevertheless, conventional CPA primarily focus on individual enterprises, lacking systematic coordination in waste management and resource recovery at the industrial or park level (Li et al., 2025). This leads to problems such as fragmented waste recycling, low resource recovery efficiency, and difficulties in forming synergistic effects with regional CE systems. For instance, in typical industrial parks, a substantial proportion of potential waste exchange synergies remain unrealized due to persistent institutional barriers and inadequate audit mechanisms (Sokka et al., 2020; Fraccascia et al., 2020).

Currently, the CPA system is confronted with three fundamental challenges in adapting to the requirements of the CE. First, there is a mismatch in audit scope. conventional CPA is confined within the boundaries of individual enterprises, while the CE demands consideration of cross-organizational material flows (General Office of the Ministry of ecology and environment, 2022; de Oliveira et al., 2023). This discrepancy gives rise to what scholars refer to as the "island effect" in CP, where individual enterprises achieve internal optimization, yet the systematic resource circulation loops remain unclosed (Fraccascia et al., 2020). Second, there exists a deficiency in methodologies. Existing CPA lack standardized approaches for tracking waste streams across different enterprises and industries. The absence of material flow analysis frameworks tailored for industrial symbiosis makes it difficult to identify and quantify opportunities related to the CE (Gupta et al., 2021). Third, there is a gap in the evaluation system. Current performance indicators mainly center on in-enterprise pollution control and energy efficiency, failing to incorporate metrics that reflect CE performance—such as cross-facility resource productivity and waste valorization rates (Ferrante et al., 2025; de Oliveira et al., 2023). Leading countries in CE development, including Germany and Japan, have established extended producer responsibility systems and industrial symbiosis promotion mechanisms, thereby substantially enhancing their national resource efficiency and reducing environmental pollution (Kripalani et al., 2025; Environmental Research & Education Foundation, 2025; Helena Dickinson, 2024; Alev et al., 2020). However, these experiences cannot be directly applied in China due to differences in industrial structure, governance systems, and development stages. Therefore, developing an innovative path of CPA mechanism from the perspective of CE in waste management that suits China's national conditions not only holds theoretical value but is also crucial for achieving the dual carbon goals.

Despite growing recognition of CE principles in waste management, a critical research gap persists: existing CPA lack systematic frameworks for tracking cross-enterprise resource flows and quantifying inter-organizational circularity performance. This study addresses this gap by constructing an innovative CPA framework that operationalizes CE principles within waste management. By integrating theories of industrial ecology, institutional analysis, and environmental management, we develop a tool to advance system-level circularity through auditable enterprise actions. The analysis proceeds through a critical review of current CPA limitations and the presentation of a new CPA framework from the perspective of CE. The research provides theoretical contributions by bridging CE and CPA scholarship, and practical value by offering policymakers an actionable roadmap to boost resource efficiency through audit mechanism innovation.

2. THEORETICAL BACKGROUNDS

2.1 CP and the CE

CP and the CE are core pathways driving the green transformation of industry. The two approaches form a complementary system in the fields of waste management and resource utilization, characterized by "source control–system closure". Clarifying their conceptual boundaries and coupling logic provides the theoretical foundation for establishing a CE-oriented CPA mechanism.

CP (Cleaner Production): Guided by the concept of "holistic prevention", CP takes reducing pollutant emissions, conserving resources, and improving production efficiency as its core objectives, and implements comprehensive control throughout the production process (covering raw material procurement, product design, and production packaging and transportation) (UNEP, 2001). Its key measures include process optimization, clean energy substitution, and internal resource recycling, with the goal of minimizing waste generation at the source and laying a foundation for subsequent waste management and resource recovery.

CE (Circular Economy): Centered on the "3R Principles" (Reduction, Reuse, Recycling), CE extends the scope of resource management beyond individual enterprises to the entire industrial chain and regional system (ISO, 2023). It focuses on building closed-loop of waste recycling and resource recovery systems, realizing the transformation of waste into renewable resources through multi-level coordination across enterprises, industries, and regions, and ultimately achieving the dual goals of waste minimization and resource utilization maximization (Ellen MacArthur Foundation, 2013).

2.2 Coupling relationship between cleaner production and circular economy

CP and CE are not mutually independent; rather, they form a deeply integrated system characterized by "front-end reduction and back-end recycling" (Figure 1). Recent research demonstrates CP-CE coupling through the sustainable energy conversion of lignocellulosic and urban waste via modified downdraft gasification, producing clean fuel within a circular economy framework while reducing waste disposal burdens and environmental pollution (Saravanakumar et al., 2026). Studies further indicate that waste-to-hydrogen technologies utilizing municipal solid waste and biomass as feedstocks embody CP-CE coupling via material valorization and clean energy generation. Substituting diesel with hydrogen in fuel-cell vehicles from 2025 to 2045 is projected to substantially reduce 8.00-14.43 million tonnes of CO_2 and 2.30-4.09 million tonnes of CO emissions (Rahman et al., 2025). This structure creates

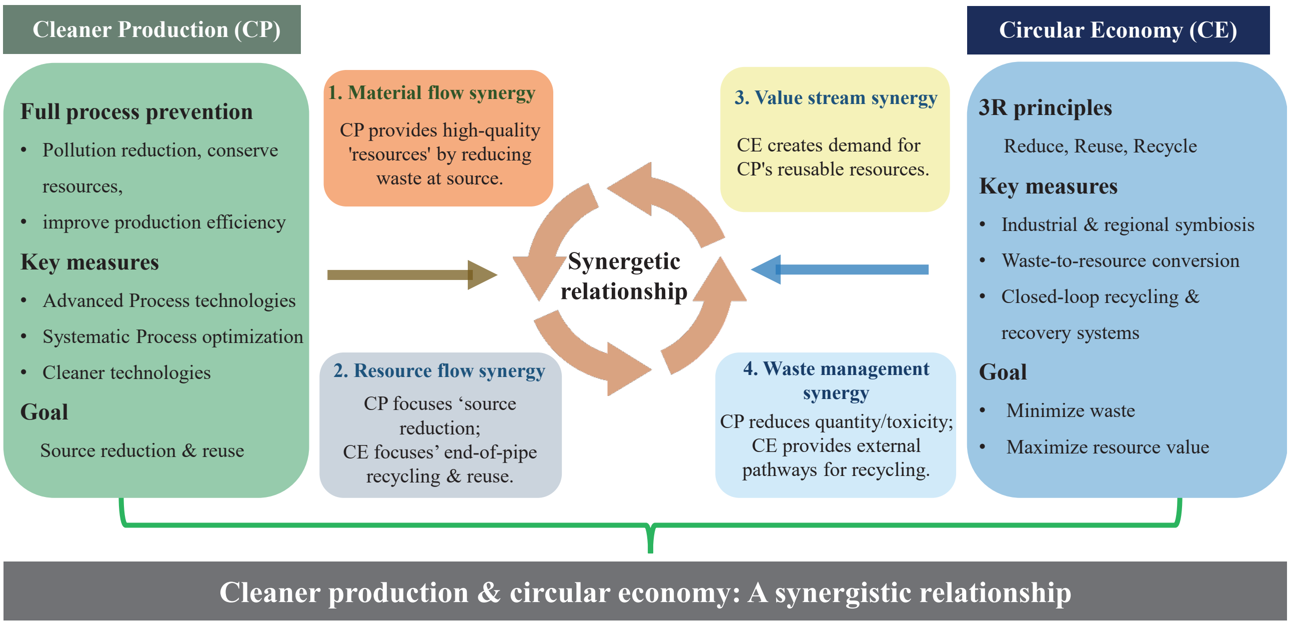

FIGURE 1: Coupling relationship between CP and CE.

a synergistic, mutually reinforcing effect in the fields of waste management and resource recovery, which is specifically manifested in two dimensions: material flow synergy and waste management synergy (Geng et al., 2012).

Material flow synergy: CP optimizes material utilization efficiency within enterprises, reducing waste generation at the source and thereby alleviating the pressure of subsequent waste treatment and provides high-quality "recyclable raw materials" for the CE system. In turn, CE expands channels of resource recovery, enabling waste from one enterprise to be reused as raw materials for another, which further promotes enterprises to deepen CP practices (Lieder & Rashid, 2016).

Waste management synergy: CP focuses on "source reduction" of waste, while CE focuses on "end-of-pipe recycling" and "systematic reuse" of waste. The combination of the two forms a "source reduction-recycling-reuse" full-chain waste management model, avoiding the limitations of single-stage management and improving the overall efficiency of waste management (Sousa-Zomer et al., 2018).

3. LIMITATIONS OF CONVENTIONAL CLEANER PRODUCTION AUDIT IN WASTE MANAGEMENT

The conventional CPA in China predominantly concentrate on individual enterprises, exhibiting significant limitations in effectively supporting waste management and resource recovery (Sokka et al., 2020).

Narrow scope of audit: The conventional CPA only covers the internal production process of the enterprise, ignoring the connection of waste and resources with upstream and downstream enterprises in the industrial chain (Li et al., 2016). For example, a chemical enterprise may reduce its own wastewater discharge through CP. However, the slag or solid waste it generates often cannot be effectively recycled due to a lack of coordinated planning with downstream treatment or recycling facilities. This disconnect not only leads to secondary pollution but also results in suboptimal resource recovery rates, undermining the systemic benefits of CP (Lyu et al., 2022).

Inadequate management of waste and material flows: The conventional CPA pays more attention to the quantitative reduction of pollutants but lacks refined tracking and analysis of waste generation stage (the type, quantity, and composition of waste generated in each production stage). This makes it difficult to identify the key stages of waste generation and formulate targeted waste reduction and recovery plans (Huang et al., 2024).

Incomplete evaluation criteria: The assessment of CP performance primarily relies on indicators such as pollutant emission reduction and energy savings, while largely excluding metrics specifically related to waste management and resource recovery. This incomplete evaluation system creates a skewed incentive structure, where enterprises prioritize emission reduction in isolation but neglect resource recovery from waste. This focus prevents a deeper integration of corporate CP activities with the broader goals of the regional CE system, limiting the transition towards a more sustainable industrial paradigm (Peng et al., 2016).

Systemic collaboration deficit: A fundamental weakness lies in the absence of mechanisms to foster cross-enterprise collaboration. The audit process does not incentivize or guide enterprises in forming industrial symbiosis networks, where one entity's waste could become another's raw material. This lack of a systemic perspective confines the environmental and economic benefits of CP within factory boundaries, missing significant opportunities for collective resource efficiency gains across industrial parks or regions (Dang, 2021).

Institutional and governance barriers: Beyond internal enterprise behavior, conventional CPA is severely constrained by systemic institutional and governance barriers. Fragmented regulatory oversight, characterized by siloed policies across different agencies, often imposes conflicting mandates on enterprises. This makes the implementation of holistic audits administratively prohibitive (Zhang et al., 2023; Geng et al., 2012). This structural complexity is further exacerbated by the significant absence of market-pull policy incentives, such as green credits or fiscal rewards; without these, audits remain a compliance-push cost center rather than a strategic value driver (Zhang et al., 2021). Consequently, weak enforcement and the lack of standardized monitoring allow these audits to degenerate into a superficial "check-the-box" exercise, where the absence of rigorous third-party verification decouples regulatory compliance from genuine environmental performance (Peng et al., 2016).

4. PATH INNOVATION OF CP AUDIT MECHANISM BASED ON CE (FOCUS ON WASTE MANAGEMENT)

To address the limitations of conventional CPA, this study proposes three innovative pathways underpinned by the CE concept. Guided by this concept, a novel CPA framework focused on enhancing waste management and resource recovery efficiency has been formulated, as illustrated in Figure 2.

4.1 Methodological transformation: from enterprise-level audit to industry/park-level overall audit

Taking key industries (e.g., iron and steel, petrochemical) and industrial parks as audit objects, the CE-oriented CPA expands the audit scope to cover the entire industrial chain or regional waste and resource system. This breaks the island effect of conventional single-enterprise audits and aligns with the systemic requirements of CE (Velenturf et al., 2021).

Industry-Level Audit: Establish an inter-enterprise audit team composed of enterprise representatives, industry associations, and environmental institutions. The team maps the material flow and waste flow network of the entire industry, identifies bottlenecks in waste recycling, including inconsistent waste standards between upstream and downstream enterprises, lack of waste recycling technology, and formulates industry-wide CP improvement plans

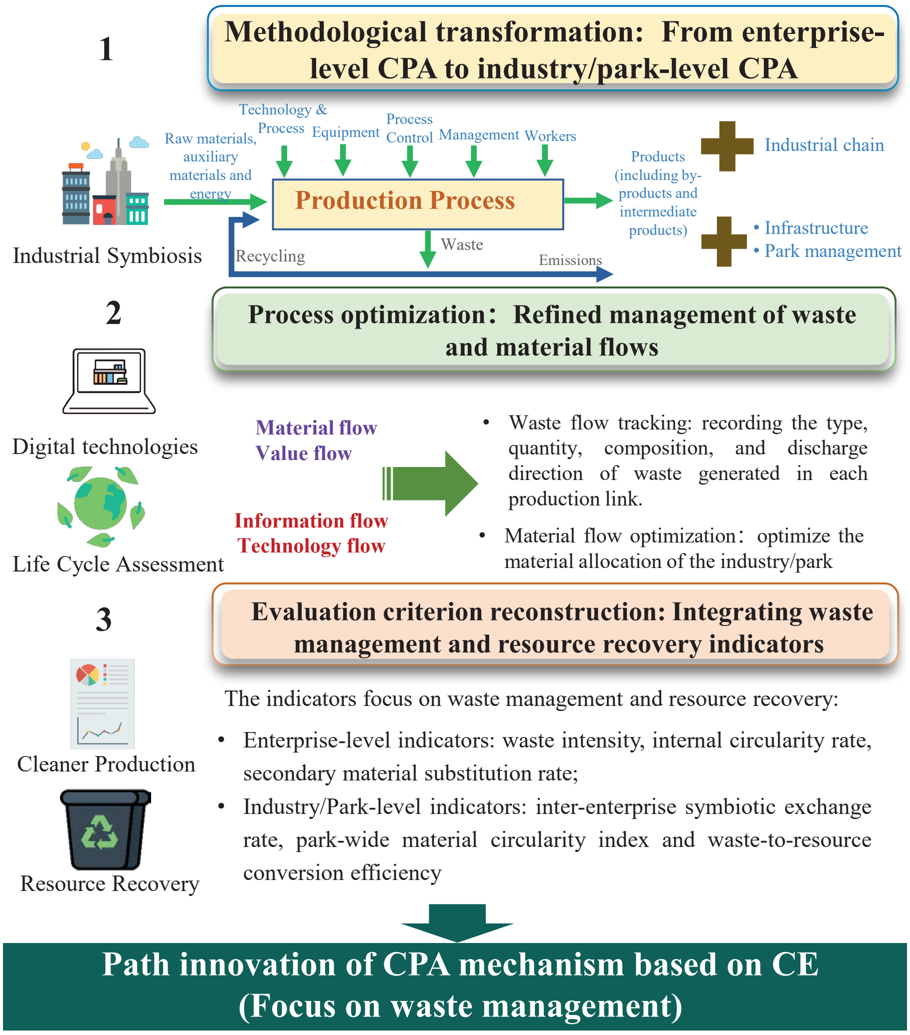

FIGURE 2: Innovative CPA pathways based on the CE (focus on waste management).

(Chen et al., 2024). For example, in the iron and steel industry, the audit promotes the recycling of blast furnace gas between iron and steel enterprises and power plants, and the reuse of steel slag in the cement industry, thereby realizing cross-enterprise waste resourceization.

Park-Level Audit: Take the industrial park as a unit, integrate the CPA of all enterprises in the park, and build a centralized waste management and resource recovery system. For example, the park constructs a centralized waste treatment center to classify, treat, and recycle waste from different enterprises; at the same time, it plans the cascade utilization of waste heat and wastewater in the park to maximize the efficiency of waste resourceization (Figure 3, Wen et al., 2025).

Potential barriers: Practical implementation may encounter potential bottlenecks, including data confidentiality concerns regarding proprietary intellectual property (Ji et al., 2020), elevated coordination costs arising from multi-stakeholder synchronization (Li et al., 2025), and data inconsistencies stemming from disparate enterprise systems, which could complicate the integration of fragmented information into a unified regional audit system (Li et al., 2024).

4.2 Process optimization: refined management of waste and material flows

Introduce digital technologies to realize refined tracking, analysis, and management of waste and material flows in the audit process, thereby solving the problem of information asymmetry in conventional audit material flow management (Zhao et al., 2025).

Waste flow tracking: Establish a waste flow accounting system for industries/parks, recording the type, quantity, composition, and discharge direction of waste generated in each production stage (Zhan et al., 2025). Through data analysis, identify waste generation hotspots and formulate targeted waste reduction measures. For example, by implementing an AI-powered dosing system that precisely controls chemical input, a wastewater treatment company successfully reduced its annual sludge production by 10% (Wu et al., 2025).

Material flow optimization: Based on the material flow accounting system, optimize the material allocation of the industry/park, promote the replacement of virgin raw materials with recycled resources, and reduce the generation of non-recyclable waste (Pilipenets et al., 2025). In a typical chemical park, several enterprises have implemented waste cascade utilization strategies to achieve substantial reductions at the source. For instance, enterprise A now directs sludge to boiler co-processing, reducing landfill-bound sludge by approximately 1,000 tonnes annually. Enterprise B has technologically enabled the full valorization of dimethyl ethanolamine distillation residues, converting a waste stream previously destined for incineration into a resource. Complementing these efforts, a steel plant has commissioned a 3-million-tonne low-carbon cement production line to utilize steel slag and other bulk solid wastes, transforming them into valuable raw materials (Wu et al., 2025).

4.3 Evaluation criterion reconstruction: integrating waste management and resource recovery indicators

The performance evaluation system for CP should be reconstructed to integrate both enterprise-level and CE system-level indicators, with a dedicated focus on waste management and resource recovery efficiency (Battiston et al., 2025; Cui et al., 2022). This integrated framework goes beyond singular metrics, enabling a holistic assessment of the synergies between environmental protection and

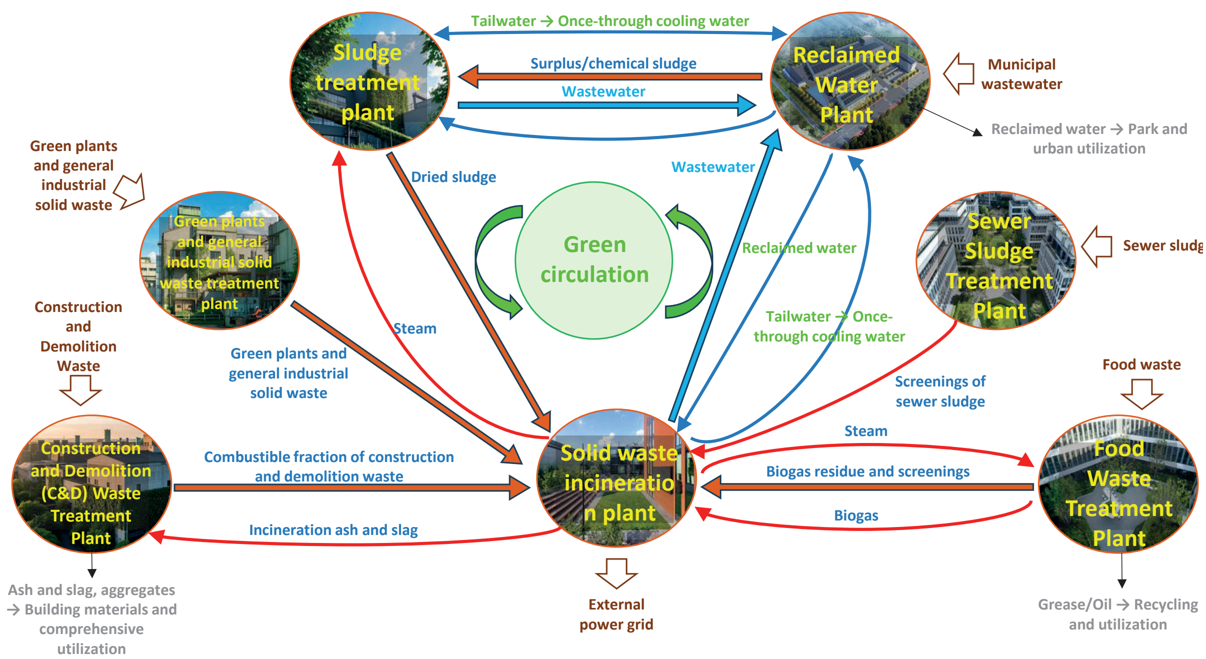

FIGURE 3: Recycling strategy of CE in industrial park (Wen et al., 2025).

economic development. This dual perspective promotes source waste minimization, incentivizes industrial symbiosis and resource circularity, and aligns micro-level production activities with macro-level CE sustainability objectives.

Enterprise-level indicators: From a life cycle perspective (Cui et al., 2022), the key metrics include: (1) waste intensity (i.e., waste generated per unit product), which is measured using material flow accounting covering the entire process from raw material extraction to end-of-life disposal; (2) internal circularity rate, which quantifies the proportion of waste recycled within closed-loop systems; and (3) secondary material substitution rate, which tracks the extent to which virgin materials are replaced by recycled resources. This approach helps identify environmental hotspots beyond individual facility boundaries and across the entire value chain.

Industry/Park-level indicators: Guided by the core principles of CE—closing material loops, slowing resource flows, and narrowing resource input scales (de Oliveira and Oliveira, 2023), the critical metrics include: (1) inter-enterprise symbiotic exchange rate, which reflects the maturity of industrial symbiosis; (2) park-wide material circularity index, which assesses the retention of materials through recycling and energy recovery; and (3) waste-to-resource conversion efficiency, which quantifies the effectiveness of transforming waste into secondary materials or clean energy.

5. CONCLUSIONS

Under the dual constraints of resource scarcity and environmental protection, innovating the CPA mechanism from a CE perspective is imperative for enhancing waste management efficiency, promoting resource recovery, and achieving China's dual carbon goals. This study clarifies the intrinsic coupling relationship between CP and CE in the context of waste management, identifies the limitations of conventional enterprise-level CPA in facilitating waste recycling, and proposes three core innovation pathways: shifting the audit methodology from the enterprise level to industry/park-level assessments, optimizing audit processes through refined waste and material flow management, and reconstructing evaluation criteria to incorporate waste-related indicators.

This proposed green, low-carbon, and circular development model effectively bridges enterprise-level CP practices with regional CE systems, enhancing the overall efficiency of waste management and resource recovery thereby offering a feasible trajectory for the green transformation of key industries. By transforming CPA from an isolated environmental management tool into a systemic driver of the CE transition, this study contributes to China's green industrial upgrading and supports global efforts in tackling climate change and resource scarcity.

Future research should focus on applying this audit mechanism to specific sectors—such as e-waste recycling and construction waste valorization—and exploring the integration of advanced technologies, including artificial intelligence, to further optimize the management efficiency of waste and material flows.

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EFFECTS OF A GAMIFIED SELF-MONITORING APP ON HOUSEHOLD FOOD WASTE REDUCTION

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ABSTRACT
Food waste is a global issue, with approximately half of this waste occurring at the consumer stage. In this study, we focused on refrigerator management behaviors in Japan and conducted an intervention study involving 126 households assigned to intervention and control groups, based on the Motivation–Opportunity–Ability (MOA) framework. Four target behaviors were established: “searching for food that should be used sooner,” “moving such food to visible places,” “using food that should be used sooner,” and “finishing meals.” To promote these behaviors and reduce food waste, a gamified self-monitoring intervention using a behavior-recording app was implemented. The study included three two-week measurement periods: a baseline period, an intervention period, and a follow-up period conducted three months after the intervention. Food waste was measured using a cloud-based automatic weighing system that recorded data every hour, and participants were instructed to separate avoidable food waste and dispose of it in designated bins. The average weekly food waste per household decreased by 190 g (45%) in the intervention group and by 60 g (13%) in the control group, corresponding to a 32 percentage-point difference between groups. A general linear model (GLM) with bootstrap inference, controlling for baseline food waste, indicated a statistically significant reduction in food waste in the intervention group compared with the control group. Among six selected behavioral indicators, four showed significant intervention effects. However, no significant associations were observed between behavioral changes and changes in food waste in the main effects model. More than 90% of participants in the intervention group used the app five or more days per week, and subjective evaluations suggested increased motivation and relatively low perceived burden. These findings demonstrate the effectiveness of a gamified self-monitoring intervention for reducing household food waste.

1. INTRODUCTION

1.1 Background

One-third of the world’s food production is wasted (FAO, 2013), significantly impacting climate change, food insecurity, and resource waste (Jobson et al., 2024). Consequently, the United Nations Sustainable Development Goal (SDG) 12.3 sets an international target to halve food waste by 2030 (United Nations, 2015). Achieving this goal requires implementing effective prevention measures to enable consumers to reduce their food waste (Casonato et al., 2023).

Nonomura (2020) and Porpino (2016) identified behaviors influencing household food waste generation, including unplanned shopping, improper storage methods during preservation and management, forgetting food items in the refrigerator, inadequate management of leftovers, and over-preparation or leftovers during consumption. Among countermeasures for these behaviors, refrigerator management actions to use up stored food in the refrigerator differ from shopping behaviors or storage and cooking techniques. Failure in refrigerator management directly leads to discarding food. Proper management, however, holds significant potential to reduce the unused ingredients and leftover food that constitute a large portion of food waste (Hebrok & Boks, 2017; Waitt & Phillips, 2016; Yamakawa, 2020).

Initiatives to encourage household food waste reduction behaviors often rely on information provision (He-

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brok & Boks, 2017; Stöckli et al., 2018; Yamakawa, 2020). However, informational interventions are generally considered to have limited effectiveness (Casonato et al., 2023; Simões et al., 2022; Stöckli et al., 2018). Non-informational interventions include those utilizing nudges or environmental modifications through physical devices (Boulet & Lauren, 2024; Cooper et al., 2023; European Commission Joint Research Centre, 2023; Farr-Wharton et al., 2014b; van der Werf et al., 2021; van Herpen et al., 2023), and food management apps based on information and communication technology (ICT) (European Commission Joint Research Centre, 2023; Farr-Wharton et al., 2014a; Ganglbauer et al., 2013; Mathisen & Johansen, 2022; Vogels et al., 2018). Smartphones are readily accessible to many consumers; therefore, interventions utilizing smartphone apps and similar tools hold significant potential for reducing household food waste (Castro et al., 2023). Furthermore, ICT tools and apps are expected to be powerful tools for policy implementation, as they have the potential to reach consumers across various socioeconomic strata (Vogels et al., 2018).

In our previous research, the use of smartphone photography and food management apps as ICT tools had a marginally significant effect on reducing food waste. The previous study identified three target behaviors within refrigerator management actions to help use up stored food, including "search for food that should be eaten sooner", "move it to a visible place", and "use the foods that should be eaten sooner". The results suggested that these actions improved refrigerator organization and effectively reduced food waste (Seta et al., 2025). On the other hand, using a food management app for refrigerator inventory management presented challenges related to the burden of data entry. Additionally, the motivation to use the app and to reduce food waste relied solely on information provision. Consequently, reducing the burden when utilizing ICT tools and developing interventions to motivate users beyond information provision are key challenges. This study examined two non-informational intervention strategies to address these challenges: (1) self-monitoring to directly promote target behaviors and (2) interventions utilizing gamification to increase motivation.

1.2 Literature review

1.2.1 Interventions involving self-monitoring

Interventions that track behaviors can be considered a form of self-monitoring. Self-monitoring involves tracking one's performance by recording actions and their outcomes, thereby gaining information about both past and present behaviors (Nkwo et al., 2021; Orji & Moffatt, 2018). Self-monitoring has applications in health and education and has gained recognition as an effective tool for behavioral change (Guo, 2022; Michie et al., 2009; Morrow et al., 2022; Page et al., 2020). When faced with an objective, self-monitoring leads to self-awareness of the gap between the goal and the current state, thereby activating motivation to bridge that gap. In experiments within the food waste field, the food waste diary (hereafter referred to as the diary) serves as an equivalent to self-monitoring. In a journal format, the diary is intended primarily to measure food waste volume by recording discarded food items and the reasons for disposal (Ganglbauer et al., 2012, 2015; Hartikainen et al., 2025). Moreover, reporting food waste is also expected to increase awareness of waste volume, thereby potentially reducing it (Visschers et al., 2016).

Pelt et al., (2020) examined three intervention groups: an information-only group, an awareness group combining information with a one-week diary, and a dissonance-based group involving persuasion and planning tasks. In this study, researchers provided information and instruction to all the participants through door-to-door interventions. Quantitative analysis of food waste through composition analysis showed no effect of the diaries on reducing food waste in the awareness-based group. However, descriptions in the participants' diaries indicated an impact on their awareness. The one-week diary period may have been too short to instigate behavioral change. This situation leaves unresolved the potential of self-monitoring through recording personal behavior to foster awareness and behavioral change. Furthermore, although a diary may be intended to be used solely for measurement purposes in intervention studies, it may still contribute to reducing food waste (Leverenz et al., 2019). Studies examining the impact of self-reporting using direct measurements also found that the more frequently measurements were taken, the greater the reduction in food waste (Ramos et al., 2024).

In addition, digital technologies have been introduced into households in ways that involve recording or measuring food-related activities, which are conceptually similar to self-monitoring. Roe et al. (2022) conducted a technology-assisted intervention in which participants used an application to photograph waste items in order to measure food waste while receiving individualized reduction advice from a coach. Plate waste in the intervention group decreased by 78.8% compared with the baseline period, and this reduction was statistically significant. In contrast, total avoidable food waste decreased in both the intervention and control groups; although the intervention group showed a 46.6% reduction, the difference was not statistically significant.

Similarly, Qi et al. (2023) asked participants to use a photo-recording application for nutritional monitoring. Their results suggested that the act of measurement itself produced incidental learning effects about food waste generation, thereby increasing awareness and contributing to reductions in food waste. Although these studies were not explicitly designed as self-monitoring interventions, they share conceptual similarities with food waste diary studies and can be regarded as forms of self-monitoring in which recording (through photographs) is conducted primarily for measurement purposes.

Wada and Shinagawa (2018) conducted a study with university students using a self-evaluation sheet for food waste reduction behaviors. Participants recorded whether they implemented eight reduction behaviors during the purchasing, cooking, and consumption stages over a one-week period. Questionnaire surveys assessing perceptions and awareness regarding food waste were administered before and after the intervention to analyze changes in awareness. The results showed a significant difference in "cooking only what can be eaten," with additional changes observed in awareness related to using up ingredients, eating all prepared food, and keeping track of refrigerator contents. However, the study examined changes in awareness rather than behavioral outcomes, and food waste quantities were not measured.

Although intervention studies using self-monitoring to reduce food waste remain limited, some evidence suggests a degree of effectiveness. However, such approaches impose a non-negligible burden on participants, including estimating or measuring food waste quantities in diaries and recording reasons for disposal. From the perspective outlined in Section 1.1, these approaches may be difficult to implement as practical interventions in their existing forms. On the other hand, a simple recording of reduction behaviors, as in the approach of Wada and Shinagawa (2018), is expected to reduce participant burden. At present, few studies have employed a control-group design to evaluate a self-monitoring intervention specifically aimed at reducing household food waste while directly measuring waste quantities.

1.2.2 Gamification-based Interventions

Another challenge identified in Seta et al. (2025) is the need for motivational approaches beyond information provision. In recent years, the use of gamification to positively motivate behavior has increased (Riar et al., 2022; Santos et al., 2025). Gamification refers to the application of game design elements to non-game contexts to increase motivation and engagement (Deterding et al., 2011; Huotari & Hamari, 2017). Common game elements (strategy types) used to increase motivation include points, badges, and leaderboards (Hamari et al., 2014; Soma et al., 2020). Points visualize a user's engagement and experience within the game and are considered a form of reward (Mathisen & Johansen, 2022; Zichermann & Cunningham, 2011). Badges are visual indicators of progress, serving as motivators, psychological rewards, and goal-setting tools (Kyewski & Krämer, 2018; Zichermann & Cunningham, 2011). Leaderboards display players' score rankings and are used for individual goal-setting, but they also increase motivation through competitive awareness by comparing players within the game (Landers et al., 2017; Zichermann & Cunningham, 2011). Approximately half of the current research on gamification has been in educational settings, followed by health and physical exercise. In studies that established a control group and performed quantitative analysis, over 60% showed positive results (Koivisto & Hamari, 2019).

A notable study applying gamification to reduce food waste at home was undertaken by (Soma et al., 2020). They implemented an intervention using an online game that reinforced information. In the game, the participants earned points by correctly answering food waste quizzes and received monetary rewards based on their points. Two other types of informational intervention groups and a control group were also established. They reported that although the game group's food waste was approximately 30% lower after the campaign, the between-group difference in changes in food waste levels was not statistically significant (Kruskal–Wallis H = 3.69, p = .30), and only a marginal within-group change was observed (one-tailed p = .07). The game group comprised 26 participating households, and food waste volume was measured using composition analysis. One possible explanation for the lack of statistical significance, despite the relatively large reduction, is the small sample size of the intervention group. Whether gamification effects can be detected as statistically significant with larger sample sizes remain an open question.

Other research on consumer-oriented app development and usability evaluation suggests impacts on awareness and knowledge; however, the effectiveness of such interventions in reducing food waste has not been empirically verified (Haas et al., 2022; Venessa & Aripradono, 2023).

Although not employing gamification, another relevant line of research has framed food waste reduction behaviors as "missions," a concept commonly used in games (Cooper et al., 2023). Cooper et al. (2023) introduced a weekly "Use-up day," during which participants were asked to prepare a meal using foods that needed to be consumed soon. In this study, the intervention motivated participants by reframing food waste reduction as an opportunity to create an additional meal from ingredients already available at home. The intervention was designed based on the Motivation–Opportunity–Ability (MOA) framework: the use-up day created opportunities for action, while simple practical guidance for using up food was provided to enhance participants' abilities.

Several variations of the intervention group were implemented; however, the overall results showed that in the first experiment food waste decreased by 14.4% from the baseline in the control group, whereas the intervention group showed a 33.4% reduction, with a significant interaction effect identified using linear mixed-effects models. In the second experiment, food waste decreased by 8% in the control group and by 46% in the intervention group, again with a significant interaction effect. These findings suggest that structured interventions targeting specific food management behaviors can reduce household food waste. However, food waste amounts in this study were estimated using questionnaire data, and the weight of food waste was not directly measured.

Further, the results of Soma et al. (2020) suggest that a gamified intervention to reduce household food waste may be effective. Although their results did not reach statistical significance, the gamification group exhibited a comparatively larger reduction than the other groups, despite relying primarily on knowledge-based quizzes that did not directly promote reduction behaviors. This suggests the potential of gamification to facilitate food waste reduction, although the effects of game elements cannot be clearly distinguished from those of monetary incentives.

In the context of the current study, gamification-based interventions are considered to have the potential to enhance motivation and engagement in pro-environmental behaviors. From the perspective of the MOA framework, such approaches may enhance motivation through engagement mechanisms, while behavior recording can facilitate opportunities and abilities for improved food management.

Taken together, these findings suggest that structured self-monitoring interventions targeting food management behaviors (as in Cooper et al.) and gamification-based approaches (as in Soma et al.) may provide complementary pathways for reducing food waste. The issue of participant burden identified by Seta et al. (2025) may be addressed by adopting self-monitoring through the recording of target behaviors, which is expected to impose a relatively low burden. At the same time, the need for motivational approaches beyond information provision may be addressed by incorporating gamification and designing interventions based on the MOA framework, thereby potentially achieving greater reductions in food waste. However, to the best of our knowledge, no studies have combined gamification elements with self-monitoring based on the recording of food management behaviors and evaluated their effects on household food waste reduction using directly measured data.

1.3 Purpose of this study

Based on the considerations in Section 1.2, this study aims to quantitatively analyze the effectiveness of an intervention that combines self-monitoring through the recording of target behaviors with gamification, using food waste weight measurement data from the intervention and control groups, and to clarify its impact on related behaviors.

2. MATERIALS AND METHODS

2.1 Intervention design

2.1.1 Conceptual framework and target behaviors

Figure 1 presents the conceptual framework of food management behaviors aimed at reducing food waste in this study. We conceptualize six behaviors representing key aspects of household food management, corresponding to a sequence of processes from refrigerator management to consumption and purchasing.

Within this process, refrigerator organization behaviors such as "searching" for food and "moving" food to a visible place are expected to enhance awareness of food stored in the refrigerator, referred to here as inventory knowledge. Improved inventory knowledge may facilitate the "prioritized use" of food that should be consumed soon and promote "finishing meals." Furthermore, it is also expected to influence purchasing behavior, contributing to "preventing over-buying."

Among these behaviors, three—"prioritized use of food that should be used sooner," "finishing meals," and "preventing over-buying"—are considered to be more directly related to food waste generation. When these behaviors are not performed, the likelihood of food being discarded increases. Previous studies have also identified the absence of these behaviors as major contributors to household food waste (Ananda et al., 2024; Boulet et al., 2023; Principato et al., 2021).

For the intervention, four of the six behaviors were selected as target behaviors. Following the approach of Seta et al. (2025), the behaviors "search," "move," and "use" were adopted, and "finishing meals" was additionally included. The first three behaviors correspond to the "use" of food that should be consumed soon and supporting actions that facilitate this behavior. Together, they simplify refrigerator management into a straightforward sequence of searching, moving, and using food items. These actions are easy to implement, have potential for widespread adoption, and represent a combination of behaviors perceived as effective, with demonstrated potential to reduce food waste (Seta et al., 2025; Yamakawa, 2020). In addition, "finishing meals" was included to address plate waste, which is an important component of household food waste (Okayama et al., 2021).

Based on this framework, while the intervention targets these four behaviors, all six behaviors—including "inventory knowledge" and "preventing over-buying," which are considered important within the process of food waste reduction—were included in the analysis. Although inventory knowledge has aspects of a psychological state variable, acquiring such knowledge is considered part of the behavioral sequence of refrigerator management in this study. Therefore, it is included among the six food management behaviors examined in the analysis.

Finally, it should be noted that Figure 1 illustrates the conceptual relationships among these behaviors. However, due to data limitations, this framework was not tested using mediation analysis. Instead, as described in Section 2.2, the analysis was conducted based on a simplified set of hypotheses.

2.1.2 Theoretical framework for intervention strategies

Following Seta et al. (2025), the MOA framework (Ölander & ThØgersen, 1995) was adopted as the theoret-

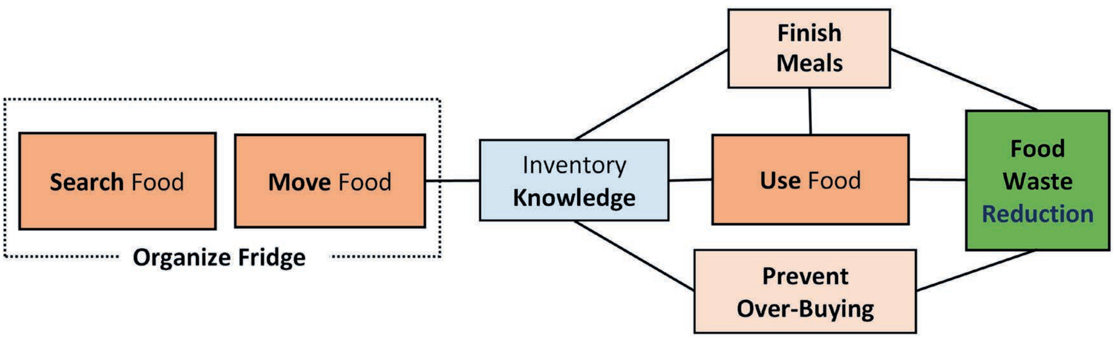


FIGURE 1: Conceptual framework of food management behaviors for food waste reduction.

ical basis for designing intervention strategies. The MOA framework posits that motivation, opportunity, and ability are necessary for action. It is frequently used as a theoretical framework for designing interventions aimed at reducing household food waste and has demonstrated effectiveness (Cooper et al., 2023; Seta et al., 2025; Soma et al., 2021; von Kameke & Fischer, 2018; Van Herpen et al., 2023). In our previous intervention using the support tools, the focus was on ability (A) within the MOA framework, specifically improving knowledge and skills for refrigerator management, whereas opportunity (O) was created through the use of support tools. Motivation (M) was addressed solely through an informational intervention (Seta et al., 2025). This study also used informational intervention to influence motivation. Additionally, it employed a non-informational intervention, tracking one's own behaviors in a food waste reduction self-monitoring app (hereafter, the self-monitoring app), to create opportunities for the target behaviors. Furthermore, it aimed to further enhance motivation for the target behaviors through game elements integrated into the app. Regarding ability, participants were generally considered to possess the necessary skills for the target behavior. Therefore, it was hypothesized that changes in motivation and opportunity would prompt behavioral change. Furthermore, it was expected that the target behaviors would promote refrigerator organization and improve inventory knowledge, and that this ripple effect would enhance the ability to manage food, leading to further reductions in food waste.

2.1.3 Intervention Method 1: Information provision

The informational intervention for participants in the intervention group was delivered by holding an online briefing session (with an option to watch a recorded version) held one week prior to the start of the app-based intervention period, as described in Section 2.1.4. The session covered the importance of refrigerator management for reducing food waste and introduced simple, actionable practices, namely the "search," "move," and "use" behaviors. It also included instructions on how to use the self-monitoring application designed to encourage these target behaviors.

During the two-week intervention period, participants were asked to use the application and engage in efforts to reduce food waste. A leaflet containing the same information presented in the briefing session was also prepared and distributed to all households in the intervention group. In contrast, participants in the control group were asked to continue their usual routines during the intervention period, as in the baseline period. All participants were instructed to dispose of any food waste in the designated bin during the intervention period, in the same manner as during the baseline period. Approximately three months later, during the follow-up period, participants in both groups were asked to maintain their usual routines and to dispose of any food waste generated in the designated bin.

2.1.4 Intervention Method 2: Food waste reduction self-monitoring app

As a non-informational intervention, participants were asked to use the gamified self-monitoring app designed to support and motivate the practice of four target behaviors: "search", "move", "use", and "finishing meals". The researchers determined the necessary functions and specifications for the app, while the development and image creation were outsourced to a company with experience in similar app development. The app was developed in Japanese. Screenshots of the application interface and its core functions are provided in Appendix A.

The developed app enables daily self-monitoring by allowing users to evaluate and record their level of implementation for five items by answering the following five questions.

1. Did you check for foods to be eaten soon? (corresponding to "search")
2. Did you move the foods to be eaten soon to a visible place? ("move")
3. Did you prioritize using the foods to be eaten soon? ("use")
4. Did you finish eating your meal? ("finishing meals")
5. Did any food waste occur during this day?

Questions 1-4 correspond to the four target behaviors to help reduce food waste and were rated on a three-point scale as "Not great", "So-so", or "Perfect". Question 5 assessed food waste quantity, rated as "Quite a bit", "A little", or "None". For questions 1-3, considering the possibility of eating out, a "Not applicable" button was also provided. Figure 2 illustrates game elements used in the self-monitoring app.

The key game elements of points, badges, and leaderboards (PBL) were incorporated into the app structure. Points (P) were derived from self-assessment during behavior checks. For all five items, high ratings were given 20 points, medium ratings were given 10 points, and low ratings were given 5 points. "Not applicable" was assigned the same 10 points as a medium rating. Daily points were a total of these scores up to a maximum of 100 points. Daily points were displayed immediately after recording, accompanied by a message. This aimed to provide motivation by displaying messages of praise for high performance and messages of encouragement to try harder for lower performance.

Badges (B) were earned based on weekly cumulative scores, with four tiers: Bronze (0-349 points), Silver (350-489), Gold (490-629), and Platinum (630-700). Badges were awarded weekly and reset at the start of each new week, encouraging participants to maintain motivation for the following week.

The leaderboard (L) displayed a list of individual cumulative scores for the week up to that point, ordered from highest to lowest. It was placed on the home screen, which was the first screen displayed each time the user logged into the app.

2.2 Hypotheses

As described in Section 2.1.1, four behaviors—"searching for food that should be used sooner," "moving such food to a visible place," "prioritized use of food that should be used sooner," and "finishing meals"—were defined as the

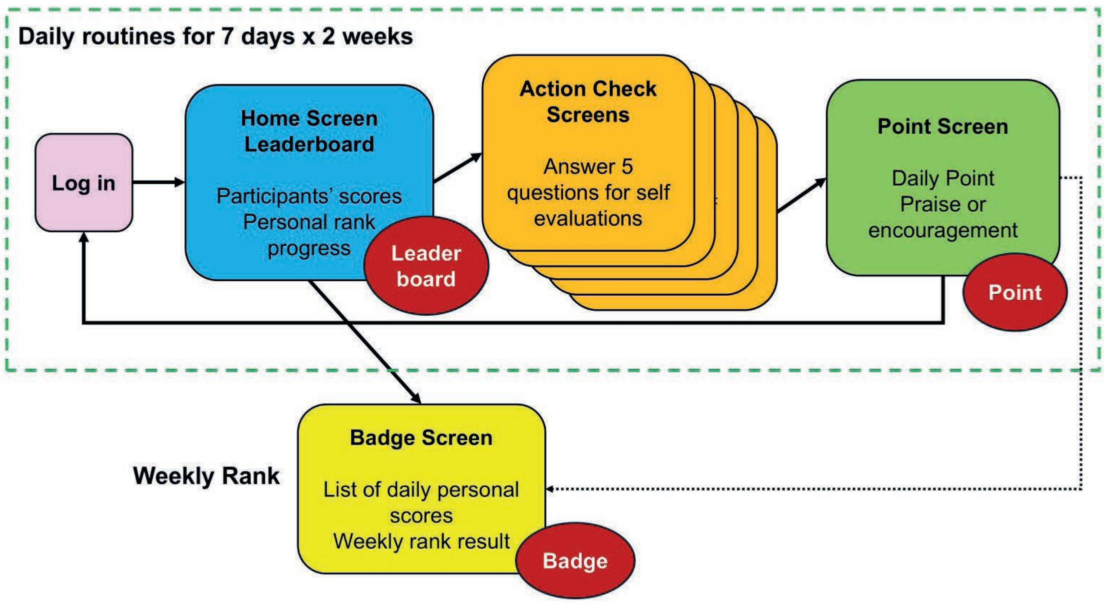


FIGURE 2: Game elements used in the food waste reduction self-monitoring app.

target behaviors of the intervention. In addition, "inventory knowledge" and "preventing over-buying" were included as behaviors to be examined in the analysis.

Although the conceptual framework presented in Figure 1 assumes interrelationships among these behaviors, the primary outcome of this study is the reduction of food waste. Therefore, the research hypotheses were formulated around three key relationships: (1) the effects of the intervention on each behavior (H1 group), (2) the relationship between behavioral changes and food waste reduction (H2 group), and (3) the overall effect of the intervention on food waste reduction (H3). Figure 3 illustrates these three hypothesized relationships as separate analytical components.

When examining the relationship between behavioral changes and food waste reduction (H2), the analysis focuses on three behaviors—"prioritized use of food that should be used sooner," "finishing meals," and "preventing over-buying"—as these are considered to be more directly related to the occurrence of food waste, as indicated in Section 2.1.1.

- Hypothesis 1a (H1a): An intervention using the self-monitoring app leads to more frequent searching for food that should be used sooner.
- Hypothesis 1b (H1b): An intervention using the self-monitoring app leads to more frequent moving of food that should be used sooner.
- Hypothesis 1c (H1c): An intervention using the self-monitoring app leads to an increased knowledge of refrigerator inventory.
- Hypothesis 1d (H1d): An intervention using the self-monitoring app leads to more prioritized use of food that should be used sooner.
- Hypothesis 1e (H1e): An intervention using the self-monitoring app leads to a reduction in over-buying.
- Hypothesis 1f (H1f): An intervention using the self-monitoring app leads to more meals being finished.
- Hypothesis 2a (H2a): More frequent prioritized use of food that should be used sooner reduces food waste.
- Hypothesis 2b (H2b): Preventing over-buying reduces food waste.
- Hypothesis 2c (H2c): Finishing more meals reduces food waste.
- Hypothesis 3 (H3): An intervention using the self-monitoring app leads to a reduction in food waste.

2.3 Participants

An a priori power analysis was conducted using G*Power 3.1 (Faul et al., 2007, 2009) to determine the sample size required for verification. For two groups across three periods (baseline, intervention, and follow-up), with a moderate effect size (f = 0.25; Cohen, 1988), a significance level of 5% (α = 0.05), and a target power of 80% ($1 - \beta$ = 0.80), the required total sample size was calculated as 82 participants (minimum 41 per group). For analyses involving two phases (pre- and post-intervention), 130 participants were required (a minimum of 65 per group).

A total of 130 individuals aged 30 or older who prepared meals at home and lived in households with 2 or more members were recruited. To ensure engagement with the intervention, eligibility criteria included the ability to use a smartphone or personal computer to operate the application for two weeks. Recruitment was conducted in September 2024 through municipal newsletters, websites, and other channels in six municipalities in Kyoto Prefecture, as well as through press release websites in Japan; a total of 152 individuals applied from across Japan (88% female). Six individuals whose eligibility could not be verified and 15 who had not disposed of any food waste in the previous two weeks were excluded because the study aimed to evaluate the intervention among individuals who generate food waste. This also helped reduce the prevalence of zero observations in the data.

This study aimed to achieve approximately equal rep-

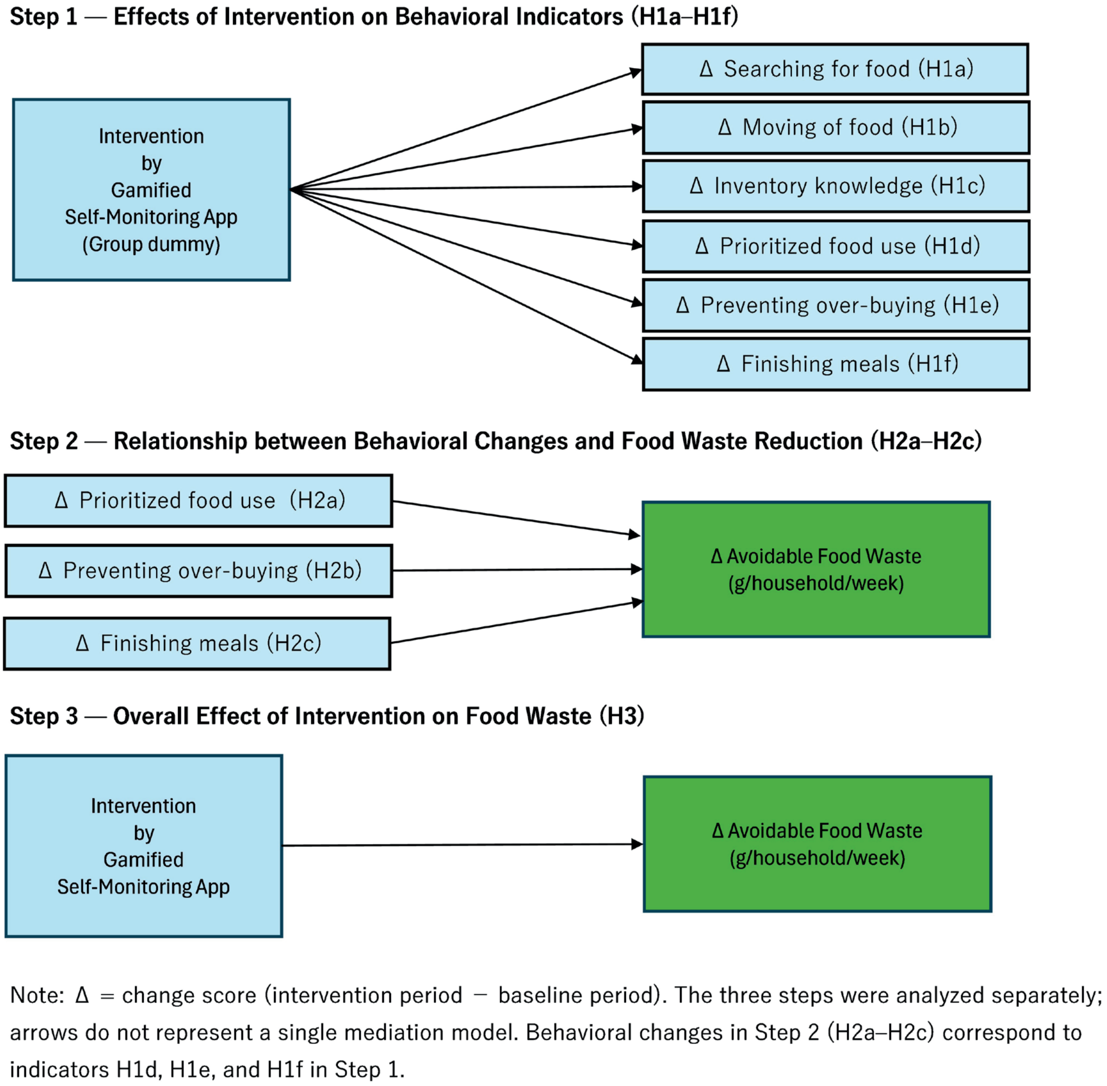


FIGURE 3: Hypothesized Relationships among intervention, behavioral changes, and food waste reduction.

resentation across age groups (30s-60s), but applications varied substantially by age group. Because eligibility criteria required the ability to use the application, younger applicants were overrepresented, while relatively few applicants were aged 60 or older. To address this imbalance, 20 applicants in their 30s—where applications were most numerous—were randomly selected for exclusion, resulting in a total of 110 accepted applicants (39 in their 30s, 36 in their 40s, 29 in their 50s, and 6 aged 60 or older). Due to the low number of applicants aged 60s or older, 20 additional participants were recruited from a research company panel, increasing this group to 26. The final enrolled sample was 130 participants; after withdrawals and dropouts, 126 completed the study. Participants who completed the full study period and all three questionnaires received a compensatory gift certificate worth 6,000 yen.

2.4 Experimental procedure

A six-week experiment was conducted between October 2024 and March 2025 (Figure 4), employing a controlled design with systematic allocation. A two-week unit was adopted to reduce variance in food waste measure-

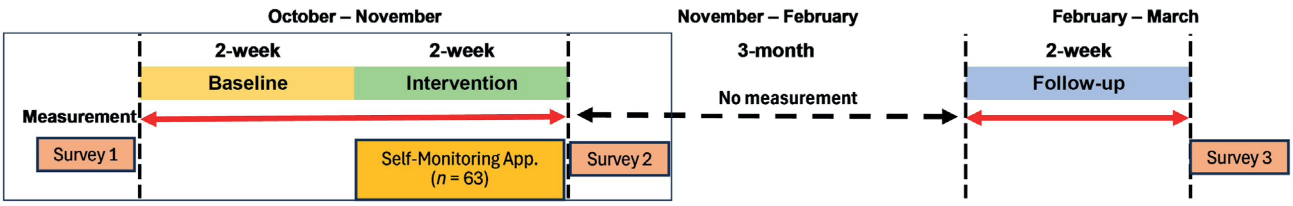


FIGURE 4: Timeline of the experimental procedure (N = 126). Note. The boxed area indicates the period analyzed in the present paper.

ments and limit the frequency of zero observations. During each period, all participants were instructed to separate food waste and dispose of it in designated waste bins. Food waste was measured 24 times per day, at 60-minute intervals, using the cloud-based weighing system.

The first phase of the study consisted of four consecutive weeks: a two-week baseline period during which only measurement was conducted, followed by a two-week intervention period during which measurement continued, and the intervention group used the self-monitoring app. Approximately three months after the end of the intervention period, a two-week follow-up period was conducted, during which only measurements were performed, as in the baseline period. Participants were ordered by age, gender, household size, and food waste frequency. After randomly selecting the starting point, every second participant was assigned to the intervention group, and the remainder were allocated to the control group to achieve approximate balance across characteristics. As a result, 63 households were assigned to each group.

The intervention included a briefing session for the intervention group participants as described in Section 2.1.3. During the two-week intervention period, these participants were asked to use the self-monitoring app described in Section 2.1.4 as a non-informational intervention. Meanwhile, the control group participants were asked to maintain their usual routines during the intervention period.

During the follow-up period, approximately three months after the end of the intervention period, participants in both groups were asked to continue their usual routines while placing any food waste generated into dedicated waste bins.

2.5 Food waste definition and measurement method

In this study, food waste was defined in accordance with the Japanese government's definition as "food that is edible but discarded." The food waste measured in this study was limited to avoidable food waste, consistent with Seta et al. (2025). Following Okayama et al. (2021), avoidable food waste was operationalized as comprising two categories: unused food and leftovers.

When providing instructions to participants, food waste to be measured was defined as plate leftovers, unfinished beverages, remaining prepared foods, and food discarded due to expiration or spoilage. Participants were asked to place such items into a designated waste bin. Inedible parts, such as vegetable or fruit peels, were explicitly excluded. However, for measurement purposes, participants were asked not to place liquids in the dedicated waste bins.

Regarding containers and packaging, if they were lighter than the food itself, they were to be placed in the waste bin as is. If the food contents were lighter than the packaging, participants were instructed to remove the packaging and discard only food contents. While the Japanese government's definition includes excessive removal (see Note 1) in food waste, this study did not. In Japan, household food waste is generally disposed of as combustible waste. Though a small number of municipalities separate food waste for composting, this practice remains uncommon. The measurement method was explained during an online briefing session for all participants before the baseline period began (with the opportunity to view a recorded video). Leaflets summarizing the briefing content were also distributed to all the participating households.

To measure food waste, the cloud-based measurement system used in the study by Seta et al. (2025) was adopted. Specifically, a system combining a 20 L waste container with a mat-type automatic weighing device ("SmartMat", developed by S-Mat, Inc., Tokyo, Japan) was employed, and measurement data were transmitted and collected via a Wi-Fi router in a cloud-based management system. The measurement system is shown in Figure 5. Although the setup resembled organic waste separation for collection, participants were instructed to place only food waste in the designated waste bin.

The cloud-based weighing system conducted automatic measurements 24 times per day at fixed hourly intervals, with data transmitted to the cloud system each time. The weighing device had a maximum capacity of 5 kg, a measurement unit of 1 g, and a maximum measurement error of ±0.15% (2.5 g per 1 kg). As in Seta et al. (2025), a threshold of 5 g was applied, and only increases exceeding this threshold were treated as food waste weight.

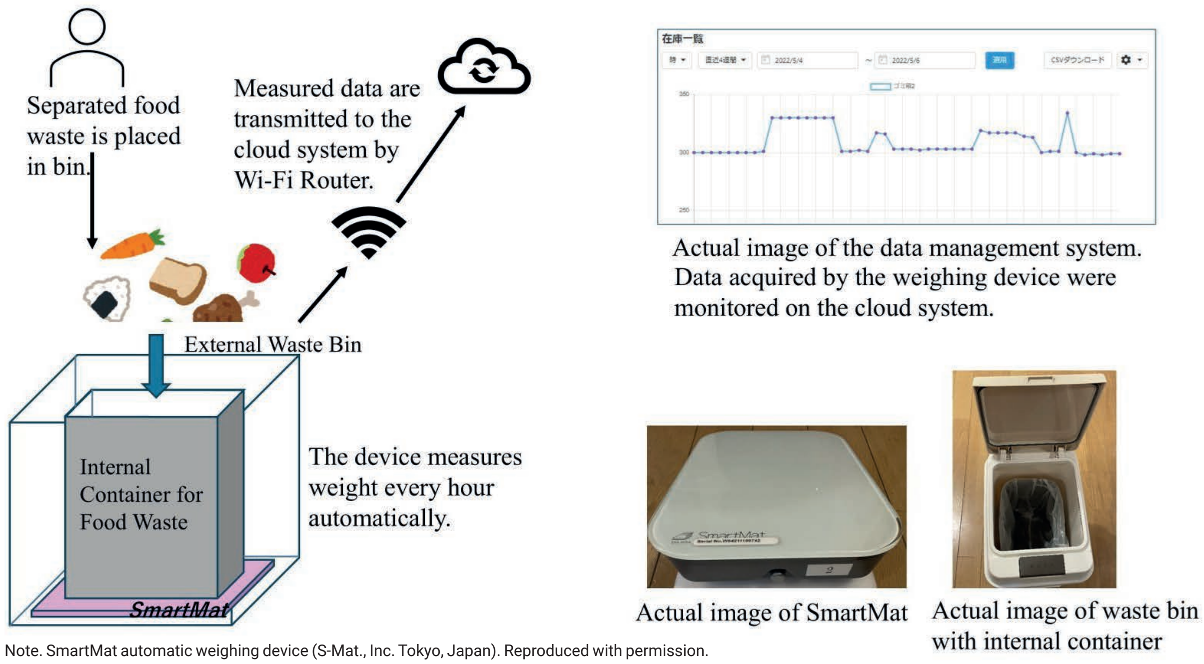
Note 1. Excessive removal refers to the elimination of edible portions during the removal of inedible parts, such as peeling vegetables too thickly.

2.6 Questionnaires

The questionnaire was primarily adapted from the instrument used by Seta et al. (2025). The items were originally developed with reference to previous studies conducted in Japan (Consumer Affairs Agency, 2020; Osaka Prefectural Government, 2019; Yamakawa et al., 2020), but several were modified to fit the experimental design of the present study. The survey was administered online using the Google Forms platform at three points: before the start of the experiment, after the intervention period, and after the follow-up period.

In this study, 13 food management behaviors were measured to assess the extent to which participants engaged in behaviors related to refrigerator management, food use, inventory knowledge, and purchasing behavior. The questionnaire items and response scales used to measure these 13 behaviors are presented in Appendix B. These indicators were designed to capture multiple dimensions of household food management practices.

For hypothesis testing, however, the analysis focused on six behavioral indicators—one for each of the six behaviors specified in the conceptual framework—to ensure interpretability of the analytical model and statistical stability. These six indicators were selected based on their direct correspondence to the intervention target behaviors and their ability to best capture the relevant behavioral construct. Although multiple behavioral indicators were measured for domains such as food use, inventory knowledge, and purchasing behavior, these indicators were not combined into composite scales. This is because each indicator was designed to capture a distinct aspect of food management behavior rather than a single underlying con-



Note. SmartMat automatic weighing device (S-Mat., Inc. Tokyo, Japan). Reproduced with permission.

FIGURE 5: Images of the cloud-based automatic weighing system.

struct. As a result, the correlations among these indicators were not sufficiently strong to justify aggregation based on internal consistency. The remaining indicators were analyzed using descriptive statistics and correlation analysis to provide an overview of behavioral patterns. These results are presented in Appendix D and Appendix E.

The six selected behavioral indicators were: (1) searching for food that should be used sooner, (2) moving such food to a visible place, (3) being aware of expiration dates, (4) prioritized use of food that should be used sooner, (5) buying appropriate quantities, and (6) finishing meals. These six behaviors correspond directly to the conceptual model shown in Figure 1 and the hypothesized relationships presented in Section 2.2 (Figure 3).

Regarding indicator (3), inventory knowledge, effective household food inventory management depends on awareness of both the presence of stored food and its expiration dates. Accordingly, inventory knowledge was operationalized using the item: "During the past two weeks, to what extent did you know expiration dates of the foods stored in your refrigerator?"

For indicator (4), food use behaviors, several indicators were measured; however, "prioritized use of food that should be used sooner" (hereafter, prioritized food use) was selected because it directly corresponds to the intervention target. As for indicator (5), "buying appropriate quantities" was selected from several shopping-related indicators as a representative indicator of purchasing behavior and is treated as synonymous with "preventing over-buying" in subsequent analyses.

Refrigerator organization was measured as a broader indicator encompassing both searching and moving behaviors; however, it was not included among the six indicators as it encompasses two distinct behavioral constructs rather than mapping onto a single intervention target.

Each item of six behaviors was measured on a five-point scale referring to the past two weeks, using frequency for most behaviors and degree for inventory knowledge and finishing meals. These behavioral indicators were analyzed individually as variables corresponding to theoretical constructs. In addition, self-reported food waste frequency was measured using a five-point scale across four categories: plate leftovers, leftover cooked food, partially used ingredients, and unused food items. After the intervention period, participants were also asked whether the requirement to separate food waste influenced their food waste reduction behaviors, using a four-point scale. Details of the questionnaire are provided in Appendix B.

Furthermore, to assess the effects of the intervention on issues commonly associated with ICT-based interventions—such as perceived burden and motivation—participants in the intervention group were asked additional questions after the intervention period regarding their evaluation of the intervention, including perceived burden, motivation, and competitiveness. Details of these items and their results are presented in Appendix C.

2.7 Internet survey by online panels

In parallel with the experiment described in Section 2.4, questionnaire surveys using online panels without food waste measurement were administered. This approach follows the national comparison group approach adopted by Shu et al. (2023), who used it to enhance the precision and reliability of campaign evaluations. In the present study, this method was employed to examine whether the measurement procedure itself influenced participants' behavior.

Online panel participants were selected through a screening survey to match the characteristics of the experimental participants, resulting in 130 individuals, of whom

88 completed all three surveys. The questionnaire items were identical to those used in the experiment, except for items directly related to the experimental procedures. The response period was the same as that for the experimental participants.

2.8 Analysis

In this study, data were collected during the baseline, the intervention, and follow-up periods, conducted three months after the intervention. However, because the primary objective of this paper was to examine the direct effects of the intervention, the analysis was limited to data from the baseline and intervention periods. Data from the follow-up period were not included in the analyses reported here. The long-term effects and persistence of the intervention will be examined separately in combination with previously reported data (Seta et al., 2025).

To examine the hypothesized mechanisms, analyses were conducted in three steps: first, the overall effect of the intervention on food waste was tested (H3); second, the effects of the intervention on food waste reduction behaviors were examined (H1); and third, the relationship between behavioral changes and reductions in food waste was analyzed (H2).

2.8.1 Effect of the intervention on food waste

First, to test Hypothesis H3, the effect of the intervention on food waste was examined. The dependent variable was the change in food waste (intervention period – baseline period), and a general linear model (GLM; i.e., an ordinary least squares regression framework) was estimated.

The independent variable was a dummy variable representing the intervention group (intervention = 1, control = 0). As a covariate, the household's average food waste during the baseline period was included after mean-centering using the overall sample mean. In addition, as an exploratory analysis, a model including an interaction term between the intervention dummy variable and baseline food waste was also estimated.

The change in food waste was used as the dependent variable to directly evaluate the magnitude of change attributable to the intervention while controlling for baseline differences. Baseline food waste was included as a covariate not only to account for regression to the mean but also because participants with low baseline values may have limited reduction potential (floor effects), whereas those with higher baseline values may have greater reduction potential. The interaction model was estimated to examine whether the intervention effect differed depending on baseline food waste levels.

Previous studies have reported that household food waste exhibits substantial variability across households and a highly skewed distribution with many zero values (Van Herpen et al., 2019, 2023; Visschers et al., 2016). Consistent with these findings, the present study exhibited similar distributional characteristics, as discussed in Section 3.1. Given these characteristics, to reduce reliance on the normality assumption and ensure robust statistical inference, standard errors, p-values, and 95% confidence intervals were calculated using a bootstrap procedure stratified by group (intervention vs. control), with 1,000 resamples and percentile-based confidence intervals. Stratification ensured that the group structure was preserved during resampling.

2.8.2 Effect of the intervention on food waste reduction behaviors

Next, to test the hypotheses in H1 (H1a–H1f), the effects of the intervention on food waste reduction behaviors were examined. As in the analysis for Hypothesis H3, estimation was conducted using GLMs. The dependent variables were the changes in the degree of implementation of each of the six food waste reduction behaviors (measured on five-point scales), calculated as the difference between the intervention and baseline periods.

The independent variable was the intervention group dummy variable, and the baseline level of each behavior (mean-centered) was included as a covariate. The rationale for this specification was the same as that described for Hypothesis H3.

To test the six behavioral hypotheses presented in Section 2.6 (H1a–H1f), the corresponding null hypotheses were treated as belonging to the same hypothesis family. To control the inflation of Type I error due to multiple testing, p-values were adjusted using the Holm–Bonferroni procedure.

As non-normality was also observed in the residuals of these models, p-values were calculated in SPSS using percentile-t pivotal tests based on the empirical distribution of studentized bootstrap statistics (1,000 resamples).

2.8.3 Association Between Behavioral Changes and Changes in Food Waste

Next, to test the hypotheses in H2 (H2a–H2c), the relationship between behavioral changes induced by the intervention and changes in food waste was examined. A GLM was estimated using the change in food waste (as defined in Section 2.8.1) as the dependent variable. The model simultaneously included the changes in three behavioral indicators: prioritized food use, finishing meals, and preventing over-buying. These behaviors were selected because they represent proximal food use and purchasing behaviors most directly linked to reductions in household food waste in the hypothesized process model (Figure 3).

By comparing this model with the group coefficient estimates reported in Section 2.8.1, changes in the estimated intervention effect after incorporating behavioral variables were also examined. The group variable was included to control for differences between intervention and control groups.

As in Section 2.8.1, baseline food waste (mean-centered) was included as a covariate to control for initial differences and potential regression-to-the-mean effects. As an exploratory analysis, an interaction model was also estimated to examine whether the effects of behavioral changes varied by baseline food waste levels. This model included interaction terms between each behavioral change varied by baseline food waste levels.

Standard errors, p-values, and 95% confidence intervals were calculated using a bootstrap procedure stratified by

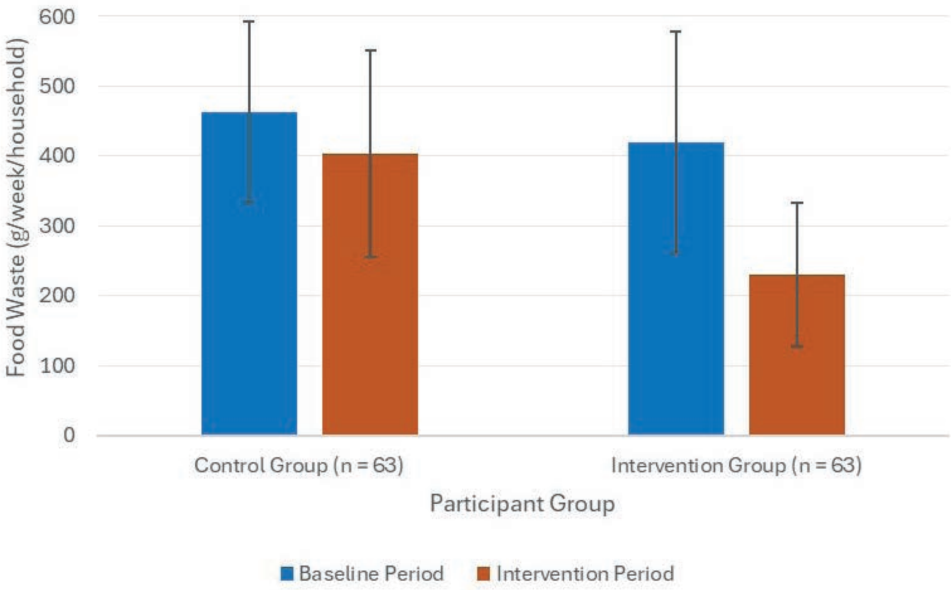


FIGURE 6: Food waste weekly average per household. Error bars represent 95% confidence intervals.

group (1,000 resamples and percentile-based confidence intervals), as described in Section 2.8.1.

2.8.4 Participant Evaluation of the Intervention

The perceived effects of the intervention in terms of reducing perceived burden, enhancing motivation, and fostering a sense of competition were analyzed using descriptive statistics based on evaluations provided by participants in the intervention group. IBM SPSS Statistics 29 was used for the analyses.

This study was reviewed by the Ethics Committee of Kyoto Prefectural University and approved on August 30, 2024 (Application No. 320).

3. RESULTS

3.1 Changes in food waste and effects of the self-monitoring app intervention

Figure 6 presents the average weekly food waste per household during the baseline and intervention periods for both the intervention and control groups, while Table 1 reports descriptive statistics. In the intervention group, food waste decreased by 190 g per household per week from the baseline to the intervention period, corresponding to a 45% reduction. In contrast, the control group showed a decrease of 60 g per household per week (a 13% reduction). Based on these descriptive comparisons, the difference in change between the two groups was 32 percentage points. In both groups, skewness exceeded 2, indicating right-skewed distributions, and excess kurtosis was also high. These results suggest that the distribution of food waste deviated from a normal distribution.

To examine the effect of the self-monitoring app intervention, a main-effects model was estimated using the change in food waste (intervention period – baseline period) as the dependent variable, with an intervention group dummy variable (intervention = 1, control = 0) and baseline food waste (mean-centered) included as predictors (Table 2, Model 1). The GLM was estimated using 1,000 stratified bootstrap resamples. The results indicated that, even after controlling for baseline food waste, the intervention group showed a significantly greater reduction in food waste compared with the control group ($B = -145.42$, 95% CI [−265.56, −17.66], $p = .036$). The 95% confidence intervals were estimated using bootstrap procedures, and the same approach was applied in subsequent analyses. Although deviations from residual normality were observed, statistical significance was evaluated using bootstrap-based confidence intervals that do not rely on the normal approximation, providing robust inference that is not affected by violations of the normality assumption.

Next, to explore potential heterogeneity in the intervention effect, a model including the intervention group dummy variable, baseline food waste (mean-centered),

TABLE 1: Descriptive statistics for weekly household food waste (grams).

Group	Period	N	Mean	SD	Min	Max	Skewness	Kurtosis
Intervention	Baseline	63	419.6	644.1	0	3161.5	2.56	6.92
	Intervention	63	230.1	413.3	0	2500.0	3.66	15.85
Control	Baseline	63	462.7	528.1	0	2528.0	1.77	3.36
	Intervention	63	403.0	598.3	0	3249.5	2.80	9.33

Note. Values are expressed in grams per measurement period.

TABLE 2: Effects of the intervention on change in food waste (stratified bootstrap GLM, n = 126).

Dependent variable: Change in food waste (Intervention – Baseline)				
Model 1: Main Effects				
Predictor	**B**	**Bootstrap SE**	**95% CI**	**p**
Intervention (1 = intervention)	-145.42	64.44	[-265.56, -17.66]	.036
Baseline food waste (centered)	-0.364	0.137	[-0.637, -0.094]	.014
Intercept	-51.83	43.63	[-141.25, 35.84]	.261
Model 2: Interaction Model				
Predictor	**B**	**Bootstrap SE**	**95% CI**	**p**
Intervention (1 = intervention)	-143.03	58.9	[-263.64, -20.42]	.045
Baseline food waste (centered)	-0.035	0.148	[-0.402, 0.177]	.808
Intervention × Baseline food waste (centered)	-0.55	0.224	[-0.949, -0.083]	.028
Intercept	-58.95	37.5	[-138.68, 10.61]	.151

Note. 1,000 stratified bootstrap resamples; two-tailed tests.

and their interaction term was estimated (Table 2, Model 2). The interaction between the intervention group dummy and baseline food waste was statistically significant ($B = -0.55$, 95% CI [−0.949, −0.083], $p = .028$). This result indicates that households with higher baseline food waste experienced larger reductions as a result of the intervention. In the interaction model, the main effect of baseline food waste for the control group was not statistically significant ($B = -0.035$, 95% CI [−0.402, 0.177], $p = .808$), whereas the corresponding effect for the intervention group was significant ($B = -0.584$, 95% CI [−0.917, −0.298], $p = .005$). These results suggest that the influence of baseline food waste differed between the two groups.

Taken together, these results support H3, indicating that the self-monitoring app reduced household food waste, although the magnitude of the effect appears to depend on baseline levels of food waste.

3.2 Effects of food waste measurement

A cloud-based automatic weighing system was used to measure food waste. In the questionnaire conducted after the intervention period, participants were asked to evaluate the influence of this measurement on their food waste–reduction behaviors using a four-point scale. Regarding food waste separation and the use of dedicated bin, 79% of the intervention group and 70% of the control group responded that these requirements “greatly influenced” or “somewhat influenced” their behavior.

To analyze the impact of food waste measurement on both groups, the frequency of food waste disposal among online panels (as described in Section 2.7) was measured using the same questions as for the control group. A two-way mixed ANOVA was conducted using the waste frequency data from the experimental control group and the online panels before and after the intervention period. The results showed no significant effects for leftovers from served meals ($F(1,146) = 0.012$, $p = .912$), leftovers from unserved meals ($F(1,142) = 0.340$, $p = .561$), unused fresh food ($F(1,143) = 1.238$, $p = .268$), or unused items ($F(1,147) = 0.143$, $p = .706$).

We also examined differences in disposal frequency between the intervention and control groups. A significant interaction effect was found for unused fresh food ($F(1,120) = 9.513$, $p = .003$). The mean difference in the simple main effect was −0.233 ($p < .05$) for the intervention group, indicating a significantly lower rate after the intervention, whereas the control group showed a significantly higher rate of 0.274 ($p < .05$).

3.3 Effects of the intervention on food waste reduction behaviors and their association with food waste reduction

3.3.1 Effects of the intervention on food waste reduction behaviors (H1)

First, descriptive statistics for the behavioral indicators during the baseline and intervention periods are presented in Appendix D. In the intervention group, mean scores increased from baseline to the intervention period for all behavioral indicators. In particular, “searching for foods to be used sooner” increased by 0.89, “inventory knowledge” by 0.81, and “preventing over-buying” by 0.67. As shown in Section 3.1, the amount of food waste in the intervention group decreased over the same period. In contrast, in the control group, only “inventory knowledge” and “prioritized food use” showed slight increases (both by 0.30), and no substantial changes were observed.

Correlations among the behavioral change scores are presented in Appendix E. The analysis showed that three behavioral changes were significantly associated with changes in food waste: “inventory knowledge” ($r = -.214$), “finishing meals” ($r = -.186$), and “preventing over-buying” ($r = -.232$). All three variables exhibited negative correlations, indicating that greater improvements in these behaviors were associated with larger reductions in food waste.

To examine the effects of the intervention on these behavioral indicators, GLMs were estimated (detailed results are presented in Appendix F). Table 3 reports the coefficients of the intervention group dummy variable and the bootstrap standard errors for the six behavioral indicators. As the six indicators belong to the same hypothesis family (H1a–H1f), p-values were adjusted using the

TABLE 3: Effects of the intervention on six behaviors (stratified bootstrap estimates with Holm–Bonferroni–adjusted p-values).

Variable	B	Bootstrap SE	Adjusted p value	95% CI
Searching for food that should be used sooner	0.672	0.156	.012	[0.374, 0.983]
Moving food that should be used sooner	0.681	0.176	.012	[0.345, 1.033]
Knowledge of the refrigerator inventory	0.437	0.150	.028	[0.145, 0.721]
Prioritized food use	-0.135	0.103	.194	[-0.333, 0.071]
Finishing meals	0.201	0.101	.128	[-0.004, 0.404]
Preventing over-buying	0.463	0.174	.027	[0.119, 0.798]

Note. B represents the unstandardized regression coefficients of the Intervention dummy. Standard errors were estimated using 1,000 stratified bootstrap resamples. P-values were adjusted using the Holm–Bonferroni procedure.

Holm–Bonferroni procedure (adjusted p-values; hereafter Adj-p). After adjustment, statistically significant intervention effects at the 5% level were observed for "searching for food" (Adj-p = .012), "moving food to a visible place" (Adj-p = .012), "inventory knowledge" (Adj-p = .028), and "preventing over-buying" (Adj-p = .027). In contrast, no significant effects were observed for "prioritized food use" (Adj-p = .194) or "finishing meals" (Adj-p = .128). These results indicate that among the H1 hypotheses, H1a, H1b, H1c, and H1e were supported, whereas H1d and H1f were not supported.

3.3.2 Effects of Behavioral Changes on Food Waste Reduction (H2)

Among the six behavioral indicators, three behaviors—"prioritized food use," "finishing meals," and "preventing over-buying"—were examined to assess whether changes in these behaviors were associated with reductions in food waste. GLMs were estimated using stratified bootstrap resampling (n = 1,000) (Table 4). The dependent variable was the change in food waste amount (intervention period – baseline period). Baseline food waste (mean-centered) and the change scores for the three behaviors were included as covariates, and the intervention group dummy variable was included as a between-subjects factor.

In the main-effects model without interaction terms (Table 4, Model 1), baseline food waste was statistically significant (B = −0.26, 95% CI [−0.487, −0.076], p = .012), indicating that households with higher baseline food waste tended to achieve greater reductions. The coefficient for the intervention group dummy variable was B = −85.82 (95% CI [−189.98, 22.64], p = .107), which was smaller in magnitude than in the model reported in Section 3.1 (B = −145.42, 95% CI [−265.56, −17.66], p = .036) and was no longer statistically significant.

Regarding the main effects of the behavioral variables, neither "prioritized food use" (B = 60.68, 95% CI [1.47, 127.44], p = .053) nor "finishing meals" (B = −81.91, 95% CI [−180.73, 12.54], p = .095) reached statistical significance. "Preventing over-buying" also showed no significant association with the change in food waste (B = 4.38, 95% CI [−33.01, 41.72], p = .821). Thus, none of the H2 hypotheses (H2a, H2b, and H2c) were supported in the confirmatory analysis.

Next, to explore whether the associations between behavioral changes and food waste reduction differed depending on baseline food waste levels, a model including interaction terms between baseline food waste and each behavioral change variable was estimated (Table 4, Model 2). No significant interaction was observed for "preventing over-buying" (B = 0.024, 95% CI [−0.139, 0.133], p = .673). A statistically significant interaction was observed for "prioritized food use" (B = 0.245, 95% CI [0.075, 0.449], p = .004). For "finishing meals," the estimated interaction term was negative, and the p-value indicated statistical significance (B = −0.177, 95% CI [−0.269, 0.034], p = .006); however, the 95% bootstrap confidence interval included zero.

Specifically, increases in "finishing meals" were associated with larger reductions in food waste among households with higher baseline food waste. In contrast, the positive coefficient for "prioritized food use", indicates that increases in this behavior were associated with increases in food waste among households with higher baseline food waste. Consistent with this finding, the simple correlation between the change scores of "prioritized food use" and food waste amount was also positive (r = .129; see Appendix E), although correlations between the corresponding non-change variables were negative (see Appendix G).

The coefficient of the intervention group dummy variable in Model 2 (Table 4) was B = −80.31 (95% CI [−184.73, 43.37], p = .158), which was similar in magnitude to that in the main-effects model (Model 1; B = −85.82) and remained statistically non-significant. Furthermore, the interaction between the intervention dummy variable and baseline food waste amount, which was significant in Section 3.1 (Table 2, Model 2; B = −0.55, 95% CI [−0.949, −0.083], p = .028), decreased substantially in magnitude in the present model (Table 4, Model 2; B = −0.269, 95% CI [−0.621, 0.166], p = .085) and was no longer statistically significant.

Overall, the results can be summarized as follows: among the H1 hypotheses, H1a, H1b, H1c, and H1e were supported, whereas H1d and H1f were not supported. None of the H2 hypotheses (H2a–H2c) were supported, while H3 was supported.

3.4 Evaluation of the self-monitoring app by participants

Participants in the intervention group (N = 63) were asked in the post-intervention questionnaire about their use and evaluations of the self-monitoring app. The questionnaire items and results are presented in Appendix C. Unless otherwise noted, the percentages reported below represent the combined proportion of the two most posi-

TABLE 4: Effects of the intervention and behavioral changes on change in household food waste (GLM with stratified bootstrap).

Dependent variable: Change in food waste (Intervention – Baseline)				
Model 1. Main-Effects Model				
Predictor	**B**	**Bootstrap SE**	**95% CI**	**p**
Intercept	-63.28	40.08	[-149.64, 9.59]	.127
Intervention group (1 = intervention)	-85.82	51.69	[-189.98, 22.64]	.107
Baseline food waste (centered)	-0.26	0.101	[-0.487, -0.076]	.012
Prioritized food use (change score)	60.68	31.74	[1.47, 127.44]	.053
Finishing meals (change score)	-81.91	49.47	[-180.73, 12.54]	.095
Preventing over-buying (change score)	4.38	19.63	[-33.01, 41.72]	.821
Model 2. Interaction Model				
Predictor	**B**	**Bootstrap SE**	**95% CI**	**p**
Intercept	-80.22	39.47	[-163.85, -3.47]	.061
Intervention group (1 = intervention)	-80.31	57.52	[-184.73, 43.37]	.158
Baseline food waste (centered)	-0.179	0.139	[-0.501, 0.068]	.171
Prioritized food use (change score)	57.98	33.09	[-10.35, 126.30]	.070
Finishing meals (change score)	-63.3	38.3	[-117.60, 38.73]	.075
Preventing over-buying (change score)	4.86	22.06	[-41.78, 45.55]	.836
Intervention × Baseline food waste	-0.269	0.187	[-0.621, 0.166]	.085
Baseline × Prioritized food use	0.245	0.093	[0.075, 0.449]	.004
Baseline × Finishing meals	-0.177	0.077	[-0.269, 0.034]	.006
Baseline × Preventing over-buying	0.024	0.066	[-0.139, 0.133]	.673

Note. Estimates are based on 1,000 stratified bootstrap resamples (stratified by group). Two-tailed tests. Baseline variables were mean-centered.

tive response categories. For five-point scales, responses in the middle category were excluded from this calculation.

The vast majority of participants (94%) reported using the app five or more times per week. The perceived influence of the app on food waste reduction behaviors was measured using a four-point scale ("had no effect at all" to "had a significant effect"), and 75% of participants reported that the app had at least some influence.

The perceived influence of individual app features was measured using five-point scales ("had no effect at all" to "had a significant effect"). The combined proportion of the two highest categories was 78% for "Behavior checks," 67% for "Daily score," 60% for "Encouraging messages," 58% for "Leaderboard," and 58% for "Badges."

Perceptions related to usability and motivation were also measured using five-point scales. The highest proportion (combined top two categories) was observed for "Made me want to reduce food waste" (81%), followed by "Prompted me to take action" (73%) and "Motivated me" (71%). Regarding social and competitive aspects, 30% agreed that they "did not want to lose," 48% agreed that they "paid attention to the rankings," and 73% agreed that they "felt like working together with others."

Perceived burden was also measured using five-point scales, with 24% indicating that they "felt it was a hassle" and 32% indicating that they "felt it was a burden." In contrast, positive usability evaluations were high, with 90% indicating that the app was "easy," 83% that it was "easy to understand," and 79% that it was "easy to use."

All evaluations reported here reflect subjective assessments by participants in the intervention group at the time of the post-intervention questionnaire.

4. DISCUSSION

This study aimed to quantitatively examine the effects of an intervention on household food waste using a self-monitoring app with gamification features, based on objectively measured waste weight data from intervention and control groups, and to clarify its effects on related behaviors.

Six behavior-related indicators were analyzed: four direct target behaviors—"searching for food that should be used sooner," "moving such food to a visible place," "prioritized food use," and "finishing meals"—as well as two related behaviors, namely "inventory knowledge" (knowledge of food stocks and expiration dates in the refrigerator) and "preventing over-buying."

4.1 Impact of the intervention on target behaviors and effectiveness in reducing food waste

First, as shown in Section 3.2, although the measurement procedure had some psychological influence on participants, its impact on both the frequency and amount of food waste was limited. While the main effect of measurement was partially accounted for by comparing the intervention and control groups, the interaction between the weight measurement method and the intervention could not be addressed in this study. If an intervention group had also been assigned to the online panel participants, it would have been possible to examine the effect of measurement by comparing differences between the intervention groups; however, this was not done in the present study.

Next, as reported in Section 3.1, the intervention group showed a reduction of 190 g per household per week (a 45% decrease), and a further reduction of 130 g (32 percentage points) relative to the control group. Results from the general linear model further confirmed that the intervention using the self-monitoring app was associated with reduced food waste. In addition, the significant interaction with baseline food waste suggests that households with higher initial levels of food waste achieved greater reductions. This finding is consistent with the learning-based explanation proposed by Qi et al. (2023), which suggests that accumulating experience in recognizing one's past food waste through measurement and similar activities drives food waste reduction. However, because no significant association between baseline food waste and change was observed in the control group, despite the measurement system (including waste separation and the use of dedicated bins) being considered a form of self-monitoring, this learning mechanism does not appear to have operated in this context. It is likely that the combination of explicit behavioral guidance and motivational elements through gamification played a critical role in translating accumulated awareness into actual behavioral change. This interaction effect is also important from a policy perspective, as it indicates greater effectiveness among high-waste households and warrants further investigation.

Although strict comparisons are limited due to differences in measurement methods and baseline levels, the intervention effect observed in this study can be contextualized relative to previous studies based on the difference in reduction rates between the intervention and control groups (32 percentage points). This level is broadly comparable to the app-based intervention reported by Seta et al. (2025) (29%). However, the effect observed in this study is smaller than that reported for photo-based interventions (42%) and organizing tools (50%) in the same study. The effect is also comparable to that reported in Cooper et al. (2023) (27% and 33%), although their estimates were based on questionnaire data and therefore differ in measurement approach from the automated weighing system used in this study. For Pelt et al. (2020) and Soma et al. (2020), direct comparison is difficult because reduction rates relative to control groups were not reported. While these studies provide pre–post comparisons or post-intervention levels, differences in indicators limit their direct comparability. Taken together, the intervention effect observed in this study may be considered moderate within the existing literature, although careful interpretation is required given differences in measurement methods and baseline conditions.

Although a larger effect was expected for the gamified intervention in this study compared with Cooper et al. (2023; see Section 1.2.2), the observed effect was of a similar magnitude. One possible explanation is that Cooper et al.'s intervention combined not only motivational elements but also opportunity creation and ability support, as outlined in the MOA framework.

With respect to behavioral outcomes (Section 3.3.1), two of the four target behaviors ("search" and "move") showed significant effects. In addition, "inventory knowledge" and "preventing over-buying," which were conceptually linked to these behaviors, were also significantly affected. These findings suggest a behavioral pathway in which increased refrigerator organization enhances inventory knowledge, which in turn influences purchasing behavior and helps prevent over-buying.

In contrast, the remaining target behaviors, "prioritized food use" and "finishing meals," were not significant. These behaviors had relatively high baseline levels (mean = 4.08 for prioritized food use and 4.44 for finishing meals on a five-point scale), suggesting that ceiling effects may have limited observable changes.

The analysis examining the relationship between behavioral changes and reductions in food waste indicated that, although the behavioral changes themselves were not statistically significant, their inclusion attenuated the estimated intervention effect in the model, suggesting that behavioral changes may partially explain the intervention effect. For "finishing meals," the interaction with baseline food waste showed a statistically significant p-value, although the confidence interval included zero. This suggests that changes in behavior may have contributed to reductions in food waste, although the evidence should be interpreted with caution.

However, the results for "prioritized food use" were complex. Although this behavior is conceptually expected to reduce food waste, its change score was positively associated with changes in food waste, and its interaction with baseline waste was significant. One possible explanation is that the measure of prioritized food use reflects subjective evaluation conditional on recognizing food that should be consumed soon. As participants become more aware of such food through the intervention, their self-evaluation of prioritized food use may decrease even without an actual decline in behavior. At the same time, as more foods are identified as requiring prioritized food use, the amount of food that can be prevented from being discarded may increase, thereby contributing to reductions in food waste. This mechanism may account for the positive association observed between changes in prioritized food use and food waste. Furthermore, households with higher baseline food waste may become aware of more similar items through the intervention, potentially strengthening the interaction with baseline waste. Therefore, further refinement of the measurement scale and analytical approaches, including addressing potential ceiling effects, is required.

Regarding "preventing over-buying," although the intervention had a significant effect on this behavior, no direct association with food waste reduction was observed. While correlation analysis (Appendix D) suggested a relationship with food waste, the effect was not statistically significant in the multivariate model. This suggests that "preventing over-buying" may function in conjunction with other food management behaviors, and its independent effect on reducing food waste may be limited.

Taken together, these findings suggest that interventions combining structured behavioral guidance through self-monitoring with motivational design elements such as gamification may help reduce household food waste by promoting food management behaviors. However, their effects on the use-up and consumption stages were not clearly detected.

4.2 Effect of gamification on motivation

Based on the subjective evaluations of participants in the intervention group reported in Section 3.4, many participants were influenced by both self-monitoring through behavior recording and the app's gamified elements, which encouraged behavioral engagement and supported motivation.

In Soma et al. (2020), participants earned points by correctly answering quiz questions, and the value of coupons varied based on the number of points earned. Thus, the observed effects may have been influenced by financial incentives. In contrast, in the present study, all participants received the same reward regardless of their performance, and no monetary incentives were tied to points. Nevertheless, a substantial proportion of participants reported being motivated by points, suggesting that points served as an effective psychological reward. These results indicate that points earned through greater engagement in daily food waste reduction behaviors (linked to leaderboards and badges as part of a gamification mechanism) supported motivation, influenced food waste reduction behaviors, and may have contributed to reductions in food waste. The influence of the leaderboard was comparable to that of weekly ranking badges, whereas competitiveness-related indicators, presumably associated with the leaderboard, were somewhat lower. This finding may reflect that participants were less inclined to adopt a competitive mindset in the context of pro-environmental behavior, such as reducing food waste.

Notably, 73% of participants reported feeling they were "working together with others," despite having limited opportunities to directly recognize other participants beyond viewing the leaderboard on the home screen. Although the leaderboard was introduced primarily to enhance competitiveness, it may have fostered not only a competitive environment but also a sense of collaboration (Grech et al., 2024; Morschheuser et al., 2019; Riar et al., 2022). This interpretation is consistent with prior research suggesting that gamification can promote not only individual motivation but also collective and cooperative behavior, even among individuals who do not know each other, such as in online environments (Koivisto & Hamari, 2019).

If such characteristics can be effectively leveraged, gamified interventions may support both individual-level behavior change within households and collaborative behavior change at the group level, such as in communities or schools. Although the present study primarily examined intervention effects at the individual level, further research is needed to investigate how gamification functions within real social groups and to evaluate its effects on cooperative, group-based interventions.

Finally, because this study targeted individuals who voluntarily applied to participate as survey monitors, the sample cannot be considered representative of the general population in Japan. Participants may already have had a certain level of motivation to reduce food waste, which limits this study. Future research should examine the extent to which gamification-based motivation is effective among individuals without pre-existing motivation to reduce food waste, in contrast to the self-selected participants in the present study.

4.3 Effect of reducing participant burden

Reducing participant burden was key challenge addressed in this study, as 32% of participants reported that they found the intervention burdensome, and 24% reported that it was troublesome. In contrast, in the previous study, a majority (77%) of participants using a food management app reported that the intervention was troublesome. These results suggest that the present intervention substantially reduced perceived burden. In addition, the high ratings for "easy," "understandable," and "user-friendly" indicate that the intervention also helped reduce psychological burden.

From the perspective of dropout rate, an indirect indicator of participant burden, the present study demonstrated extremely low attrition, with only 4 out of 130 participants withdrawing, suggesting that participant burden was small. In Cooper et al. (2023), approximately 50% of participants dropped out during the five-week baseline period in one of the experiments, suggesting that participant burden may have been substantial. One possible explanation for this difference is that Cooper et al. (2023) required participants to complete specific tasks, such as preparing meals using "use-up" recipes on designated days. In contrast, the present study employed a simpler intervention based on daily behavior recording through the app. This simplified design may have reduced participant burden. Furthermore, incorporating gamification elements (e.g., points, badges, and leaderboards) into the self-monitoring process may have provided ongoing motivational incentives that sustained engagement, thereby contributing to the low dropout rate observed in this study.

It should also be noted that the recruitment criteria for this study required participants to be able to use a smartphone or PC to access the app. This requirement likely contributed to a higher proportion of younger participants and a lower proportion of older participants. As a result, the sample may have been biased toward individuals for whom the burden of using the app was relatively low. Therefore, the reported levels of perceived burden should be interpreted as subjective evaluations within a self-selected sample, and caution is needed when interpreting and generalizing the findings. However, it is worth noting that, in Seta et al. (2025), participants were also expected to use an app as part of the intervention. Therefore, the observed differences in perceived burden cannot be fully attributed to differences in recruitment conditions alone.

5. CONCLUSIONS

This study aimed to reduce household food waste by targeting four key behaviors: "searching for food that should be used sooner," "moving such food to a visible place," "prioritized use of food that should be used sooner," and "finishing meals." Building on Seta et al. (2025), which demonstrated the effectiveness of the first three behaviors, this study added "finishing meals" as an additional target behavior. To directly promote these behaviors while reducing the perceived burden of ICT tools and enhancing motivation, we designed and implemented a self-monitoring intervention using a gamified behavior-recording app. Food waste was objectively measured using a cloud-based weighing system. In addition to the four target behaviors, two complementary behavioral indicators, "inventory knowledge" and "preventing over-buying," were included to reflect the broader household food management process, resulting in six behaviors analyzed in this study.

The average weekly food waste per household decreased by 190 g (45%) in the intervention group, compared with 60 g (13%) in the control group, corresponding to a between-group difference of 32 percentage points. A GLM model with bootstrap inference, using the change in food waste as the dependent variable and baseline food waste as a covariate, showed that the intervention group achieved a significantly greater reduction in food waste than the control group ($B = -145.42$, 95% CI [−265.56, −17.66], $p = .036$).

Regarding behavioral outcomes, the intervention had significant effects on two target behaviors ("search" and "move"), as well as on "inventory knowledge" and "preventing over-buying," providing partial support for the H1 hypothesis set. In contrast, no significant effects were observed for the remaining target behaviors ("prioritized food use" and "finishing meals").

Further analysis examining the effects of behavioral changes in "prioritized food use," "finishing meals," and "preventing over-buying" on food waste reduction showed no significant associations in the main-effects model. However, exploratory analyses revealed significant interactions between baseline food waste and behavioral changes. Although the confidence interval for "finishing meals" included zero, this behavior was considered to have the potential to contribute to reductions in food waste. In contrast, for "prioritized food use," the observed relationship was not fully consistent with theoretical expectations, suggesting that the effects of this behavior may depend on its complex relationship with changes in awareness of food items that should be used sooner.

Subjective evaluations by participants in the intervention group indicated that daily self-monitoring increased awareness of food waste behaviors and that gamification elements enhanced motivation. In addition, perceived burden was lower than that reported in Seta et al. (2025). As these findings are exploratory, further confirmatory research is required.

The primary contribution of this study lies in the design and experimental validation of a self-monitoring intervention that directly promotes food waste reduction behaviors. In particular, this study proposes a ICT-based intervention framework that integrates gamification into a self-monitoring app, enhancing motivation while minimizing user burden. Furthermore, the finding that behavioral change can be promoted through psychological rewards without relying on financial incentives has practical implications for the design of sustainable interventions and policy implementation.

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FROM AWARENESS TO ACTION: ENGAGING STUDENTS IN ZERO WASTE INITIATIVES

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ABSTRACT
Within the circular economy, zero waste is an aspirational concept and practical approach aimed at keeping materials at their highest value for as long as possible through rethinking, reducing, reusing, and only subsequently recycling and composting. Rather than focusing solely on waste management, zero waste also seeks to strengthen local economies, protect the environment, sustain livelihoods, and promote community empowerment. Cooperation with social actors such as youth—often excluded from policy processes—can help address gaps in waste reduction and resource diversion. With youth representing a significant and growing share of the global population, and in the context of escalating environmental challenges, engaging young people in sustainability and climate action has become increasingly important. Meaningful engagement depends on creating spaces for learning and capacity building that enable youth to act as innovators and local champions. Initiated in 2024, this research takes place in Victoria, Canada, and in São Bento do Sapucaí and Gonçalves in southeastern Brazil. The project engages youth in participatory research on waste management and promotes sustainable practices in schools and communities. Through interviews, workshops, and student mentoring, middle school students explored waste, recycling, and sustainability, developing practical solutions such as improved sorting stations, reduced plastic use, and awareness campaigns. Students also extended their efforts beyond schools by mapping neighborhood waste hotspots and proposing initiatives including tree planting, community gardens, curriculum integration, and student-led ambassador programs. The project demonstrates the potential of youth-driven, grassroots initiatives to foster environmental responsibility and contribute to more sustainable and resilient communities.

1. INTRODUCTION

Waste management has emerged as one of the most urgent environmental challenges of present times, driven by rapid urbanization, population growth, and unsustainable production and consumption patterns. Addressing this issue requires not only long-term systemic changes but also the implementation of practical, immediate strategies to reduce waste generation at the source. Emphasizing achievable actions can foster more sustainable habits and build momentum for broader environmental transformation (Marín-Beltrán, et al., 2022).

Zero Waste is a working method to keep materials in their highest value for as long as possible (Hannon & Zaman, 2018). It is an aspirational goal and an approach that encourages communities, organizations, and individuals to fundamentally rethink how resources are used and discarded, emphasizing the importance of minimizing waste at both the source and the end of a product's life cycle (Favoino & Kriipsalu, 2018). This involves not only reducing the amount of waste produced, recycling or composting, but also reusing materials whenever possible. Zero Waste strategies seek to keep materials within the economy for as long as possible, preserving their highest value and thus reducing the environmental impact not only associated with disposal, but also with extraction and manufacturing. By promoting circularity, Zero Waste initiatives inspire innovative solutions such as designing more durable products,

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establishing community composting programs, or implementing extended producer responsibility policies (Zaman, 2022).

Educational campaigns, programs, and participatory research can play a critical role in reinforcing this shift by empowering citizens - particularly youth - to become active agents of sustainability within their schools and communities (Cox et al., 2019). The Zero Waste framework is also closely linked to broader processes of sustainable urban development, seeking more equitable, resilient, and resource-efficient cities.

Youth participatory action research is a strategy that creates opportunities for young people to exercise voice and agency by engaging them as active contributors to research and action processes. Including children and adolescents in discussions about their territory and empowering them with critical thinking are strategic for enhancing children's and adolescents' resilience, adaptability to climate change, and citizenship (Dias et al., 2023). Recent studies exploring geographical knowledge within urban environments have engaged children and youth, whose perspectives offer valuable insights into tackling complex challenges such as climate change, disaster risk reduction, and resource security, while also proposing more effective and tailored solutions (Marchezini & Trajber, 2016). The knowledge and perspectives of young people are often disregarded despite their disproportionate vulnerability to socio-environmental impacts. Youth represent a significant portion of the global population: 1.2 billion young people aged 15 to 24 years, accounting for 16% of the worldwide population, of whom the majority live in the global South (UN, 2020). Moreover, they have a high capacity to change community behaviour due to their strong communication and engagement skills (Trajber et al., 2019; Aerts et al., 2018). Their experiences and innovative ideas can offer valuable insights into waste management while contributing to responses to climate change and urban sustainability. Furthermore, as the generation most likely to face the long-term consequences of today's environmental decisions, they are vital to shaping effective policies and solutions. By excluding youth voices, we miss opportunities to harness their creativity, resilience, and willingness to drive meaningful and transformative change (Percy-Smith, et al. (Eds.), 2023).

Both Brazil and Canada face significant challenges and opportunities in waste management, particularly in engaging young people and fostering sustainable practices. In the research project conducted between 2024 and 2025, participatory action approaches were implemented in Victoria, Canada, and in the Brazilian cities of São Bento do Sapucaí and Gonçalves. These case studies with youth highlight both the differences and similarities in the waste management landscapes of the two countries, as well as the potential for youth-driven initiatives to address local waste issues.

2. THEORETICAL FRAMEWORK

Urban Political Ecology (UPE) is a robust framework for studying cities and their waste flows and gaps, taking into consideration structural challenges, diverse actors and their power dynamics, involved in managing, diverting and reducing waste. In addition, UPE draws attention to questions of social justice, inequality and the connection between political economy and everyday material lives. The theory incorporates understandings of circularity as a pre-requisite for achieving greater sustainability (Stahel, & MacArthur, 2019; Suárez-Eiroa, et al., 2019).

Supported by theories on human-environment interactions (Turner & Kaplan, 2019; Swyngedow, 2009; Gregson & Crang, 2010; Hacking, 2019) and Assemblage (Anderson & McFarlane, 2011; Spies & Alff, 2020), this study sheds light on the composite and heterogeneous elements involved in waste reduction, with particular attention to the agency of youth as grassroots actors, and thus provides a more relational and dynamic understanding of UPE.

A lens situated in the local and regional context recognizes the specific geographic, historical, political, socio-economic and environmental urban circumstances (Lawhon, et al., 2014; Lawhon, Le Roux, Makina & Truelove, 2020). Within UPE, the Urban Metabolism analogy (Fernandez, 2014) and Assemblage theory help understand waste flows and reveal the actors, ideas, materials and technologies involved in these flows, e.g., identifying who benefits and who is excluded; disentangling social and power relations that underpin the predominant forms of generating and managing waste under the current waste regime (Gille, 2013). This theoretical framework incorporates understandings of circularity (Circular Economy) as a prerequisite for advancing sustainability outcomes (Kirchherr, Reike & Hekkert, 2017; Stahel, & MacArthur, 2019; Suárez-Eiroa, et al., 2019). Waste regimes describe the multifaceted aspects of governance and waste management, helping to understand the relationships between waste and society. We seek to expand these approaches by situating concepts within local contexts to capture the particularities and textures of place, thereby contributing to the overcoming of Eurocentric views on urban development (Frey, 2012; Frey, Gutberlet & Jacobi, 2019; Mabin, 2014).

Moreover, engaging youth in understanding waste management across different contexts through the UPE lens supports the development of contextualized alternatives and solutions, helping to fill critical gaps in urban planning (Adelina, et al, 2024; Hendra et al, 2025). It is crucial to consider the potential of young people´s arguments to drive changes in urban public policy sectors, such as waste management (Walker, 2019).

In the context of circular urban flows, the concept of Zero Waste is important, as a driver for designing and managing products and processes to systematically avoid and eliminate the volume and toxicity of waste and materials, particularly plastics (Zaman, 2022). It is a visionary concept that encompasses people changing their lifestyles and practices so that waste is avoided and that all discarded materials are designed to become resources for future uses (Tamminen & Lobin, 2022). Zero Waste challenges the assumption of waste as valueless and unavoidable consequence of consumption (Gutberlet, 2018).

3. METHODS

The study site in Canada is the City of Victoria (population of 91,867), located on Southern Vancouver Island, British Columbia, covering an area of 19.47km^2. Victoria is widely recognized as a leader in sustainability and climate action and, in March 2019, declared a climate emergency, uniting with cities across the country to address the crisis, accelerate the transition toward net-zero carbon emissions, and advance a Zero Waste strategy. The two Brazilian study sites (population of 17,000), while characterized by a more rural profile, share a nature- and culture-based tourism economy, like that of the Canadian case. This economic profile places increasing pressure on local governments to pursue socio-environmental innovations, particularly in response to the growing urgency of waste reduction. Yet the region hosts relatively few community-based initiatives working with recycling, composting, and repair. The project was conducted in partnership with three middle schools (Monterey Middle School in Victoria, Escola Estadual João Ribeiro da Silva in Gonçalves, and Escola Estadual Professor José Maria Priante in São Bento), identifying four grade 6 classrooms (60 students in each city) in Brazil and one grade 7 classroom (24 students) in Canada.

We applied a participatory community-based methodology (Amauchi et al., 2021; Clifford, French & Valentine, 2010), developing a set of five workshops with discussion groups, participatory mapping, Virtual Reality (this activity was only conducted in Victoria), and the use of creative tools to elicit students' reflections and ideas (Figure 1).

Participatory mapping uses several tools to capture citizens' perceptions and knowledge, resulting in maps that represent community understandings in multiple ways (Etmanski, et al., 2014). City planners can then spatialize this information and analyze it alongside other information using geoprocessing software, thereby supporting planning and decision-making processes, including those related to waste management (McCall, 2003). Participatory mapping and related approaches constitute powerful instruments for social change, and engaging youth offers additional benefits, such as stimulating social protagonism and strengthening a sense of community responsibility. Moreover, young people can contribute meaningfully to changing their urban environments and express their desire to be active participants in their communities (Kallio et al., 2013; Kraftl, 2013).

The main objective of these activities was to identify problems, bottlenecks, and possible solutions related to waste within the school environment, while promoting student's active engagement in the process, and the co-production of impactful products capable of influencing waste management practices within the school, in other schools, and in their wider communities. Student volunteers were selected to serve as Zero Waste Ambassadors through a democratic voting process: five students in each of the two Brazilian cities and four ambassadors in Victoria. These ambassadors took on a leadership role within the project, serving as student representatives and a key link between their classmates and the research team. Their responsibilities included co-developing project outputs, supporting awareness-raising activities, and helping to sustain the initiative within their school communities. Through their engagement, the ambassadors played a critical role in maintaining momentum, fostering peer-to-peer learning, and ensuring that the project remained grounded in the students' perspectives and everyday experiences.

The participatory approach adopted in this project provided valuable insights into students' perceptions of waste management and the broader environmental challenges associated with urbanization, tourism growth, and climate change. Through interactive activities and discussions, the project enabled the identification of key waste-related issues and potential areas for improvement, both within school environments and in the surrounding neighborhoods. This engagement also facilitated the co-creation of educational and policy-support materials that have the potential to strengthen Zero Waste strategies and reinforce integrated urban development policies in the study areas.

4. RESULTS AND DISCUSSION

4.1 Key informant semi-structured interviews

Interviews with school principals and teachers in Victoria (Canada), Gonçalves, and São Bento do Sapucaí (Brazil) reveal several shared and divergent challenges regarding Zero Waste education and practices. Across both countries, educators are familiar with the Zero Waste concept; however, they perceive that students generally lack understanding and practical engagement. In Canada, students may have heard about Zero Waste but rarely practice it. In contrast, in Brazil, the concept is predominantly associated

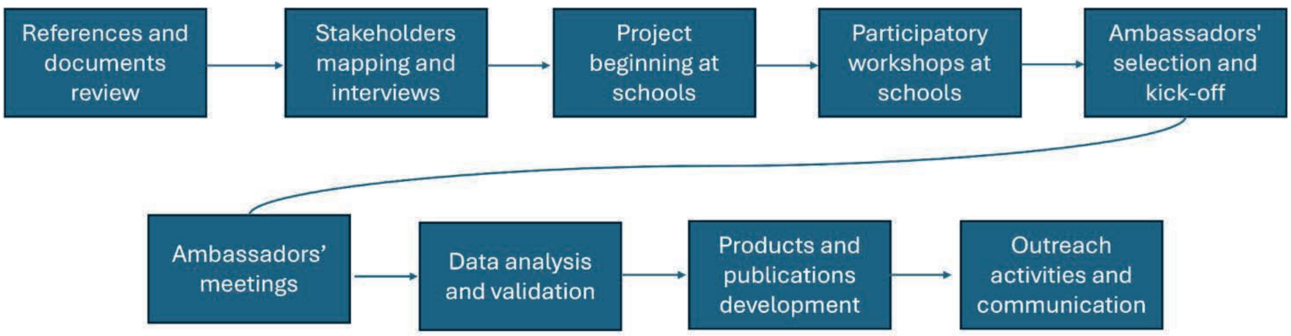

FIGURE 1: The research process.

with inorganic recycling, with limited recognition of organic waste and broader sustainability issues.

Interviewees in both contexts reflected on the social inequalities that shape students' environmental behavior:

- In Brazil, teachers expressed concern that students from lower-income households may have fewer options to reduce waste and should not be burdened with environmental guilt.
- In both countries, conversely, more affluent students may be detached from the impacts of consumption, viewing sustainability as an abstract or optional concern.

Despite general awareness, all interviewees highlighted significant gaps between knowledge and practice:

- In Victoria, recycling systems were suspended during the COVID-19 pandemic and have not been fully reinstated. Only office paper is currently recycled, while general student waste is disposed of as garbage.
- In Gonçalves, waste separation is neither systematically practiced nor meaningfully addressed within the curriculum. A prior school project aimed at reducing classroom waste failed mainly due to a lack of student engagement.
- In SBS, some awareness-raising initiatives exist, and collaboration with a local waste picker cooperative has brought speakers into classrooms. Yet, there are still no structured Zero Waste guidelines or consistent waste management practices in place.

A notable difference between the two countries is the presence in Brazil of local waste-picker cooperatives that could engage with schools to offer community-based learning opportunities, which is not evident in the Canadian setting. Nonetheless, both contexts reveal behavioral barriers, including students' difficulty in adopting correct waste habits, and a disconnect between environmental knowledge and daily practices. Social inequality further complicates these dynamics; educators highlight disparities in students' consumption patterns and levels of environmental responsibility, which are closely associated with students' socioeconomic conditions.

Several pedagogical limitations were noted:

- Waste is not yet systematically integrated into curricula. In Brazil, coverage is often indirect or limited to occasional events (e.g., science fairs).
- Teachers face time constraints and lack coordinated opportunities for interdisciplinary planning of environmental content.
- There is a shortage of teaching materials focused on Zero Waste, particularly in Portuguese.
- In Canada, environmental clubs and periodic litter collection activities exist, but are not fully leveraged to sustain waste education.

Overall, interviews suggest that effective Zero Waste education requires systemic support, including adequate infrastructure, curricular integration, community partnerships, and targeted awareness campaigns. Parting from an urban political ecology perspective and highlighting waste in the urban metabolism provides a visually attractive form of communication with teachers and students to be explored in the classroom. The metabolism analogy (Heynen, et al. (Eds.), 2006) visualizes the pathways of waste in the city and surrounding areas, and it highlights the environmental, social and economic impacts and possible alternatives. In both regional contexts, coordinated efforts between schools and municipal authorities to foster consistent practices and empower students as active agents of sustainability would be beneficial.

4.2 Classroom activities

In 2024, five participatory workshops were conducted in each of the schools involved in the project. The workshop outcomes revealed a strong capacity among students for critical reflection, place-based environmental awareness, and creative problem-solving regarding waste management, as reiterating by Marchezini and Trajber (2016). Despite contextual differences, several shared themes emerged (Table 1). Students in both countries understood waste as a byproduct of human consumption, linking it not only to local issues, such as littering or inadequate disposal infrastructure, but also to broader environmental concerns, including pollution, climate change, and the unsustainability of prevailing consumption modes. Canadian students critically questioned the very concept of "zero waste" as an unattainable ideal, demonstrating a nuanced understanding of systemic challenges.

Students identified a range of practical issues in their immediate environments. In Canada, students highlighted improper waste separation, unclear bin labeling, gum and plastic waste (e.g., sushi containers used during school lunches organized by the Parents Advisory Council-PAC), and limited student engagement in recycling. In Brazil, the key points mentioned by the students were a lack of separation at home, litter in schoolyards, and insufficient infrastructure for proper waste disposal.

These observations were grounded in students' everyday experiences and demonstrated, at least among some of them, a strong awareness concerning the tangible impacts of waste in their communities. From these perspectives, some solutions and creative ideas emerged during our workshops and conversations.

Students proposed a variety of actionable solutions, including:

- Increasing the number of waste and recycling bins on school premises and in the community and clearly labeling what should go into each bin.
- Encouraging recycling and reuse practices, such as using biodegradable or reusable containers during school lunches and school-related activities.
- Creating awareness campaigns in the school through posters, blogs, and peer-led presentations.
- Incorporating sustainability into school routines (e.g., clean-up field trips, bike-to-school initiatives).
- Installing green infrastructure, such as solar panels or rain gardens.

Brazilian students also highlighted the importance of tree planting and environmental preservation near rivers.

TABLE 1: Comparative Analysis of Participatory Workshop Results – Canada and Brazil.

Thematic Area	Canada (Monterey Middle School)	Brazil (São Bento do Sapucaí & Gonçalves)
Student Engagement	High engagement with open discussion; students showed critical thinking and proposed concrete actions.	Strong enthusiasm from the beginning; students volunteered and were elected as ambassadors.
Understanding of Waste	Defined as materials like plastic, food packaging, and gum, linked to broader issues like climate change.	Understood as leftovers from consumption, associated with pollution, dirt, and environmental harm.
Observed Problems at School/Home	Lack of proper waste separation; unclear bin labeling; plastic waste (e.g., sushi containers); gum littering.	No separation at home; littering at school, especially wrappers and gum on the floor.
Proposed Solutions	More bins with clear labeling; student awareness campaigns; school-wide presentations; use of reusable materials; solar panels; rain gardens.	Selective collection; proper disposal infrastructure; tree planting; recycling education.
Participatory Mapping Outcomes	Identified local waste hotspots; proposed community gardens, solar panels, bike lanes, and improved signage.	Mapped key landmarks and environmental problems; highlighted the river as a key asset; proposed photo-documentation walk.
Creative/Arts-Based Activities	Used Virtual Reality to explore Brazilian waste picker cooperatives; created maps and awareness materials.	Created a recycling mosaic using painted cardboard squares; the artwork was displayed in school.
Final Student-Led Initiatives	Developed student ambassador-led presentations; proposed lunchtime waste monitoring; advocated for a shift to the circular economy.	Built a "Dream Tree" expressing personal and collective visions for a sustainable future.
Focus on Social Dimensions of Waste	Emphasis on the role of school practices and institutional limitations (e.g., staff constraints, contract limitations).	Highlighted the role of waste pickers in the recycling chain; strong awareness of social aspects of waste.
Educational Tools Used	Workshops, focus groups, participatory mapping, VR, ambassador program, peer presentations.	Workshops, focus groups, participatory mapping, arts-based methods, and an ambassador program.
Key Takeaways	Youth can act as change agents with the right tools and institutional support; the importance of linking local action with global awareness.	CBR and arts-driven approaches promote local ownership, a strong link between identity, place, and environmental stewardship.

In contrast, Canadian students emphasized system-wide change, linking waste to climate policy and the transition from a linear to a circular economy.

Students in all three cities showed a growing sense of environmental responsibility and agency. They recognized the role of individual behavior (e.g., "people are lazy," "we need to do better") but also critiqued institutional barriers, such as a lack of school policies and staff limitations. Brazilian students expressed respect for waste pickers and a desire to support them, while Canadian students called for teachers and staff to lead by example.

One workshop was dedicated to a participatory mapping activity, in which students identified waste-related problems and proposed solutions by annotating maps of the school premises and the wider neighbourhood. Figure 2 shows the consolidated map summarizing the issues the students identified in the neighbourhood.

In another workshop, we constructed a "Dream Tree" (Figure 3) to allow students to express their hopes for the future. These included dreams of a more conscious society, better public infrastructure, and stronger environmental education programs in their schools. Students emphasized the importance of being heard and recognised their own capacity to initiate meaningful change within their schools and communities. The word cloud was constructed with the keywords collected from the students' responses.

The workshop results underscore that, when provided with adequate space, tools, and support, students are not only capable of critically analyzing environmental problems but also of generating innovative, place-based solutions rooted in lived experience and collective action. Their insights contribute valuable perspectives to local sustainability planning and broader discussions on environmental justice and youth participation. Moreover, the activities allowed the research team to observe differences in the students' perspectives, connected to the urban context they live in and to the structure of the education system. For example, in Canada, the research team faced time constraints put on by the school in developing additional project activities, whereas in Brazil, more flexibility was given to the researchers.

Students reported a deeper understanding of waste origins, its environmental impacts, and the broader zero-waste concept, including the roles of waste pickers in both the Global South and the Global North. They recognized specific local issues, such as plastic packaging, and valued learning about social inequities associated with waste management. The Virtual Reality experience applied in Victoria was convenient in enabling Canadian students to engage with and understand the realities of waste pickers in Brazil. Students expressed enthusiasm for expanding the project, suggesting the inclusion of more grades, a broader geographic reach, and the development of teaching materials or courses. They saw ambassadors as vital leaders in awareness-raising and community engagement. Overall, students appreciated the project's interactive and participatory approach, noting its importance for fostering environmental responsibility and empowerment.

4.3 Student ambassadors for zero waste

The ambassadors were elected by their peers, fostering a sense of belonging and responsibility. In Victoria,

FIGURE 2: Waste-related issues mapped by students in Oak Bay, Victoria.

the ambassadors delivered a presentation of the project to teachers and staff. They also planned a presentation in other classrooms, but this activity could not be completed due to time constraints. As a final output, the ambassadors produced an educational publication on fast fashion and the impacts on waste management and policies to be distributed among students and schools.

FIGURE 3: Students' dreams for a zero-waste future.

In Brazil, the Zero Waste ambassadors also presented their proposals to their teachers and to peers in other classrooms (Figure 4). In Gonçalves, they proposed school activities such as environmental assessment walks and demonstrated interest in leading awareness campaigns both inside and outside the school. They also requested a meeting with the local mayor and the Environmental Officer to discuss waste-related challenges in their communities, and they wanted to plant trees.

In São Bento do Sapucaí, the ambassadors stood out for their ability to connect with school staff and their appreciation for local partnerships, such as with the waste pickers' cooperative. In these schools, students were motivated to continue the project, develop educational initiatives, and maintain dialogue with other young participants, including through online networks. The role of ambassadors has established itself as an effective strategy for encouraging student leadership, strengthening ties with the community, and promoting a zero-waste culture in their schools.

The ambassador program was concluded by the end of 2025. The next phase will be focused on the dissemination of the research findings and the materials produced to other classes in the same schools and to contribute to broader citizen education on Zero Waste. In Brazil we want to explicitly target rural areas adjacent to the towns under study, which have been identified as critical challenges for waste management. Students are committed to organizing a community clean-up day and to presenting a poster on zero waste to increase awareness during the forthcoming "Environment Day" event.

FIGURE 4: Students presenting the zero-waste proposal.

As part of the project, each ambassador was invited to record a short video introducing themselves and sharing their motivation for engaging in zero-waste activism. These video clips were then shared among all ambassadors, enabling students to recognize themselves as part of a broader network of youth actors committed to sustainability. The videos were translated into Portuguese for the Brazilian students, and many appreciated also the opportunity to engage with the original English versions, viewing it as a meaningful and enjoyable challenge.

At Monterey Middle School, in Victoria, Canada, the educational program with the ambassadors was conducted from November 2024 to June 2025. During the meetings, the concepts of zero waste and the impacts of waste generation were discussed, along with related topics such as climate change. A first presentation was delivered by the ambassadors to the staff meeting. The second product was a booklet about Fast Fashion, which is currently under development, with the main aim of online distribution.

4.4 Research limitations

While the Zero Waste project demonstrated strong potential to foster youth engagement in sustainability and participatory environmental education, its implementation revealed several structural and logistical limitations that merit careful reflection. These challenges, common in school-based research and intervention projects, underscore the need for more supportive institutional frameworks and adaptive project design to ensure broader, more equitable participation.

One of the most significant limitations was the restricted availability of time within the formal school schedule. Teachers consistently reported difficulty in allocating time for project activities, including the workshops, due to the demands of meeting prescribed curricular goals. As schools are under pressure to deliver standard content within fixed timelines, integrating extracurricular or cross-disciplinary projects, such as Zero Waste, often competes with other educational priorities. This constraint not only limited the depth of engagement possible within each workshop but also hindered follow-up activities that could have reinforced learning outcomes.

Closely related to this, there was minimal time available to work with the student ambassadors during school hours. Although the ambassador model proved highly effective in fostering leadership and peer-led awareness, the scheduling of regular, dedicated sessions with ambassadors was challenging. Specifically in Victoria, these meetings had to be condensed or postponed due to competing school activities or a lack of availability in the timetable. As a result, the full potential of the ambassador-led initiatives was not fully realized.

Ethical guidelines and institutional policies around student privacy posed another notable challenge. Communication with students outside designated project hours was impossible due to limitations on accessing student emails or digital communication platforms. These restrictions, while necessary for safeguarding student welfare, also made it difficult to maintain continuity between sessions, respond to student queries, or provide ongoing mentorship to ambassadors. The absence of a flexible communication strategy reduced opportunities for sustained engagement and deeper collaboration beyond workshop settings.

The project's cross-national and multi-regional nature, spanning Canada and Brazil, also introduced logistical and financial barriers. Due to resource constraints, it was not feasible to organize interactions between ambassadors from Brazil and Canada, which could have enriched the project's intercultural and comparative dimensions. Although virtual tools were considered, limitations in infrastructure, internet access, time zone differences, and language mediation made such exchanges difficult to implement meaningfully within the available timeframe.

The project successfully empowered several highly motivated and engaged students, and it gave particular attention to fostering inclusive participation. Activities were designed to encourage contributions from quieter students, including small-group discussions and targeted efforts to involve those who were less outspoken or less confident. Despite these efforts, it remained a challenge to fully overcome the pre-existing dynamics of classroom participation. Students who were already perceived as natural leaders tended to take on more visible roles, including selection as ambassadors. This highlights a continued limitation in terms of equitable representation, as students with learning difficulties, lower academic engagement, or social reticence may have participated less actively. Future iterations of the project should further explore strategies to democratize access to environmental education and leadership, ensuring that diverse voices and experiences are meaningfully included. Addressing these limitations requires a multi-faceted approach, including stronger institutional support for integrating sustainability projects into curricula, clearer communication protocols that allow for safe yet flexible engagement, and targeted strategies to include a broader spectrum of students. Despite these constraints, the Zero Waste project has laid the necessary groundwork for future school-based initiatives and has highlighted key areas for structural improvement in participatory environmental education.

5. CONCLUSIONS

The Zero Waste project, implemented across educational institutions in Victoria, Canada, and in the municipalities of Gonçalves and São Bento do Sapucaí in Brazil, provides a valuable lens for analyzing the intersections of environmental education, youth participation, and structural inequalities in urban sustainability. Framed through the theoretical perspectives Urban Political Ecology (UPE) and Urban Metabolism, the project's findings contribute to ongoing discussions about the socio-material processes shaping waste governance in urban and peri-urban contexts.

Urban political ecology foregrounds the uneven power relations that structure urban environments and the socio-natural processes that define access to, and control over, urban resources and infrastructures (Heynen, Kaika & Swyngedouw, 2006). Waste, within this framework, is not merely a technical or managerial problem but a socio-political artifact, shaped by the spatial, institutional, and class dynamics that govern urban life. The Zero Waste project made these dynamics visible by exposing how waste is differently experienced across geographical contexts and within urban social groups, particularly through students' reflections on the roles of waste pickers, the visibility of litter in schools, and the unequal burdens of environmental degradation.

Students' recognition of waste pickers as "environmental heroes," especially in the Brazilian context, aligns with UPE's emphasis on marginalized labor and informal infrastructures that sustain the formal operations of urban metabolism. These actors, often excluded from mainstream sustainability narratives, were repositioned by students as central to the city's ecological functioning. Their acknowledgment marks a critical pedagogical and political intervention, challenging dominant narratives that render such labor invisible and re-signifying it as an essential component of circular and just urban futures (Tamminen & Lobin, 2022).

Moreover, the project sheds light on the scalar dynamics of urban environmental governance. Students identified both micro-scale interventions (e.g., improving school recycling systems, reducing lunch packaging) and macro-scale concerns (e.g., links between waste and climate change, zero waste policies at the city level) (Nelson, Ira & Merenlender, 2022). This scalar awareness reflects an emergent understanding of urban metabolism, understood as the circulation of energy, materials, and labor through urban systems (Kennedy et al., 2007). By engaging students in mapping and localized diagnostics, the project invited them to conceptualize their schools and neighborhoods as metabolic nodes, sites where socio-environmental flows can be visualized, contested, and potentially transformed.

In future iterations of the project, this participatory mapping approach could be expanded to include continuous monitoring and evaluation of progress in collaboration with students. Teachers could work with students to track changes in waste generation, both reductions and increases, across specific locations, thereby fostering greater student engagement and a stronger sense of responsibility. The resulting data could then be analyzed to refine strategies and inform targeted interventions, while also serving as a valuable tool for communicating outcomes and impact to the broader public.

The project also revealed limitations in how schools operate as spaces of socio-ecological transformation. In both countries, students and educators highlighted structural barriers to effective waste management, including inconsistent recycling infrastructure, limited environmental education in curricula, and a disconnect between knowledge and practice. These findings echo UPE critiques of technocratic and depoliticized approaches to sustainability, which often fail to engage with the lived realities of urban residents or to confront the deeper political-economic logics that produce waste in the first place (Swyngedouw, 2009).

Furthermore, the fragmentation of responsibility—between schools, municipalities, and households—revealed by the interviews underscores a metabolic disjuncture, whereby the social and material flows that constitute urban waste remain poorly coordinated and unevenly governed. Students' efforts to visualize and intervene in these flows, for instance, through mapping hotspots or proposing changes to packaging norms, represent an attempt to re-politicize waste by linking individual actions to systemic patterns of consumption and disposal.

Notably, the project's methodological design, centered on participatory research and youth agency, serves as a prefigurative political practice within the UPE tradition, pointing toward more democratic, place-based forms of environmental governance. The student ambassadors' proposals for greater inclusion, curricular integration, and community outreach reflect an emergent ecological citizenship, one that resists passive environmental messaging in favor of co-produced, justice-oriented sustainability.

Through the lenses of urban political ecology and urban metabolism, the Zero Waste project illustrates the pedagogical and political potential of engaging youth in critical environmental praxis, echoing the findings of other scholars (Cox et al., 2019, Han & Ahn, 2020, Ritchie, 2021). The findings reinforce the idea that waste is not only a material byproduct but a reflection of broader urban power relations, metabolic configurations, and cultural narratives (Hird, 2022). As students began to recognize and challenge these dynamics, through reflection, mapping, and proposal-making, they also began to enact alternative imaginaries of the urban, rooted in equity, responsibility, and collective action. Future interventions should build on these insights to further embed political-ecological literacy in schools and to strengthen youth roles as co-producers of more just and sustainable urban futures.

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UPCYCLING OF PLASTIC WASTE FOR RESOURCE RECOVERY: UNVEILING THE TECHNICAL CHALLENGES AND STRATEGIES TOWARDS THE COMMERCIALIZATION OF PLASTIC-BASED CIRCULAR ECONOMY

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ABSTRACT

The study aimed to analyze the effects of different plastic wastes, including Polystyrene (PS), Polyethylene (PE), and Polypropylene (PP), and their 50:50 mixture on the yield and quality of liquid oil through pyrolysis. A small-scale batch pyrolysis reactor with the total capacity of 10kg was commissioned and operated at 550°C with a retention time of 90minutes. Results revealed that the highest feedstock conversion to liquid oil (51%) was recorded for PS compared to other types of plastic waste, whereas among mixed plastics, PE:PS produced the highest liquid oil yield (39%). The physicochemical analysis demonstrated that the obtained oils were predominantly aromatic compounds, with some alkanes and alkenes. Moreover, liquid oils from all types of plastic waste showed the density between 0.734 and 0.892g ml-1, viscosity (1.99 to 3.1mm2 s-1), flash point (29 to 48°C), and high heating value (37.2 to 42.4MJ kg-1). Based on the obtained results, an in-depth discussion has been conducted on the utilization of the produced liquid oil and gases in several energy-related applications, including transportation, heating, and electricity production, along with the applicability of the resultant char for several energy and environmental applications. Moreover, it has been emphasized that the key bottleneck in commercializing the plastic-based circular economy concept requires the continuous feedstock supply, characterization and pretreatment of feedstock to eliminate toxicity, approaches for reducing wax formation, technological advancements to enhance the quality and yield of pyrolysis, and detailed life cycle assessment to achieve maximum environmental and human health benefits.

1. INTRODUCTION

Plastic materials have been developed to meet human needs due to their properties such as lightweight, chemical stability, easy availability, and wide applicability in day-to-day life (Mishra et al., 2023). However, the exponential increase in global plastic production is driven by its durability and low cost also result in a monumental amount of plastic waste production (Yang et al., 2024). It has been reported that current global plastic waste production is about 1.7 to 1.9 billion metric tons per annum, which is expected to reach around 27 billion metric tons per annum by 2050 (Fayshal, 2024). Among the generated plastic waste, only 9% is recycled, 12% is incinerated, whereas the remaining major portion (79%) is landfilled without any material/resource recovery (Hou et al., 2021).

The substantial generation along with non-degradable nature, plastic waste can pose serious risk to the environment by remaining in landfills for decades, thus making space scarce for landfills, and may lead to soil and water pollution (Gebre et al., 2021). For example, single-use plastic bags takes an average of about 1,000 years to completely degrade and often end up in soil and water bodies

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(Dey et al., 2023). Hence, the production of anthropogenic plastic waste can lead to both ecological degradation and social impacts that urgently require serious action to prevent environmental degradation.

The current plastic waste management strategies include landfilling and recycling via incineration; however, the high space and resource requirements along with the release of toxic emissions hinders the effective implementation of these techniques (Yang et al., 2024). There is a dire need for such a strategy to deal the plastic waste according to environmental deliberations. Previous studies have shown that pyrolysis technology is a sustainable solution for recycling plastic waste, producing valuable products, including liquid oil, gases, and char (Gebre et al., 2021; Pan et al., 2024a). Pyrolysis is a thermochemical process carried out at elevated temperatures ranging from 400 to 900°C under oxygen-deficient conditions (Pan et al., 2024a). Elevated temperatures break down high-molecular chains into low-molecular products along with the production of liquid oil, solid residue, and gases (Mishra et al., 2023). For treatment of plastic waste, pyrolysis has been reported as a feasible and environmentally friendly technology (Putra et al., 2022). Moreover, pyrolysis technology is being employed not only to reduce plastic waste in landfills but also to recover energy and valuable products for wide range of applications (Sakthipriya, 2022).

Extensive research has been performed on pyrolysis using single type of plastic waste, including polyethylene (PE) (Al-Yaari & Dubdub, 2020), polypropylene (PP) (Xu et al., 2018), polystyrene (PS) (Chowlu et al., 2009), polyvinyl chloride (PVC) (Matsuzawa et al., 2004), and polycarbonate (PC) (Charde et al., 2018) under various parameters such as temperatures and heating rates. However, limited research has been reported on the pyrolysis of mixed plastic waste to recover liquid oil under various temperature protocols. Moreover, pyrolysis of single waste types such as PE generates olefins of various chain lengths and aromatic compounds, including toluene, styrene, and benzene. Hence, mixing various types of plastic waste such as PS, with these polyolefin feedstocks (PP and PE) accelerates pyrolysis and results in rapid decomposition, yielding high-oil products with shorter chain lengths.

Therefore, this study is designed to (i) assess the suitability of real plastic waste from the mixed municipal solid waste into liquid oil using pyrolysis technology along with the examination of individual and mixing at 50:50% of various types of plastic waste such as PS, PE, and PP on the quality and yield of produced liquid oil, (ii) characterization and evaluation of the pyrolysis-derived oil for resemblance with commercial fuel, (iii) integration of circular economy commercialization through highlighting the opportunities and approaches to cope with the challenges under the plastic based refinery concept for the effective management of plastic waste and encourage a shift to more sustainable consumption of derived oil as a source of clean energy.

2. MATERIAL AND METHODS

2.1 Feedstock collection and preparation

The real municipal plastic waste samples were collected from four waste transfer stations located in different localities in Peshawar, Khyber-Pakhtunkhwa, Pakistan. The collected plastic wastes were categorized into PE, PS, and PP. Given the economic and market value of PET, this research considers only PE, PP, and PS. The selection of these plastic types was made based on the fact that these components reflect the major components of the waste stream of District Peshawar, Khyber-Pakhtunkhwa, Pakistan. Each type of plastic waste was weighed and crushed into fine pieces, approximately 1 to 2cm to obtain a homogeneous mixture. The crushed samples were washed to remove impurities and sundried to remove moisture. After drying, the feedstock was ready for pyrolysis.

2.2 Experimental setup

For pyrolysis, a small-scale batch pyrolysis reactor with a carrying capacity of 10kg, made of stainless steel was used to convert plastic waste into liquid oil. The schematic diagram of the pyrolysis reactor is shown in Figure 1, and the reactor's detailed features are listed in Table 1. The reactor was comprised of a reactor system, a cooling system, and a storage tank. For each pyrolysis reaction, 1kg of accurately weighed feedstock including PE, PS, and PP was individually loaded into the reactor (100%) and in a 50:50 mixture. The pyrolysis was carried out at 550°C with the heating rate of 10 to 15°C per minute and residence time of 90minutes. For temperature measurement, a thermostat was adjusted in conjunction with a temperature controller.

These pyrolysis conditions, with a temperature of 550°C and a residence time of 90minutes were based on the thermal stability and decomposition temperatures of various types of plastic waste under controlled conditions, as well as safety considerations reported in the literature (Miandad et al., 2017). As the temperature increased, the feedstock was broken down and converted into vapors, which were condensed into liquid after passing through the cooling system and subsequently collected in the collection tank. The char (remaining unburnt feedstock) was collected from the heating chamber after the reactor system was cooled to room temperature. Likewise, the mass balance of pyrolysis products after each experiment was determined by accurately weighing the obtained oil and char using a standard digital balance, while the remaining weight to make up 100% was assumed to be the gas product. Moreover, to eliminate interference from human or other factors and ensure the reproducibility of the experiment, each experimental trial was replicated three times, and the obtained average values are reported with their standard deviations.

2.3 Characterization of liquid oil

The pyrolysis-derived liquid oils were subjected to various characterizations using appropriate procedures based on ASTM standard methods. The liquid oil was characterized for density, viscosity, pour point, flash point, and high heating value (HHV), as well as by spectrometric analysis such as Fourier Transform Infrared (FT-IR) spectroscopy and Gas Chromatography coupled with Mass Spectrometry (GC-MS).

To measure the density of pyrolysis-derived liquid oils, a portable density meter (DMA35 from Anton Paar) was

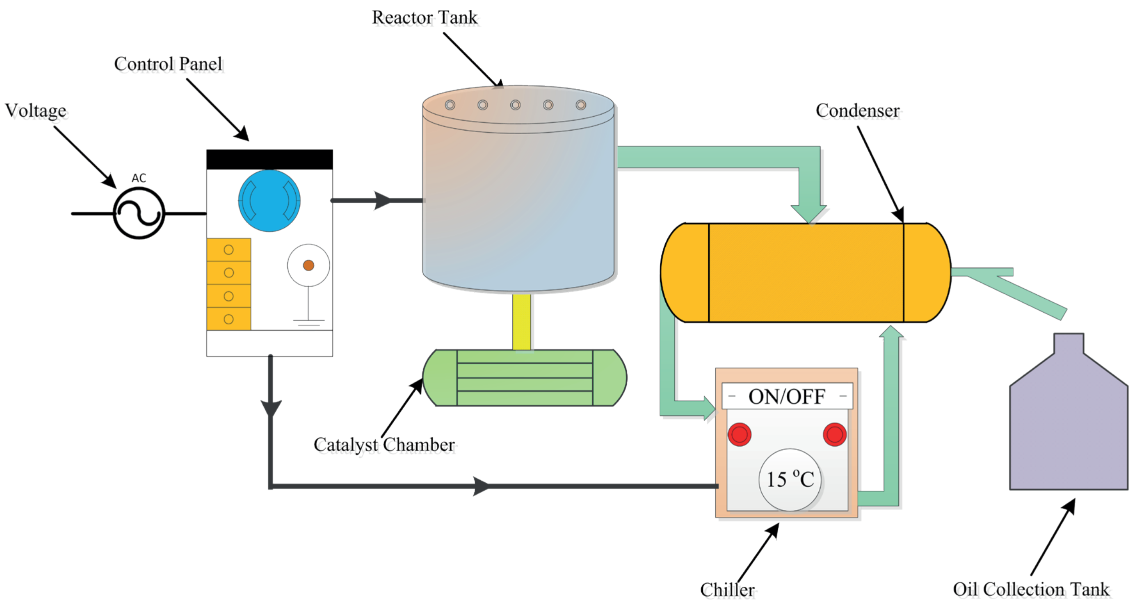

FIGURE 1: Schematic diagram of the small-scale batch pyrolysis reactor.

used. Prior to sample analysis, the density meter was calibrated with distilled water after rinsing with acetone and then allowed to dry completely. The variation in the viscosities of the derived liquid oils were determined using a hybrid rheometer (HR1 from TA Instruments) with a 40mm parallel-plate geometry. For viscosity analysis, a small amount of liquid oil was placed at the bottom of the horizontal plate and sandwiched between the upper 40mm plate. During analysis, the shear rate range and temperature of the rheometer were set to 1-500 $1/s^{-1}$ and 40°C, respectively.

Likewise, the AWD-12 pour point analyzer was used for determining the pour and freezing points. For analysis, the temperature range was kept at -10°C in one tank (left side tank), whereas in the right side tank, it was kept at -65°C. For each sample, the sampling tube was filled to the designated mark and first placed in the left tank until the temperature reached 0°C. Consequently, the sample was transferred to the right-side tank. The sample tube was periodically removed from the tank with the temperature reduced by 2°C to observe the liquid flow by holding the tube horizontally for 4 seconds. The procedure was repeated several times until the pour point and freezing points were achieved. Furthermore, the flash points of the liquid oil from various types of plastic waste and their mixtures were determined using a flash point analyzer (Automatic Pensky-Martens Closed Tester, Koehler, US) in accordance with ASTM D93. Likewise, the energy content of the pyrolysis-derived liquid oils was determined using a bomb calorimeter (Parr 6200 Calorimeter, US) to obtain high heating values (HHV) in accordance with ASTM D240.

TABLE 1: Features of the pyrolysis reactor.

S. No	Reactor components	Features
1	Height of heating tank	609 mm
2	Diameter of heating tank	550 mm
3	Rated heating power	0.5kW
4	Reactor capacity for feedstock	10 kg
5	Length of condenser	609 mm
6	Diameter of condenser	305 mm
7	Heating rate	10 to15°C min^{-1}
8	Maximum temperature	550°C
9	Residence time	90 minutes

The functional groups present in the derived liquid oils from all plastic types and their mixture (50:50) were investigated through FT-IR spectroscopy (Perkin Elmer's, UK). The analysis was carried out in the range of 500 to 4000cm^{-1} with a minimum of 32 scans at an average IR signal at 4cm^{-1} resolution. Moreover, the detailed composition of the liquid oils was analyzed by GC-MS (Hewlett-Packard HP7890, US) equipped with a 5975 quadrupole detector. The length of the GC capillary column was 30mm, whereas the diameter was 0.25mm, coated with a 0.25mm thick film of 5% phenyl-methypolysiloxane. For the analysis, the initial temperature was set to 50°C for 2 minutes, then increased to 290°C at a rate of 5°C per minute and upon reaching 290°C, splitless injection was applied. Both the ion source and transfer line temperatures were 230 and 300°C, respectively. The resulting data were obtained in full-scan mode between m/z 33 and 533 with a solvent interval of 3 minutes. The obtained chromatographic peaks were identified using the NIST08 mass spectral data library against standard compounds.

3. RESULTS AND DISCUSSION

3.1 Effect of plastic waste on the yield of liquid oil

The results in Table 2 depict the end products from the pyrolysis of individual plastics and mixture of plastic waste types. The results showed that the highest conversion of the feedstock to liquid oil (51%) was recorded for PS compared with other types of plastic waste. Similar results for the maximum liquid oil for PS compared with PP and PE have also been reported by Miandad et al. (2017). The maximum degradation and conversion to liquid oil in PS was due to its lower molecular complexity compared to other types of plastics (Liu et al., 2022). The thermal degradation of PS to oil comprises four steps: initiation, transfer, decomposition, and termination (Peng et al., 2022). Likewise, the lowest liquid oil content (21%) and the highest gas yield (68%) were recorded for PP (Table 2). Kiran et al. (2000) also observed low liquid oil yield with large amounts of gases from the pyrolysis of PP. The comparatively lower liquid oil yield from the pyrolysis of PP is due to differences in polymer structure, degradation pathways, and radical stability that affect the formation of condensable hydrocarbons and gases during thermal decomposition. Another key factor in the lower oil production from PP is the secondary cracking of the pyrolysis vapors. The less thermally stable aliphatic hydrocarbons produced during PP degradation further undergo thermal cracking at temperatures between 400 and 500°C, that results in the conversion of these intermediate liquid hydrocarbons into non-condensable gases, which reduces oil yield (Al-Salem et al., 2017).

The pyrolysis of mixed plastic waste also showed variation in the yields of pyrolysis products, especially the liquid oil. The results showed that the lowest oil yield (21%) was obtained when PE was mixed. Miandad et al. (2017) also reported that pyrolysis of mixed PE and PP yields lower oil and higher gas and char. Ciliz et al. (2004) also observed a similar trend of lower oil and higher gas yields from the pyrolysis of mixed PP and PE. Likewise, mixing PS with PP yield lower oil yield of 29% compared to the individual pyrolysis of PS (Table 2). The slight reduction in oil yield of mixed plastic waste compared to the individual plastics is attributed to the differences in thermal degradation mechanisms, radical interactions, and secondary cracking reactions occurring during co-pyrolysis of mixed plastic polymers. In addition, during pyrolysis of the mixed plastic, various polymers produce different radical species that interact with each other, and these cross-radical reactions promote secondary cracking, hydrogen transfer, and β-scission that convert the intermediate liquid hydrocarbons into gaseous products, including methane, propylene, and ethane, thereby slightly decreasing the oil yield as compared to the pyrolysis of single plastic waste (Lopez et al., 2018). However, compared with individual PE, the liquid oil yield increased when PS was mixed with PE at 50:50% ratio. The results showed the maximum oil yield (39%) when PE was mixed with PS at 50:50% (Table 2). The production of free radicals from PS facilitates the conversion of PE into liquid oil instead of wax (Valizadeh et al., 2024). The comparatively high liquid oil yield due to the co-pyrolysis of PS with PE, as compared to the individual PE is mainly due to the synergistic interactions between the aromatic radicals from PS and aliphatic radicals from PE that enhance the stabilization of intermediate fragments and suppress excessive gas formation. Furthermore, the mixed pyrolysis of PS with PE changes the degradation pathway as depolymerization of PS results in the formation of styrene monomer and other aromatic radicals (Woo et al., 2000). These aromatic radicals are thermodynamically stabilized by resonance within the benzene ring, hence making them less susceptible to rapid fragmentation. Hence, during co-pyrolysis, these stabilized radicals interact with the reactive alkyl radicals produced from PE degradation, thereby suppressing excessive secondary cracking reactions and promoting the formation of larger condensable hydrocarbon molecules (Faravelli et al., 2003; Baeck et al., 2024).

3.2 Density (g ml^{-1})

Density is a key physicochemical parameter that reflects the hydrocarbon distribution and molecular composition of oil produced by thermal degradation of various polymers during pyrolysis (Baskar et al., 2021). The density of pyrolysis oils varied with plastic waste type, depending on the polymer feedstock, pyrolysis temperature, and the presence of catalysts that affect cracking reactions and product composition (Sharuddin et al., 2016). Densities of the liquid oil produced from the pyrolysis of individual and mixed plastic waste were analyzed and found in the range between 0.734 to 0.892g ml^{-1} (Table 3). The densities of PE, PS, and PP were 0.831g ml^{-1}, 0.892g ml^{-1}, and 0.786g ml^{-1}, respectively (Table 3). The findings of the current study are consistent with those of Syamsiro et al. (2014a), who reported the density of PE-derived oil of 0.854g ml^{-1}. Likewise, Mangesh et al. (2020) observed a density of 0.771g ml^{-1} for PP-derived oil, however, the density of PS-derived oil (0.945g ml^{-1}) was slightly higher than the current study. During pyrolysis, PE primarily decomposes into long-chain aliphatic hydrocarbons, including olefins and paraffins that are structurally similar to those in the diesel and gasoline fractions, resulting in relatively low-density liquid fuels (Sharuddin et al., 2016). Likewise, the pyrolysis products of PP are branched alkanes and alkenes due to its methyl side

TABLE 2: Experimental scheme and pyrolysis yields of individual and mixed types of plastic waste.

S.No	Sample	Ratio	Feed Quantity (Kg)	Retention Time (minutes)	Temperature range	Liquid Oil (%)	Gases (%)	Char (%)
1	PE	100	1	90	550	25±0.16	31±0.03	44±0.11
2	PS	100	1	90	550	51±0.13	21±0.01	28±0.08
3	PP	100	1	90	550	21±0.17	68±0.03	11±0.10
4	PE:PS	50/50	1	90	550	39±0.12	45±0.04	16±0.16
5	PS: PP	50/50	1	90	550	29±0.18	59±0.03	12±0.12
6	PE: PP	50/50	1	90	550	21±0.10	61±0.05	18±0.13

groups, resulting in oils with densities ranging from 0.75 to 0.81g cm^{-3}, indicating the predominance of light hydrocarbon fractions compared to conventional petroleum fuels (Adoe et al., 2023). Conversely, during pyrolysis, the PS undergoes depolymerization reactions that primarily produce aromatic compounds, including toluene, ethylbenzene, and styrene, which have higher molecular density than aliphatic hydrocarbons (Miandad et al., 2017). Hence, pyrolysis oil derived from PS often exhibits higher density than other types of plastic waste due to the dominance of aromatic hydrocarbons in the liquid oil (Miandad et al., 2017). The liquid oil produced from the mixed pyrolysis of PE:PS, PE:PP, and PS:PP showed densities of 0.821g ml^{-1}, 0.874g ml^{-1}, and 0.734g ml^{-1} respectively (Table 3). Moreover, the density of liquid oil in the current study is similar to that of naturally produced commercial diesel ranging from 0.81 to 0.87g ml^{-1} (Arjharn et al., 2022). Panda et al. (2010) reported the density of 0.815g ml^{-1} for pyrolytic oil from LDPE and 0.778g ml^{-1} for liquid oil from PP. Research studies on the mixed plastic waste pyrolysis have demonstrated that the density of resulting oil depends on the composition of the mixing feedstock as well as process parameters, where the higher pyrolysis temperatures and catalytic cracking tend to produce lighter hydrocarbons that affect the density of the derived oil (Marwani & Trifarizy, 2024). The variations among the densities are linked to the degree of aromacity, carbon chain length distribution, and cracking intensity during pyrolysis, which are determined by the type of plastic waste and hence collectively affect the physicochemical properties as well as the potential fuel applications of the produced oil (Sharuddin et al., 2016; Miandad et al., 2017).

3.3 Viscosity (mm^2 s^{-1})

Viscosity of plastic waste-derived oil is another important physicochemical characteristic that defines the hydrocarbon composition and molecular weight distribution. It also represents the flow resistance of the fluids and thus directly related to pressure, temperature, and film formation (Yin et al., 2021). Moreover, viscosity also reveals and signifies the flow of fuel in automobile engines (Kass et al., 2022). Highly viscous fluids are often not recommended for engines because they cause mechanical inefficiency, whereas low-viscosity fuels burn faster in the engine and are also not recommended (Taylor, 2021). Furthermore, the high viscosity of fuel reduces its fluidity at low temperatures, thereby affecting fuel injector operation due to poor fuel spray atomization (Pham et al., 2020). The pyrolytic liquid oil in the current study showed the viscosity of 1.9mm^2 s^{-1} for PE, 3.1mm^2 s^{-1} for PS, and 2.1mm^2 s^{-1} for PP (Table 3). The oil derived from the pyrolysis of PE usually shows relatively moderate viscosities because during the thermal treatment, PE predominantly degrades into long-chain aliphatic hydrocarbons such as olefins and paraffin that result in the oil similar to diesel and exhibit the viscosities ranging between 1.8 and 4.1mm^2 s^{-1} depending on the extent of secondary cracking reactions during pyrolysis (Lopez et al., 2018). Likewise, the pyrolysis of PP result in the formation of branched alkanes and alkenes due to the methyl substituents in its polymer structure, which tend to generate lighter hydrocarbon fractions and hence show viscosities in the range of 1.5 to 3.0mm^2 s^{-1} (Miandad et al., 2016). However, the pyrolysis oil obtained from PS often exhibits higher viscosity due to the depolymerization of PS that results in aromatic compounds such as ethylbenzene, toluene, and styrene that possess stronger intermolecular interactions and higher molecular structure than aliphatic hydrocarbons. The PS-derived pyrolysis oils exhibited a viscosity range between 3 and 5mm^2 s^{-1} (Miandad et al., 2017).

Moreover, the mixed pyrolysis of PE:PS, PE:PP, and PS:PP revealed densities of 2.2, 2.3, and 2.1mm^2 s^{-1}, respectively (Table 3). The oils from the pyrolysis of mixed plastic waste often represent intermediate viscosities because the liquid fraction comprised of the complex mixture of olefinic, aliphatic, and aromatic hydrocarbons originating from the various feedstocks. The reported viscosities from the pyrolysis of mixed plastic waste typically range from 1.2 to 4.0mm^2 s^{-1}, depending on the process and pyrolysis temperature (Budsaereechai et al., 2019).

3.4 Flash point (°C)

Flash point is an important safety and fuel quality parameter that indicates the lowest temperature at which a liquid fuel can ignite when exposed to an external ignition source (Costa et al., 2024). Flash point is strongly influenced by the concentration of light volatile hydrocarbons produced during the thermal cracking of polymer chains. At higher temperatures, flash points are significant and are used to assess the hazardous potential of oil (Narayanasarma & Kuzhiveli, 2021). The pyrolytic oil of PE showed the flash points of 34°C, PP (44°C), and PS with the highest among all the individual plastic waste of 48°C (Table 3). Generally, plastic pyrolysis oils exhibit relatively low flash points compared to conventional diesel fuels because pyrolysis produce a significant fraction of low-boiling hydrocarbons, such as C5 to C10 alkanes and alkenes, that read-

TABLE 3: Properties of pyrolysis-derived liquid oil.

S. No	Properties	PE	PS	PP	PE:PS	PE:PP	PS:PP
1	Density (g ml^{-1})	0.831±0.13	0.892±0.33	0.786±0.21	0.821±0.16	0.874±0.03	0.734±0.08
2	Viscosity (mm^2 s^{-1})	1.9±0.98	3.1±0.33	2.1±0.41	2.2±1.10	2.3±1.03	2.1±0.94
3	Flash point (°C)	34±2.31	48±2.76	44±3.07	32±1.87	31±2.53	29±3.02
4	Pour point	-12±1.03	-19±2.11	-15±1.01	-10±2.43	-13±1.05	-11±2.11
5	High heating value (MJ kg^{-1})	39.6±2.41	38.5±3.02	42.4±1.88	37.2±3.78	41.9±2.74	38.7±3.88

ily vaporize at lower temperatures (Sharuddin et al., 2016). For instance, the oils derived from the pyrolysis of PE have flash points in the range of 20 to 40°C, which can be attributed to the formation of light aliphatic hydrocarbons during the degradation of the long PE chain (Miandad et al., 2017). Likewise, the pyrolysis of PP produce branched alkanes and alkenes due to methyl substituents, result in liquid oils with flash points between 18 and 35°C, indicating a high proportion of volatile hydrocarbons in the derived oil (Syamsiro et al., 2014a). In contrast, the comparatively high flash point of PS-derived oil was due to the high aromatic compounds produced during the depolymerization of PS, which have higher boiling points and lower volatility than aliphatic hydrocarbons (Syamsiro et al., 2014b).

The pyrolysis of mixed plastic waste yielded lower flash points than those of liquid oil produced from individual plastic waste. It has been observed that the highest flash point of 32°C was for the liquid oil obtained from the mixture of PE and PS, while the flash points of PE:PP and PS:PP were 31 and 29°C, respectively (Table 3). The obtained results are in line with those of Palmay et al. (2022).

3.5 Pour point (°C)

Pour point is the property of liquid fuels that determines the minimum temperature at which liquid oil stops flowing when cooled without agitation (Veríssimo et al., 2023). The quantity and amount of long-chain paraffines in petroleum fractions are measured through pour point (Elbanna et al., 2022). Fuels with high paraffin percentage usually have high wax content, which solidifies at low temperatures and creates difficulties in transportation and storage. Hence, it is an important attribute, especially in places where the temperature drops below freezing, as liquid fuel may clog the supply to the combustion chamber. The pour points of all oil samples were found between -10 and 19°C (Table 3). The pour point of liquid oil obtained from PE, PS, and PP was -12, -19, and -15°C, respectively, whereas the liquid obtained from the mixture of different plastic waste was -10, -13, and -11°C for PE:PS, PE: PP, and PS:PP respectively (Table 3). The current results are consistent with Soni et al. (2021), who also reported pour points for pyrolytic liquid oils in the range of gasoline and kerosene.

3.6 High heating value (MJ kg^{-1})

High heating value (HHV) is an important characteristic that quantifies the upper limit of energy released during combustion of a fuel (Oyebanji et al., 2023). It is measured in units of energy per unit mass or volume of the fuel (Waqas et al., 2023). The higher HHV represents the higher energy content of the fuel (Miandad et al., 2017). The HHVs of the current study ranged between 37.2 and 42.4MJ kg^{-1} (Table 3 and Figure 2). The highest HHV (42.4MJ kg^{-1}) was recorded for the pyrolytic oil obtained from PP, whereas for PE and PS, the HHVs were 39.6 and 38.5MJ kg^{-1} respectively (Figure 2). The results of the current study are consistent with those of Miandad et al. (2017) who evaluated the pyrolytic oil of PS and reported it as 39.3MJ kg^{-1}. In addition, Syamsiro et al. (2014a) also reported 36.3MJ kg^{-1} for liquid oil produced from the pyrolysis of PS, with a slight variation relative to the current study. Moreover, the liquid oil produced from the mixed plastic waste of PE:PP showed the HHV of 41.9MJ kg^{-1}, while HHVs for PS:PP and PE:PS were 38.7 and 37.2MJ kg^{-1} respectively that were close to the HHV of conventional diesel. Kasar et al. (2020) obtained similar HHV results for the pyrolytic oil and suggested that the liquid oil has a slightly lower HHV than diesel and hence can be used as fuel after mixing with kerosene oil.

3.7 Fourier transform infrared analysis

FT-IR analysis provides comprehensive data on different functional groups and the types of atomic linkages present in an organic compound. The polymers produced during pyrolysis are identified by their hydrocarbon composition, including alkenes, alkanes, aromatics, and aldehydes (Hasan et al., 2023). FTIR analysis was conducted to identify the functional groups present in the liquid oil obtained from the pyrolysis of plastic waste. The pyrolysis oils were analyzed over a wide range of 500 to 4000cm^{-1} and the spectra represent typical hydrocarbon vibrations in the derived oils. Based on absorption bands, the spectra are categorized into three wavenumber ranges including 3100 to 2800cm^{-1}, 1700 to 1300cm^{-1}, and 1000 to 600cm^{-1}. The details of each spectrum are plotted in Figure 3.

The liquid obtained from the pyrolysis of PE revealed the presence of an aliphatic group at the start at 2924 and 2854cm^{-1}. At 1456cm^{-1}, 1377cm^{-1}, CH_2 bending and C-H olefinic were observed (Figure 3a). Likewise, aromatic compounds were observed at a wavenumber of 696cm^{-1}, corresponding to the aromatic group. Furthermore, the FTIR analysis of the pyrolysis of PS showed the presence of aliphatic groups, CH_2, and aromatic compounds (Figure 3b). A weak absorption band at 3082cm^{-1} was observed at the start followed by a medium absorption peak at 2924 and 2854cm^{-1}, which can be attributed to CH_3 aliphatic functional group. In the middle of the graph, a medium peak was observed at a wavenumber of 1495cm^{-1} correspond to CH_2 group (Figure 3b). At the end, the aromatic and alkenic groups were observed at 696 and 775cm^{-1} respectively (Figure 3b). The current results are in agreement with the study conducted by Panda et al. (2012) who confirmed the presence of aromatic group at peaks at 1495cm^{-1} and 906 to 696cm^{-1}. For PS-derived oil, the band at 1495cm^{-1}

FIGURE 2: High heating value (MJ kg-1) of thermal pyrolytic liquid oil.

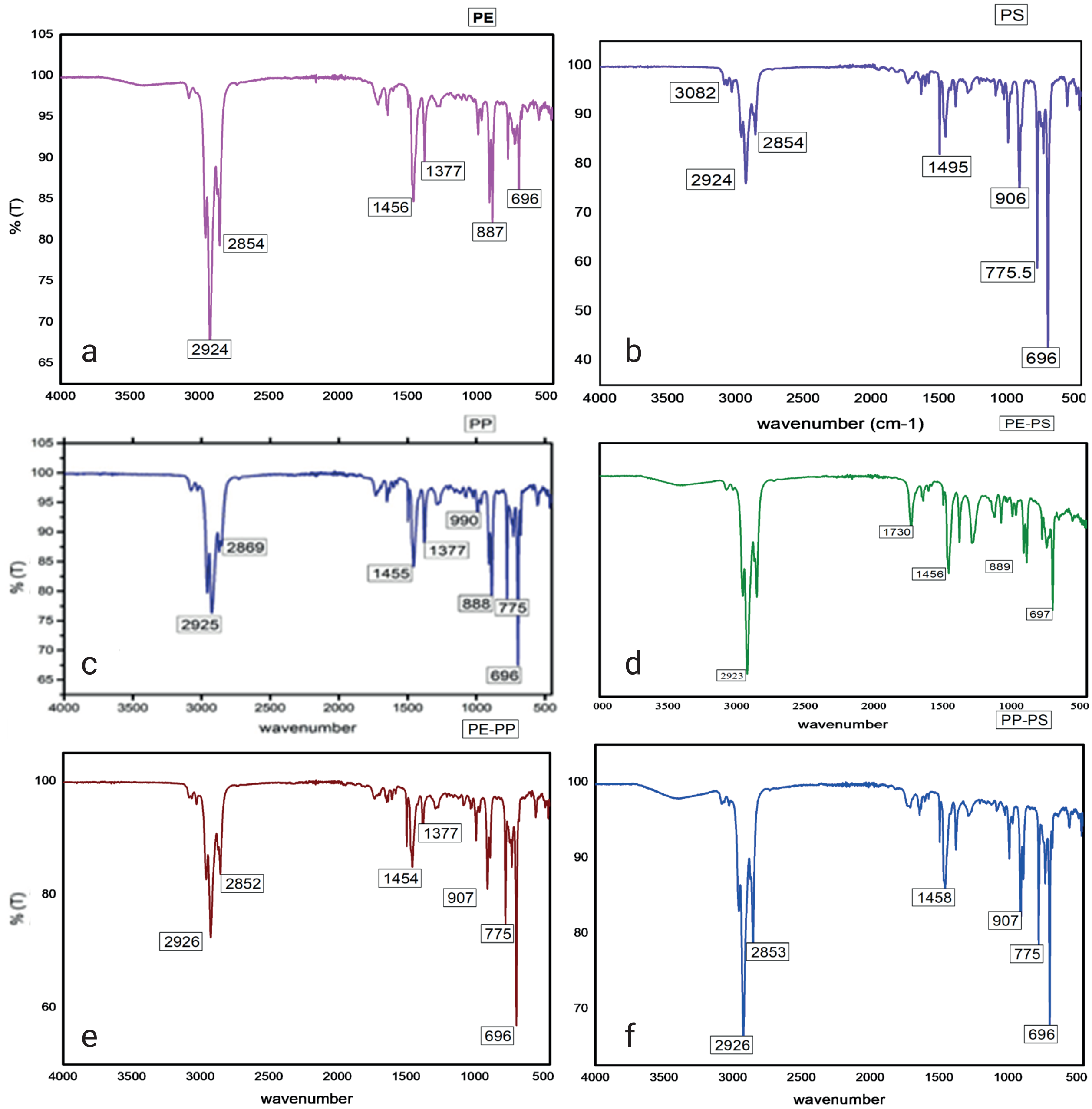

FIGURE 3: FT-IR spectra of liquid oils from the pyrolysis of individual and a mixture of different types of plastic waste.

corresponds to C–C stretching vibration and indicate the existence of aromatic group (Panda et al., 2012). The presence of C–H scissoring and bending vibrations at $145 cm^{-1}$ further indicates the presence of a benzene derivative in the PS-based oil (Singh et al., 2020). Likewise, the two large absorption peaks centered around 2953 and $2868 cm^{-1}$, a weak peak at $1620 cm^{-1}$, and two medium peaks at 1456 and $1377 cm^{-1}$ are visible in the spectra of the liquid product derived from PP (Figure 3c). Aliphatic C-H stretching (for CH_3 and CH_2), olefinic C=C stretching, CH_2 bending vibrations, and C-H scissoring and bending vibrations of alkanes respectively, correspond to these peaks. Olefinic C-H is visible as an ill-developed peak centered at $888 cm^{-1}$ (Figure 3c).

FTIR analysis of the liquid oil obtained from the pyrolysis of mixed plastic waste of PE and PS showed strong peaks at 2923 to $2862 cm^{-1}$, which can resemble aliphatic C-H stretching and reveal the presence of alkyne functional groups (Figure 3d). Similarly, weak peaks were also noticed at $1730 cm^{-1}$, $156 cm^{-1}$, $889 cm^{-1}$, and $697 cm^{-1}$, which showed the presence of C=C (Olefinic), CH_2 bending, and C-H (olefinic) functional groups (Figure 3d). The results revealed that the obtained liquid oils mostly comprised of aliphatic and some olefinic hydrocarbons. Likewise, the FTIR spectra of the mixture of PE and PP showed the presence of alkanes/aliphatic, olefinic, and aromatic groups (Figure 3e). The production of alkanes is observed at the start, followed by CH^2 bending and the formation of an olefinic group (Liu et al., 2023). Strong bonding at $2926 cm^{-1}$ was observed at the start, corresponding to the presence of an alkanes group. At the end, a strong aromatic group was observed at 696cm^{-1}, while a medium aromatic band was observed at 775cm^{-1} (Figure 3e). For PP:PS, the major peaks at 2926 and 2853cm^{-1} showed stretch single carbon and hydrogen bonding (C-H) and correspond to the alkanes (CH_3)/aliphatic functional group (figure 3f). Weak bonding at CH_2 bending at 1458cm^{-1}, while in the middle at 907cm^{-1} (C-H) olefinic group, followed by aromatics and alkenes at the right side were observed at 775 and 696cm^{-1}, respectively (Figure 3f).

3.8 Gas chromatography mass spectrophotometry analysis

The GC-MS data revealed that pyrolysis of individual and mixed plastic waste produced a variety of chemicals (Hasan et al., 2023). The liquid oil comprised of different compounds of alkanes, olefins, and paraffins. Each liquid oil showed different composition and number of compounds, ranging from 32 to 43. Details and number of compounds in each liquid oil are given in Table 4. The identified compounds were grouped into six categories by carbon number: C6 to C10, C11 to C16, C17 to C20, and C21 to C30. However, compounds ranging from C1 to C4 to C5 to C6 were negligible and therefore they are not mentioned. Compounds with carbon numbers ranging from C7 to C10 were abundant in liquid oil obtained from PP, accounting for 83.2%, followed by liquid oil from PS and a mixture of PE and PP, at 78.1 and 69.8% respectively (Table 4). PE showed 61% of the carbon number in the C7 to C10 range, while 65.1% was found in a mixture of PE and PS. The least number of compounds in the range of C7 to C10 was noticed in the mixture of thermal liquid oil obtained from the mixture of PE and PP. Specifying the distribution of oil fractions obtained from the thermal pyrolysis of PP showed that more than 41% of oil is constituted by C7 to C10 hydrocarbon range products, representing the light naphtha range. Likewise, the liquid oil constituted 26.60% of hydrocarbons ranging from C11 to C16 representing the kerosene range (Table 4).

The oil fraction yielded by thermal pyrolysis of PE showed most hydrocarbons (29.7%) in the range of C11 to C16, representing the kerosene range, followed by hydrocarbons in the range of C17 to C20, which corresponds to the fuel oil range. The liquid oil obtained from the pyrolysis of PS also consists of styrene as a major component, and styrene was also observed as a dominant compound when PS was mixed with other plastic types. Such an observation of styrene as a major compound has been reported in the literature (Jaafar et al., 2022). The overall results show that hydrocarbons in the light naphtha C7 to 10 range were the major component (64.53%), followed by hydrocarbons (C11 to C16), with 26.6% products representing kerosene (Table 4). Moreover, the liquid oil also revealed significant quantities of other fractions, such as diesel and lubricant oil, which have potential uses, including as substitutes for conventional fuels in transport, refineries, and industry, and as chemical feedstocks (Zhang et al., 2022).

4. COMPARISON OF PLASTIC-BASED FUEL WITH COMMERCIAL FUEL

The properties of liquid oil obtained from the pyrolysis of plastic waste were assessed and compared with those of conventional fuels such as gasoline, diesel, and kerosene. The density and viscosity of liquid oil obtained from individual plastic and mixed pyrolytic liquid oil were found to fall within the ranges of conventional diesel, gasoline, and kerosene (Table 5). However, slight variations were observed in the flash points of the derived oils compared with those of conventional fuels. For instance, the flash point of conventional diesel ranges from 55 to 60°C, whereas the flash point of the derived oils from individual and mixed plastic waste ranges from 29 to 48°C. The lower flash point of pyrolysis oil is due to its high volatility and aromatic content, compared with conventional diesel (Miandad et al., 2017). Moreover, the obtained results were slightly lower than those for gasoline (37 to 42°C) and kerosene oil (38°C). The lower flash point of the pyrolysis-derived oil as compared to the conventional gasoline and kerosene oil is due to the high volatility and low boiling point hydrocarbons, including olefins, C5 to C9 fractions, and light aromatics, produced through random chain breaking and secondary cracking during pyrolysis that readily vaporize at lower temperatures (Sharuddin et al., 2016). Moreover, the composition of pyrolysis-derived oil, as well as the presence of unsaturated compounds, affects flammability and vapor pressure, thereby reducing the flash point compared to more refined, compositionally controlled fuels such as gasoline and kerosene (Al-Salem et al., 2017).

Pour points and HHVs were also observed within the ranges of conventional diesel and kerosene oil, while some of the liquid oils showed slightly lower HHVs (Table 5). The slightly lower HHV values of pyrolysis-derived oils com-

TABLE 4: Distribution of carbon number among different pyrolytic liquid oils.

Sample	Naphtha % (C6 to C10)	Kerosene % (C11 to C16)	Diesel % (C17 to C20)	Lub Oil % (C21 to C30)
PP	83.2	12.3	4.1	0.2
PS	78.1	15.6	6.0	0.3
PE	61.0	29.7	9.0	0.4
PE:PS	69.8	20.4	3.9	1.3
PP:PS	65.1	29.6	5.4	0.0
PE: PP	30.0	52.0	17.6	0.4
Mean	64.53	26.60	7.66	0.433

TABLE 5: Comparison of different plastic waste with conventional fuels.

Parameters	Density (g ml^{-1})	Viscosity (mm^2 s^{-1})	Flash Point (°C)	Pour Point	HHV (MJ kg^{-1})	References
PE	0.831±0.13	1.9±0.98	34±2.31	-12±1.03	39.6±2.41	Current study
PS	0.892±0.33	3.1±0.33	48±2.76	-19±2.11	38.5±3.02	Current study
PP	0.786±0.21	2.1±2.76	44±3.07	-15±1.01	42.4±1.88	Current study
PE:PS	0.821±0.16	2.2±1.10	32±1.87	-10±2.43	37.2±3.78	Current study
PE: PP	0.874±0.03	2.3±1.03	31±2.53	-13±1.05	41.9±2.74	Current study
PS: PP	0.734±0.08	2.1±0.94	29±3.02	-11±2.11	38.7±3.88	Current study
Conventional diesel	0.815 to 0.870	2.0 to 5.0	55 to 60	Max 18	43.06	Syamsiro et al., 2014b; Kamal and Zainuri, 2015
Conventional gasoline	0.72 to 0.78	1.0 to 2.1	37 to 42	– 12	44	Lee et al., 2015
Kerosene oil	0.78 to 0.82	1.54 to 2.20	38	-18	43.4	Hakeem et al., 2018; Lee et al., 2015

pared to conventional fuels are due to their lower hydrogen-to-carbon (H/C) ratio and lower energy density which correspond to the presence of unsaturated hydrocarbons (olefins), oxygenated compounds, and light fractions (Sharuddin et al., 2016). Furthermore, incomplete cracking and the presence of various impurities and heteroatomic species in pyrolysis oil also reduce the HHV compared to refined fuels (Al-Salem et al., 2017).

Based on the obtained results and comparisons with the conventional fuels, several post-treatment technologies can enhance the fuel characteristics of the pyrolysis-derived oil, including hydrotreatment and catalytic upgrading, that will remove the impurities and enhance the saturation level, thereby increasing the overall stability and HHV. Moreover, fractional distillation to obtain fuel-range fractions, blending pyrolysis oil with conventional fuels, and optimizing pyrolysis conditions (residence time and temperature) could further improve the physicochemical properties and combustion performance of pyrolysis oil.

5. POTENTIAL APPLICATIONS OF PYROLYSIS-DERIVED PRODUCTS

5.1 Liquid oil

The liquid oil produced through pyrolysis of plastic waste is composed of numerous organic compounds, including naphthalene, olefins, and aromatic compounds similar to those found in petroleum products (Miandad et al., 2019). Moreover, it has been found that the HHV values of the obtained pyrolytic oil are slightly lower but close to those of conventional diesel, as observed in the current study, where HHV values ranged from 37.2 to 42.4MJ kg^{-1} (Figure 2 and Table 5). Hence, successful post-treatment could enhance the stability and HHV of pyrolysis-derived oil, thereby making them a viable alternative energy source. In this regard, Saptoadi & Pratama (2015) conducted an experiment on the pyrolysis of plastic waste and successfully utilized the liquid oil as an alternative to kerosene in kerosene stoves. Lee et al. (2015) and Rehan et al. (2016) also successfully reported the suitability of pyrolysis-derived liquid oil for use in diesel engine. However, as discussed above, to enhance engine performance and reduce vehicle emissions, several researchers blended pyrolysis-derived oil with conventional diesel at various ratios for utilizing as transportation fuel. Various studies investigated blending pyrolytic liquid oil with diesel at ratios of 10%, 20%, 30%, and 40% to assess suitability for various types of diesel engines in terms of engine performance and exhaust emissions (Nileshkumar et al., 2015). Lee et al. (2015) and Nileshkumar et al. (2015) demonstrated that 80:20% blending ratio of pyrolysis-derived oil and conventional diesel yields engine performance comparable to that of conventional diesel. In addition to the direct application of pyrolysis oil, the produced aromatic compounds can also be used as raw materials in several chemical processes for polymerization (Miandad et al., 2019).

5.2 Gases

Various gases, including hydrogen, butane, methane, propene, ethene, and propane are produced during pyrolysis of several types of plastic waste (Kartik et al., 2022). However, the only hazardous chlorine gas is produced from the pyrolysis of polyvinyl chloride (PVC) (Li et al., 2023). It has been reported that increasing the pyrolysis temperature enhances gas production (Mlonka-Mędrala et al., 2021). It has been estimated that pyrolysis of 1kg of plastic waste generates about 13 to 26.9% gas (w/w) (Chen et al., 2014). As like liquid oil, the pyrolysis-derived gases also possess high HHVs. In this regard, Miskolczi et al. (2009) reported that the gases produced from the pyrolysis of plastic waste possess the HHV of 45.9 to 46.6MJ kg^{-1}. Jung et al. (2010) also reported that the gases produced from PE and PP have calorific values of 42 and 50MJ kg^{-1} respectively. The high HHV of the produced gases indicated their suitability for energy production. Moreover, the produced gases can be used in gas turbine to generate electricity and as heating source for boiler (Leme et al., 2018). Likewise, the recovery of isoprene and 1-butene through condensation from mixed gases can be used in tire production (Miandad et al., 2016). Moreover, ethane and propene gas can be used as chemical feedstock to produce polyolefins (Miandad et al., 2016).

5.3 Char

Char is produced as a by-product during pyrolysis and is essentially the unburnt feedstock plastic left over in the pyrolysis reactor (Dwivedi et al., 2019). However, compared with other pyrolysis products, such as liquid oils and gases, the yield of char is very low, ranging from 1 to 1.3g from 1kg of plastic (Miandad et al., 2019). The produced char can be potentially used for several energy and environmental applications. The research by Syamsiro et al. (2014a) reported HHV of 23.04 and 36.29MJ kg^{-1} for the char produced from pyrolysis of HDPE and PS respectively. Jamradloedluk and Lertsatitthanakorn (2014) successfully prepared pellets (1kg) by crushing the HDPE-derived char into powder and used them to heat 1 liter of water in 13 minutes. In addition to its energy applications, the obtained char can also be used for several environmental remediation strategies, such as adsorbing heavy metals and toxic gases from municipal and industrial wastewater (Li et al., 2021). However, to enhance adsorption capacity, several researchers have successfully activated char. For instance, Lopez et al. (2009) tested thermal activation of the pyrolysis-derived char at 900°C for 3 hours and found increases in BET surface area and pore volume of 44% and 55% respectively. Likewise, steam activation makes the produced char an environmentally friendly product by reducing its sulfur content. Bernando (2011) studied activated charcoal for the adsorption of methylene blue dye and found significant adsorption results ranging from 3.59 to 22.2mg g^{-1}. Nevertheless, pyrolysis-derived char can also serve as suitable feedstock for the synthesis of activated carbon (Menya et al., 2020).

6. POTENTIAL OPPORTUNITIES FOR A PLASTIC-BASED CIRCULAR ECONOMY

Generally, there are two broad categories of plastic waste including post-consumer and post-industrial (Horodytska et al., 2019). The characteristics of these two plastic waste streams also differs. Consumer plastic waste is contaminated because it is mixed with other municipal solid waste, whereas post-industrial plastic waste is comparatively clean with a defined composition and consistent quality (Qureshi et al., 2020). This difference makes post-consumer plastic waste less suitable for recycling and usually leads to its disposal in landfills or incineration. On the other hand, it has been well understood that plastic materials are persistent and degrade slowly over time. In such situation, pyrolysis technology offers a sustainable option for valorizing plastic waste into liquid oil and other beneficial products (Fulgencio-Medrano et al., 2022). Moreover, pyrolysis can tolerate considerably higher levels of contaminants in feedstock, hence all types of plastic waste can be pyrolyzed, making it economically attractive by reducing pretreatment steps (Miandad et al., 2019).

Moreover, considerable engineering efforts have been made to design new reactors capable of treating various feedstocks and to optimize yield with minimal energy requirements (Waqas et al., 2018). Being a simple and one-step treatment process, pyrolysis has the potential to treat various types of plastic waste ranging from simple packaging waste to more complex and heterogeneous materials such as rubber, plastics from waste electrical and electronic equipment, and hospital waste that are contaminated with various toxic substances (Dogu et al., 2021). Furthermore, pyrolysis is also considered as a self-sustainable technology because it produces hydrocarbon-rich gas with high HHV of 25 to 45MJ kg^{-1}, making it ideal for energy recovery (Oasmaa et al., 2019). Hence, the generated energy can be recirculated back into the process to meet its energy requirements, thereby making the process self-sustainable at commercial scale (Qureshi et al., 2020). Moreover, among the key advantages of pyrolysis technology is the minimal infrastructure requirement, as it can be installed in small, mobile units, making it easy to move to the feedstock-abundant site (Oasmaa et al., 2019). This approach reduces both the carbon footprint and transportation cost to treatment/recycling units. Furthermore, the oil and wax obtained from the pyrolysis of waste plastic are rich in hydrocarbons, making them an ideal raw material for a refinery process. In this regard, several studies have examined integrating pyrolysis with conventional refinery. The integrating approach shows that thermal technology for product recovery enables the completion of the loop of plastic waste circular economy. It has been estimated that by 2030, about one-third of the total plastic entering the global market could be manufactured from recycled plastics (Miandad et al., 2016). This estimate will bring an economic benefit of about 75USD per barrel in oil prices to the plastic and petrochemical industry, along with the dual benefit of fulfilling the regulatory framework for both consumer and industry plastic consumers.

7. TECHNICAL CHALLENGES AND APPRAISING OPTIONS TOWARDS THE COMMERCIALIZATION OF A PLASTIC-BASED CIRCULAR ECONOMY

7.1 Feedstock and process operation

The key consideration for an effective and economical plastic waste pyrolysis technology is the continuous supply chain of feedstock where the non-availability of continuous plastic waste feedstock has been reported as one of the main factors in the failure of plastic waste recycling initiatives (Bening et al., 2022). It has been reported that several countries import considerable amounts of plastic waste from other countries to ensure continuous feedstock supply (Nizami et al., 2017).

Moreover, the plastic waste collected from various waste streams is heterogeneous, originating from packaging materials to electrical and electronic equipments and containing a mix of polymers. Likewise, PVC and PET are rich in polyolefins, making them an ideal feedstock for pyrolysis due to their chemistry and synergistic effects (Qureshi et al., 2020). However, upon thermal degradation, PVC releases chlorine-containing compounds that have adverse effects, including equipment corrosion and oil halogenation. To overcome the problems associated with PVC, several steps have been taken including avoiding PVC in the feedstock and designing pyrolysis technology to tolerate high PVC concentrations (Al-Rumaihi et al., 2022). Avoiding PVC in the feedstock requires additional examination to separate it. However, PVC is not considered a major contributor to plastic waste, as it is primarily used in the construction sector and thus accounts for only a small portion (Ciacci et al., 2017). On the other hand, PET is a major contributor to the plastic waste stream and is present in a wide range of materials.

Furthermore, pyrolysis is considered a high-energy-consuming technology that hinders its scalability for large-scale treatment of plastic waste. The energy supply in conventional pyrolysis is provided by electricity, auto-thermal heating, induction heating, and microwave-assisted heating. Except for auto-thermal heating, which partially uses heat generated from feedstock oxidation, all other energy supply pathways are energy-intensive (Pan et al., 2024a). However, the recent research trend is the utilization of solar energy to meet the energy demands of pyrolysis technology is receiving significant attention. The key benefits of using solar energy for pyrolysis include its renewable, clean, and abundant availability. However, appropriate reactor designs are critical for concentrating ambient solar energy to achieve high operating temperatures, high solar energy utilization, and high conversion efficiencies (Yadav and Banerjee, 2016). Recently, Pan et al. (2024a) designed a solar-driven pyrolysis reactor to address the energy and carbon-emissions challenges associated with heating. Using direct irradiated solar energy, they assess various operating and porous media parameters to determine the reactor's thermal performance. Their findings revealed that using SiC as a porous skeleton enhanced energy absorption up to 30% due to its high solar-absorbing capacity. They also reported that the simplified structure and integration with solar energy, enables the commercialization of solar-driven pyrolysis for large-scale treatment of plastic waste.

7.2 Toxicity and pretreatment of the feedstock

The heterogeneous nature of plastic waste from various sources may contain hazardous additives, halogens, and other toxic substances that necessitate appropriate characterization of the feedstock prior to pyrolysis (Kusenberg et al., 2022). The characterization could enhance the overall treatment cost, however, it has the dual benefits of ensuring good quality of products along with operational safety because most of the toxic substances could escape from the recycling and hence pose serious threats to human and environmental health (Nizami et al., 2017). Furthermore, the variation in size and shape of plastic waste types also requires uniform size, achieved by crushing into small particles prior to pyrolysis (Miandad et al., 2019). Crushing and size reduction are beneficial, however, this step incurs an additional operational cost for the treatment technology (Nizami et al., 2017).

7.3 Wax formation and unstable nature of pyrolysis oil

Pyrolysis of plastic waste yields a variety of products mainly polyolefins and wax. Wax results from inefficient condensation during pyrolysis, which scales on the inner surfaces of the reactors and makes the recovery difficult (Miandad et al., 2019). Hence, the recovery systems must be designed to recover waxes produced during pyrolysis effectively. Kaminsky et al. (2004) developed an approach using heated impact precipitators in condensing tank to keep waxes in liquid form during pyrolysis. Furthermore, stability of pyrolysis oils is the key property that determines the quality of the derived liquid oil (Qureshi et al., 2020). Generally, pyrolysis oils are thermodynamically unstable and tend to repolymerize. Thus, it requires post-treatments, including blending and dewaxing the liquid oil to maintain quality over an extended period (Butler et al., 2011).

However, the wax fraction is not only an undesirable residue but could also be a valuable intermediate (Brown et al., 2024). During pyrolysis, several conditions, such as short vapor residence time, result in high-molecular-weight wax fractions that comprise the major portion of the condensable products and a significant portion of the feedstock carbon. Such condensable products exhibit high energy density and molecular weight, making them valuable intermediates compared to raw plastic waste (Duque et al., 2023). In addition to high energy density, the semi-solid or liquid state of the wax also facilitates transportation, storage, and handling. Through technologies such as catalytic cracking, waxes could be readily upgraded to value-added olefins such as propylene and ethylene (Brown et al., 2024). However, rational care should be taken during the thermal upgrading of wax fractions due to the low volatility and high viscosity. Furthermore, from process engineering perspective, wax fractions enable a distributed pyrolysis approach to centralized upgrading facilities, thereby improving the logistical efficiency and overall process economics (Brown et al., 2024).

7.4 Life cycle assessment and kinetic models

The gases produced during the pyrolysis of certain types of plastic waste, such as PVC, are highly toxic and pose risks to human and environmental health (Moranda & Paladino, 2023). In this regard, pyrolysis emissions need to be refined to the greatest extent to maximize environmental and human health benefits (Tan et al., 2023). Likewise, significant efforts are needed to develop pyrolysis-derived oil to make it cleaner before its application to minimize environmental impacts (Miandad et al., 2019). Pyrolysis oil, being rich in aromatic compounds such as toluene, benzene, and styrene is attractive to the oil market hence, upon refining, these compounds can be sold (Lam et al., 2016). Though some of the aromatic hydrocarbons present in the pyrolysis oil are carcinogens and can cause serious human health impacts. Hence, extensive considerations are required to evaluate and minimize human health impacts (Tan et al., 2023). Furthermore, a detailed economic and environmental impact assessment of plastic-based refineries are also critical during design through specialized tools and techniques such as life cycle assessment (LCA) (Mannheim, 2021). The LCA study can fully analyze the refinery concept in terms of environmental impacts and all resultant products through a detailed materials and energy balance across all life stages, from raw feedstock collection/extraction, processing, manufacturing, product yield, and distribution. Such assessment helps to determine the sustainability of plastic-based circular economy, which is crucial for making the right decision (Schwarz et al., 2021).

Likewise, controlling the quality and yield of pyrolysis products is a key factor in estimating the economic benefit of the pyrolysis technology. Several researchers have conducted detailed studies on the kinetic modeling of pyrolysis because it can provide reaction mechanisms for the pyrolysis of plastic waste (Pan et al., 2024b). In this regard, Wei and Kuo (1969) and Kuo and Wei (1969) developed a lumped reaction kinetic model that proposed dividing complex chemical constituents into several equivalent "lumps". These lumps can be modeled through various kinetic models used for various molecular compounds. Moreover, this kinetic model has been successfully applied to a range of complex reactions, including catalytic cracking and hydrocracking. Jiang et al. (2022) lumped a kinetic model of pyrolysis technology and distributed the products from plastic pyrolysis into oil, gas, and paraffin. As the current study focused on the yield and physicochemical characterization of individual mixed pyrolysis of various types of plastic waste, with no detailed kinetic modeling performed to elucidate the pyrolysis reaction pathways. Hence, given the complex reactions during thermal degradation, such as parallel and consecutive reactions, including depolymerization, β-scission, chain fragmentation, and secondary cracking, the application of advanced kinetic modeling is critical for future research on the pyrolysis of plastic waste. Furthermore, modeling such as lumped kinetic models and distributed activation energy models, would enable the quantitative description of the heterogeneous nature of plastic waste and product recovery. Moreover, the implementation of such models can provide critical insights into activation energies, reaction rates, and product-distribution mechanisms under varying thermal conditions, thereby improving the predictive capability of pyrolysis technology.

8. CONCLUSION AND OUTLOOKS

Pyrolysis of different types of plastic waste and their mixture at 50:50% ratio was carried out in a small-scale batch reactor. Among the plastic waste, the maximum liquid oil yield was recorded for PS, due to its lower molecular complexity compared to other types of plastic waste. The lowest oil yield with high gas content was observed for PP, that could be attributed to degradation pathways, secondary cracking of pyrolysis vapors, and radical stability that affect the formation of condensable hydrocarbons and gases during thermal degradation. The HHV ranged between 37.2 and 42.4MJ kg^{-1}. However, the highest HHV was recorded for pyrolytic oil obtained from the pyrolysis of PP (42.4MJ kg^{-1}), followed by PE and PS with HHVs of 39.6 and 38.5MJ kg^{-1} respectively. HHVs of liquid oil produced from mixed plastic waste of PE:PP were 41.9MJ kg^{-1}, followed by PS:PP and PE:PS with HHV of 38.7 and 37.2MJ kg^{-1}, respectively. The FTIR spectra revealed the presence of aliphatic group at 2924 and 2854cm^{-1}. At 1456cm^{-1}, 1377cm^{-1} CH_2 bending and C-H olefinic were observed. Aromatic compounds were observed at 696cm^{-1}, corresponding to the aromatic group. Moreover, it was observed that hydrocarbons in the light naphtha range (C7 to C10) were the major component (64.53%), followed by hydrocarbons (C11 to C16), with 26.6% products representing kerosene. The comparison of pyrolysis-derived fuel with conventional fuel revealed that the density and viscosity of the individual plastic and mixed pyrolytic oil were found in the range of conventional fuel oil. However, slight variations were observed in the flash points and HHV of the derived oils compared with those of conventional fuels. Likewise, in-depth discussions have been made on the utilization of the produced gases for energy production, including in gas turbines for electricity generation and in boilers for heating, as well as on the applicability of the derived char for several energy and environmental applications. However, the presence of certain aromatic compounds in the pyrolysis-derived oil makes it unsuitable for direct use as fuel until upgradation, and various post-treatment methods, including distillation, refining, and/or blending with conventional fuel, are required to use the derived liquid oil as an energy source. It has been emphasized that valorizing plastic waste into a successful waste-to-energy concept requires overcoming several problems associated with continuous supply and the heterogeneous nature of the feedstock, appropriate characterization and pretreatment of the feedstock to reduce toxicity, and ensuring good quality products and operational safety. Likewise, approaches to reduce wax formation, technological advancements to enhance the quality and yield of pyrolysis, detailed life cycle assessment, and implementation of advanced kinetic modeling are critical for improving the capability of pyrolysis technology. Furthermore, there is also a dire need to create and expand the market for pyrolysis-derived products to attract the interest and funding of relevant stakeholders and make the concept of plastic waste as a resource more successful and practical.

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CHEMICAL RECYCLING OF POLYVINYL CHLORIDE CONTAINING PLASTIC WASTE FOR LIGHT-EMITTING DIODES RECYCLING

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ABSTRACT

The recycling of critical metals using chemical recycling of polyvinyl chloride containing plastic waste is a promising way to solve two important problems in waste management. The first problem is the disposal of polyvinyl chloride. The second problem is the recovery of critical metals. This is being transferred to demonstration scale as part of the "CHM-Technologie" project. Different polyvinyl chloride containing plastic wastes were pyrolyzed. This hydrochloric acid rich vapor is used in a second step to chlorinate indium in light-emitting diodes. Indium chloride has a lower boiling and vaporizes. This is cooled and, together with the decomposed volatile substances in the light-emitting diodes, produces a metal concentrate. The products are solid residues, metal concentrate and gas, which can ultimately be used for other purposes. For metal purification, the liquid metal concentrate is filtered, mixed with water, distilled and electrolyzed to obtain metallic indium qualitatively.

1. INTRODUCTION

Plastic products are used extensively in various fields for building and construction, packaging, agriculture, and many other applications, due to their low price, light weight, long life and mouldability (Geyer et al., 2017). Plastic production has continuously increased in the last decade. The annual production exceeded 330 million metric tons (Mt) from 2016 to 2020. Polyvinyl chloride (PVC) accounted for 9.6% of all plastics in 2020, ranking in third place. There are different methods to dispose plastic waste (Geyer et al., 2017; Geyer, 2020). First, incineration decreases the volume of waste, and the resulting energy can be used for heating and/or generating electricity. Nevertheless, incineration of plastic waste emits excessive CO_2 and may release some hazardous substances, such as polychlorinated biphenyls, dioxins, furans, and persistent organic pollutants (POPs) (Shibamoto et al., 2007).

In some countries, such as Germany or Austria, the landfilling of Total Organic Carbon (TOC)-containing waste is prohibited (Bundesministerium der Justiz und für Verbraucherschutz, 2009). In Germany, of the total 861,000 metric tons of PVC waste in 2021, 1% is still disposed of or landfilled, 57% is used for energy recovery, and 42% is mechanically recycled (Conversio Market & Strategy GmbH, 2022).Second, plastic waste can be dumped in sanitary landfills, which is a convenient and cost-effective, but landfill space is limited in many countries and an inadequate landfill can cause serious environmental pollution (Hopewell et al., 2009; Teuten et al., 2009; Wang et al., 2021). Third, mechanical recycling is suitable for various types of plastic waste and results in lower value materials (Braun, 2002). A fourth method called "chemical recycling" summarized the development of alternative techniques for plastics recycling like pyrolysis, gasification and liquefaction (Quicker et al., 2022; Scheirs & Kaminsky, 2006). For PVC-containing plastic waste gasification and pyrolysis are mainly in the focus of research. For example, the company Ecoloop in Germany in Goslar produces synthesis gas from PVC-containing plastic waste, but the chlorine is absorbed with calcium oxide, where calcium chlorine is generated (VinylPlus, 2015). Here hydrogen chloride or chlorine can`t be used for further processes. Therefore, pyrolysis of PVC can be used and the techniques like two-stage pyrolysis, co-pyrolysis or ad-/absorption of halogens in the vapor phase were tested for different purposes like removing chlorine in oil from mixed plastic waste (Bockhorn et al., 1998; Liu et al., 2013; Muhammad et al., 2015; Shen et al., 2016).

Electronic products are another essential part of modern society, but their importance has perhaps never been as palpable as when the COVID-19 pandemic forced almost every aspect of human interaction to go online. How-

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ever, the pandemic also revealed that the supply chains that provide crucial raw materials for manufacturing electronics are increasingly vulnerable to social, geopolitical, and technical disruptions. These vulnerabilities are likely to escalate in the future, due to global health crises, natural disasters, and global political instability, all of which will be magnified by looming climate change impacts almost 40 metals and minerals that provide critical functionality to electronic products (Althaf & Babbitt, 2021). A lot of these metals used in electronic products, especially specialty metals like rare earth elements, gallium or indium have End-of-Life-recycling rates (EoL-RR) of less than 1% (Graedel et al., 2011). In the EU, total indium consumption is estimated at 64 tonnes per year from 2012 to 2016, with 60% of the total indium used in flat panel displays (FPDs), mainly in the form of indium tin oxide (ITO). In addition, 11% and 9% of the consumption is used in solders and photovoltaics, respectively, while the remaining 20% is used in thermal interface materials, batteries, alloys/compounds, and semiconductors & light emitting diodes (LED) (European Commission, 2020). In Germany there are six different collection groups for electronic devices, where most electronic devices with FPDs are collected in collection group 2, LEDs in collection group 3 and photovoltaics in collection group 6 for further treatment (UBA 2019). LEDs are recycled in integrated copper smelters (Adams, 2016). Indium is not recycled in these integrated copper smelters and is lost due to its currently low value (Reuter et al., 2019).

Pyrolysis of PVC was tested to use the generated hydrogen chloride for the recovery of indium from indium-tin-oxide powder and LCD-panels (Park et al., 2009). At the ForCycle II project "Chlorplattform" the utilization of hydrogen chloride from PVC-waste for the recovery of indium from FPDs was successfully tested at small scale. For the recovery of indium from LED bar lights, only an indium enriched metal concentrate was generated. First ecological and economical estimations have shown that CO_2 emissions could be reduced by this new profitable method (Berninger & Peer, 2022). This was inspiring to do further research with PVC-containing plastic waste for the recovery of indium from LED at a bigger scale in the project "CHM-Technologie".

2. MATERIALS AND METHODS

2.1 PVC-containing plastic waste and LED

PVC plastic mixture, a sorting residue from commercial waste, which is similar to the yellow bag in Germany was used from a sorting plant. The PVC-containing plastic waste was sampled for analysis and the rest was pelletized. PVC plastic mixture contains 1.3 wt.-% chlorine and has a calorific value of 25.56 MJ/kg. Industrial PVC containing waste (short: PVC waste from industry) from a manufacturing facility in Germany was used. The PVC waste from industry was sampled for analysis and the rest was pelletized. PVC waste from industry contains 2.9 wt.-% chlorine and has a calorific value of 24.33 MJ/kg. EoL – LED bar lights with a length of 0.8 m or 1.2 m in mixture were shredded to <20 mm for the experiments. A sample from this was analyzed. It contains 1 ppm of indium and the calorific value is 13.52 MJ/kg.

2.2 Energy Dispersive X-Ray Fluorescence Spectroscopy

The element content in the input materials and products was analyzed using the Epsilon 3XLE X-ray spectrometer from PANalytical Kassel. The device was calibrated using the "omnian" standard from PANalytical Kassel and the data was evaluated using the Epsilon Benchtop software from the same manufacturer. The solid samples were crushed to <1 mm for analysis using the Retsch cutting mill at 600 rpm.

2.3 Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES)

ICP measurements were performed using Spectro Arcos ICP-OES in dual side on plasma mode. ICP was equipped with cross flow nebulizer, Scott spray chamber and fixed glass torch with 1.8 mm injector. Measurements conditions were RF power 1350 W, plasma gas flow 14 l/min, nebulizer flow 0.75 l/min and auxiliary gas flow 1.3 l/min. Sample aspiration rate was set to 2.0 ml/min. The wavelength for Cl was 134.724 nm and regression coefficient (r2) of calibration curve was 0.9995.

2.4 Experimental set-up

For each pyrolysis test, the corresponding feed material was placed in the system's collection container. Before starting the pyrolysis treatment, a pressure test was carried out in a cold state to check whether the system was tight. Compressed nitrogen was used to pressurize the system to a level higher than the expected overpressure during the test. The test was not started until the system maintained the overpressure and it could therefore be assumed that there were no leaks in the pyrolysis plant combined with the chlorination reactor (Figure 1).

The system was then flushed with nitrogen (28 l/min) to create an inert atmosphere. Finally, the reaction chamber was heated to the test temperature using an electric jacket heater. The material was then conveyed via a screw conveyor into the heated screw reactor of the system and from there conveyed through a second screw conveyor in the reactor for the specified dwell time. The solid coke produced during the pyrolysis process was continuously discharged into a container. The first discharge was observed after a residence time of approximately 30 min.

The gas phase leaving the pyrolysis reactor was used to chlorinate LED in the chlorination reactor. Here the indium reacts to indium chloride and evaporates. The indium chloride condenses with the liquid oil fraction of the pyrolysis vapor and generates a metal concentrate. The remaining gas was then cleaned from halogens, especially excess HCl in a water scrubber to generate hydrochloric acid and other than the gas was further cleaned in the sodium hydroxide scrubber. Aerosols were removed at the ESP. The gas phase was then analyzed with a gas analyzer from the company pollutek. The measuring principles for the gases CO, CO_2, CH_4, and C_nH_m were a non-dispersive infrared sensor, O_2 was an electrochemical detector and for H_2 it was

FIGURE 1: Picture of the pyrolysis plant combined with the chlorination reactor.

a thermal conductivity detector. The rest is assumed to be nitrogen. The gas was then flared at approx. 950°C using a gas flare for safety reasons.

2.5 Recovery of the critical metal indium from the liquid metal concentrate

The critical metal indium is enriched in the liquid metal concentrate and mixed with organic material from the plastic decomposition of the LED. This must be separated before the indium can be recovered. The metal concentrate with 1 ppm indium was filtered with a 2 µm filter. It was then mixed with water.

The volume ratio was 1:2 (water : metal concentrate). After phase separation, 0.7 kg of water phase with an indium content of 4 ppm was produced. For electrolysis, the indium concentration in the solution must be enriched. The filtrate was distilled to remove the solvent. Electrolysis was carried out at a current of 5.2 volts using platinum coated titanium electrodes and an indium content of 199 ppm indium.

3. RESULTS AND DISCUSSION

In the first test with PVC plastic mixture 21.0 kg PVC plastic mixture, 7.6 kg LED, 10.0 kg water for the first scrubber, and 8.7 kg sodium hydroxide (25%) for the second scrubber were used. The masses of the products produced were 7.7 kg of solid residue from the PVC plastic mixture, 6.4 kg of solid residue from the LED, 1.4 kg of filtered metal concentrate, 12.7 kg of water from the first scrubber, and 8.2 kg from the sodium hydroxide scrubber. ICP-OES/EDXRF analysis of the products show a distribution of chlorine. 88% of the chlorine remains in the solid residue of the PVC plastic mixture, 9% in the solid residue of the LED, and 2% in the filtered metal concentrate. The remaining 1% is in the gas scrubber. The high chlorine content in the solid residues of the PVC plastic mixture from commercial waste can be explained by the formation of salt – probably calcium chloride – due to calcium-containing fillers in plastics. In addition, two circumstances favor salt formation in the pyrolysis process. First, the high temperature due to the removal of plastics from the fillers leads to salt formation. Here, a lower pyrolysis temperature could reduce the amount of chlorine remaining in the solid residue of the PVC plastic mixture.

Secondly, granulation of the material leads to better mixing of the various plastics, as well as of the plastic with fillers and PVC.

A washing step of the solid material from PVC plastic mixture was performed to reduce the chlorine content from 11.00 wt.-% to 2.88 wt.-% and increase the calorific value from 10.2 MJ/kg to 12.5 MJ/kg, but further treatment of the solid material is necessary to use it for cement production. The pyrolysis gas purified in the gas scrubber can be used for energy purposes. The lower heating value is 24.7 MJ/m^3. In addition to indium, the filtered metal concentrate contains organic components that could be used for energy purposes. The lower heating value is 37.6 MJ/kg.

In the second test with PVC waste from industry 7.9 kg PVC waste from industry, 20.0 kg LED, 10.0 kg water for the first scrubber, and 10.0 kg sodium hydroxide (25%) for the second scrubber were used. The masses of the products produced were 1.3 kg of solid residue from PVC waste from industry, 14.7 kg of solid residue from the LED, 0.9 kg of filtered metal concentrate, 11.1 kg of water from the first scrubber, and 9.7 kg from the sodium hydroxide scrubber. ICP-OES/EDXRF analysis of the products shows a distribution of chlorine. 19% of the chlorine remains in the solid residue of the PVC waste from industry, 79% in the solid residue of the LED, and 2% is in the gas scrubber.

A washing step of the solid material from PVC waste from industry was performed to reduce the chlorine content from 7.88 wt.-% to 2.79 wt.-% and decreased the calorific value from 18.0 MJ/kg to 16.4 MJ/kg, but further treatment of the solid material is necessary to use it for cement production. The lower calorific value is not so significant and could be explained by inhomogeneous composition of the solid residue after pyrolysis. The pyrolysis gas purified in the gas scrubber can be used for energy purposes. The lower heating value is 17.1 MJ/m^3. In addition to indium, the filtered metal concentrate contains organic components that could be used for energy purposes. The lower heating value is 31.7 MJ/kg. Indium was recovered from the metal concentrate of the first test with PVC plastic mixture by mixing with water, phase separation, distillation, and electrolysis. The filtered metal concentrate was mixed with water. The indium accumulates in the water phase. 40% of the indium from the LED was found in the water phase. The content of the indium increased from 1 ppm in the 7.6 kg LED bar lights to 20 ppm in the water phase with 153 g. After distillation, the solution contains 0.2 g In/L and a total weight of 15 g. The metal indium was recovered qualitatively from electrolysis.

4. CONCLUSIONS

Products like metal concentrate or gas from the pyrolysis process of PVC plastic mixture or PVC waste from industry can be used for energetic purposes. By washing the solid residue from PVC plastic mixture or PVC waste from industry the chlorine content could be reduced significantly, but the chlorine content is still too high to use for cement production or direct energetic use. Then additional tests like for dioxins/furans or heavy metals for further characterization is needed to find an area of application for this solid residue.

Depending on the chlorine content and especially further filler materials, chlorine could be removed from PVC containing waste. Pyrolysis is a promising recycling route for PVC containing waste in the future, but more research for optimizing process parameters and processing of the products – mainly the solid residue is needed. The yield of indium recovery reached 40% for a 0.2 g/L solution, which resulted in an enrichment factor of 494 compared to the indium content in the LED. The recovery of indium from LED is possible with the combination and further process steps. Here the limits are the heaters and material for the chlorination reactor to handle the heat together with the corrosive environment in an industrial application. For further byproducts from the process steps from the metal concentrate to the metal indium recycling a strong focus should be on reuse in further research activities to keep the cost for an industrial process low and more possible to realize it.

The chemical recycling of PVC-containing plastic waste to recover critical metals is a promising way to solve two important problems in waste management.

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IMPACT OF DIFFERENT SCREENING TECHNOLOGIES ON THE SEPARATION OF PLASTIC, METAL AND GLASS IMPURITIES FROM COMPOSTS

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ABSTRACT

The application of compost is regulated in the EU member states mainly based on the quantity of hazardous chemical elements and compounds and on physical contaminants, such as glass, metals and plastics. A large fraction of impurities is removed by screening of the rotting material usually before the composting process is started or at the end of the process. Different screening technologies are used to obtain high quality composts. However, the removal efficiency of impurities for frequently used screening technologies was not thoroughly studied so far. In this study raw compost (rotting duration 6 weeks) from a composting plant, was treated by 6, 8, and 10 mm flip-flop screens and 12 and 25 mm drum screens. The produced composts were analyzed on their properties as well as quantities of impurities. In addition, plastic impurities in fraction down to 0.63 mm were investigated for their quantity in mass, the particle number, polymer, and form type (fiber, film and fragments). The results show that all investigated screening technologies were able to remove plastic-impurities to a level below the thresholds (limit-value 0.3% DM in the fraction > 2 mm) for composts according to the EU fertilizer regulation. The deeper analysis, however, showed that plastics of different form types were separated with different efficiencies by flip-flop and drum screens. Additionally, microscopic analyses of the separated plastics indicated that film and fiber materials that were larger than the mesh sizes were not entirely separated by screening.

1. INTRODUCTION

In the EU in 2022, 42 million tons of biowaste were composted (European Compost Network, 2022) and converted to valuable and renewable soil conditioners that can be applied in farming or to remediate soils (Cogger, 2005; Heyman et al., 2019). Moreover, composts are applied in organic farming (Martínez-Blanco et al., 2013) in place of mineral fertilizers leading also to a reduction of greenhouse gas emissions (Chojnacka et al., 2020). However, compost quality is important for becoming a product and be marketed. Compost quality is determined, among other parameters, by its quantity of contaminants composing hazardous materials, such as certain chemical elements (e.g., heavy metals), and so-called physical contaminants that are not considered hazardous, but do not add any benefits to the compost, such as particles of other metals, glass, stones and plastics (>2 mm). Although, source separation of biowaste helped to reduce the contamination level of composts, massive quantities of these contaminations are still entering the composting process. The main sources of contamination are littering in case of green waste inputs or mis-directed disposal of impurities into bio-bins, with plastics as dominating fraction (Le Pera et al., 2023). The acceptable contamination levels of the output materials are regulated at the EU level by the EU Fertilising Products Regulation 2019/1009 (EC, 2019), as well as at the national regulations in the member states, or voluntary quality assurance schemes (ECN 2021). The EU Fertilising Products Regulation (EC, 2019) for composts and digestates defines an upper threshold of 5 g kg^{-1} DM (or 0.5% DM) for the sum of impurity particle types glass, metals, and plastics. Moreover, individual thresholds of 0.3% DM for each type of impurity are defined too, whereas a further reduction of the limit value for plastics to 0.25 g kg^{-1} DM is planned for 2026 (ECN 2021). However, these thresholds apply to impurities of particle sizes above 2 mm for practical reasons. The improved restrictions towards plastics originate from the dis-

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cussions on the (micro-)plastic pollution and their potential negative impacts on soil health (Souza Machado et al., 2019). In particular, microplastic pollution was shown to cause harm to soil organisms (Huerta Lwanga et al., 2017, 2016; Prendergast-Miller et al., 2019) and crops (Rillig et al., 2019), and to be transferred to the humans via consumption of contaminated food (Cox et al., 2019). Various publications show that composts are contaminated with (micro-)plastics which are transferred to soils (Braun et al., 2021; Weithmann et al., 2018; Zafiu et al., 2023; Zafiu et al., 2020). Plastic contaminations cannot be removed from soil, which leads to their accumulation and the particles remaining there for an unforeseeable time due to the persistence of most plastics (Albertsson and Karlsson, 1988; Allen et al., 1994) to degradation (Bläsing and Amelung, 2018). Although efforts have been already undertaken to reduce the plastic contamination in the preprocessing of biowaste (Alessi et al., 2020; do Carmo Precci Lopes, Alice et al., 2019; Ferreux et al., 2020; Jank et al., 2017), plastics still remain in the input materials for the rotting process.

Plastics that enter the composting process become a source of plastic contaminant > 2 mm as well as microplastics < 5 mm due to their disintegration during the composting processes (Zafiu et al., 2023). Due to the very high water content of the collected biowastes, a mechanical separation of impurities prior the rotting process appears to be feasible only at considerable effort and therefore mitigation strategies of plastic during and before collection are desirable.

In Austria source separation of biowastes at household level is obligatory since 1995 (BGBl. 68/1992, 1992). Although local authorities made huge efforts to reduce incorrect disposal into biogenic waste bins, analyses of the input material at Austrian composting plants still show sometimes high levels of contamination with impurities. The draft of the new Composting Ordinance takes this into account: for the first time in Austria, the impurity content in the input material is to be limited (limit value for impurities in the initial composting mixture < 2% FM). The main factor for high impurities in biowaste is the settlement structure. The degree of urbanisation (higher anonymity of the residents) correlates with higher contaminant content in the collected biowaste.

For composts, the remaining plastic contamination can cause negative economic impacts, when the contaminated compost is not accepted for utilization and, e.g., must be landfilled or thermally treated (Le Pera et al., 2023). On the other hand, composts represent a major source of plastic and microplastic pollution (Bertling et al., 2018). Thus, methods for separation of impurities from final compost must be evaluated and developed. After composting, impurities and bulking materials are usually separated during the final treatment step (mostly screening, sometimes additional use of wind shifters, ballistic separators etc.). Screening typically is made after the end of the thermophilic phase and before maturation. Besides the removal of impurities, the screening step is made also to homogenize the compost for maturation. Although different technologies are available to screen compost efficiently, no information is available so far that thoroughly reports the efficiency of compost homogenization and impurity separation. Comparative studies on final screening can help in optimizing the removal efficiency of impurities in composts.

To close this knowledge gap, this study was conducted on raw compost from one treatment plant operated according to the Austrian state-of-the-art. The compost was treated using different types of screens and different meshes (6, 8, and 10 mm flip-flop screens as well as 12 and 25 mm drum screens). The composition and the quantity of physical contaminants > 2 mm in the produced composts were investigated, to answer the question whether the currently mostly used screening technologies enable compliance with actual quality requirements in principle, or whether requirements beyond those currently defined will be necessary (e.g. with regard to microplastics < 2 mm, which are not yet regulated in composts). Thus, plastic contaminations were objected to a deeper analysis determining also particles < 2 mm and the polymeric composition of particles > 2 mm which were categorized too. This investigation was also undertaken to broaden the understanding of the type of plastic morphology and size that can be separated by different screening technologies.

2. MATERIALS AND METHODS

2.1 Raw compost sampling and screening

For this investigation rotting material from an industrial open windrow composting plant in Austria was used. Rotting technique uses triangular windrows with frequent turning by a commercial windrow turning machine. The duration of the rotting process (until screening step prior to maturation of rotting material) is approx. 6 weeks. The final mechanical treatment in the plant is made using drum screens with mesh sizes of 25 and 12 mm (Figure 1). The rotting material first is screened to < 25 mm. Compost < 12 mm is produced from the screen passage (= throughflow) in a second screening step.

This two-stage process was retained for the study. Raw-compost ready for final treatment to separate the compost from undegraded coarse particles was screened < 25 mm by the drum screen. During the whole screening process subsamples (triplicates) from raw-compost, fraction > 25 mm (overflow) and fraction < 25 mm (throughflow) were taken and brought to the laboratory (Figure 1). From the fraction < 25 mm 4 sub-samples were generated for further screening tests with different screening technologies.

Directly in the composting plant (as reference) one of the four sub samples was separated by the existing drum screen at 12 mm mesh size. The further three sub-samples were filled into big bags and transported to a company operating flip-flop screening. The samples were separated there six days later using 10, 8, and 6 mm mesh screens. From each of these fractions (throughflows and overflows) two representative samples were taken and brought to the laboratory (Figure 1).

Additionally, the final composts were analyzed on some relevant parameters describing the compost quality according to the Austrian Compost Ordinance (BGBl. II 292/2001): organic matter, inorganic carbon, nitrogen,

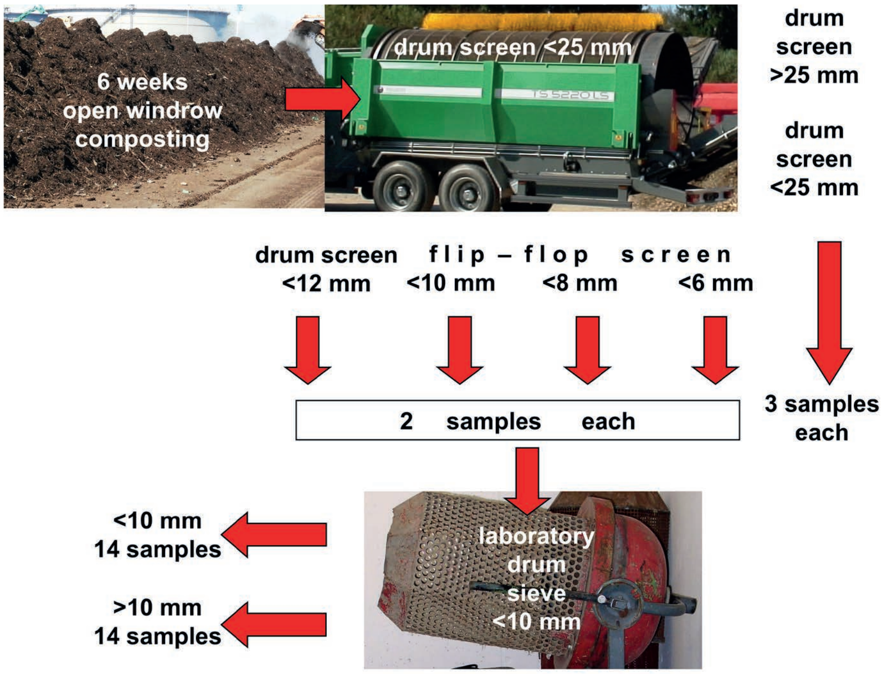

FIGURE 1: Screening and sampling for impurity analyses (triplicates of fractions > 25 mm and < 25 mm and duplicates of fractions 12 mm, 10 mm, 8 mm and 6 mm). Prior analyses of impurities, all samples were sieved by laboratory drum sieve to fractions > 10 mm and < 10 mm.

C/N-ratio, AT_4 (respiration activity within four days) and physical contaminants > 2 mm (particles of glass, metals, plastics).

2.2 Impurity analyses

Each sample consisted of approx. 6.4 to 31.4 kg wet matter (WM) (10 to 50 litres), whereby raw composts before screening had larger sample sizes than those in the final composts after screening. In the laboratory, the entire sample masses were sieved (regardless of the sample size) by a laboratory drum screen equipped with a 10 mm mesh. The dry mass (DM) was determined from a subsample by drying at 105°C. After the fractionation sub samples of 1.0 - 3.8 kg > 10 mm and 1.0-4.5 kg < 10 mm were taken for further sieving. The fraction < 10 mm was further sieved by a vibratory sieve shaker (AS 200, Retsch) using sieves with 6.3, 2 and 0.63 mm mesh sizes, which was operated in wet sieving mode using tap water. Fractions < 0.63 mm were not analysed to their impurity content. Statements about microplastics therefore refer only to particles > 0.63 mm. The fractions were transferred to aluminium trays and dried at 60°C for at least 2 days. Impurities (particles of metals, glass, and plastics) were separated manually in the fraction > 6.3 and 2 - 6.3 mm, while the fractions 0.63 - 2 mm were separated under a stereomicroscope (SZX-ILLD 200, Olympus Optical) with tweezers. The separated particles were then weighted, photographed, and identified by diamond ATR-FTIR Spectroscopy (Attenuated total reflection Fourier transform infrared Alpha, Bruker) using a DTGS (Deuterated triglycine sulphate) sensor. The spectra of the plastic particles were compared to a commercial ("Know it all", Biorad) and a custom-made polymer spectral database, which contained also biodegradable plastics recorded in earlier investigations. Particles were classified as plastics when the hit quality exceeded 40% and characteristic peaks for the identified polymer were observable. This threshold was chosen based on experience with the data bases. While most of plastics reached hit qualities >70%, low hit qualities were obtained in rare cases of small and/or thin and colored polymers with attachments that cannot be entirely removed.

Quantitative data was processed and presented by Microsoft Excel 365. Means were made from triplicates and error bars represent standard deviations of the replicates. Pearson linear correlation was calculated also in Microsoft Excel.

3. RESULTS AND DISCUSSION

3.1 Compost separation efficiency

As described, composts were screened by different techniques (drum or flip-flop screening) using different mesh sizes (25, 12, 10, 8, 6 mm). The efficiency of these separation techniques was assessed by drum sieving in the laboratory into the fractions > 10 mm and < 10 mm (Figure 2). Different to the on-site screening, the laboratory separation was maintained as long as no particles visibly passed the sieve anymore, which means that more aggregates were disassembled allowing more material to pass the screen. Therefore, a larger quantity of finer fractions can be separated in the laboratory.

For screen cutoff-sizes of 10, 8 and 6 mm flip-flop screens were used, while 12 mm screening by drum screen was performed by the standard screening method available at the composting plant. The input, which was the raw compost before screening, was almost evenly distributed

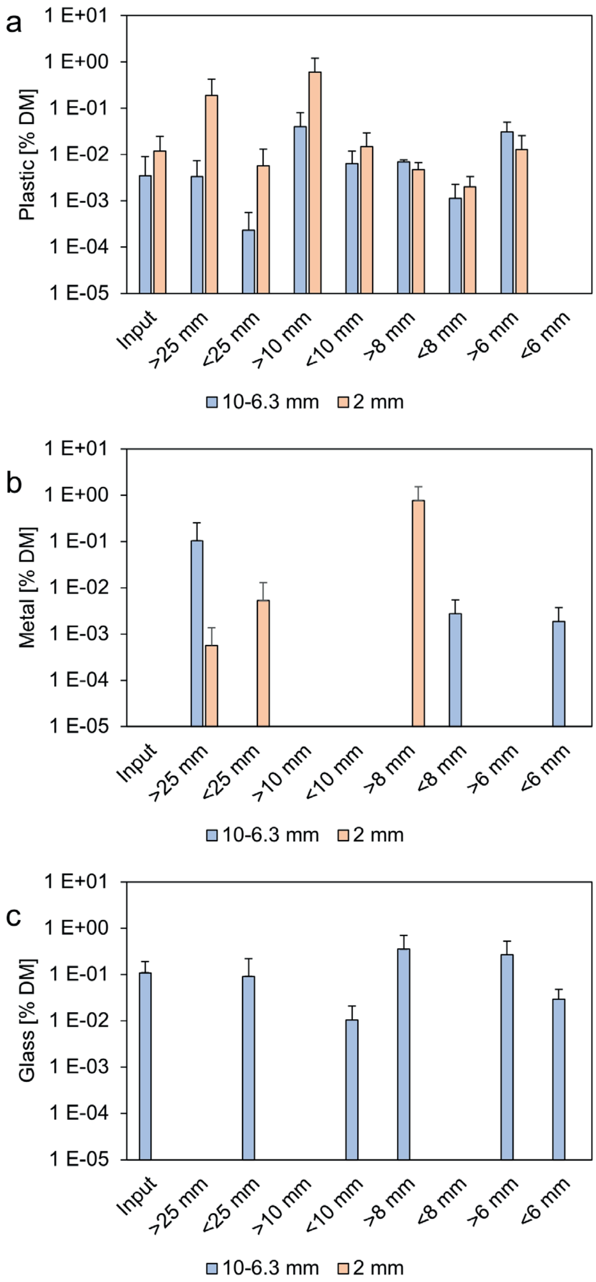

FIGURE 2: Mass fractions of differently separated rotting material after fractionation at 10 mm in the laboratory by a drum sieve. Screening in the composting plant at 25 and 12 mm (from fraction < 25 mm) was made by the facility's own drum screen system. Flip-flop screening (from fraction < 25 mm) at 10, 8, and 6 mm was made in another facility.

between > 10 mm (44.4% WM) and < 10 mm (56.4% WM) fractions. Within the fractions that were larger than or the same size as the screen size of the drum screen (10 - 25 mm) 17 - 28% WM of the total share had a particle size that was < 10 mm. This is remarkable, as it would have been expected that particularly in the fraction > 25 mm the share would not be measurable, yet it was found to contribute to about a quarter of the total fraction, which indicates that a large fraction of fine material is still aggregated in larger particles and gets rejected by the standard screening. The minimal quantity of < 10 mm grain size was found in the fraction > 10 mm after flip-flop screening, which appears to be the optimal separation method of this particle size. As expected, the screening by 8 and 6 mm flip-flop screening rejects more > 10 mm fraction - 32 and 59% WM respectively. In the fractions < 25 mm and < 12 mm the mass of > 10 mm fraction is larger than in the fractions > 25 mm and > 12 mm.

3.2 Efficiency of separation of impurities

The quantity of impurities was analyzed in all available fractions in the size ranges > 10 mm, 6.3 - 10 mm, and 2 - 6.3 mm, whereas no impurities > 10 mm were found in any sample. Figure 2 shows that the plastic quantities found after separation in the overflow (Figure 3 a) and in the throughflow fraction (Figure 3 b) varied strongly for both investigated size ranges (where physical contaminants were found). However, the pollution level correlated well with the plastic quantity in the size range 6.3 - 10 mm, with a Pearson linear correlation coefficient (ρ) of 0.656 and highly for the fraction 2 - 6.3 mm (0.989), thus showing that the variation originated from the individual pollution levels in the single samples used for the individual screening procedures. This finding is expressed by the large error bars in Figure 3. Therefore, an interpretation of the removal of impurity relative to the individual pollution level must be applied, to draw conclusion on the separation efficiency. In addition, the analysis shows that the majority (by mass) of plastics could be removed from the compost by the screening step. A comparison of the quantities of plastics in the overflow and throughflow fraction shows that in the size range of 6.3 - 10 mm screening by 25, 12, 10, 8, and 6 mm screens separated 93.6%, 100%, 86.3%, 85.9%, and 100% of the plastics from the throughflow. In the smaller size range of 2 - 6.3 mm 97.0%, 97.7%, 97.6%, 70.4%, and 100.0% of the plastics were removed by screening at 25, 12, 10, 8, and 6 mm. The results show that smaller particles than the cutoff were removed too by the screening step, because they were aggregated with other matrix components, as also observed in an earlier study (Zafiu et al., 2020). Remarkably the screening by the finest screen (6 mm) removed the entire plastic impurities in both investigated size ranges. The threshold for the highest quality class of composts, which is 0.2% DM of particles > 2 mm, and allows the application of the compost as soil conditioner, was achieved by all screening procedures. However, it must be noted that the raw compost before screening already showed a low plastic contamination. The other regulated impurities, glass and metals did not exceed the threshold of 0.2% DM of particles > 2 mm. Interestingly, the drum screening (12 mm) processes removed metal impurities in size ranges of 6.3 - 10 mm entirely, while the flip-flop screens failed to do so (Figure 3 d). However, due to the low level of contamination of metals, the difference may have been caused due to the inhomogeneous distribution of the metals in the material. In case of glass, the drum screens did not remove the impurities, but the flip-flop screens.

Table 1 shows the influence of the different final treatments (screenings) on some selected compost parameters. Organic matter content was hardly influenced by

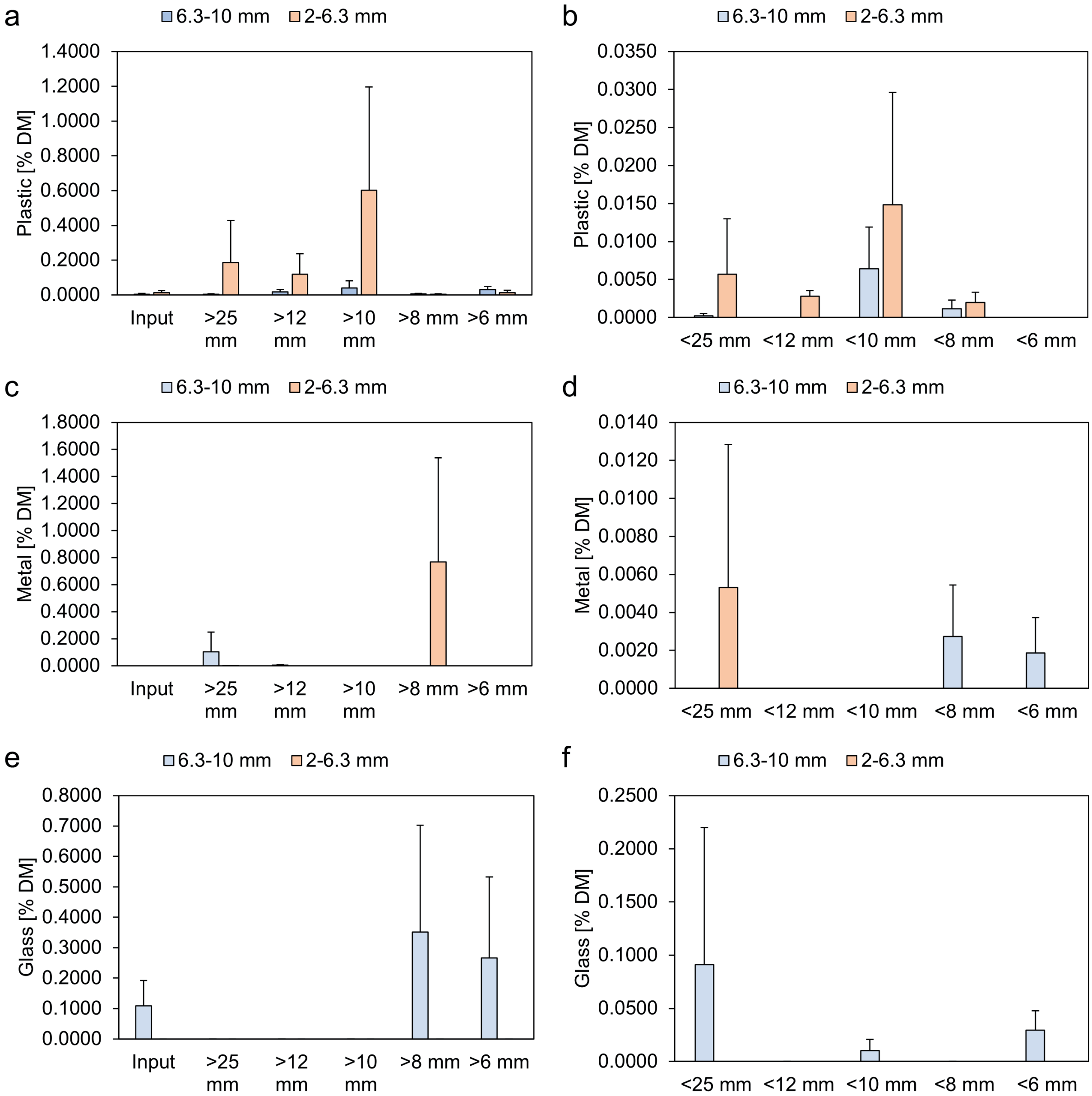

FIGURE 3: Quantity of impurities in raw composts before (input) and in the throughflow (drum screen) < 25 mm and composts after screening the material < 25 mm by different screening techniques and cut-offs. Plastics in the fractions are larger and smaller than the screening cut-off are shown in a) and b), respectively. Metals in the fractions larger and smaller than the screening cut-off are shown in c) and d), respectively. Glass in the fractions larger and smaller than the screening cut-off are shown in e) and f), respectively. The error bars represent the standard deviation of duplicate samples.

screening. The slightly larger value after flip-flop screening at 8 mm was rather caused by sample inhomogeneity. Inorganic carbon content was slightly reduced by smaller screen mesh. Nitrogen content appeared slightly increasing by smaller screen mesh. The much lower respiration activity (AT_4) (as well as the slightly lower C/N-ratio) in the "flip-flop screen composts" was most probably caused by a much longer interval between drum screening < 12 mm and flip-flop screening. The big bags were stored for 6 days before flip-flop screening was performed – samples arrived at the laboratory 19 days after the drum screen samples. Thus, it is strongly assumed that further degradation (stabilization) took place in case of the flip-flop screened samples. The time delay in screening could influence the formation of aggregates during storage, but we didn't observe a trend confirming this effect.

Already after 6 weeks of intensive rotting all four compost materials met the requirements of the Austrian Compost Ordinance (BGBl. II 292/2001) for use in agriculture – the other applications allow the same or even higher impurity content (if the limit values of the draft of the NEW Compost Ordinance will be used as a reference, the AT_4 in drum screened compost < 12 mm would have exceeded the limit value – maturation would be necessary). The content of impurities can generally be described as very low. A clear tendency between screen cutoff and plastics content > 2 mm could not be determined (the order from lowest to highest plastics content is 6 mm = 8 mm < 12

TABLE 1: Organic matter (LOI, C_{org}), inorganic carbon, total nitrogen, C/N-ratio, respiration activity and impurities in final composts after different screening procedures.

	< 12 mm drum screen	< 10 mm flip-flop screen	< 8 mm flip-flop screen	< 6 mm flip-flop screen
Loss on ignition (LOI) [% DM]	32.5	32.6	34.1	31.5
C_{Org} [% DM]	17.4	17.4	18.3	16.1
C_{Inorg} [% DM]	1.4	1.5	1.6	1.8
N_{Dumas} [% DM]	1.19	1.45	1.46	1.38
C/N	15	12	13	12
AT_4 [mg O_2 g^{-1} DM]	15,9	4.2	4.7	4.4
Impurities > 2 mm (glass, metals plastics) [% DM]	0.03	0.07	0.16	0.02
Plastics > 2 mm (mass) [% DM]	0.007	0.036	0.003	0.003
Plastics > 2 mm (area) [cm^2 / l]	2.5	4.0	1.3	1.0

mm < 10 mm). Mass evaluation and area evaluation for plastic impurities correlate well with each other (ρ=0.929). Due to the low initial contamination and the high variability, the results on the separation efficiency cause a limited significance on the comparability of the separation efficiency between the screen sizes. Nevertheless, the results show that even in the worst case scenarios presented here separation efficiency > 70% are achieved in all investigated fractions.

3.3 Composition of plastic impurities

The plastic particles of the investigated size fractions were classified into fibers, films and fragments based on morphological features and quantified by numbers and mass for each class (Table 2). The classification shows that most of the particles found were films (58%), followed by fibers (41%) and only to a small extent of fragments (4%) in terms of numbers. As expected, fibers made a very small fraction in mass (9%) compared to the few fragments that contribute to 37% of the total mass. 10 different polymers were identified by ATR-FTIR spectroscopy, whereas by the majority of the particles consisted of PE (33%), PP (20%), PET (16%) and PS (9%) (Figure 4 a). 7% of the particles could not be identified by the ATR-FTIR databases (< 40% hit quality) but were qualitatively identified as plastics due to their mechanical properties (e.g. flexibility). These particles were films and fibers found in all three fractions. Although the quantity of such objects is small, they add uncertainty to the data, showing the limits of the detection method. In terms of mass fraction PS (51%) was dominant followed by PET (17%) and PE (15%).

3.4 Separation of fibers, films, and fragments

The separation of the single categories (fibers, films and fragments) by the different screening methods is shown in Figure 5. The analysis was made on a fraction of the materials that were received by the 10 mm laboratory sieve (for the distribution see Figure 2). The smallest number of fibers in the investigated fractions was found after screening at 12 mm (Figure 5 a). In the input and the 25 mm drum screened fraction almost similar quantities of fibers were found in all investigated fractions, which indicates that the 25 mm drum screening processes removed similar amounts of the matrix compounds and fibers. This suggests that the fibers are aggregated to particles < 25 mm. The 12 mm drum screen could separate more fibers, which were only found in the smallest size fraction. In case of the flip-flop screening a maximum quantity of fibers was observed in the fraction screened at 8 mm, which suggests that this screening represents the least efficient choice for the removal of fibers. Only screening at 6 mm resulted in similar quantities of fibers as those that were found in the input and after 25 mm drum screening, which suggests that the fibers were mainly aggregated to matrix material > 6 mm. The difference for the minimum quantity of the 12 mm drum screening was the dilution effect, as drum screening breaks up aggregates efficiently and allows therefore more matrix material to pass through the screen, compared to flip-flop screens. Therefore, increased quantities of fibers in the smallest screening sizes are caused by the small size of the particles that accumulate as larger matrix materials are removed. Screening increased also the relative quantity of film materials in the separated fraction (Figure 5 b), except for the 25 mm drum screen, that

TABLE 2: Numbers and mass of classes (fibers, films and fragments) of microplastics in different size fractions of the final composts after screening.

	number of plastic particles [number kg^{-1} DM]			mass of plastic particles [mg kg^{-1} DM]		
fraction [mm]	fibers	films	fragments	fibers	films	fragments
0.63 - 2	19	20	0	7	11	0
2 - 6.3	26	34	2	34	171	20
> 6.3	12	24	3	15	175	220
sum	57	78	5	56	357	240

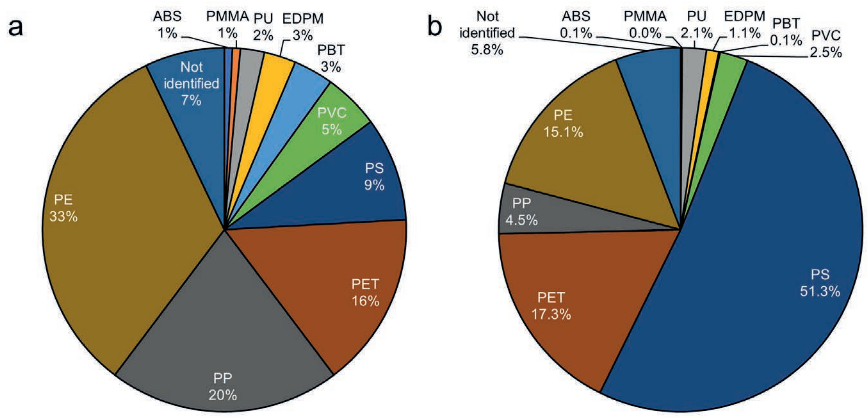

FIGURE 4: Polymeric composition of plastics found in the final composts. a) fractions by numbers and b) fractions by mass.

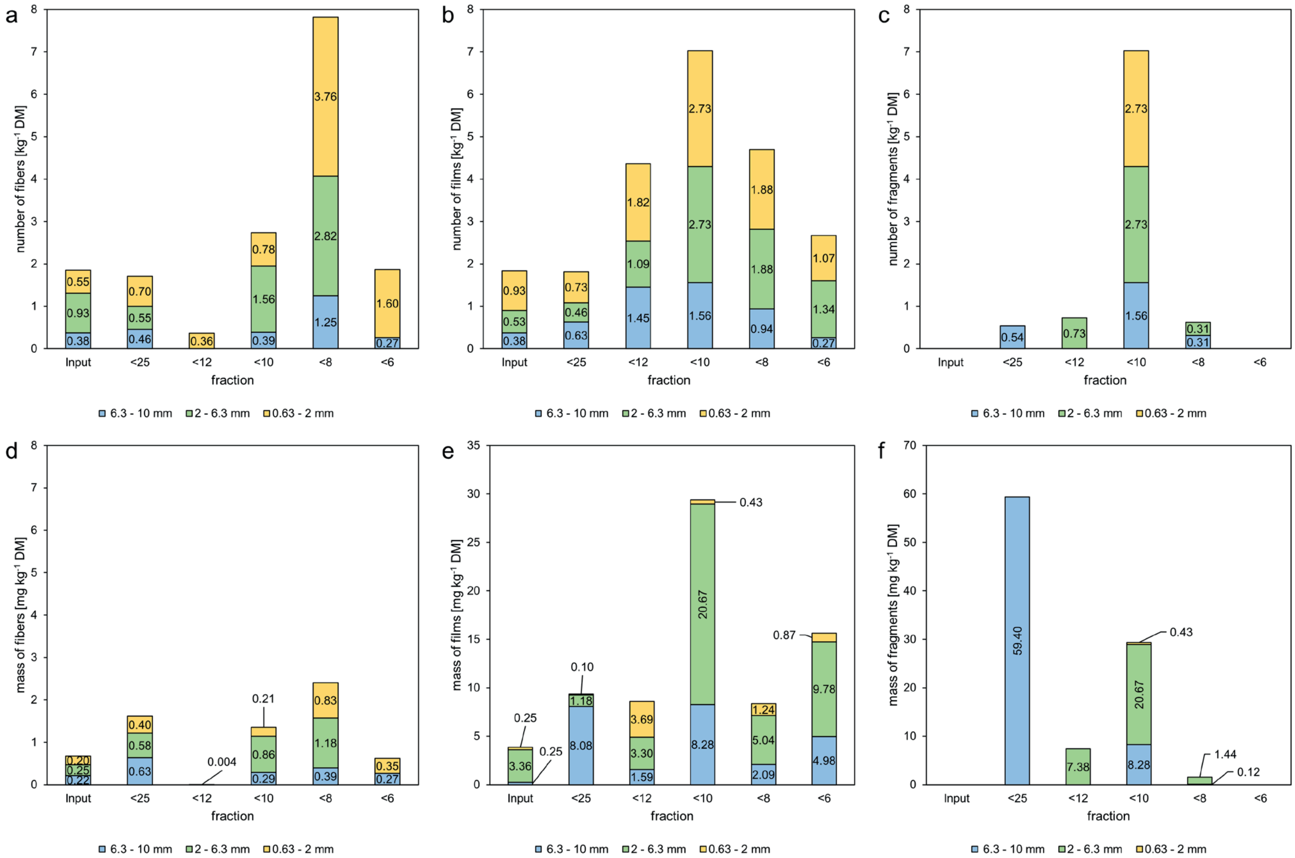

FIGURE 5: Fragments in the input, the on-site drum screening at 25 and the following screening steps 12 mm drum screening, as well as 10, 8 and, 6 mm flip-flop screening. Number of a) fibers, b) films, and c), mass of d) fibers, c) films, and e) fragments. Fibers, films and fragments were analyzed in the fractions 6.3-10 mm (blue), 2-6.3 mm (green), and 0.63-2 mm (yellow).

was equally contaminated as the input. However, for films, 12 mm drum screening did not yield the lowest contamination. That suggests that films were not aggregated to matrix particles and separated almost exclusively according to their size. The lowest efficiency was found for the 10 mm flip-flop screen, while 12 mm drum and 8 mm flip-flop screening yielded the same quantity of films in the separated fraction. The size distribution indicates that flip-flop screening removes the largest fraction (6.3 - 10 mm) more efficiently than the smaller ones, particular in case of 6 mm screening. However, also in the case of films the dilution effect of the removal of less polluted larger matrix materials is visible. This effect was also visible for fragments (Figure 5 c), that were not found in the input samples as well as after 6 mm flip-flop screening, while after drum screening (25 and 12 mm) and 8 mm flip-flop screening almost no particles were found. The reason for not finding fragments in the input could be that this type of contaminant is rare (4% of all microplastics) and probably too diluted in the input, and that the sample size of the input was too small to quantify it. The largest number of fragments were found in the flowthrough of the 10 mm flip-flop screen. The mass of the particles was also recorded (Figure 5 d-f). For fibers, the determined mass correlated to the particle number well (Figure 5 a), as most of the fibers were found in the fraction < 8 mm and the lowest in < 12 mm after drum screening. In contrast, the mass of films and fragments did not show a correlation with their number, whereas the largest mass of films was found in the fraction < 10 mm after flip-flop screening. In case of fragments the largest contamination by mass was found after drum screening at 25 mm. Such a variation, particularly in case of fragments, was already observed earlier (Zafiu et al., 2020). In general, the cumulative (sum of all fractions and all types) plastic impurities were very low with 4 - 17 particles per kg DM over all fractions, in comparison with data published by Zafiu et al. (2023) of 9 composts, who shows approximately 60 particles per kg DM in a comparable size range.

The evaluation of the size of each plastic object was made after separation and placing each sample on a glass slide and recording an image. This evaluation leads to different results than that by the cut-off mesh size of screen. Particles that were analyzed after screening are often still bound to aggregates and appear large. Films and fibers may be folded and pass mesh sizes that they would exceed in one or two dimensions. For the evaluation of the absolute object sizes the area and the Feret's diameter, which corresponds to the largest (maximum) diameter of the projection of a particle on a microscopic image, were determined (Figure 6). The histogram in Figure 6 a shows that particles as large as 4 cm were still found after sieving. Most of the objects in all screened fractions had the largest diameter around 0.5 - 0.75 cm, which was around the cut-off size of the smallest mesh size of the screens that were used (6 mm) and around the limit for being considered as microplastics. This means that most of the objects must have strongly differing aspect ratios, such as fibers, that allow them to pass through a mesh in one dimension. The distributions over all screening techniques show no large differences, which suggest that the removal efficiency of plastic objects was independent from the screening technique or the mesh size. The reason for this is that plastics in this size range are mainly bound to larger aggregates that are retained by the screens. Interestingly, the histograms made from the area of the object show that flip-flop screening was mostly contaminated with particles with an area of ca. 0.05 cm², while in the input and drum screened samples particles of areas of 0.5 cm² and 0.05 cm² were found in almost equal quantities (Figure 6 b). The results suggest that flip-flop screening is more selective for retaining larger

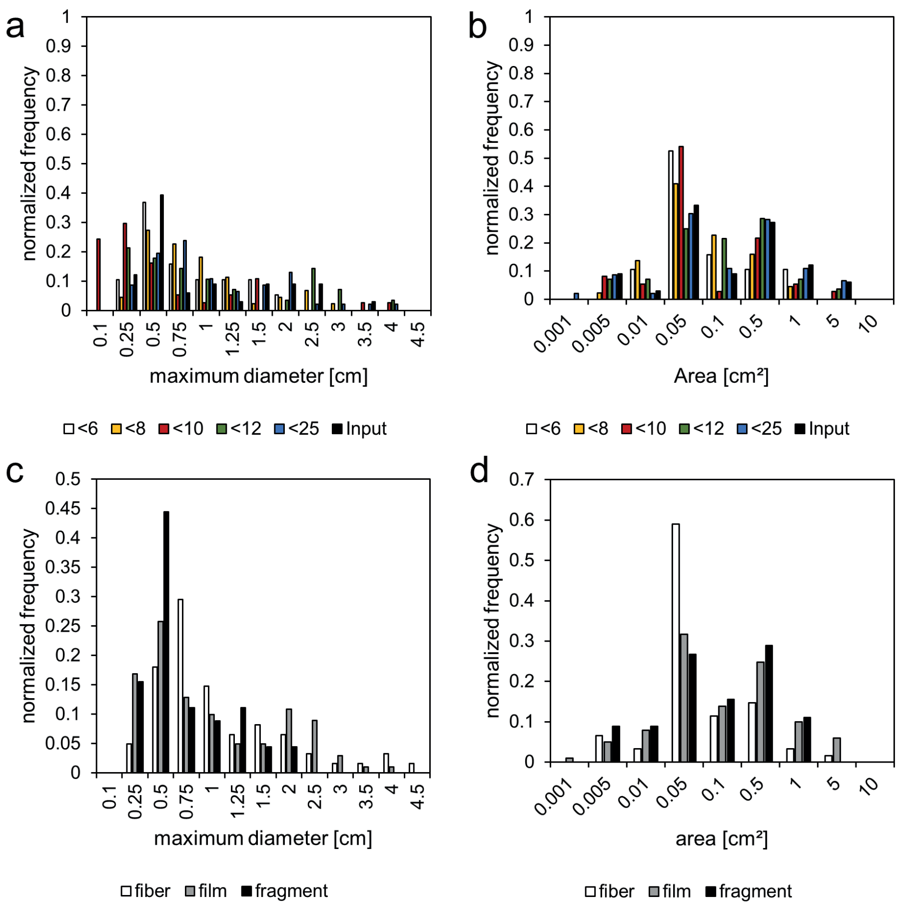

FIGURE 6: Normalized frequency histograms of plastic objects found in rotting material before and after screening. a) maximum diameter (Feret's diameter) and b) area of plastic objects found in different fractions. c) maximum diameter (Feret's diameter) and d) area of the objects depending on the category (fiber, film or fragment).

particles that have a larger area. This would suggest that films are more effectively removed by these techniques as the vibration during flip-flop screening would allow a film to spread and increase its surface, while in case of fibers it could assist in moving it through a mesh. The evaluation of maximum diameter and type of object shows that fibers and films exhibited a flat distribution that peaked at 0.75 cm, while fragments were only found between 0.25 - 2 cm, with a peak at 0.5 cm (Figure 6 c). The distribution of the area of different types of objects exhibited a strong peak at 0.05 cm² for fibers, while most films and fragments had areas between 0.05 - 0.5 cm² (Figure 6 d).

4. CONCLUSIONS

Screening rotting material after processing is necessary to remove undegraded structural material. Removing impurities during this process depends strongly on the screen type, the screen mesh and the method for removing macroscopic objects. Small plastics are usually bound to larger aggregates of matrix materials and can also be partially removed by screening, but with the effect that larger amounts of organic materials must be rejected, thus increasing the quantity of material that must be disposed of. It can be expected that factors influencing the formation of aggregates between impurities and matrix materials play the key role for the separation efficiency. The water content could be the main influencing factor to foster the aggregation and influence the separation efficiency. Composting operations in closed vessels may have a different impact on aggregate formation compared to the case of open windrow composting, which is shown in this study. However, the conclusions of this work are limited to the humidity of the compost sample when the separations were made in the plant. Changes in the degree of separation may be possible at higher or lower water content, which was not studied here and would need further investigation. In addition, input materials and the quantity of bulking agents can play a role in the formation of aggregates or attachment and removal of flexible impurities (such as film material or fibers), as well as on the quantity of impurities. Moreover, composting duration and operations can influence the formation of fragments and their aggregation with matrix materials.

Therefore, the study is limited with respect to compost's humidity, operation time and composition, but general findings that aggregates are formed, and drive separation can be deduced from it. Further studies, analysing impurity removal depending on the humidity and eventually on operational time (duration and number of turns and in vessel compared to open windrow) of the compost before screening could add valuable information in choosing the ideal conditions for screening of composts to obtain the lowest microplastic impurities in composts at the end of the process. Due to the variability of the impurities, caused also by their low number, recommendation on the best performing screening technology based on separation efficiency cannot be given by this study, but may be investigated in future by applying defined spiking experiments.

Although the different screening techniques remove different types of plastics, the benefit remains small and depending on the object type (fiber, film, or fragment) even objects as large as 10 mm in at least one dimension are not retained even by the smallest state-of-the-art screening technologies. The facts that smaller plastic objects are formed during composting process, that cannot be removed at the final screening step, and that no methods exist today to remove plastics from soils, where the composts are used, lead to the conclusion that more plastics need to be avoided or removed before entering the composting process. Optimization of screening may be used as a contribution to further reduce impurities. Finally, novel methods that are tailored for removing particularly microplastics to a higher degree from composts still have to be developed to drastically reduce the transfer of plastics to agricultural soils.

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A COMPOSITE INDEX FOR PREDICTING PERFORMANCE OF MUNICIPAL SOLID WASTE INCINERATION SYSTEMS

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ABSTRACT

Municipal solid waste incineration is pivotal in contemporary waste management strategies, offering waste mass and volume reduction, energy recovery, and pathogen destruction.However, it depends on various operational, environmental and economic parameters that affect the performance of an MSW incineration system, and their optimization is essential for maximizing efficiency, minimizing environmental impact, and ensuring sustainable incineration operation. This creates a need for developing a simple yet robust tool to evaluate and benchmark the incineration performance. This study develops a composite index to predict the performance of an MSW incineration plant based on the key parameters known to influence its performance or performance prediction. The index assesses 12 parameters over three categories to rank various MSW incineration facilities based on their performance. It does this by expressing the performance in the form of a numerical value ranging from 0 to 100, where a higher index value implies better performance of the incineration plant. It is developed using a multi-criteria decision-making (MCDM) approach by incorporating the expertise of more than 150 experts from the field of solid waste management. The literature review helped identify 21 parameters that were known to affect MSW incineration performance. Then, expert opinions were utilized to cut down and prioritize these 21 parameters to the 12 most crucial ones using the Fuzzy Delphi-Fuzzy Analytic Hierarchy Process. The index is then finally constructed by aggregating the weighted scores of these identified parameters. The proposed index is then demonstrated using hypothetical plant data from three MSW incineration plants. It reflects the effectiveness of this tool in predicting and comparing the performance of MSW incineration plants. This tool will be valuable in assessing overall incineration plant performance. It can also be utilized by policymakers, plant operators, and academicians to improve and optimize the performance of the MSW incineration system.

1. INTRODUCTION

Rapid urbanization, industrialization, and increased population have led to increased waste generation, posing a challenge regarding its management and disposal. Globally, waste generation is projected to rise by 70% by 2050 (Planning Commission Submission Certificate of the Report of the Task Force, 2014). Therefore, it is imperative to identify strategies for sustainable waste management that reduce environmental impact and help with resource recovery (Wang et al., 2024). Among the available waste management strategies, MSW incineration is one of the promising ones and has become an essential part of the waste management sector. It simultaneously addresses multiple objectives of an efficient waste management strategy as it allows waste mass and volume reduction by 85% and 90% respectively, destroys pathogens, and recovers usable energy and material (heavy metals, for example) in this process (Ouda et al., 2013). The performance of an MSW incinerator is multifaceted; that is, it depends on various parameters broadly classified as operational, environmental, and economic. These wide range of parameters and their interdependence make assessing the overall plant performance challenging. Traditionally, researchers have conducted studies focusing on individual parameters to determine their impact on the MSW incineration plant performance. These evaluations typically were based on single metrics for example combustion efficiency, loss on ignition, toxicity characteristic leaching procedures, pollutant emission standards or techno-economic studies. However, there remains a lack of a holistic framework incorporating all the affecting parameters to assess the overall plant performance that can handle trade-offs between indi-

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vidual parameters(Wehbe & Baroud, 2024). This creates a need for a comprehensive yet simple tool for evaluating the overall performance of an MSW incineration system. This tool will integrate indicators for process optimization, environmental compliance, and economic viability. It will help in straightforward cross-plant comparisons, tracking the plant performances on a routine basis, and communicating with stakeholders. This integration will be done by applying multi-criteria decision-making (MCDM) methods, which have found a wide range of usability in the waste management sector. The choice of methods for constructing this composite tool will determine its reliability, robustness, and practical applicability (Güdemann & Münnich, 2023).

Despite much research on the effect of individual parameters on the performance of MSW incineration, there is a lack of significant studies on an integrated performance evaluation framework that could act as a standardized comparison tool across different MSW incineration plants globally. This study is a demonstration of the steps involved in the construction of the Incineration Performance Index that addresses these gaps and quantifies incineration performance in the form of a numerical score ranging from 0 to 100, with higher values implying better performance in the form of high efficiency, better economics, and lower emissions. The index integrates all the operational, environmental, and economic factors into a single index and is used as a plant-level indicator. It measures the overall performance of an MSW incineration plant and is constructed in such a way that the parameters chosen for its construction also incorporate the impact of feedstock quality and intrinsic design parameters of the plant.

2. METHODOLOGY

2.1 Parameter Identification

A literature survey was conducted to help identify the parameters that affect the performance prediction of an MSW incineration system. This review helped us develop a list of 21 parameters, which were later narrowed down to the 12 most important ones using the Fuzzy Delphi method (Ishikawa et al., 1993), which incorporates the fuzzy theory (Zadeh, 1965) into the traditional Delphi method, which was incompetent in handling uncertainty, subjectivity, and ambiguity associated with expert judgements. This was done using the expertise of 120 experts worldwide, working in the field of solid waste management. These experts were provided with a questionnaire with the list of 21 parameters and were required to linguistically rate the importance of each parameter on a 9-point scale. Their responses were then converted to triangular fuzzy numbers. After iterative rounds of expert opinion, only the parameters with expert consensus and agreement > 75% and a threshold value of more than 7 were accepted for the next stage of parameter weighting; the rest were rejected. As a result, nine out of the initially chosen 21 parameters were dropped because they did not meet the selection criteria. Figure 1 shows the structural hierarchy for parameters affecting MSW incineration performance.

The identified 12 parameters were divided into three domains:

1. Operational efficiency
2. Environmental impact
3. Economic viability

Some parameters within these domains are primarily sensitive to feedstock quality (for example, the incinerability index, which quantifies the suitability of incinerating MSW), while others are controlled by plant design parameters (for example, pollutant emissions). Instead of evaluating these individually, these characteristics are combined in the formulation to define the integrated incineration performance.

The two economic parameters used in this study are the total cost and total revenue per tonne of waste incinerated. The annuitized capital investment for plant installation and the operational expenditure are both included in the total levelized cost. The rating curves for these characteristics were created using cost and revenue data for the demonstration with Indian MSW plants. By expressing cost and revenue in local currency per tonne and rescaling the breakpoints using either (a) locally representative ranges of levelized cost and revenue per tonne or (b) dimensionless ratios, like the ratio of plant-specific costs to a national median or benchmark facility, the economic rating curves can be applied in other countries while maintaining the same functional form.

2.2 Parameter prioritization and weighting

The next step in the index construction process is quantifying the relative importance of each parameter in affecting the incineration performance. This is done by assigning weights to the identified parameters. The literature reports some studies that assign equal weightages to the constituent parameters (Saaty, 1977). Still, this is generally a poor practice as it assumes that all the parameters affect/ influence the incineration performance to the same extent, which is not the case in real-world scenarios. This oversimplification of assuming equal weights generates noise in the composite index, significantly affecting its robustness and accuracy (Wehbe & Baroud, 2024). Among the other methods that assign weights to parameters (for example, principal component analysis), AHP (Saaty, 1977) is the most widely used and chosen for this study because of its simplicity of calculation for this multi-criteria problem. However, traditional AHP failed to account for the vagueness and uncertainty inherent in experts' knowledge due to the subjective nature of the problem. So, it used to render ambiguous results. This limitation was addressed by incorporating fuzzy set theory (Zadeh, 1965) into the traditional AHP, which constitutes the Fuzzy AHP method. The experts were requested to perform a pairwise comparison among the three criteria (operational efficiency, environmental impact, and economic viability) and the sub-criteria under each criterion. Experts performed the comparisons using linguistic judgements translated to fuzzy pairwise comparison matrices. Table 1 represents the relative scoring scale for FAHP pairwise comparisons and Table 2 represents the pairwise comparison matrix among the three criteria of operational efficiency, economic viability, and environmental impact. Similarly, pairwise

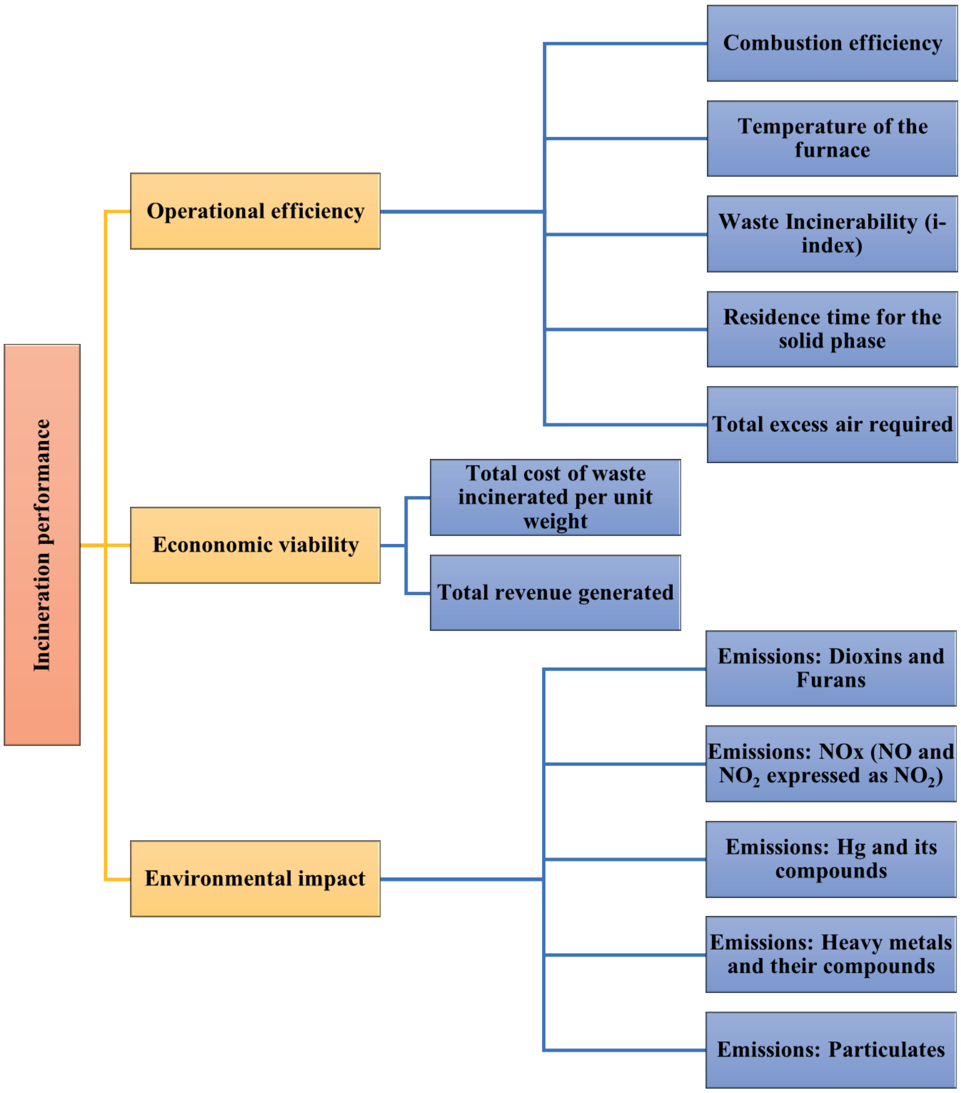

FIGURE 1: Structural hierarchy for parameters affecting MSW incineration performance.

comparisons were conducted among the parameters under each criterion.

Several algorithms evaluate the priority vectors using FAHP, such as extent analysis (Chang, 1996), eigenvalue method (Krejčí, 2017), and the fuzzy inverse of column sum method (Ahmed & Kilic, 2019), to name a few. Statistical metrics were used to make comparisons among the priority weight vectors and calculated using five algorithms to

TABLE 1: Relative scoring scale for FAHP pairwise comparisons.

Linguistic scale	Fuzzy number	Linguistic scale	Reciprocal fuzzy scale
Equally important	1 = (1,1,1)	Equally Unimportant	1 = (1,1,1)
Equal to moderately important	2= (1,2,3)	Equal to Moderately Unimportant	1/2= (1/3,1/2, 1)
Moderately important	3 = (2,3,4)	Moderately Unimportant	1/3 = (1/4, 1/3, 1/2)
Moderately to strongly important	4 = (3,4,5)	Moderately to Strongly Unimportant	1/4 = (1/5, 1/4, 1/3)
Strongly important	5 = (4,5,6)	Strongly Unimportant	1/5 = (1/6, 1/5, 1/4)
Strongly to very strongly important	6 = (5,6,7)	Strongly to Very Strongly Unimportant	1/6 = (1/7, 1/6, 1/5)
Very strongly important	7 = (6,7,8)	Very Strongly Unimportant	1/7 = (1/8, 1/7, 1/6)
Very strongly important to extremely important	8 = (7,8,9)	Very Strongly Important to Extremely Unimportant	1/8 = (1/9, 1/8, 1/7)
Extremely important	9 = (8,9,9)	Extremely Unimportant	1/9 = (1/9, 1/9, 1/8)

TABLE 2: Matrix - Pairwise comparison of the criteria based on the effect on MSW incineration.

Effect on MSW incineration	Operational efficiency	Environmental impact	Economic viability
Operational efficiency	1	a12	a13
Environmental impact	X	1	a23
Economic viability	X	X	1

find the most accurate and robust one (Bisht et al., 2023). From the comparative analysis, logarithmic fuzzy preference programming (LFPP) (Mikhailov, 2003) was the most promising for the current scenario. The LFPP algorithm was used to calculate the normalized priority vectors for the 12 identified parameters. Table 3 shows the weights calculated for the parameters affecting the performance of MSW incineration.

2.3 Normalization of parameters

All the parameters identified and prioritized and known to affect the performance of MSW incineration vary in their units, formulations, and scales. We must bring them to a standard measurement scale to be meaningfully compared and aggregated. This stage is called normalization. Some normalization methods may include categorial scaling, ranking, standardization etc. (Ott, 1978)proposed methods to construct normalization curves by assigning a score to the parameters depending on their numerical values. The indices that were generated using the graphical technique of normalization are: Water quality index (Chidiac et al., 2023), Leachate pollution index (LPI) (Bisht et al., 2022; Kumar & Alappat, 2005) and revised Leachate pollution index(r-LPI) (Bisht et al., 2022), Incinerability index (i-index) (Sebastian et al., 2019), etc. Rating curves were generated, both explicitly and implicitly, for each of the 12 parameters and reflected how the individual parameters contributed to the performance of an MSW incineration facility. The generated curves were then sent to 30 experts for review and consideration. They were encouraged to modify/ redraw the proposed curves as per their understanding. Incorporating these modifications to the initially proposed curves gave us the final rating curves. Figure 2 represents the normalization curves for each of the 12 MSW incineration parameters.

TABLE 3: Priority weights of MSW incineration parameters.

S.No.	Criteria	Parameter	Parameter Weights
1	Operational efficiency	CE	0.247
2		TEMP	0.067
3		i-index	0.091
4		RT(S)	0.053
5		EA	0.054
6	Environmental impact	EM:D&F	0.164
7		EM: NOX	0.075
8		EM: Hg	0.050
9		EM: HM	0.037
10		EM: PART	0.023
11	Economic viability	Total cost	0.078
12		Total revenue	0.061

2.4 Aggregation

This is the final stage of index construction, which includes selecting a suitable aggregation function to combine all the identified parameters into the final composite index (Den Butter & Van Der Eyden, 1998). This step decides how robust or erroneous the constructed index is. It decides the usability of the index built. Literature suggests several aggregation functions used for constructing various composite indices, namely, weighted and unweighted linear sum, weighted and unweighted root sum power, multiplicative aggregation, maximum and minimum operators, etc. The choice of method depends on the purpose of index construction and its potential users (researchers, academicians, policy makers, etc). If not chosen correctly, an unsuitable aggregation method might lead to manipulated, ambiguous, and eclipsed results. The Environmental Performance Index constructed by Yale University used a Linear weighted addictive function for aggregation, a widely used aggregation function that provides ambiguity-free and non-eclipsed results Click or tap here to enter text. (Block, 2024). After careful consideration of the available literature and the study of sensitivity (which is separately conducted) in the index value by the different aggregation functions, the weighted linear sum method was found to be the most suitable one for aggregating the parameters and quantify them into a single value, representative of the incineration performance. It is calculated as:

$$Incineration\ Performance\ Index,\ IP\text{-}Index = \frac{\sum wipi}{\sum wi}$$

Where wi is the relative weight of the ith parameter, pi is the normalised value of the ith parameter, and ∑wi=1. The aggregated index not only provides a single value indicating the performance of an incineration plant but can also be decomposed into three sub-indices: operational efficiency, environmental impact, and economic viability. These sub-indices enable us to identify which sub-index primarily constrains performance, thereby prioritizing suitable interventions accordingly.

3. RESULTS AND DISCUSSION

This section demonstrates the calculation and application of the Incineration Performance Index by evaluating performance for three hypothetical MSW incineration plants in India. This can help several stakeholders: researchers, plant engineers, multi-level regulatory bodies, and decision makers, to compare and benchmark MSW incineration performance across various plants and suggest measures to optimize the performance.

Table 4 shows the raw and normalized data for the hypothetical plants A, B, and C in India. The raw parameter data is normalized using the normalization curves, generated for each of the 12 parameters. Next, the normalized data is multiplied by the parameter weightages derived by the LFPP-FAHP algorithm. Finally, the IP-index was calculated by aggregating the parameters using a weighted lin-

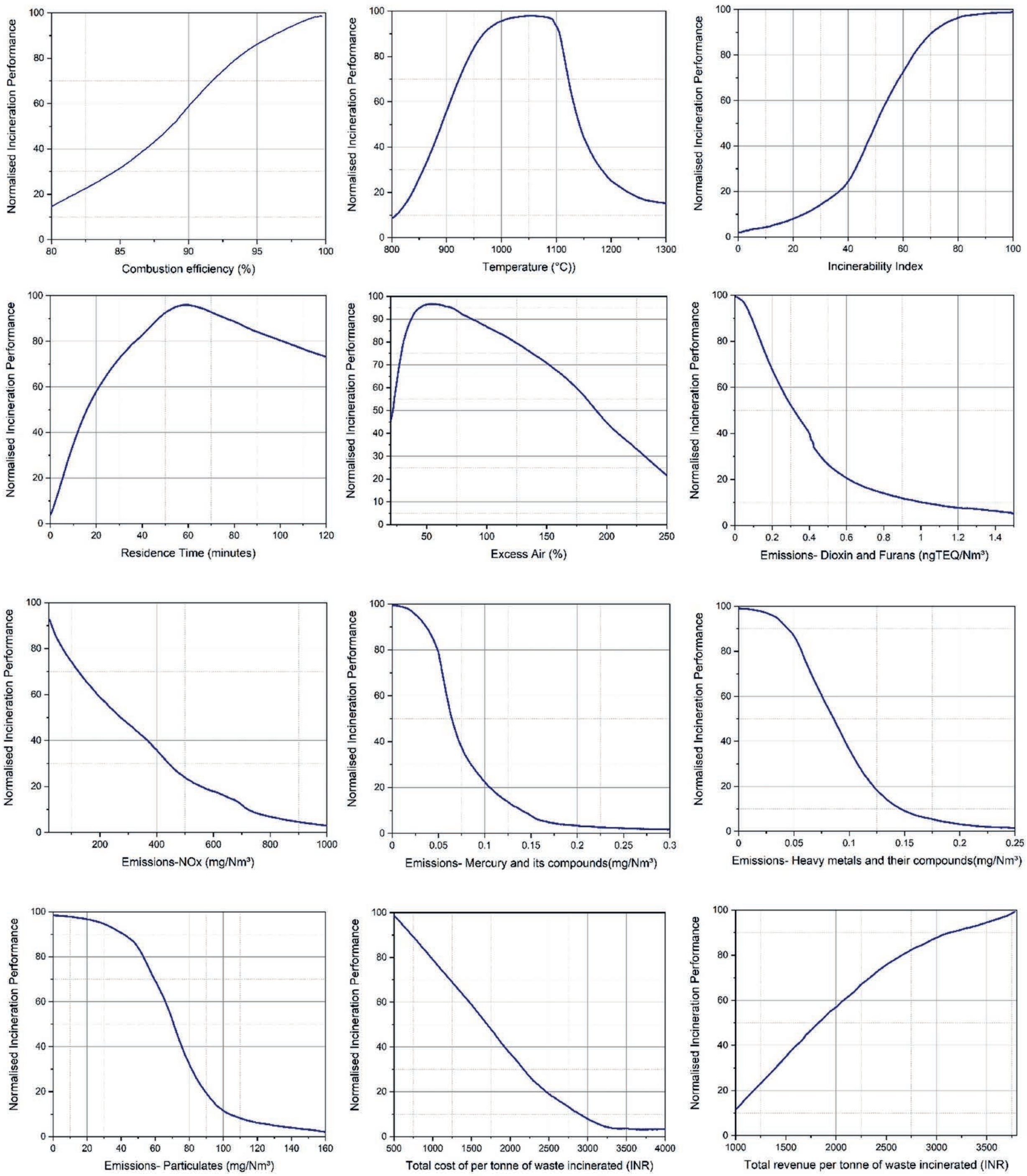

FIGURE 2: Normalization curves for the 12 parameters affecting MSW incineration performance.

ear additive function. Table 5 shows the weighted data for the three plants, for all 12 parameters.

The value of IP-index estimated for the three plants A,B, and C are 87.8, 79.3, and 65.6, respectively. When decomposed into sub-indices, Plant A scores highest in all three domains, which can be attributed to better combustion efficiency, favourable incineration index, more effective emission control system etc. Due to comparatively higher unit costs and lower income per tonne, Plant B's economic sub-index is lower than Plant A's, while having somewhat high operational and environmental sub-indices. The lowest operational and environmental sub-indices are found in Plant C. This demonstration helps the stakeholders to identify and prioritize the specific process, design, or policy actions for performance improvement of an MSW incinerator.

4. CONCLUSIONS

The incineration performance index developed in this study to quantify the overall performance of MSW incineration systems by holistically integrating the operation-

TABLE 4: Raw and normalized data for Plant A, B, C.

S.No	Parameter	Weight	Planta raw data	Planta normalized data	Plantb raw data	Plantb normalized data	Plantc raw data	Plantc normalized data
1	CE	0.247	99.4	98.25	96.4	90.83	94.4	83.92
2	TEMP	0.067	1060	97.95	900	56.09	850	26.44
3	i-index	0.091	76	94.38	64	80.6	59	70.78
4	RT(S)	0.053	55	95.23	45	88.08	40	82.84
5	EA	0.054	60	96.42	80	92	100	86.68
6	EM: D&F	0.164	0.03	98.09	0.04	97.56	0.12	83.72
7	EM: NOX	0.075	170	63.04	200	58.81	420	33.02
8	EM: Hg	0.050	0.01	98.84	0.03	93.42	0.06	57.71
9	EM: HM	0.037	0.02	97.77	0.041	91.80	0.07	65.42
10	EM: PART	0.023	20	96.52	35	92.77	69	54.18
11	Total cost	0.078	3100	6.18	3800	3.27	3900	3.36
12	Total revenue	0.061	3780	98.68	3000	86.40	2500	74.52

TABLE 5: Weighted data for Plant A, B, and C.

S.No	Parameter	PlantA weighted data	PlantB weighted data	PlantC weighted data
1	CE	24.268	22.435	20.728
2	TEMP	6.563	3.758	1.771
3	i-index	8.589	7.335	6.441
4	RT(S)	5.047	4.668	4.391
5	EA	5.207	4.968	4.681
6	EM: D&F	16.087	16.000	13.730
7	EM: NOX	4.728	4.411	2.477
8	EM: Hg	4.942	4.671	2.886
9	EM: HM	3.617	3.397	2.421
10	EM: PART	2.220	2.134	1.246
11	Total cost	0.482	0.255	0.262
12	Total revenue	6.019	5.270	4.546
	IP-index (~)	**87.8**	**79.3**	**65.6**

al, environmental, and economic parameters in the form of a single composite score. It shows the integration of expert opinion and quantitative analysis in addressing a multi-criteria environmental challenge: MSW incineration. This study was a step-by-step demonstration of the construction of a rigorous and handy tool that could be used to evaluate MSW incineration performance quantitatively and with ease. Its application is demonstrated for three hypothetical MSW incineration plants with overall scores of around 87.8, 79.3, and 65.6. This effectively helps the stakeholders to identify and differentiate the gaps in technology levels, reveal the dimensions where the plants underperform, making room for improvements. It replaces the traditional approaches (for example techno-economic analysis, loss on ignition, LCA based evaluations etc.) of performance evaluation by providing a handy, holistic, transparent and easy to communicate metric which can be estimated using routinely available plant data. This tool can compare the MSW incineration performance of plants nationally and internationally. It can help set benchmarks best practices, making the MSW incineration process more efficient, sustainable, and compliant with regulatory standards.

5. FUTURE PERSPECTIVES

The present work demonstrates the construction and demonstration of the Incineration Performance Index using the hypothetical data for three MSW incineration plants. Future research should validate and apply it to relevant time-series data from different operating MSW plants across varying regulatory environments. Detailed uncertainty and sensitivity analysis of the entire methodology- from assigning weightages to the parameters, development of sub-index curves, and aggregation of the parameters- would further increase the robustness and credibility of the index.

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EFFECT OF BOUNDARY CONDITIONS ON THE METHANE OXIDATION EFFICIENCY IN LANDFILL PILOT-SCALE BIOFILTERS

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ABSTRACT
This study compares the performance of two pilot-scale biofilters designed to mitigate methane emissions at the Complexe Environnemental de Saint-Michel (CESM) landfill in Montreal, Canada. Although both systems shared the same geometry, they differed in materials and boundary conditions. CESM1 used a compost-woodchip mixture, while CESM2 incorporated a compost-gravel blend (STEM) and was partially enclosed to enable continuous monitoring. Field measurements showed that CESM1 consistently achieved higher methane oxidation efficiency and greater temporal stability. In contrast, CESM2 exhibited performance variability, particularly during the summer 2024, when internal heating and surface cracking were observed under the shelter enclosure. These conditions may have affected gas distribution and methanotrophic activity. Batch tests confirmed reduced microbial oxidation capacity in CESM2, prompting corrective interventions such as surface tilling and zone-specific repairs. Despite lower efficiency, CESM2 oxidized a higher total mass of methane due to substantially greater loading rates. Both systems followed seasonal trends, suggesting ambient temperature as a contributing factor. The results underscore the importance of adapting biofilter design to site-specific boundary conditions, especially in enclosed configurations where thermal and moisture dynamics may deviate from open-field scenarios. While engineered media such as STEM can support methane oxidation, their performance is contingent on appropriate structural and environmental management. From a design perspective, ensuring adequate gas distribution, preventing excessive heat accumulation, and maintaining moisture balance are critical to sustaining methane oxidation performance. In enclosed systems, additional attention should be given to surface integrity to avoid preferential pathways and reduced performance.

1. INTRODUCTION

Anaerobic degradation of organic matter in landfills generates biogas, primarily composed of methane (CH_4) and carbon dioxide (CO_2). Landfills contribute approximately 630 Mt CO_2-equivalent globally (Gebert et al., 2022), with methane (CH_4) emissions from the waste sector accounting for 28% of total Canadian methane emissions in 2022 (ECCC, 2022). Although methane is short-lived (12-14 years), it has a global warming potential 81-86 times greater than CO_2 over a 20-year horizon. This makes it a strategic target for short-term climate change mitigation.

Methane oxidation biosystems (MOBs) offer a low-cost strategy for reducing CH_4 emissions, especially when gas production is too diluted (less than 20-30% v/v), or too low (typically below 15-30 m³/h) to allow energy recovery or flaring (Farrokhzadeh et al., 2017; Huber-Humer et al., 2008). The Intergovernmental Panel on Climate Change (IPCC) has recognized MOBs as a promising option for the waste sector (Gebert et al., 2022).

MOBs can be grouped into three categories: biocovers (integrated into the landfill cover layer), biowindows (localized oxidation zones targeting emission hotspots), and biofilters (standalone engineered systems treating collected landfill gas). They differ based on their integration with site operating conditions and their functional design. These biosystems rely on a multilayer structure where the gas distribution layer (GDL) feeds landfill gas into the methane oxidation layer (MOL), rich in organic matter and supporting methanotrophic bacteria (Duan et al., 2022).

Recent efforts have focused on optimizing biofilter design (Ahoughalandari et al., 2018; Scheutz et al., 2023), but

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technical challenges remain. A common limitation is pore occlusion and clogging of the MOL, due to extracellular polymeric substances (EPS) produced by methanotrophs, which reduce gas diffusivity (He et al., 2017). Hydraulic performance is equally critical. Poorly selected MOL materials may cause capillary barrier effects at the GDL/MOL interface. This can lead to localized hydraulic blockages, methane overload in specific areas, and lateral gas bypass along preferential pathways (Gebert et al., 2022).

To mitigate these effects, Structured Engineered Medium (STEM), composed of compost and structuring agents (e.g., woodchips, gravel), have been proposed. These media combine microbial support and air-filled porosity, improving gas diffusion, water drainage, and moisture control (Dulac et al., 2024; Dulac & Cabral, 2025; Gebert et al., 2022).

Beyond material choice, construction parameters, such as slope, geometry, and layering, also influence performance. Dulac et al. (2024) confirmed the potential of numerical models to predict hydraulic behavior and support simplified design. This approach relies on representative geotechnical and climatic data, along with well-defined boundary conditions. The authors also highlight the value of instrumented field-scale MOBs to better calibrate pre-design simulations.

This study draws on data from two biofilters built during different phases of a research project at the CESM site in Montreal, Canada. Although constructed at different times with varying materials and operational strategies, both systems shared the same geometry and location. This study aims to contrast the methane oxidation performance of two biofilters under varying boundary conditions and identify the key operational and design features influencing MOL's effectiveness. The analysis focuses on integrated system performance rather than isolating individual parameters. This is particularly relevant due to the presence of a shelter enclosure in one system, which was associated with a separate continuous monitoring study beyond the scope of this work. This study advances existing research by providing a controlled, field-scale comparison of two pilot biofilters sharing identical geometry and siting but differing in methane oxidation layer composition and boundary conditions (open versus partially enclosed). Unlike earlier studies that focused primarily on material optimization or modeling-based design, this work explicitly isolates the influence of enclosure-induced thermal and hydric constraints on biofilter performance. The results offer new, practical evidence on how boundary conditions can override intrinsic material properties and fundamentally alter methane oxidation efficiency at field scale.

2. MATERIALS AND METHODS

2.1 Description of study area

The Complexe Environnemental de Saint-Michel (CESM) is a former 72-hectare landfill site located in Montreal, now in its after-care phase. Developed within a former limestone quarry reaching depths of up to 80 meters, the site received approximately 40 million tons of waste between 1968 and 2008 (Lagos et al., 2017). As part of the City of Montreal's climate commitments (Climate Plan 2020-2030), which targets carbon neutrality by 2050 (City of Montréal, 2020), mitigating methane emissions at CESM has become a key priority (Almeida et al., 2024), making it an ideal site for field-scale validation of methane oxidation technologies.

Landfill gas (LFG) at the site is collected from two sources: (1) a network of gas wells used for electricity generation, and (2) a collection system installed in ventilation trenches. The latter, while associated with high flow rates, contains very low methane concentrations (typically below 2% by volume), mainly due to the strong vacuum applied by the blower system to prevent odor dispersion toward nearby residential areas. Given its low energy potential, this lean LFG could not be treated using conventional methods. It was therefore targeted in a research project focused on developing large-scale biofiltration as a mitigation strategy. Pilot-scale biofilters were designed, constructed, and instrumented on site to experimentally treat approximately one-tenth of the total gas flow (Almeida et al., 2024; Franzidis et al., 2008).

2.2 Selection of materials

The present study covers two phases of analysis involving biofilters installed at the CESM site, allowing direct comparison under site-specific conditions and progressive design refinement: CESM1, conducted from 2021 to 2022, and CESM2, ongoing since 2023.

For CESM1, a 1:1 volumetric blend of compost and wood chips, sourced from the CESM's on-site composting platform for leaves and branches, was selected based on its demonstrated methane oxidation capacity, field workability, and geotechnical performance. This mixture met the minimum efficiency threshold of 70% required by the City of Montreal (Almeida et al., 2024).

2.2.1 Design lessons from CESM biofilter – Phase 1

A key lesson from CESM1 was that the fine sand layer (used as a filter layer between the MOL and the GDL) caused clogging due to compost migration and cementation, highlighting the importance of layer compatibility. We hypothesize that high temperatures during the acclimatization phase accelerated wood chip degradation into fine compost, which migrated into the sand layer. Subsequent water infiltration may have promoted cementation, leading to significant clogging at the MOL interface along a substantial portion of the biofilter.

To prevent similar clogging phenomena observed in CESM1, the sand-based filter layer was eliminated in the CESM2 configuration. Additionally, MOL was reengineered using a 1:1 volumetric blend of compost and gravel mixture, favoring gravel as a structuring agent over wood chips. This approach aimed to enhance air-filled porosity and promote more uniform gas distribution within the biofilter.

2.3 MOL Material Properties

Table 1 summarizes the geotechnical and methane oxidation properties of the MOL materials employed in the CESM1 and CESM2 biofilters.

The compost-woodchips mixture (CESM1) had higher sand content and total porosity, due to the structural role of wood chips as bulking agents promoting aeration. In contrast, the compost-gravel mixture (CESM2) showed lower porosity and a predominance of coarse particles, which may offer hydraulic benefits by reducing saturation risks and limiting capillary barrier effects at the GDL/MOL interface.

A notable difference in organic matter content is observed between the two phases.

The choice of MOL material for CESM2 was guided by the work of La et al., 2018, who recommend an effective compost proportion of 12.5-25%, corresponding to a target organic matter content (measured by standard loss-on-ignition method) of 5-10% in the final mixture. For compost containing 25.1% organic matter, this translates to a recommended compost proportion of approximately 20-40% (i.e., 5-10%÷25.1%). The selected 1:1 volumetric ratio (50% compost and 50% gravel) therefore slightly exceeds this range, ensuring sufficient nutrient availability.

Column test results (not covered in this study) showed a maximum methane oxidation rate ($V_{máx}$) of 2,383 g·m^{-3}·day^{-1} for CESM1 STEM, approximately 32% higher than the value observed for CESM2 (1624 g·m^{-3}·day^{-1}). This enhanced performance appears to be associated with the physical properties of the material, particularly its higher organic matter content, which may improve moisture retention and increase the available surface area for microbial colonization. In addition, greater nutrient availability in the compost substrate may have further supported methanotrophic activity.

Moreover, the K_m value for CESM1 was significantly lower (12 g·m^{-3}) compared to CESM2 (23.4 g·m^{-3}). The parameter K_m represents the half-saturation constant from Michaelis–Menten kinetics, corresponding to the methane concentration at which the oxidation rate reaches half of its maximum value (V_{max}). Lower K_m values indicate a higher affinity of methanotrophic microorganisms for CH_4, reflecting greater oxidation efficiency at low CH_4 concentrations. However, these differences should be interpreted within the broader context of design priorities and operational conditions. While CESM1 favored microbial activity due to its more active and porous structure, CESM2 incorporated gravel, a material chosen for its structural stability and drainage performance, in line with established design recommendations.

2.4 Construction

2.4.1 CESM Biofilter – phase 1

The biofilter studied herein was built with a rectangular footprint of 50 m² (5 m × 10 m) and a total height of approximately 1.45 m. Its structure consisted of stacked concrete blocks forming vertical walls, sealed with urethane, and lined internally with an HDPE geomembrane. A geotextile layer was placed over the base to protect the geomembrane. The GDL, 0.30 m thick, consisted of two types of gravel (¾" and ¼"), overlaid by a 0.10 m sand filter layer. As previously described, the MOL was composed of a 1:1 volumetric mix of leaf compost and woodchips, with an approximate thickness of 1 m. To maintain positive temperatures within the biofilter during winter, a heat trace system was laid between the sand and MOL layers, ensuring suitable conditions for methanotrophic activity.

Water content and temperature probes were installed at different depths within the biofilter, including near the surface (0.05 m and 0.10 m) and close to the interface between MOL and GDL (0.90 m and 0.95 m), to monitor potential capillary barrier effects. Most of the sensors were allocated to Zones 1 and 2, where greater spatial variability was expected. The detailed configuration and instrumentation of CESM1 have been previously described by Almeida et al. (2024).

Prior to full-scale operation, an acclimatization phase was conducted in early July 2021 using an external setup. The apparatus consisted of a geotextile base covered with a first layer of compost, followed by the installation of a fishbone-type biogas distribution system, and a second compost layer on top, forming a sandwich-like structure. This setup was supplied with biogas containing approximately 40% CH_4. Injection was maintained at 0.05 CFM (2.03 m³.day^{-1}) for the first two weeks and increased to 0.1 CFM (4.08 m³.day^{-1}) during the third week (Almeida et al., 2024).

Once filled, the biofilter was connected to the main biogas supply system, with an average flow rate of 1 944 m³.day^{-1} (48 scfm) provided by a blower. Due to operational constraints, methane concentration at the inlet varied significantly, ranging from 0.1% to 4.6%. As a result, the biofilter operated under a transient methane loading regime.

The CESM1 phase concluded with the end of performance monitoring in November 2022. In the summer of 2023, the materials constituting the MOL and the GDL were removed in preparation for the implementation of the next phase.

2.4.2 CESM Biofilter – phase 2

By retaining the same wall structure as in the first phase, CESM2 preserved the geometry of the original biofilter while implementing a new construction plan. The GDL was reinstalled using the same gravel size fractions (¾” and ¼”), as it had been damaged during the removal of the sand filter layer. Once the concrete block walls were re-exposed, they were covered with a geotextile and sprayed with a polyurea membrane to ensure sealing equivalent to the HDPE geomembrane used previously.

Multiple sensors were installed in CESM2 to monitor water content and temperature at different depths (0.10 m, 0.35 m, 0.50 m, 0.75 m, see Supplementary Material I). The water content was monitored using 5TM sensors (Decagon Devices, USA), while temperature was measured using DRF sensors. However, due to operational issues, data acquisition was only possible from October 2024 onward (see Suplemmentary material), as the data logging system was partially damaged during the summer of 2024.

Despite this limitation, water content and temperature profiles were obtained for October 2024, along with average temperature data for the October-December period

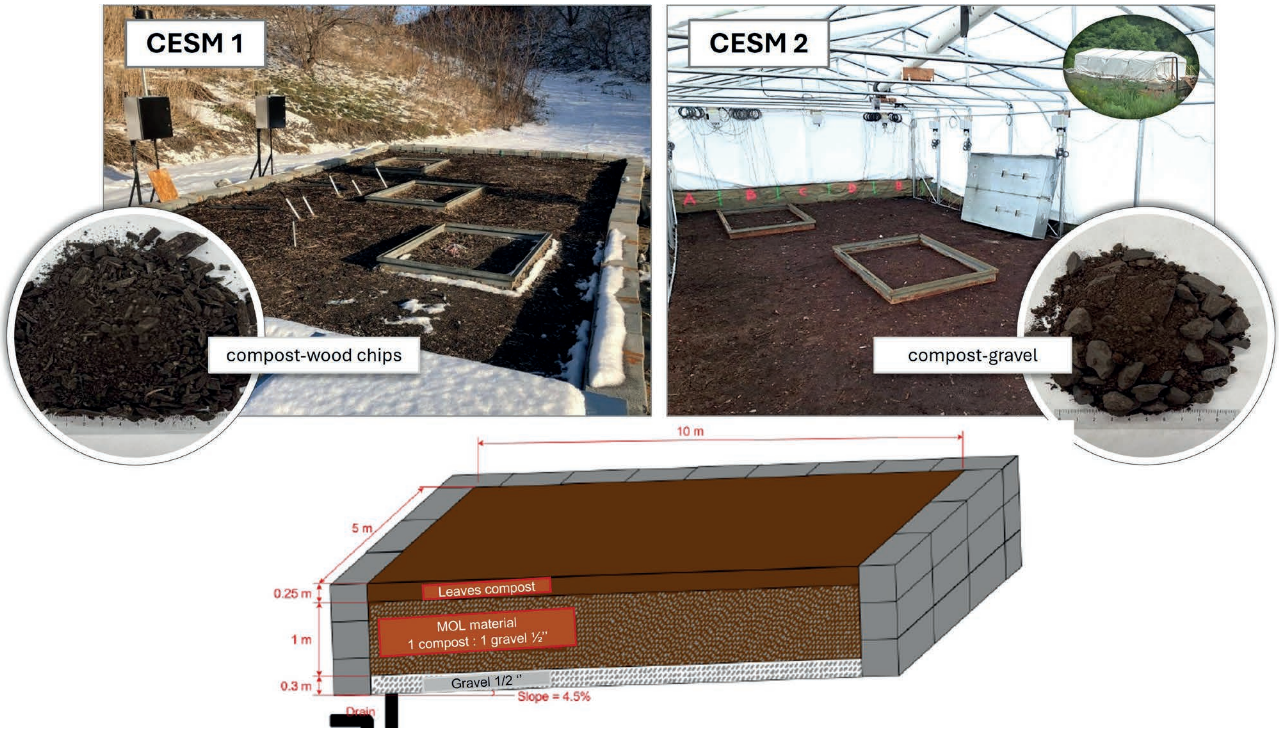

FIGURE 1: Side-by-side comparison of the CESM1 and CESM2 biofilters, showing changes in MOL structure and cross-section scheme of the biofilter.

and temperature measurements at the interface MOL/GDL, at approximately 1 m depth.

The MOL was filled in the fall of 2023. The principle of using a STEM was retained, maintaining the 1:1 volumetric ratio between compost and structural support. However, the composition was modified by replacing the woodchips used in CESM1 with gravel ½" (Figure 1).

The main distinction of CESM2 lies in its objective to enable continuous monitoring of CH_4 oxidation efficiency through a more reliable measurement approach, which, in this project, is used to support and validate the point-in-time measurements obtained with flux chambers. To achieve this, the entire biofilter was enclosed within a partially sealed shelter functioning as a full-scale flux chamber. Details of the continuous monitoring system are part of a separate publication (Souza et al. 2025).

As in CESM1, the CESM2 biofilter operated under a transient methane loading regime. Biogas injection relied on the same supply system, with inlet methane concentrations exhibiting broader variability and generally higher values, ranging from 0.1% to 9.3%. To accommodate these fluctuations, the injection flow rate was manually adjusted, as required by operational conditions, between 815 and 1200 $m^3\ day^{-1}$ (approximately 20 to 30 scfm).

2.5 Monitoring

2.5.1 Methane load

For both phases, the biogas flow entering the biofilter was measured using a thermal mass flow meter installed directly at the inlet, upstream of the fishbone-type gas distribution system. The methane loading ($gCH_4.m^{-2}.day^{-1}$) was calculated using Equation 1.

$$Load_{CH_4} = Q \times 1000 \times \left(\frac{16.04}{22.4} \times \frac{1}{S}\right) \times \frac{C_{CH_4}}{100} \times \left(\frac{273}{273 + T_{ext}}\right) \times \times \frac{Patm}{1013} \quad (1)$$

Where Q is the biogas flow rate ($m^3.day^{-1}$), S is the biofilter surface area (m^2), C_{CH4} is the inlet methane concentration (%) measured using a portable gas analyzer (SEM5000, QED Environmental Systems Inc., 2017) with laser technology to measure CH_4 from 0.5 ppm to 100 % (vol), T_{ext} is the ambient temperature (°C), and P_{atm} is the atmospheric pressure (hPa). Figure 2 presents a comparative analysis of daily methane loadings applied to the CESM1 and CESM2 biofilters using violin plots. Figure 2 shows that methane loading values are broadly distributed for both systems, with similar median values (≈309 $g \cdot m^{-2} \cdot day^{-1}$ for CESM1 and ≈303 $g \cdot m^{-2} \cdot day^{-1}$ for CESM2), but with substantial variability and a wide range of loading conditions observed in both cases.

2.5.2 Methane outlet flux

Methane surface fluxes at the biofilter were estimated using a static flux chamber. The method involves placing the chamber directly on the surface and monitoring the increase in methane concentration over a fixed time interval (10 minutes in the context of this study). Assuming a linear concentration rise, the slope of the best-fit line (dC/dt) represents the accumulation rate of methane inside the chamber. This volumetric concentration change was then converted into a mass flux using the ideal gas law (Abichou et al., 2006). Equation 2 was used to calculate the surface flux, considering the dimensions of the rectangular chamber used in this project.

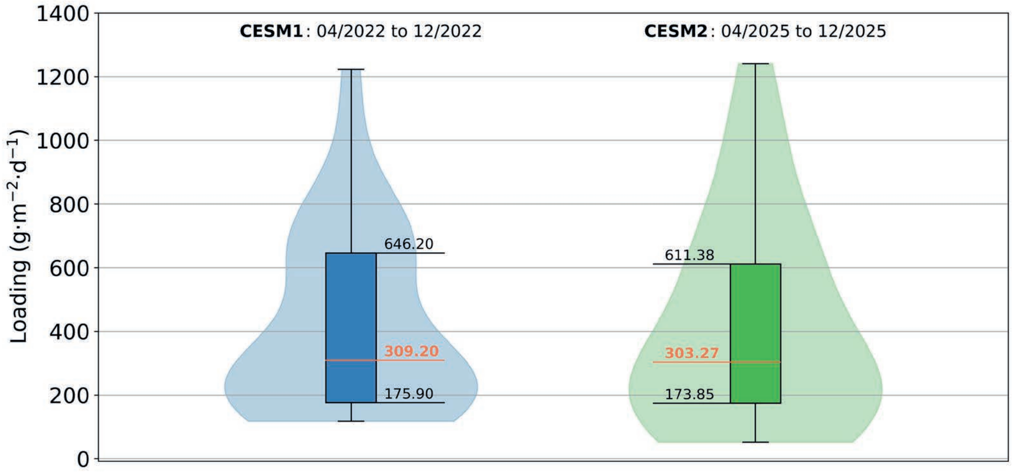

FIGURE 2: Distribution of methane loadings applied to the CESM1 and CESM2 biofilters, shown as violin plots. Both systems exhibit similar median loadings, but CESM2 shows a wider distribution and more frequent high-loading events, reflecting greater operational variability.

$$Flux_{CH_4}\left(\frac{g}{m^2.day}\right) = Slope_{ppm\,x\,s} \times \left[\left(\frac{16.04}{22.4}\right) \times \left(\frac{273}{273 + T_{ext}}\right) \times \left(\frac{Patm}{1013}\right)\right] \times \left(\frac{V}{S}\right) \times 86.4 \qquad (2)$$

Where corresponds to the rate of change in methane concentration over time (based on the linear fit between two measurements), T_{ext} is the ambient temperature (°C), P_{atm} is the atmospheric pressure (hPa), V and S represent the volume (m³) and surface area (m²) of the flux chamber, respectively.

For this project, the biofilter was divided into three distinct zones, all of which were tested using the flux chamber during the measurement campaigns. This approach aimed to provide a more representative assessment of the overall surface flux, by allowing the results to be weighted according to zone.

2.5.3 Methane oxidation efficiency

Methane oxidation efficiency was estimated under the following assumptions: (i) uniform distribution of inlet gas across Zones 1-3, (ii) negligible methane storage within the system (steady-state conditions), and (iii) no correction for CO_2 production or O_2 consumption. Surface flux measurements are assumed to be representative of average zone-scale emissions.

These assumptions are suitable for integrated field-scale comparison but may bias estimates for CESM2. As surface cracking and preferential pathways developed (Section 3.1), the assumption of uniform gas distribution was likely violated, potentially leading to apparent under- or over-estimation of oxidation efficiency at the system scale rather than reflecting intrinsic MOL performance.

Methane oxidation efficiency was determined using a mass balance approach, based on inlet and outlet CH_4 fluxes, following the methodology described in Almeida et al. (2024). This approach provides an integrated assessment of system performance under field conditions and is widely used in biosystems studies. However, CO_2 production and O_2 consumption were not measured in this study. While multi-gas monitoring could offer additional insights into the biological mechanisms involved in methane oxidation, the adopted method allows for a robust evaluation of overall CH_4 removal efficiency. As previously mentioned, flux chamber measurements were conducted in three distinct zones (Figure 3 provides a schematic overview of these zones).

For the analysis presented in this paper, we assumed that the biogas entering the GDL is evenly distributed across the entire GDL/MOL interface, implying that the different zones exert an equivalent influence on methane oxidation. We adopted this simplifying assumption to facilitate the analysis, but we will re-evaluate it in future publications. In practice, however, biofilters may exhibit non-uniform gas distribution due to physical processes such as capillary barrier effects and partial clogging. These mechanisms can reduce gas permeability in the downslope region (Zone 1), promoting preferential gas migration toward other zones, consistent with the behavior described by Almeida et al. (2024) in Scenario C.

Gas concentration profiles were not monitored in this study due to technical limitations associated with gas sampling probes. Specifically, clogging issues in several probes installed in CESM1 (Almeida et al. 2024), which compromised the reliability of the measurements. Therefore, to ensure consistency between systems, gas profiles were not included for CESM2.

2.6 Statistical analysis

Descriptive statistical analyses were performed to characterize the datasets from CESM1 and CESM2, including calculation of mean, median, minimum, maximum, and standard deviation for the main performance parameters. Data normality was evaluated using the Shapiro-Wilk test to assess whether the variables conformed to a normal distribution.

As the majority of the datasets did not satisfy the assumption of normality ($p < 0.05$), non-parametric Mann–Whitney U tests were applied to compare methane loading, oxidation efficiency, and the amount of methane oxidized

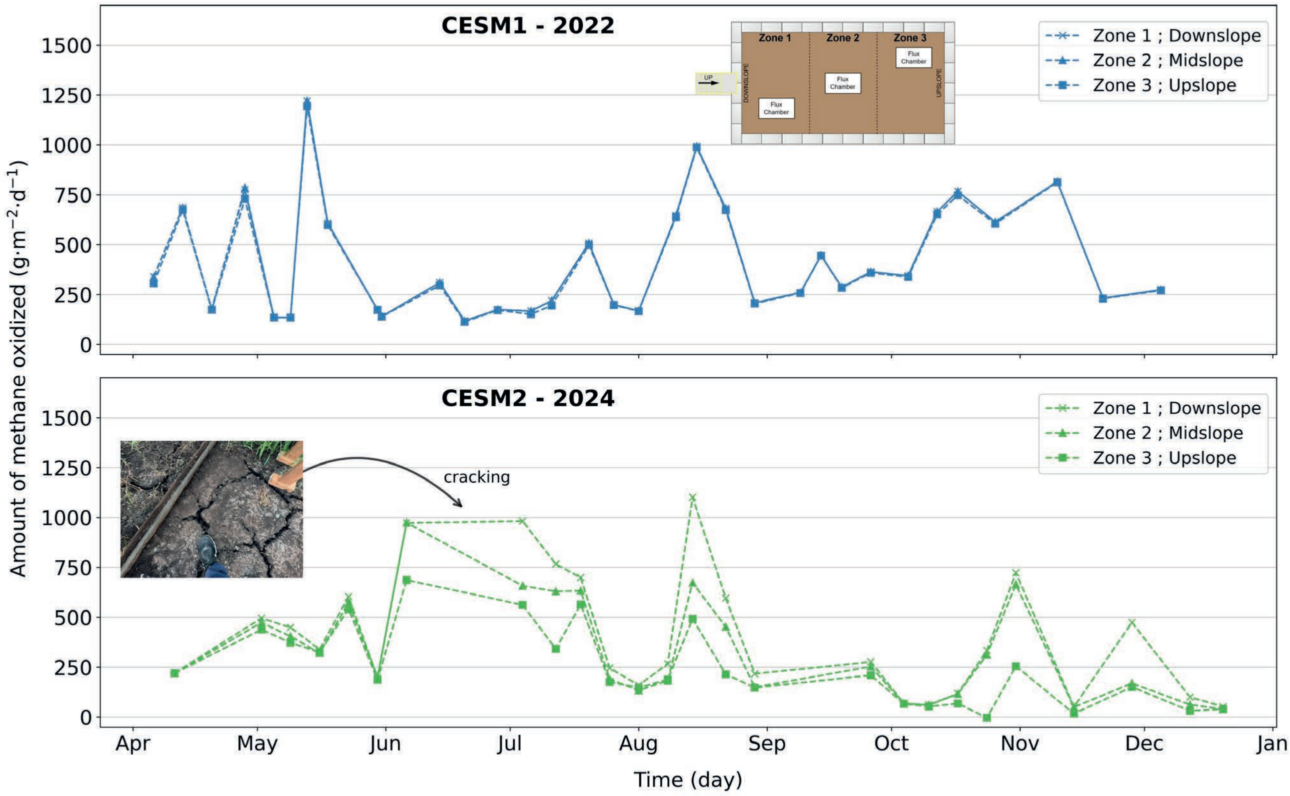

FIGURE 3: Temporal evolution of the amount of methane oxidised in the three biofilter zones for CESM1 (2022) and CESM2 (2024). CESM1 exhibits relatively uniform behavior among zones, whereas CESM2 shows pronounced spatial variability, particularly during summer months, with reduced performance in upslope zones associated with cracking and preferential flow.

between the two biofilters, as well as between zones where applicable. Statistical significance was established at $p < 0.05$.

All statistical analyses were conducted using Python (version 3.8.10).

3. RESULTS AND DISCUSSION

This section presents a comparative analysis of methane oxidation performance between the two project phases, CESM1 and CESM2. Although the systems were commissioned in different years (2021 for CESM1 and 2023 for CESM2), their initial operation began at similar times of the year (October). To minimize the influence of harsh winter conditions and exclude the initial stabilization period typical of newly commissioned experimental plots, the analysis focuses on the period from April to December. This time frame, spanning from early spring (snowmelt period) to the first weeks of winter, allows for the assessment of biofilter performance under relatively comparable meteorological conditions.

3.1 Amount of methane oxidized

Figure 3 illustrates the evolution of the amount of methane oxidized in the CESM1 (2022) and CESM2 (2024) biofilters, with data considered for each zone over time. We observe that both CESM1 and CESM2 exhibit variability in the amount of CH_4 oxidized over the monitored months. Additionally, a lower variation among zones is noted for CESM1. This observation is further supported by the descriptive statistical analysis (Table 1).

For CESM1, the amount of methane oxidized ranged from 113.1 to 1220.3 $g.m^{-2}.day^{-1}$, with median values of 297.5, 297.6, and 289.7 $g.m^{-2}.day^{-1}$ for zones 1, 2, and 3, respectively. For CESM2, the amount of methane oxidized ranged from 3.9 to 1101.4 $g.m^{-2}.day^{-1}$, with median values of 333.6, 252.9, and 187.8 $g.m^{-2}.day^{-1}$ for zones 1, 2, and 3, respectively. These results indicate that the fluctuation among zones was greater for CESM2 than for CESM1, as shown in Figure 3.

During the first quarter of the analysis period (April to June), CESM1 consistently oxidized slightly more methane than CESM2. Starting in June, a marked increase in methane oxidation was observed in CESM2, particularly in Zone 1 (downslope), reaching values close to 1000 $g.m^{-2}.day^{-1}$. However, this trend was accompanied by divergence among zones, especially from July onward, indicating an imbalance in gas distribution and/or spatial variability in microbial oxidative activity. Although gravel improves structural stability and drainage, its limited moisture retention capacity and absence of readily assimilable organic carbon may promote more localized microbial activity, which becomes strongly dependent on zones with more favorable moisture conditions and substrate availability (Huber-Humer et al., 2008).

The greater performance disparity among CESM2 zones, compared to CESM1, appears to be associated with microenvironmental modifications induced by the experi-

TABLE 1: Statistical data for CESM1 and CESM2 comparison.

Biofilter	Parameters	CH_4 loading	Efficiency	CH_4 oxidized - Z1	CH_4 oxidized – Z2	CH_4 oxidized – Z3
CESM 1	Mean	422.3	94.9	421.9	422.1	413.6
	Minimum	117.5	78.3	117.5	117.5	113.1
	Maximum	1223.1	99.9	1219.9	1220.3	1193.0
	Median	297.7	97.9	51.1	297.6	289.7
	Standar deviation	290.1	6.2	289.4	289.8	284.5
CESM 2	Mean	425.9	80.2	413.8	337.6	251.0
	Minimum	51.6	52.4	51.7	39.2	3.9
	Maximum	1240.5	100	1101.4	973.9	686.8
	Median	327.7	80.4	333.6	252.9	187.8
	Standar deviation	335.8	13.8	317.1	259.4	199.4
p-value		0.79	0.000011*	0.68	0.17	0.024*

*Values marked with * indicate statistically significant differences (p < 0.05) according to the Mann-Whitney test*

mental configuration. The installation of the shelter enclosure, which was required to enable continuous monitoring of methane oxidation, may have altered the thermal and hydric regimes within the biofilter. During the summer 2024 period, the shelter is expected to have enhanced internal heat accumulation. Combined with the lack of direct precipitation, these conditions led to accelerated desiccation of the MOL, causing a substantial decrease in its moisture content. Gómez-Borraz et al. (2025) showed that elevated temperatures in methane biofilters can shift microbial metabolism from anabolism toward catabolism due to thermal stress, ultimately impairing oxidation performance.

Taken together, these results reveal a clear trade-off between oxidation efficiency and total methane throughput. CESM1 consistently achieved higher and more stable oxidation efficiency, indicating robust performance of the open configuration and compost–woodchip MOL under a wide range of conditions. In contrast, CESM2 oxidised a larger total mass of methane, primarily because it was operated under substantially higher methane loadings during extended periods, despite exhibiting lower and more variable efficiency. From a design perspective, this highlights that systems optimized for stability and efficiency may differ from those intended to treat high methane fluxes. Enclosed configurations such as CESM2 can increase total abatement potential when higher loads are unavoidable, but require careful control of boundary conditions to prevent efficiency losses associated with drying, cracking, and preferential gas pathways.

Although the STEM material appeared adequately moist at the time of placement, progressive drying led to the development of surface fissures, predominantly in the midslope and upslope zones (zones 2 and 3). The formation of cracks facilitated preferential flow paths, thereby reducing methane residence time and limiting effective contact between the methane and the biologically active oxidation zone (Röwer et al. 2011; Gebert et al. 2022).

To mitigate these effects, we implemented corrective measures, including weekly manual irrigation applied at the surface of the biofilter and localized rehabilitation through excavation and compaction of the affected areas. These interventions led to an increase in methane oxidation from November 2024 onward in CESM2, suggesting a partial recovery of system performance following the restoration of moisture conditions and structural integrity.

Furthermore, the spatial variability in performance observed across CESM2 zones cannot be attributed to oxygen limitation, as both biofilters were supplied with a gas stream containing oxygen. This observation effectively excludes oxygen availability as a controlling factor and highlights the dominant influence of the thermal, hydric, and structural properties of the oxidation medium on methane oxidation performance under the investigated conditions.

Part of the variability observed in Figure 3 can be attributed to fluctuations in methane loading. As shown in Figure 5 (section 3.3.), methane loading influences oxidation efficiency, particularly in CESM2, which exhibits greater fluctuation across different loading ranges. This suggests that part of the apparent variation is not solely due to intrinsic system performance but is also driven by variations in inlet methane flux.

Despite the constraints, CESM2 oxidized a greater mass of methane during the summer of 2024, not due to higher efficiency, but rather because of its substantially greater methane loading (≈750 vs. 250 $g.m^{-2}.day^{-1}$). Consequently, although oxidation efficiency was lower, the total volume treated remained substantial. However, a statistically significant difference in overall oxidation efficiency was observed between CESM1 and CESM2 ($p < 0.05$), as shown in Table 2, with CESM1 showing higher performance; the oxidation efficiency itself is specifically addressed in Section 3.3. In addition, the amount of methane oxidized in Zone 3 was significantly higher in CESM1 compared to CESM2 ($p < 0.05$), indicating a spatially localized effect. This behavior appears to be associated with crack development in CESM2, particularly near Zone 3, highlighting the importance of structural integrity for maintaining biofilter performance.

To address the observed issues, targeted interventions were carried out between August and November 2024. These included manual excavation and compaction of deeply fissured areas, mainly in Zone 3, and surface tilling (≈30 cm depth) of the MOL across the entire biofilter. These adjustments led to a notable, albeit transient, increase in methane oxidation observed in November 2024, suggesting a partial restoration of uniform biogas distribution. Consequently, results from CESM2 should be interpreted with caution, as shelter induced disturbances may have disproportionately affected its performance, and do not necessarily reflect intrinsic material limitations under typical field conditions.

The dataset presented in Figure S2 (Supplementary Material II) comprises water content, temperature, and the amount of methane oxidized data for the CESM2 system from October to December 2024. Due to technical and operational constraints, sensor data were not available for other months. Nevertheless, this period provides important insights into the hydric and thermal conditions governing methane oxidation during the transition from autumn to early winter.

From October to November 2024, water content in Zone 1 remained relatively high, with values around 0.32 m^3/m^3, while Zone 2 exhibited lower moisture levels, ranging from 0.20 to 0.10 m^3/m^3, confirming the spatial heterogeneity previously identified in CESM2 (Figure S1). After November 2024, a pronounced decrease in water content was observed in both zones, with Zone 1 decreasing to 0.10–0.04 m^3/m^3 and Zone 2 reaching values as low as 0.02 m^3/m^3. Rather than being directly associated with summer conditions, this drying trend reflects the combined effects of reduced precipitation input and continued influence of the shelter enclosure, which limits natural rewetting of the MOL.

In CESM1, water content profiles were monitored over a longer period, from April to December 2022, as also reported by Almeida et al. (2024). During this period, moisture content ranged from 0.35 m^3/m^3 to 0.80 m^3/m^3 (Figure S3, Supplementary material III), indicating consistently higher water availability compared to CESM2. Similarly to CESM2, higher moisture levels were observed in Zone 1, suggesting a recurring spatial pattern within the system, probably influenced by slope and preferential water accumulation.

The temperature profile for CESM2 (Figure S4) in October 2024 revealed pronounced spatial variability among zones, with higher temperatures observed in Zone 2 (54.5°C) compared to Zone 1 (31.2-43.8°C). This indicates the presence of localized thermal hotspots within the system, probably associated with differences in gas flux distribution and microbial activity, as well as the influence of the shelter enclosure on heat retention.

At 1 m depth, corresponding to the base of the MOL (CESM2), temperatures in November 2024 were 35.3°C, 30.6°C, and 23.7°C for zones 1, 2, and 3, respectively (Figure S5, Table S5, Supplementary material V). In December 2024, a consistent decrease in temperature was observed across all zones, reaching 27.6°C, 24.3°C, and 19.6°C. This cooling trend is consistent with the transition toward colder seasonal conditions and suggests a progressive reduction in thermal energy within the system.

The elevated temperature observed in Zone 2 in October 2024 may have contributed to suboptimal conditions for methane oxidation. Although moderate increases in temperature can enhance microbial activity, excessively high temperatures, such as those exceeding 50°C, may induce thermal stress in methanotrophic communities, shifting metabolism and potentially reducing oxidation efficiency (Gómez-Borraz et al. 2025).

Considering the period from October to December 2022 in CESM1, corresponding to the same seasonal window analyzed for CESM2 in 2024, the average temperature did not vary significantly among zones, remaining within a relatively narrow range between 50°C and 62°C (see Figure S6, Supplementary material VI). This thermal uniformity contrasts with the pronounced spatial variability observed in CESM2.

The more homogeneous temperature distribution in CESM1 suggests a more stable internal environment, possibly associated with the absence of the shelter enclosure and the resulting natural exchange of heat and moisture with the atmosphere.

Furthermore, the combination of high temperatures and the previously observed moisture conditions may have intensified spatial heterogeneity in methane oxidation. While Zone 2 exhibited higher temperatures, its lower moisture content compared to Zone 1 suggests that the balance between thermal conditions, water availability, and gas diffusivity plays a critical role in controlling system performance. Nevertheless, beyond these site-specific effects, both systems exhibited similar temporal trends consistent with seasonal patterns, suggesting that ambient temperature may have influenced methane oxidation dynamics.

A decline in efficiency was observed during the summer (2022, 2024) for both biofilters, followed by a temporary peak in August and a subsequent drop in early September. An additional decrease in performance occurred at the beginning of winter, pointing to a shared seasonal response across both systems. This pattern indicates an influence of temperature and moisture on system performance. Elevated summer temperatures promoted drying, affecting methanotrophic activity, gas diffusion, and structural integrity. In CESM2, high temperatures caused surface cracking (especially in Zone 3) as discussed before. A similar trend was observed in CESM1, where temperatures reached 43-52°C in August 2022 (Almeida et al., 2024), followed by a decline below 40°C. Although continuous data in August 2024 were unavailable for CESM2, the consistency between systems suggests that seasonal heating and drying drove the observed dynamics, with the shelter amplifying these effects.

3.2 Methane oxidation capacity with batch tests

As part of the CESM2 phase, we conducted batch tests in August 2024, shortly after the marked decline in performance observed in July 2024, to assess the impact of disturbances, fissuring, on the methane oxidation capacity of the MOL. Three field samples were collected, one from each zone, and compared to a reference material from CESM1, also sampled by zone. This CESM1 material, collected at the end of the project (2022), was stored in an airtight 18 L container and kept active through weekly injections of 500 mL of pure methane.

Figure 4 illustrates the performance differences across the two biofilter phases, revealing a marked decrease in microbial activity in the CESM2 samples.

While the CESM1 compost fully oxidized the methane within 10 hours, with an initial oxidation rate of 1.55% $CH_4 \cdot h^{-1}$, CESM2 samples displayed a comparable rate during the first two to three hours (1.29% $CH_4.h^{-1}$), followed by a significant slowdown (0.27% $CH_4.h^{-1}$) reflecting microbial stress or partial dormancy due to dry and fissured field conditions in CESM2.

These findings reinforce the hypothesis that the shelter enclosure modified boundary conditions and impaired biofilter performance. The poorest-performing batch (Zone 3, upslope) aligned with the most fissured field zone, indicating that physical disruption adversely affected microbial activity. This is consistent with Figure 3, which shows lower oxidation in Zone 3 during the summer. In contrast, CESM1 exhibited high and stable oxidative capacity across all zones, in both batch and field conditions.

Considering this, adapting the operational strategy of the biofilter to the specific constraints imposed by the enclosed configuration appears necessary, particularly to mitigate heat-related effects such as cracking. Enhancing moisture content and ensuring a more homogeneous gas distribution within CESM2 are expected to improve the overall oxidation rate while simultaneously reducing the pronounced heterogeneity among zones. In parallel, an acclimatization protocol was launched in December 2024 to reestablish microbial activity, with ongoing monitoring to evaluate long-term recovery trends.

3.3 Effect of load on the methane oxidation efficiency

Figure 5 shows the distribution of oxidation efficiencies across methane loading rates for both phases. CESM1 exhibited predominantly high efficiencies (>95% in 33 instances), sustained across a wide range of methane loadings, including elevated values (>900 $g.m^{-2}.day^{-1}$). This pattern reflects the biofilter's ability to maintain high efficiency despite substantial variations in methane input.

Several studies have reported that the landfill gas loading rate can control the diffusion of atmospheric oxygen into biofilter media, thereby limiting microbial methane oxidation (Dever et al. 2011). However, in the present study, oxygen availability was not a limiting factor, as the gas supplied to the biofilters contained approximately 18.5% O_2. In the study by Farrokhzadeh et al. (2017), methane oxidation efficiencies ranging from 80 to 95% were achieved even under high methane loadings (370 - 1112 $g.m^{-2}.day^{-1}$). This sustained performance was attributed to the adopted aeration strategy, which effectively prevented oxygen limitation and ensured adequate O_2 availability for microbial oxidation.

By contrast, CESM2 displayed greater variability, with 16 of 26 measurements falling below 80%, highlighting the biosystem's operational instability. Notably, the six lowest-performing measurements (<70%) were all recorded under low methane loadings (0-150 $g.m^{-2}.day^{-1}$), suggesting reduced efficiency of the system even under moderate operating conditions. Only four CESM2 measurements exceeded 95% efficiency, all at lower loads (<650 $g.m^{-2}.day^{-1}$), comparing to CESM1, suggesting limited high-performance range. However, when compared with other studies, such as Falk et al. (2025), methane loadings of approximately 650 $g.m^{-2}.day^{-1}$ were among the highest values investigated. This comparison indicates that, although CESM2 exhibited lower performance than CESM1, the biofilter under CESM2 conditions still demonstrated generally good methane oxidation performance.

Some physical and chemical properties of the materials used in the MOL of both systems could, at first moment, explain the observed differences in performance. For instance, CESM2 exhibited a significantly lower total porosity (48%) compared to CESM1 (69%), which could theoretically limit gas diffusion through the medium. However, air permeability and air-filled porosity were comparable,

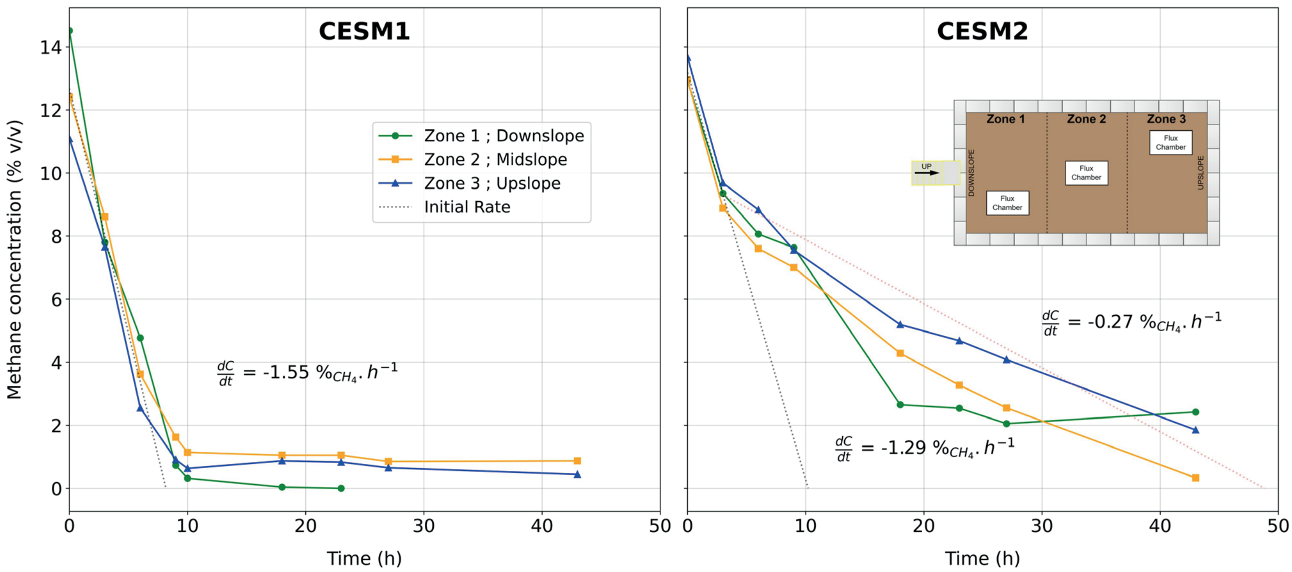

FIGURE 4: Methane consumption kinetics by zone for CESM1 and CESM2.

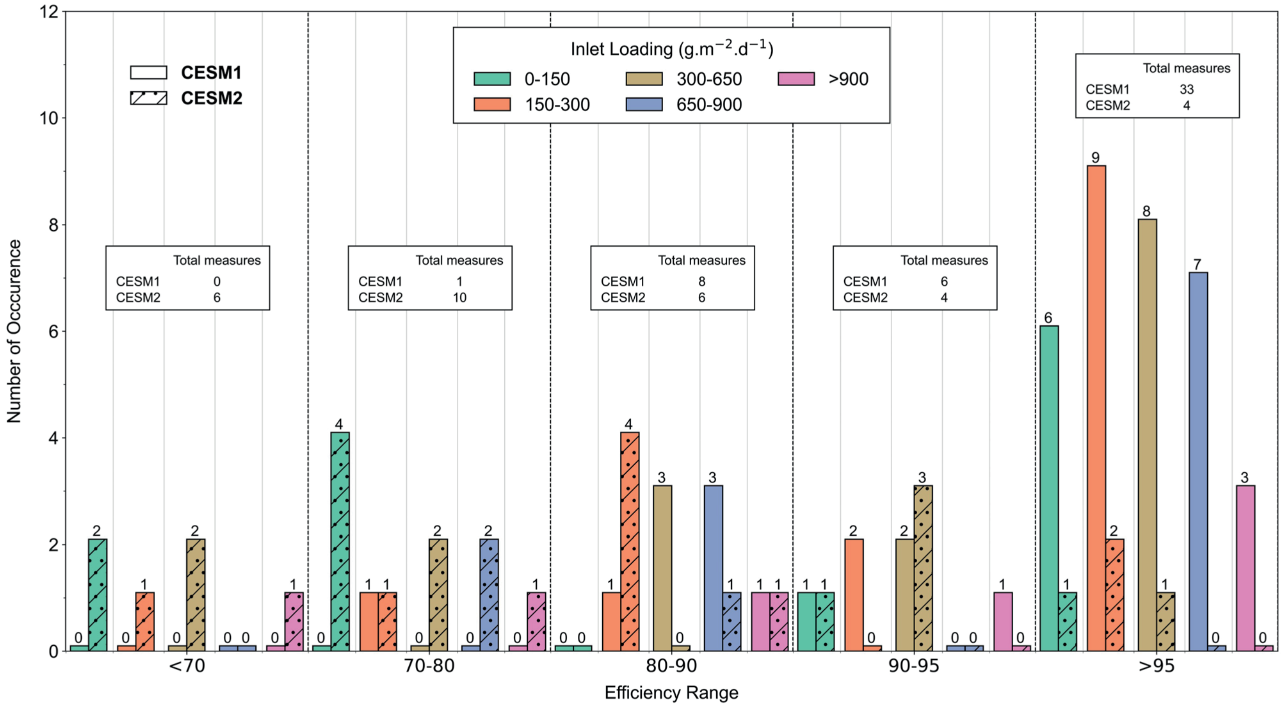

FIGURE 5: Relationship between methane loading rate and oxidation efficiency for CESM1 and CESM2. CESM1 maintains consistently high efficiencies across a wide loading range, while CESM2 displays greater variability and reduced efficiency at both low and high loadings, indicating higher sensitivity to operational and boundary-condition effects.

suggesting that gas transfer limitations were not primarily responsible for the observed performance differences. Furthermore, the air-filled porosity values of 31% for CESM1 and 28% for CESM2 (Table 2) are well above the minimum threshold of 14% identified by Gebert et al. (2011) as suitable for effective methane oxidation in biofilter systems.

In terms of organic matter content, the compost used in CESM1 (44%) was markedly richer than that of CESM2 (6.7 %), potentially supporting a denser and more active methanotrophic community. This may help explain CESM1's field performance. Nonetheless, the kinetic profile of CESM2 still reflects strong intrinsic potential, suggesting that its lower performance was not solely due to biological limitations, but also influenced by physical factors such as reduced porosity or even boundary conditions like the presence of a shelter enclosure. These findings emphasize the importance of both material composition and structural properties in determining biofilter effectiveness.

Although CESM1 benefitted from a prior acclimatization phase, the evidence points toward the shelter enclosure in CESM2 as a major limiting factor. Localized heat accumulation and surface fissuring, particularly in Zone 3, disrupted gas distribution within the MOL. In several cases, surface methane concentrations near fissures were equivalent to inlet values, confirming the formation of preferential pathways that bypassed the MOL and compromised the biofilter's overall efficiency.

The contrasted behavior of CESM1 and CESM2 highlights several practical implications for the design and operation of field-scale methane oxidation biofilters. In CESM1, the clogging observed at the MOL–GDL interface illustrates the limitations of incorporating fine sand filter layers beneath high-organic-matter compost media. Degradation and migration of organic components can lead to pore occlusion and cementation, ultimately restricting gas transfer and reducing long-term reliability. These observations underline the importance of ensuring hydraulic and textural compatibility between adjacent layers, favoring materials with comparable permeability to minimize the risk of persistent clogging.

The performance of CESM2 further emphasizes the need to carefully balance structural stability and moisture retention in the selection of structuring agents for structured engineered media. Although gravel enhanced mechanical stability and drainage, reduced water-holding capacity contributed to desiccation, spatial heterogeneity, and reduced microbial robustness under field conditions. These effects were amplified by the presence of the shelter enclosure, which modified thermal and hydric boundary conditions by limiting natural precipitation inputs and promoting heat accumulation. In enclosed or semi-enclosed configurations, such boundary-condition effects should therefore be explicitly addressed through design measures aimed at moderating temperature and maintaining adequate moisture levels, such as controlled ventilation, shading, or supplemental irrigation.

Finally, the development of surface cracking and preferential gas pathways in CESM2 demonstrates the critical role of surface integrity in maintaining effective methane oxidation. Cracking reduced methane residence time and promoted localized bypass, particularly in upslope zones, leading to reduced apparent efficiency despite high micro-

TABLE 2: Characteristics of MOL materials.

Properties	Standard	CESM1	CESM2
Grain size distribution Gravel (5 mm < D < 112 mm) Sand (0.08 mm < D < 5 mm) Silt (D < 0.08 mm)	14688-2 (ISO, 2017)	9.0% 88.0% 3.0%	77.9% 20.2% 1.9%
Specific gravity (ρ_s)	D854-23 (ASTM, 2023)	2.03 g.cm^{-3}	2.50 g.cm^{-3}
Field dry density (ρ_d)	D7263-21(ASTM, 2021)	0.63 g.cm^{-3}	1.30 g.cm^{-3}
Total Porosity (n)	-	69%	48%
Volumetric water content (θ)	D2216-19 (ASTM, 2019)	38 m³/m³	20 m³/m³
Air-filled porosity (θ_a)	-	31%	28%
Organic matter (%w/w)	D2974-20 (ASTM, 2020)	44%	6.7%
Dry Air permeability (m.s^{-1})	D6539 – 13 (ASTM_International, 2013)	8.4 x 10^{-5}	7.0 x 10^{-5}
Maximum oxidation capacity ($V_{máx}$)	-	2 383 g.m^{-3}.day^{-1}	1 624 g.m^{-3}.day^{-1}
Km	-	12 g.m^{-3}	23.4 g.m^{-3}

bial potential. Routine surface inspection and timely corrective interventions, including rewetting, recompaction, or shallow tilling, appear essential to sustain uniform gas distribution and stable performance over time. Collectively, these observations show that biofilter performance is governed not only by intrinsic material properties but also by construction details and boundary conditions, which must be jointly considered in practical design and operation.

4. CONCLUSIONS

This study highlighted key differences and shared patterns between the CESM1 and CESM2 biofilters. Seasonal trends confirmed the role of ambient conditions, while lab tests showed that CESM1's STEM had higher methane oxidation capacity. Both substrates, however, maintained a good oxidation potential. In the field, CESM1 delivered stable performance, whereas CESM2 showed higher variability and reduced efficiency.

This variability was primarily linked to the CESM2 shelter enclosure, which altered the thermal and hydraulic conditions within the system. These changes led to overheating, MOL cracking (especially in Zone 3), and gas bypass. Batch tests confirmed microbial activity loss, leading to remedial actions and a reacclimatization protocol.

Corrective measures began in fall 2024, with microbial recovery underway over winter. These findings show that while enclosures facilitate continuous monitoring, they can disrupt gas and moisture dynamics. Such effects must be addressed in the design of enclosed biosystems to ensure stable and efficient methane oxidation.

Based on these findings, the following practical recommendations can be drawn:

- Avoid full enclosure without appropriate moisture and temperature control systems.
- Monitor and mitigate drying and cracking, particularly in upslope zones.
- Ensure a balance between structural stability and organic matter content in STEM design to maintain both permeability and microbial activity.

Future work will focus on developing enclosure designs that allow continuous monitoring while minimizing adverse effects such as drying, overheating, and gas flow heterogeneity.

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LIFE CYCLE ASSESSMENT OF WASTEWATER TREATMENT IN A TEXTILE DYEING FACILITY

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ABSTRACT

This study evaluates the environmental impact of wastewater treatment in a textile dyeing plant through a Life Cycle Assessment (LCA) following ISO 14040-44, comparing three scenarios: (1) standard biological treatment, (2) electrochemical treatment (EC), and (3) an optimized system with water recirculation and hydrogen recovery. The results demonstrate that Scenario 3 is the most sustainable, achieving a 70% reduction in freshwater consumption–dropping from 1,000 L to just 300 L per 100 kg of fabric. This optimized approach also reduces chemical inputs, such as NaCl and Na_2CO_3, by 70%. From an energy perspective, the recovery of green hydrogen as a by-product provides approximately 9.9 MJ of energy per 100 kg of fabric, contributing to a 35% decrease in operating costs. Economically, the transition to Scenario 3 results in a total saving of €3.50 per kg of fabric compared to the conventional system. By effectively mitigating pollutant loads and drastically lowering the water and carbon footprints, this study provides data-driven evidence for decision-makers to adopt electrochemical processes. Ultimately, the integration of resource recovery proves that the textile industry can achieve significant industrial-scale savings, estimated at €1,050 per day, while maintaining high environmental standards.

1. INTRODUCTION

The textile industry is a major contributor to global industrial wastewater pollution, accounting for approximately 20% of total discharges worldwide (Velazquez, J., 2024). Within this sector, cotton dyeing and finishing processes are particularly critical due to their high consumption of water and chemical auxiliaries, such as sodium chloride and sodium carbonate. These processes generate large volumes of saline effluents containing recalcitrant organic matter and non-biodegradable dyes, which significantly challenge conventional wastewater treatment facilities.

Azo dyes, which account for over 80% of synthetic dyes, pose severe risks to environmental and human health due to their high stability and toxicity. When discharged into water bodies, they obstruct light penetration, inhibiting photosynthesis and depleting oxygen levels in aquatic ecosystems. Most critically, the reductive cleavage of the azo bond releases aromatic amines, many of which are known carcinogens and mutagens linked to bladder cancer and skin sensitization. These compounds tend to bioaccumulate, creating long-term ecological damage and significant health hazards for textile workers and surrounding communities. Consequently, their removal from industrial wastewater is a vital environmental priority to prevent the degradation of global water resources (Alzain et al., 2023; Boya Gao et al., 2022).

Because these complex pollutants are not effectively removed by standard biological treatments—where high conductivity can further inhibit essential microbial activity—facilities often require energy-intensive tertiary processes to meet discharge standards. This technological gap frequently results in high operational expenditures related to chemical usage and sludge management. Consequently, addressing these environmental challenges requires the integration of advanced technologies, such as electrochemical treatments, to enhance the degradation of persistent organic loads and facilitate safer discharge or water reuse (Ocampo, S., 2019; Cortazar Martínez, A., et al., 2025).

Given these characteristics, the textile finishing industry is considered a promising candidate for electrochemical treatments, which could enhance the degradation of recalcitrant organic matter while simultaneously enabling hydrogen (H_2) production—an approach especially relevant since the sector generates effluents with high conductivity

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and complex organic loads (Cuesta-Mota, D. et al., 2024a). Furthermore, it ranks among the top five industries in the European Union in terms of water use (79.6 m³ tCO_2/t of fabric produced) and CO_2 emissions (15–35 eq/t of fabric produced) (European Topic Centre on Waste and Materials in a Green Economy, 2019; Roth, J. et al., 2023). At the process level, textile dyeing itself is highly intensive in water and energy: consumption values range from 10 to 300 L of water per kg of fabric (Samanta, k. et al. 2019), with finishing-dyeing operations reaching 60–314 L/kg and peaks of up to 645 L/kg (Ketelsen, M.et al., 2020). For cotton dyeing, conventional procedures average around 120 L/kg (Reza-Ul-Hoque, M., 2023). Beyond water use, recent studies have quantified the carbon footprint of reactive dyeing, reporting emissions of 5–7 kg CO_2-eq per kg of fabric depending on the recipe and process (Zhu et al., 2024). Digital optimization of dyeing operations has been shown to significantly reduce both greenhouse gas emissions and water consumption (Kim et al., 2024). Pollutant loads remain a pressing concern, as dyeing effluents often exhibit high salinity and persistent dye content, posing serious environmental challenges (Hoque et al., 2024). These very characteristics, as discussed, make textile effluents particularly suitable for the application of electrochemical treatments. In particular, for the Catalonia region where this study is focused, the water consumption, the reduction of the carbon footprint and the emission of less pollutants are considered as priorities that the textile industry shall assess.

In this region, the environmental urgency is heightened by severe hydric stress due to the fact that this zone currently experiencing the worst drought in its recent history, with reservoir levels dropping below 16% of total capacity (Velazquez, J. , 2024).

Consequently, strict restrictions have been imposed on water usage, and regional authorities have set ambitious targets, such as reusing up to 70% of treated water by 2040 (Oria, I., 2024). Implementing advanced water recovery strategies in industrial sectors is therefore critical to mitigating water scarcity and adapting to long-term climate challenges (Palermo, F., 2024).

The shift towards sustainability in the textile sector is also driven by the need to reduce greenhouse gas (GHG) emissions. Hydrogen has emerged as a promising alternative to fossil fuels, given its high energy density and its only combustion by-product being water vapor. The integration of hydrogen production into textile wastewater treatment could simultaneously address water reuse and renewable energy generation goals (TEXTIMCA, 2025 and Zeng, K., & Zhang, D., 2010).

Electrochemical treatment processes have proven highly effective in removing dyes and complex organic pollutants from textile effluents while enabling the recovery of salts and alkalinity for reuse (Fabregas, 2021). Furthermore, electrochemical oxidation has shown energy consumption levels (approx. 3.5 kWh/m3) comparable to conventional textile wastewater treatment plants (Buscio et al., 2019). While several studies have explored these technologies for decontaminating synthetic organic dyes (Brillas & Martínez-Huitle, 2015; Sala & Gutiérrez-Bouzán, 2014), the focus has primarily been on anodic oxidation. In these systems, hydrogen is simultaneously generated at the cathode as a by-product, but it is generally extracted only for safety reasons. Consequently, very few studies have addressed the recovery of this hydrogen (Pathak et al., 2020; Cuesta-Mota et al., 2024a), despite its potential to substitute natural gas in industrial heat generation, thereby reducing fossil fuel dependency and carbon emissions (Ottosson, 2021).

To address this gap, our research group has designed and constructed a dual-compartment reactor separated by an ion exchange membrane. This configuration produces impurity-free hydrogen, similar to specialized alkaline electrolyzers (Cuesta-Mota et al., 2026). The experimental data obtained from this prototype, integrated with industrial data, has been used to generate the Life Cycle Inventory (LCI) for a Life Cycle Assessment (LCA). This allows for a comprehensive comparison of the environmental impact between this integrated water and hydrogen-recovery system and conventional biological treatments.

Life Cycle Assessment (LCA), in accordance with ISO 14040/14044 guidelines, offers a comprehensive framework to evaluate the environmental performance of such process innovations. By comparing scenarios with conventional and electrochemical treatments (with and without water reuse), it is possible to quantify resource savings, emission reductions, and the overall circularity potential of the proposed system. Scientific research into the textile sector and wastewater treatment has applied Life Cycle Assessment (LCA) to compare advanced technologies against conventional biological methods like Activated Sludge Processes (ASP). Key studies often focus on Advanced Oxidation Processes (AOPs), such as electrocoagulation and ozonation, highlighting that while these methods are efficient at removing persistent color and COD, their environmental burden is heavily influenced by electricity and chemical consumption (Bilinska et al., 2017; Muñoz et al., 2009).

This study applies life cycle assessment (LCA) to three process configurations for dyeing cotton fabrics, evaluating their environmental impact and resource recovery potential. The objective is to provide evidence-based information on the role of electrochemical treatment and hydrogen valorization in promoting circularity in the textile industry, including an economic estimate of the savings achieved through recovery and recirculation processes. The main novelty of the LCA performed in the current study is the evaluation of a circular system that simultaneously treats wastewater, recovers hydrogen (H2), and enables resources and water recirculation.

2. METHODOLOGY

Life Cycle Assessment (LCA) is a standardized methodology used to evaluate the environmental impacts associated with all stages of a product's life cycle from the extraction of raw materials, manufacturing, and distribution, to use, end-of-life treatment, and disposal or recycling. The main goal of an LCA is to provide a comprehensive and quantitative understanding of how a product or process affects the environment, enabling the identification of opportunities for improvement and more sustainable decision-making. In this work, the LCA methodology following ISO 14040–44 has been applied to assess the environmental impacts and analyze the benefits associated with three different scenarios of the same dyeing production process, with the aim of providing a comprehensive quantitative view and determining their overall environmental performance.

An LCA typically follows the framework established by the ISO 14040 and ISO 14044 standards and consists of four main phases: (1) Goal and scope definition, where the purpose, system boundaries, and functional unit are defined; (2) Life cycle inventory (LCI), involving the collection and quantification of inputs (materials, energy) and outputs (emissions, waste); (3) Life cycle impact assessment (LCIA), in which the potential environmental impacts are evaluated; and (4) Interpretation, where the results are analyzed and conclusions are drawn to support recommendations.

The goal and scope of this study are defined in accordance with ISO 14040 and ISO 14044 standards. The main objective is to compare three different scenarios of the same dyeing production process, which, depending on the configuration, may include water recirculation and recovery of heat and hydrogen.

The intended application of the study is to support decision-making regarding resource efficiency and environmental performance improvements in water-stressed regions. The target audience includes researchers, industry stakeholders, and policymakers.

The system boundaries are defined as cradle-to-gate in order to provide a comprehensive assessment of the three scenarios, considering recovery options and potential environmental savings. The study includes all relevant processes from raw material extraction for chemicals and energy production up to the finished dyed and centrifuged cotton fabric and the associated wastewater treatment processes. Upstream processes such as cotton fiber cultivation and spinning, as well as downstream use and end-of-life phases, are excluded. These exclusions are justified based on cut-off criteria related to relevance to the comparative objective and expected negligible contribution to the differences between scenarios.

The functional unit is defined as 100 kg of conventionally dyed and finished cotton fabric under industrial conditions. The reference flow corresponds to the quantity of raw materials, energy, water, and auxiliary substances required to produce this amount of finished fabric with equivalent quality characteristics across all scenarios. This functional unit ensures comparability of environmental impacts between alternatives.

The impact assessment is performed using a recognized Life Cycle Impact Assessment (LCIA) methodology, and the selected impact categories are justified according to the objectives of the study and the ISO 14044 requirements. Given the geographic context characterized by strong water stress, the following impact categories are considered: water consumption, global warming potential (expressed as kg CO_2-eq/kg of fabric), pollutant loads (salinity and dye residues in effluents), and human health impacts related to exposure to toxic substances and degraded water quality. Global warming potential is used as the indicator for climate change to avoid duplication with carbon footprint metrics.

The system boundaries therefore include:

- Water and energy inputs for dyeing and finishing operations.
- Chemical auxiliaries (e.g., sodium chloride, sodium carbonate, reactive dyes).
- Direct emissions to water (saline effluents, residual dyes).
- Direct emissions to air (CO_2 and other greenhouse gases from energy use).
- Wastewater treatment processes, including biological and physicochemical stages.

Infrastructure and capital goods are excluded from the analysis, as their contribution is considered negligible within the comparative framework. Allocation procedures are not required unless multifunctionality arises in recovery stages, in which case allocation is performed based on physical relationships or system expansion, following ISO recommendations.

Primary industrial data are used for the core dyeing and centrifugation processes, complemented by secondary data from recognized databases for background processes. The reference year of the data and data quality indicators (technological, geographical, and temporal representativeness) are documented. An uncertainty analysis and data quality assessment are conducted to ensure robustness of the results.

Figure 1 illustrates the schematic layout of the three study scenarios and defines the system boundaries, with Scenario 1 representing the current conventional process. In this configuration, the dyeing stage includes the consumption of energy, natural gas, chemicals, cotton input, and water, corresponding to 1,000 liters of water per 100 kg of cotton. After dyeing, the fabric proceeds to the centrifugation stage. Approximately 30% of the water is discharged from the centrifugation process together with dye residues and sodium carbonate, among other components. Additionally, around 70% of the water is discharged directly from the dyeing process, containing residual dyes and chemical substances such as sodium carbonate. These two effluent streams are combined and undergo biological treatment, followed by a physicochemical treatment stage before final discharge.

Scenario 2 represents the substitution of the conventional biological and physicochemical wastewater treatments with an electrochemical treatment for the 70% of wastewater generated during the dyeing stage. The remaining 30% of water discharged from the centrifugation process continues to be treated through the conventional physicochemical process.

In this configuration, the hydrogen (H_2) produced as a by-product of the electrochemical reactions is not recovered or valorized. It is assumed to be released and therefore does not contribute to energy substitution within the system. Consequently, the net energy balance reflects only the electricity demand of the electrochemical process with-

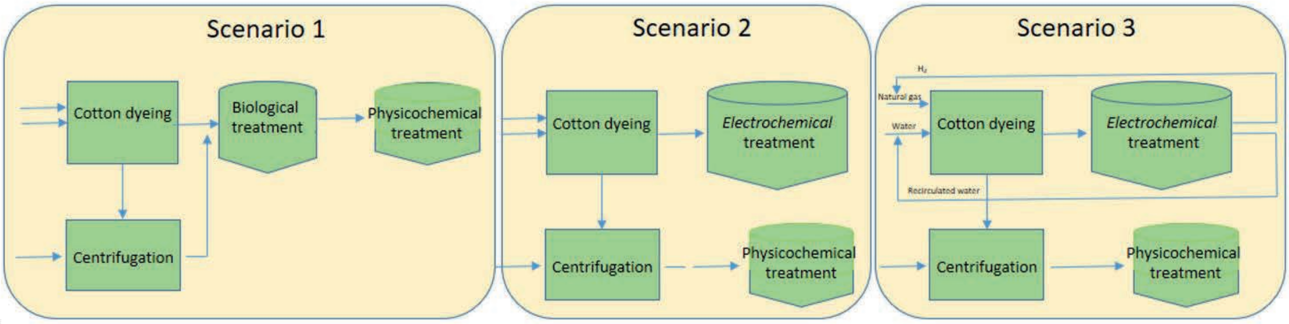

FIGURE 1: Schematic representation of the three study scenarios.

out accounting for any potential energy credits from hydrogen recovery.

Scenario 3 builds upon Scenario 2 by integrating resource recovery strategies. In addition to the electrochemical treatment, a closed-loop water recirculation system is implemented. The treated effluent exits the electrochemical reactor at approximately 60°C, enabling heat recovery and reintegration into the dyeing process, thereby reducing thermal energy demand.

Moreover, approximately 70% of the chemical auxiliaries (e.g., sodium carbonate and salts) remain in the treated stream and are recirculated into the system. The dye is not recirculated, as it is removed during the electrochemical process through indirect oxidation mechanisms involving chlorine species generated in situ.

In this scenario, the hydrogen (H_2) generated at the cathode is recovered and injected into the natural gas stream used in the dyeing process. This partial substitution contributes to a reduction in fossil fuel consumption and associated greenhouse gas emissions.

Additionally, the electrochemical operating conditions (voltage and current density) are optimized to maximize hydrogen production efficiency while maintaining adequate pollutant removal performance. This optimization improves the overall environmental and energetic performance of the system.

The energy mix assumed corresponds to the European electricity mix for the reference year 2024, reflecting average grid composition and emission factors. This assumption is critical, as regional variations in energy sources (renewables vs. fossil fuels) can significantly alter both the carbon footprint and the global warming potential results.

Regarding the choice of data for the LCA, this study comprises the use of both primary data coming from industry and secondary data, from commercial datasets, Primary data includes measurements collected directly from industrial operations and pilot-scale dyeing processes, including measured water consumption (10–300 L/kg), cotton-specific averages (120 L/kg), and effluent characteristics. Secondary data were obtained from established LCA databases (e.g., Ecoinvent, LCA for Experts) and peer-reviewed literature, which provide emission factors, energy mix data, and background processes.

The environmental characterization is performed considering a pool of different impact categories, as suggested by Product Environmental Footpring Category Rules for Apparel and Footwear (PEF Apparel & Footwear, 2025) he inclusion of human health impacts and global warming potential broadens the scope of the analysis, allowing for a more holistic evaluation of the environmental performance of textile dyeing. This framework highlights critical hotspots in resource use, pollutant discharge, and climate-related emissions, while also providing a basis for assessing alternative technologies such as electrochemical treatment.

The Life Cycle Assessment (LCA) methodology, following ISO 14040-44 (Figure 2), has been applied to assess the environmental impacts and benefits associated with the

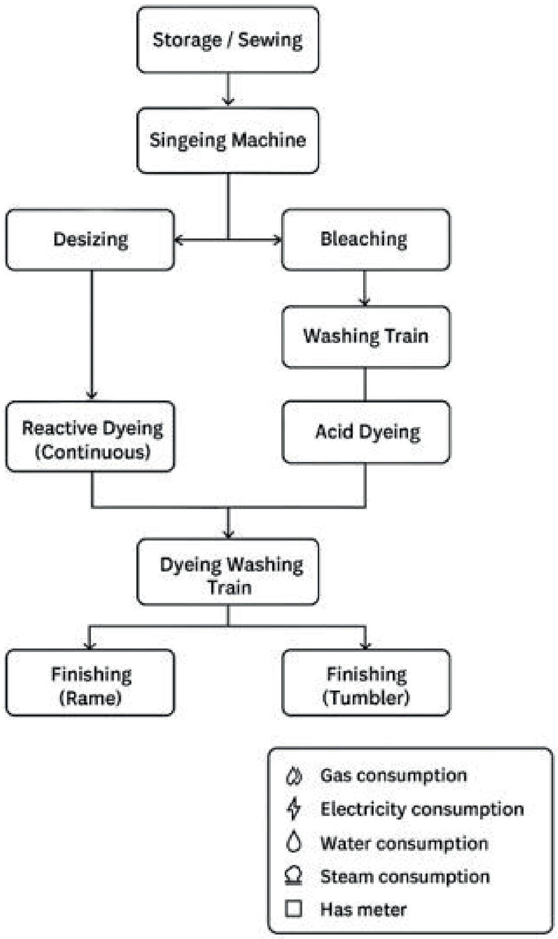

FIGURE 2: LCA process (ISO 14040).

three scenarios. LCA is a systematic approach to evaluate the environmental aspects and potential impacts of a product, process, or system throughout its entire life cycle. The aim of this study is to provide a comprehensive quantitative view of the scenarios and determine their performance in terms of environmental sustainability.

The study was conducted in two main LCA stages:

- Description (Goal and Scope Definition): This stage provides a qualitative description of the processes for the three scenarios, which is complemented with schematic representations. The objective is to compare the three scenarios and evaluate the benefits of water recirculation. The system boundaries, functional unit, and main assumptions are also defined in this stage.
- Inventory Data (Life Cycle Inventory, LCI): This stage specifies the type of data used rather. Primary data were obtained directly from the plant operations, while secondary data were sourced from commercial LCA databases. The LCA calculations were performed using the software LCA for Experts (formerly known as GaBi) from Sphera, together with the following commercial databases for secondary data: Professional, ecoinvent, among others.

The research is conducted by analyzing the dyeing process of the company ABSA (Figure 2) and following the ISO 14040 and 14044 guidelines for the application of LCA. Three scenarios are defined and presented in detail, with a functional unit of 100 kg of dyed cotton fabric.

Scenario 1: As previously mentioned, this scenario corresponds to the conventional process with biological and physicochemical treatment (Figures 3). It represents the current industrial practice at ABSA. The process includes the standard dyeing operations, followed by biological treatment and subsequent physicochemical treatment of the generated wastewater streams. No water recirculation or resource recovery strategies are applied in this configuration. This scenario serves as the baseline for comparison, , enabling the quantification of the environmental impacts associated with the existing production system and providing a reference point against which the performance improvements of Scenarios 2 and 3 can be assessed.

Scenario 2: As previously seen, it involves the replacement of the conventional treatment with an electrochemical process achieving 95% decolorization (Figure 3). The electrochemical process also generates hydrogen as a by-product, while consuming electrical energy for its operation. All other steps of the dyeing process remain the same. This scenario allows evaluation of the environmental benefits and potential trade-offs associated with implementing the electrochemical technology compared to the conventional approach.

Scenario 3: Building on Scenario 2, this stage incorporates the reuse of treated water in subsequent dyeing processes (Figure 3). The use of recirculated water reduces overall fresh water and chemical consumption by 70%, significantly lowering the environmental footprint of the operation. Additionally, the hydrogen generated during the electrochemical treatment is injected alongside natural gas, further decreasing fuel consumption. Energy efficiency is also improved by recovering heat from the electrochemical process discharge, which remains at 60°C. Since the dye-

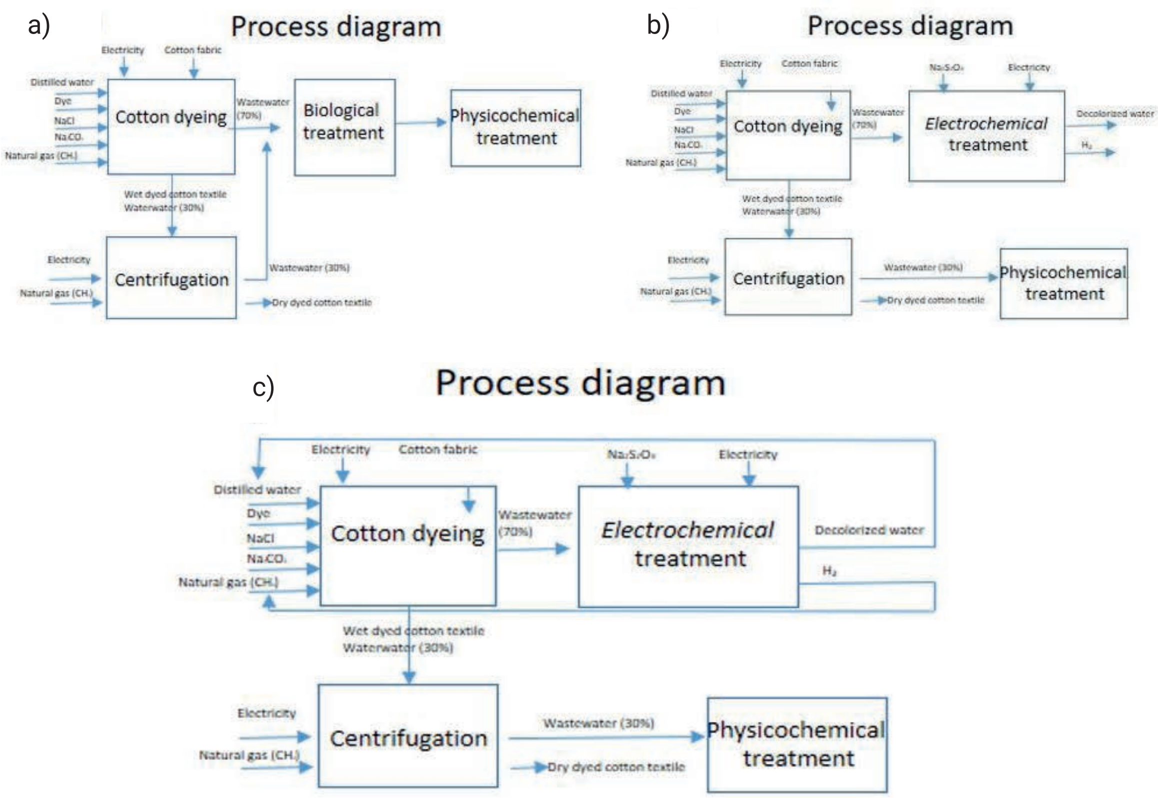

FIGURE 3: Flow diagram from ABSA company (https://absa.es/).

TABLE 1: Data from the three scenarios.

Dyeing process		Scenario 1	Scenario 2	Scenario 3
INPUT	cotton textile (kg)	100	100	100
	Electricity (MJ)	97.8	97.8	97.8
	Distilled water (L)	1000	1000	300
	Dye (kg)	3	3	2.1
	Sodium Chloride (NaCl) (kg)	70	70	21
	Sodium Carbonate (Na_2CO_3) (kg)	20	20	6
	Thermal energy (CH_4) (MJ)	432	432	130
	Decolorized water (reused) (kg)	0	0	700
	Heat of the water (MJ)	0	0	337
	Thermal energy(H_2) (MJ)	0	0	34.6
OUTPUT	Wastewater (L)	764	764	764
	Dyed wet cotton fabric (kg)	429	428	429

ing process requires higher temperatures, this pre-heated water (representing 70% of the total volume) only requires a 20°C increase, drastically reducing natural gas demand. As in Scenario 2, the electricity required for the electrochemical process is fully accounted for in the LCA. This scenario evaluates the benefits of both the technological upgrade and the resource recirculation strategy.

For each scenario, material and energy inputs and outputs were modeled using the LCA for Experts software, including electricity, natural gas, water, salt, and sodium carbonate consumption, as well as by-products such as the hydrogen generated (Table 1). The system boundaries encompass the dyeing and centrifugation processes, the environmental impacts of biological, physicochemical, and electrochemical treatments, and the final disposal of residues, providing a comprehensive assessment of the operational environmental impacts for each scenario. As we can see, the description of Scenario 3 has been updated to explicitly highlight the significant reduction in inputs required for the optimized system. Specifically, the table 1 now clearly reflects that fresh water consumption is reduced from 1,000 L in the baseline to 300 L in Scenario 3. Furthermore, the required amount of NaCl is decreased from 70 kg to 21 kg. These substantial reductions directly emphasize the efficiency and environmental benefits of the closed-loop system implemented in this scenario.

In addition to the environmental assessment, this study also considers the potential economic improvements, particularly the savings achievable through optimized dyeing processes in terms of reduced water, energy, and chemical consumption.

3. RESULTS AND DISCUSSION

The dyeing process (Figure 4) for cotton fabrics comprises a sequence of carefully designed steps aimed at achieving a uniform and durable coloration. It begins with the preparation of a dye bath containing demineralized water, the selected dye, sodium chloride (NaCl) and sodium carbonate (Na_2CO_3), where the demineralized water prevents the formation of precipitates that could compromise dye quality, the dye type (commonly reactive dyes for cotton) is chosen according to the desired color and process, sodium chloride promotes dye fixation by reducing the solubility of the dye in water and enhancing its absorption by cotton fibers, and sodium carbonate acts as an alkaliz-

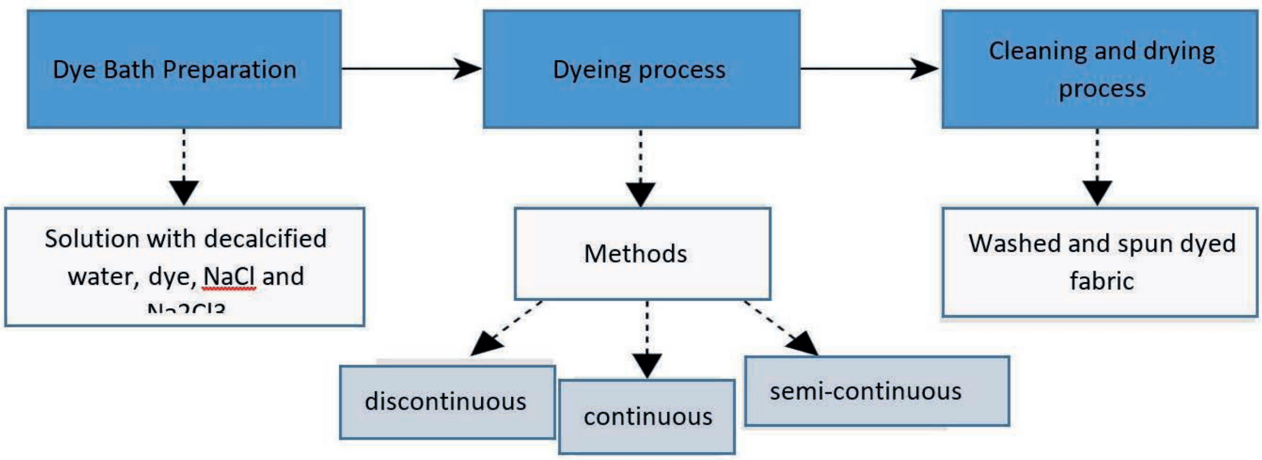

FIGURE 4: Diagram of the conventional process.

ing agent that activates the dye's reactive groups and facilitates chemical bonding with the fibers. Once prepared, the cotton fabric is immersed in the bath under constant agitation to ensure uniform color distribution, and the solution is heated, often using thermal energy from natural gas combustion, to reach the optimal temperature for dye–fiber reaction, which may require several hours depending on the dye type and desired shade. Different dyeing methods can be employed, such as the traditional discontinuous or batch process (which can produce between 5 and 20 tonnes of fabric per day), the continuous process, where production rates range from 30 to 100 tonnes per day, and semi-continuous approaches like the "pad-batch" method, where the fabric is impregnated with dye, rolled, and stored to allow color fixation before washing. Regardless of the method used, dyeing is highly water-intensive: for every 100 kg of dried cotton fabric produced, approximately 1,000 liters of water are consumed. After dyeing, the fabric is rinsed to remove unfixed dye, a critical step for ensuring colorfastness during washing and wear, and is then centrifuged to eliminate as much residual water as possible before subsequent finishing operations (Mazharul Islam K., 2012 and FDTEXTIL 2020).

In addition to the environmental considerations, the three scenarios also incorporate potential economic improvements. In the first scenario, representing the current factory process, costs are mainly associated with biological and physicochemical treatments, which require significant operational expenditures in energy, chemicals, and sludge management.

In the second scenario, the substitution of conventional treatments with electrochemical process introduces opportunities for cost savings through reduced chemical consumption and the added value of hydrogen generation, which can be utilized as an energy carrier.

The third scenario further enhances economic performance by reusing treated water, recovering salts and dyes, and injecting the generated hydrogen together with natural gas, thereby reducing both raw material costs and fossil fuel dependency. These potential savings highlight the dual benefit of the proposed technological alternatives, combining environmental impact reduction with improved economic efficiency.

The conventional cotton fabric dyeing process involves four main stages: dyeing, centrifugation, biological wastewater treatment, and additional tertiary physico-chemical treatment. The latter two are essential for removing residual organic and inorganic contaminants. Biological treatment promotes the growth of microorganisms that degrade organic compounds, while tertiary physico-chemical treatment (typically using activated carbon or coagulation-flocculation) removes residual color. Following these steps, water undergoes sedimentation, filtration, and disinfection before being discharged or reused (Martínez-Huitle, C. A., & Brillas, E., 2009 and Cuesta i Mota, D.,et al. 2024b).

The study evaluated the replacement of these post-dyeing treatment stages with a single electrochemical treatment process. This technology applies direct electric current in an electrolytic cell containing an anode and cathode immersed in alkaline wastewater from dyeing, rich in dyes, NaCl, and Na_2CO_3. Electrochemical oxidation at the anode produces hydroxyl radicals and oxygen, which effectively degrade dyes and complex organic contaminants. At the cathode, water reduction generates hydrogen gas, a potentially valuable by-product. Additionally, chlorine generated from chloride ions can form hypochlorite under alkaline conditions, enhancing dye oxidation (Martínez-Huitle, C. A., & Brillas, E., 2009 and Cuesta i Mota, D.,et al. 2024b).

Depending on current density and treatment time, electrochemical processing can partially break down dye molecules (decolorization) or fully mineralize them to ensure water quality suitable for reuse. Full mineralization requires higher energy input than decolorization alone (Cuesta i Mota, D.,et al. 2024b).

The process also produces ~0.016 kg of hydrogen per 100 kg of fabric, equivalent to 9.9 MJ of energy, offering potential partial substitution for natural gas in heating applications (Figure 5). While hydrogen reuse in this context has not yet been implemented, its integration would require efficient capture and storage systems, adaptation of heat-

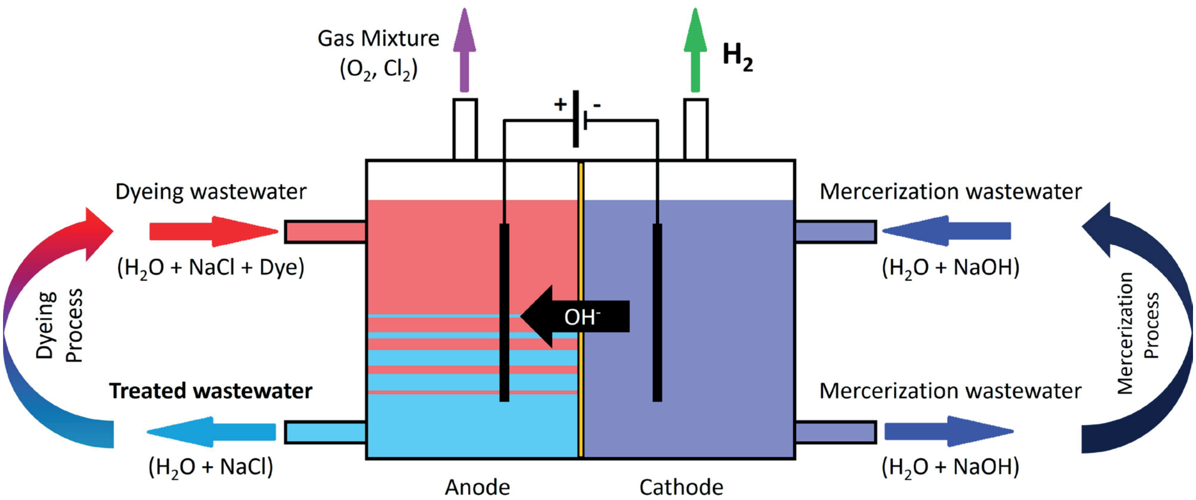

FIGURE 5: Flow diagram of the electrochemical treatment process..

ing equipment to hydrogen fuel, and process optimization to maximize production (Zeng, K., & Zhang, D., 2010).

Life Cycle Assessment (LCA) results indicate that incorporating electrochemical treatment reduces effluent pollutant load and eliminates the need for additional physico-chemical treatment. In Scenario 2, chemical consumption decreases significantly, whereas Scenario 3 achieves the highest savings in water and salts, also reducing water footprint. Overall, Scenario 3 demonstrates the lowest total environmental impact and the greatest resource efficiency.

Figure 6 illustrates the schematic layout of the three study scenarios . As depicted in the graph, Scenario 1 (blue line) represents the current conventional process, serving as the baseline for comparison. In contrast, Scenario 2 (orange line) shows a significant increase in environmental impacts, particularly in Global Warming Potential (GWP) and Acidification Potential (AP), due to the high electricity consumption of the electrochemical process without resource recovery. Finally, Scenario 3 is designed to mitigate these impacts through a closed-loop system, utilizing recovered heat, chemicals, and hydrogen to drastically reduce the overall environmental footprint across most impact categories compared to the other two scenarios.

Figure 7 illustrates the comparative results of the three scenarios regarding water consumption, primary energy demand, and Global Warming Potential (GWP). As shown,

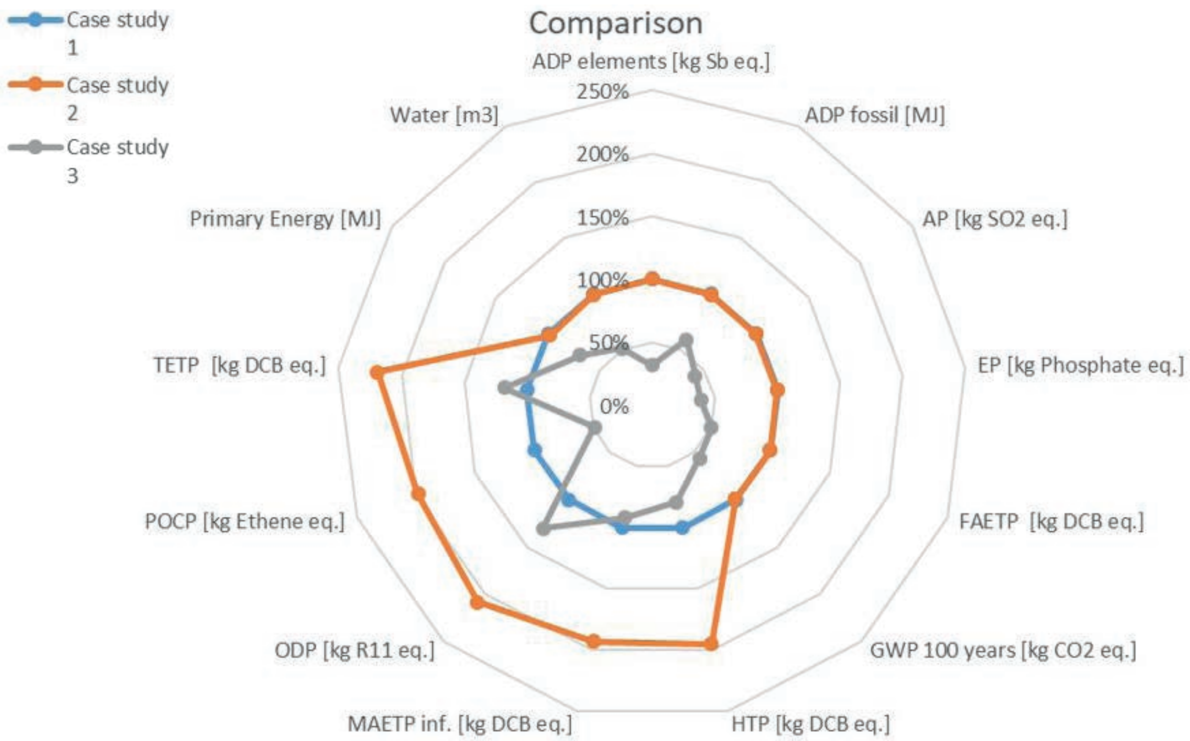

FIGURE 6: Flow diagram of the electrochemical treatment and reuse process.

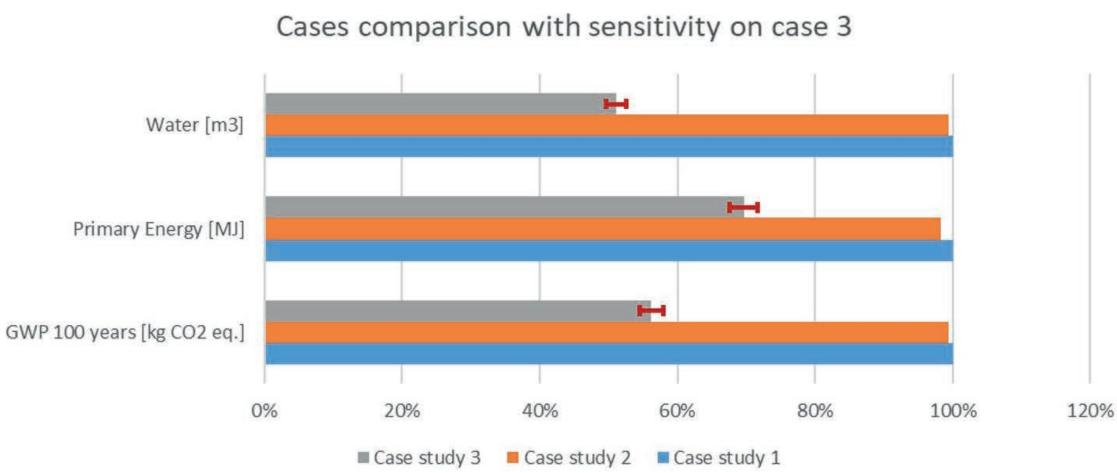

FIGURE 7: Dyeing process.

Scenario 3 (grey bar) demonstrates the most significant improvements, achieving a 50% reduction in water usage and a substantial decrease in GWP compared to the baseline Scenario 1. The red error bars on Scenario 3 indicate the sensitivity range of +-20% with respect to the energy consumed in the electrochemical process

Based on the analysis of Figure 8, the results demonstrate distinct environmental profiles for each scenario, highlighting the impact of each system process. When examining the processes individually, the dyeing stage consistently presents the highest impact across all scenarios and indicators due to energy and chemical consumption. This is followed by the centrifugation stage, which shows a lower relative impact. In terms of wastewater treatment, substituting the conventional biological and physicochemical treatment with electrochemical treatment significantly increases energy-related impacts (GWP and Primary Energy) in Scenario 2 due to high electricity demand without resource recovery. However, when this electrochemical process is coupled with heat and hydrogen recovery in Scenario 3, the environmental footprint is drastically reduced, making it the most sustainable option.

In Figure 9, the laboratory setup is presented for evaluating both the quantity of hydrogen recovered and its purity.

As shown in Table 2, the calculations indicate that the implementation of electrochemical treatment with water and salt reuse leads to a reduction in operating costs of approximately 35% compared to the stages without reuse. This corresponds to an estimated saving of €350 per 100 kg of processed fabric when compared to the conventional dyeing process. Extrapolated to an industrial scale, with an average of three dyeing cycles per machine per day, this results in potential savings of around €1,050 per day. However, the investment costs of electrochemical technology

FIGURE 8: Conventional process.

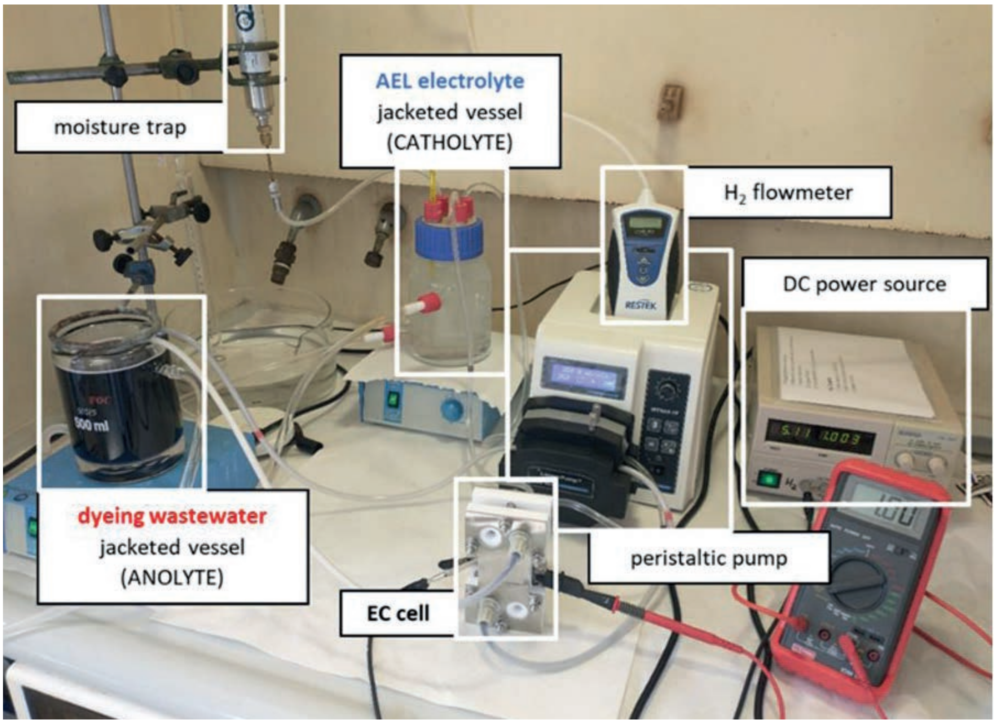

FIGURE 9: Scenario 2: Electrochemical treatment process.

at an industrial scale have not yet been determined, as no commercial reactors for this application are currently available.

This study highlights that transitioning from conventional biological treatments to electrochemical processes with water recirculation (Scenario 3) is the most sustainable path for the textile industry. Key insights include the ability to significantly reduce resource consumption: Scenario 3 cuts freshwater use by 70% (from 1,000 L to 300 L per 100 kg of fabric) and reduces chemical inputs like sodium chloride and sodium carbonate by 70%. Furthermore, electrochemical treatment enables the recovery of hydrogen as a green energy by-product, providing approximately 9.9 MJ of energy per 100 kg of fabric.

The electricity consumption data for the electrochemical treatment used in the inventory were obtained from an experimental prototype. However, the results obtained at a laboratory scale are extrapolable to an industrial scale, as electrochemical technology is highly scalable. Electrochemical technology is highly scalable. At the laboratory scale, an optimal current density is determined. For scaling up to industrial equipment, the ratio between the current and the electrode surface area is maintained. The authors of this article have experience in the industrial scale-up of electrochemical reactors for the treatment of textile dyeing wastewater containing reactive dyes. In the ECUVal project (Eco-innovation project ECO/13/630452), based on laboratory results, they built a reactor with an electrode surface area of 0.6 m² and an optimal amperage of 100 A, which enabled the treatment of 4 m³/h of dyeing effluent (Buscio et al., 2019).

TABLE 2: Economical calculation.

	Cost (Euros)		
	Scenario 1	**Scenario 2**	**Scenario 3**
Dyeing process	983	983	574.4
Centrifugal process	16.8	16.8	16.8
Electrochemical process	0	0.2	59.5
TOTAL	999.8	1000	650.7

Finally, a sensitivity analysis was performed exclusively on hydrogen production to optimize the generation process by fine-tuning energy consumption.

Figure 10 illustrates the sensitivity analysis for Scenario 3, evaluating the impact of varying the energy consumption required for hydrogen generation by +-5% and +-20%. The graph demonstrates a linear relationship between primary energy input and the resulting environmental impacts, specifically Global Warming Potential (GWP) and Abiotic Depletion Potential (ADP). As depicted, even with a $\pm$20% variation in energy consumption for the electrochemical process, the overall environmental impact remains lower than that of Scenario 2. This indicates that the closed-loop system and resource recovery strategies in Scenario 3 are robust and provide a net environmental benefit regardless of minor fluctuations in energy efficiency. Finally, a sensitivity analysis was performed exclusively on hydrogen production to optimize the generation process by fine-tuning energy consumption. This analysis should be revisited at the industrial scale, as it will provide critical insights for achieving optimal process efficiency and adjustment. This analysis should be revisited at the industrial scale, as it will provide critical insights for achieving optimal process efficiency and adjustment.

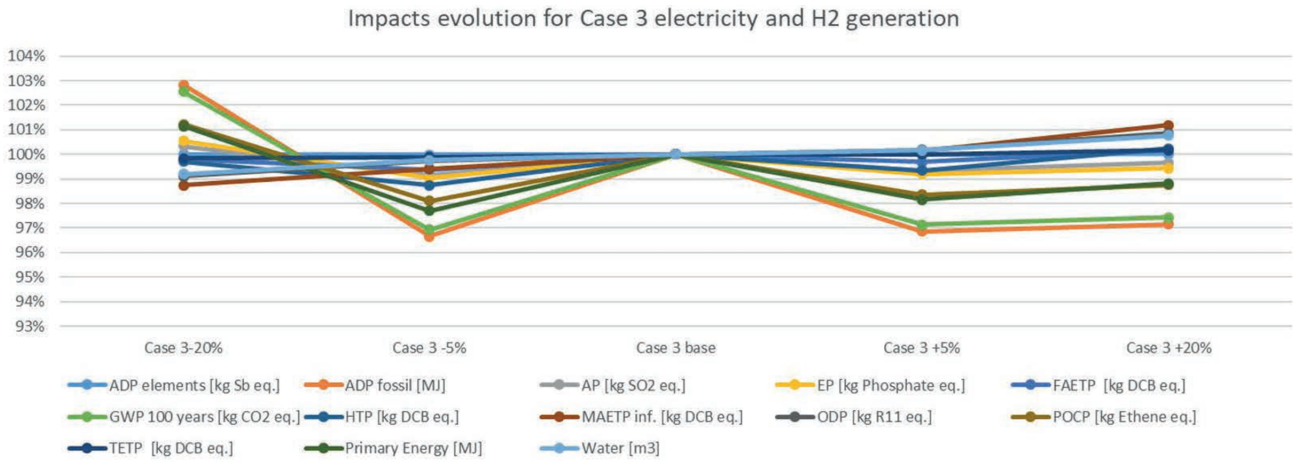

FIGURE 10: Scenario 3: Electrochemical treatment and reuse process.

4. CONCLUSIONS

The implementation of electrochemical treatment in cotton dyeing processes, particularly when coupled with water reuse, provides substantial environmental benefits by significantly reducing water and chemical consumption while enabling the energy valorization of hydrogen. Life Cycle Assessment (LCA) highlights that the reuse of water effectively closes the resource loop, thereby enhancing the overall sustainability of the process. It is advisable that future studies explicitly state, within their methodological sections, which considerations are applied in the initial phases, ensuring greater clarity and traceability throughout the research. This analysis further indicates that the adoption of these technologies at an industrial scale could considerably advance the sustainability of the textile sector, supporting the transition towards a circular economy. Collectively, these findings emphasize the critical importance of developing innovative technologies that not only reduce reliance on natural resources but also promote improved waste management and energy efficiency.

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CISA

DEVELOPMENT OF BIOLOGICAL TECHNOLOGY AND NANO TiO_2 MODIFIED CERAMIC MEMBRANES FOR RECIRCULATION OF SHRIMP AQUACULTURE WASTEWATER: BOTTLENECKS AND PROSPECTS

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ABSTRACT

The shrimp aquaculture industry generates wastewater rich in organic matter, suspended solids, nutrients, pathogens, and residual antibiotics, posing environmental challenges. Conventional biological treatments, including constructed wetlands, biofloc systems, microalgae cultivation, and recirculating aquaculture systems (RAS), are widely used due to low cost and environmental compatibility; however, their performance is often constrained by recalcitrant organics and unstable effluent quality under water reuse conditions. This review focuses on recent advances in integrating biological processes with nano TiO_2 modified ceramic membranes. Ceramic membranes provide mechanical strength, chemical stability, and tolerance to saline and harsh conditions, while TiO_2 modification enhances hydrophilicity, antimicrobial activity, and photocatalytic degradation of refractory pollutants. Reported studies show chemical oxygen demand (COD) removal efficiencies of 85-92% and near complete total suspended solids (TSS) removal, while TiO_2 modified membranes achieve over 90% removal of dyes, proteins, and oils and reduce membrane fouling under ultraviolet (UV) irradiation. Membrane fouling mechanisms, photocatalytic performance, bioreactor integration, and economic considerations are discussed. The combination of biological treatment and modified ceramic membranes represents a promising approach for enhancing water reuse and long term treatment stability in shrimp aquaculture.

1. INTRODUCTION

The shrimp farming sector in Vietnam has been developing rapidly, making a significant contribution to aquaculture export value and agricultural economic growth. However, along with the increasing stocking density and production intensity, the volume of wastewater generated has grown substantially. Wastewater from shrimp ponds may contain organic pollutants, suspended solids, nitrogenous compounds, phosphates, pathogenic bacteria, and residual (Szczepanik, 2017). If these components are not effectively controlled, they can degrade the quality of receiving water bodies, cause eutrophication in aquatic environments, and increase the risk of disease outbreaks in farming areas. Therefore, the application of highly efficient, stable, and shrimp farming compatible wastewater treatment technologies is an important research direction. Shrimp aquaculture wastewater can be treated using physical, chemical, and biological methods. Among these, biological treatment stands out due to its environmental friendliness, low operating costs, and effectiveness in removing organic matter and nitrogenous compounds. Current biological treatment technologies of interest include constructed wetlands, biofloc technology, microalgae systems, high-rate algal ponds (HRAP), and RAS. Among them, RAS is considered a promising approach, allowing precise control of culture conditions, enhancing biosecurity, while reducing freshwater demand and limiting environmental discharge (Bohnes & Laurent, 2021).

However, in practical operation, RAS still faces limitations related to the accumulation of dissolved organic matter, recalcitrant compounds, suspended solids, and microorganisms in the recirculating system. When water is reused over multiple cycles, pollutants that are difficult to remove via conventional biological treatment may accumulate, degrading water quality and affecting animal growth.

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To improve effluent water quality in recirculating systems, membrane technologies are increasingly integrated into treatment systems due to their ability to effectively retain suspended solids and microorganisms, providing a more stable water stream for reuse (Banu et al., 2009). Most current systems use polymeric membranes due to low investment costs and versatile fabrication. However, this material type faces several long-term operational limitations, particularly lower mechanical and chemical stability, decreased performance under temperature, cleaning chemicals, or high pollutant loads. Moreover, membrane fouling occurs rapidly, reducing flux, shortening membrane lifespan, and increasing maintenance and replacement costs. To address these limitations, inorganic membranes, particularly ceramic membranes, have attracted considerable attention due to their stable performance under harsh conditions. Ceramic membranes exhibit high chemical and mechanical stability, tolerance to a wide pH range, high temperature, and pressure, long operational lifespan, and lower fouling propensity compared to polymeric membranes (Danfá et al., 2021). Nevertheless, conventional ceramic membranes still have limitations in antibacterial properties, self-cleaning ability, and fouling resistance during long-term operation. To overcome these issues, recent studies have focused on modifying ceramic membranes with nanomaterials, particularly titanium dioxide (TiO_2). Nano TiO_2 modified ceramic membranes retain their inherent mechanical and chemical properties while enhancing antibacterial activity, self cleaning, and fouling resistance through photocatalytic mechanisms, thereby improving the removal efficiency of organic matter and microorganisms in wastewater. In recent years, nano TiO_2 modified ceramic membranes have been widely applied in industrial wastewater, oil-containing wastewater, protein-rich effluents, and dye-laden wastewater due to their high separation efficiency and superior durability (Hemavibool et al., 2022; Shan et al., 2010). The pollutant retention capability of nano TiO_2 ceramic membranes combined with photocatalysis is evident for several typical compounds. Methylene blue (MB, 320 Da) can be retained at over 90% by ultrafiltration membranes with an average pore size of 10-50 nm, while UVA-assisted photocatalysis increases the removal efficiency from 40.8% to 97.7%. Bovine Serum Albumin (BSA, 66 kDa) is retained up to 98% by a 14 nm ultrafiltration membrane and nearly 100% when combined with TiO_2 - Ag photocatalysis under visible light. For oil-contaminated wastewater, TiO_2 coated microfiltration ceramic membranes retain over 90% of oil emulsions, and photocatalysis can enhance oil removal from 91% to 98.5% under UVC irradiation, even for droplets smaller than the membrane pore size. Therefore, nano-TiO_2 modified ceramic membranes demonstrate the combination of mechanical retention and photocatalytic mechanisms, effectively removing recalcitrant organic compounds, from azo dyes and proteins to oil emulsions, while maintaining high permeate flux and membrane lifespan, highlighting their potential for industrial and aquaculture wastewater treatment. Given the characteristics of shrimp aquaculture wastewater, often containing recalcitrant antibiotics and organic pollutants, integrating nano-TiO_2 modified ceramic membranes with biological treatment processes can create an efficient and sustainable recirculating system, optimizing pollutant removal while maintaining stable water quality for reuseIntegrating biological technology with nano-TiO_2-modified TiO_2 modified (Ghamarpoor et al., 2024).

Despite recent advances, studies on integrating biological treatment with nano TiO_2 modified ceramic membranes for shrimp aquaculture wastewater remain relatively limited and fragmented. Most current publications focus individually on pollutant removal efficiency, membrane fouling, or photocatalytic activity, while comprehensive assessments under aquaculture conditions are still lacking. Therefore, this review presents the current status, environmental issues, and technological trends in shrimp aquaculture wastewater treatment, particularly emphasizing the integration of biological treatment with nano TiO_2 modified ceramic membrane filtration toward effective and sustainable water recirculation and reuse.

2. MATERIALS AND METHODS

2.1 Methodology and search strategy

The objective of this study was to evaluate the feasibility and effectiveness of integrating biological treatment technologies with nano-TiO_2 modified ceramic membranes to improve shrimp aquaculture wastewater treatment efficiency and support water reuse objectives in aquaculture systems. The review covered both theoretical and experimental studies published between 2017 and 2024 to ensure the relevance and reliability of the collected data. This period was chosen to encompass the most recent developments in photocatalytic membrane engineering and aquaculture wastewater treatment technologies. To enhance search precision, a Boolean search strategy was employed. Keywords such as “shrimp aquaculture wastewater”, “ceramic membrane”, “nano-TiO_2”, “photocatalysis”, “recirculating aquaculture systems (RAS)”, and “biological treatment” were systematically combined using logical operators (AND, OR, NOT). This allowed refinement of queries, exclusion of irrelevant records, and expansion of coverage where necessary

The literature search strategy was structured around four main analytical dimensions: research subject, technological approach, operational context, and application objective (Table 1).

2.2 Inclusion and exclusion criteria

To ensure that the review remained focused and relevant, specific inclusion criteria were established. Studies were considered suitable if they addressed biological treatment technologies such as biofloc systems, microalgae cultivation, constructed wetlands, or RAS applied directly

TABLE 1: Search strategy and keyword structure.

Analytical dimension	Search terms
Subject	(“TiO_2 photocatalyst”) OR (“nano TiO_2”) OR (“modified ceramic membrane”)
Approach	(“wastewater treatment”) OR (“photocatalysis”) OR (“recirculation”) OR (“MBR”)

to aquaculture wastewater. Research was also included when it investigated the use of ceramic membranes or nano TiO_2 modifications, particularly in relation to pollutant removal efficiency, fouling resistance, or photocatalytic performance. Furthermore, eligible publications were required to provide quantitative treatment outcomes, including indicators such as COD, BOD, TSS, nutrient removal, or antimicrobial effectiveness. Finally, studies that discussed the integration potential between biological processes and advanced membrane systems were prioritized, as these offered insights into sustainable and scalable wastewater management solutions.

In contrast, several exclusion criteria were applied to filter out studies that did not align with the objectives of this review. Research focusing exclusively on polymeric membranes, without consideration of ceramic or TiO_2 based modifications, was excluded due to its limited relevance to the scope of this study. Similarly, studies that examined wastewater streams unrelated to aquaculture, i.e. municipal, textile, or industrial effluents, were not considered, as their findings could not be directly extrapolated to shrimp aquaculture systems. Publications that lacked experimental validation, relying solely on theoretical models or conceptual frameworks without supporting data, were also excluded to maintain the scientific rigor and reliability of the analysis.

By applying these inclusion and exclusion criteria, the review ensured that only methodologically robust and contextually relevant studies were analyzed, thereby strengthening the validity of the findings and enhancing their applicability to shrimp aquaculture wastewater management.

2.3 Data extraction and categorization

For each study that satisfied the inclusion criteria, a systematic data extraction protocol was implemented to ensure consistency and comparability across sources. Information was collected on the characteristics of aquaculture wastewater, including pollutant type, concentration, salinity, and microbial load, thereby establishing a baseline for understanding the complexity and variability of shrimp aquaculture effluents. Details regarding membrane specifications were also recorded, such as pore size, material composition, TiO_2 coating techniques, and the irradiation source employed to activate photocatalytic processes.

Data concerning the biological treatment technologies applied were documented, covering systems such as biofloc, microalgae cultivation, RAS, and constructed wetlands. To assess treatment efficiency, performance indicators were extracted, including COD and BOD removal, nutrient reduction, antimicrobial activity, fouling resistance, and flux recovery. Operational parameters, i.e. pH, temperature, hydraulic retention time, and exposure to UV or visible light, were noted to contextualize treatment outcomes under varying environmental conditions. In addition, studies were evaluated for economic and scalability considerations, including capital investment, energy requirements, and maintenance demands, which are critical for practical application in aquaculture systems.

To enable structured comparison, the extracted data were organized into four analytical dimensions. The first dimension, research subject, distinguished studies focused specifically on shrimp aquaculture wastewater from those addressing other aquaculture systems. The second dimension, technological approach, classified studies according to whether they employed biological treatment, ceramic membrane filtration, TiO_2 photocatalysis, or hybrid systems integrating multiple methods. The third dimension, operational context, identified whether the research was conducted at laboratory, pilot, or full scale levels. The final dimension, application objective, highlighted the intended outcomes of each study, including pollutant removal, water reuse, fouling mitigation, or antimicrobial enhancement.

This structured categorization provided a coherent framework for comparative analysis, ensuring that both technical performance and practical applicability were critically assessed within the broader context of shrimp aquaculture wastewater management.

2.4 Analytical tools

To explore prevailing research directions and identify critical bottlenecks, VOSviewer software was utilized to construct keyword co occurrence maps. This bibliometric technique enabled the visualization of associations among frequently cited terms, i.e. TiO_2 photocatalysis, shrimp aquaculture, and membrane fouling, and provided valuable insights into emerging thematic clusters within the field.

Complementing this bibliometric analysis, a comparative matrix evaluation was performed to systematically assess differences in treatment performance across technological strategies. The comparison encompassed conventional biological processes versus hybrid biological membrane systems, polymeric membranes versus ceramic membranes, and unmodified ceramic membranes versus those enhanced with nano TiO_2 coatings.

By integrating bibliometric mapping with comparative performance analysis, this dual methodological approach offered both a conceptual overview of research trends and a quantitative assessment of technological efficiency, thereby reinforcing the robustness of the evaluation framework for wastewater treatment strategies in shrimp aquaculture.

3. RESULTS AND DISCUSSION

3.1 Shrimp farming systems and wastewater generation context

3.1.1 Development trends and technological transformation in shrimp farming

Vietnam ranks among the five leading countries in global shrimp production and is a key supplier of shrimp products worldwide. The shrimp farming area has increased by an average of 5% per year, primarily driven by the growth in white-leg shrimp farming. White-leg shrimp production has increased by an average of 13%, while black tiger shrimp production has declined by 8% over six years, with no significant improvement in productivity compared to whiteleg shrimp. Shrimp export is a key sector of Vietnam's economy, contributing significantly to agricultural growth and generating substantial revenue. However, numerous challenges caused a decline in global demand in 2023. Notably, the United States, Vietnam's largest shrimp export market, experienced a 32% decrease, negatively impacting domestic production. Despite this, Vietnamese shrimp exports to other markets such as Japan, South Korea, and China achieved strong growth. The shrimp pond area in Vietnam has rapidly expanded in recent years to meet export demands. Although current profits are high, the success rate remains low, resulting in higher production costs for farmed shrimp than in other countries.

Meanwhile, Vietnam possesses a significant advantage in advanced and deep processing technologies. Therefore, to enhance the competitiveness of Vietnamese shrimp, a clear transformation is needed in the farming sector. The shrimp farming industry in Vietnam is changing, focusing on production growth and sustainability, along with the adoption of new technologies.

Many science and technology enterprises have recently introduced shrimp farming solutions that apply Industry 4.0 technologies, contributing to improved accuracy in environmental monitoring and disease management (Iber & Kasan, 2021). One notable application is the automated feeding system, which supplies feed according to the actual demand of the shrimp. Parameters such as feeding duration and rest intervals can be easily adjusted based on the remaining feed, helping to control appropriate feed amounts, increase feed conversion efficiency, reduce costs, and minimize environmental pollution. Although the initial investment cost is relatively high, the system's durable materials help regulate temperature, withstand weather fluctuations, and prevent water stratification, thereby enabling multiple yearly production cycles. A practical current strategy is the development of ecological and organic shrimp farming models, particularly integrated shrimp-mangrove systems (Ahmed et al., 2017). About 60,000 ha of shrimp ponds in the Mekong Delta region operate under this model. It leverages natural resources to maintain ecological balance and contributes to mangrove forest conservation, creating a sustainable, environmentally friendly farming ecosystem with high economic value. Simultaneously, switching to biological products and probiotics emphasizes reducing antibiotics and chemicals in aquaculture (Zhang et al., 2016). These solutions help control diseases effectively, improve water quality, reduce pollution, and enhance product quality.

Many shrimp broodstock still depend on imports, posing quality and disease control challenges. Therefore, investing in modern broodstock production facilities that meet biosecurity standards and can supply high-quality broodstock is essential. In parallel, long-term selective breeding programs should be implemented with criteria such as fast growth, high survival rates, adaptability to harsh environmental conditions, and especially resistance to serious diseases. In addition to the five main shrimp export markets, China, the United States, Japan, the EU, and South Korea, which account for 76% of total shrimp export value, the country is expanding into potential markets such as the United Kingdom, Canada, and Australia, as well as rapidly growing regions including the Middle East, Africa, and Southeast Asia.

3.1.2 Shrimp farming technologies

Multi-stage shrimp farming technology is divided into stages based on the developmental phases of shrimp - typically two or three stages. It is designed to optimize farming conditions at each stage, minimize risks, and increase production efficiency. The model is currently widely adopted in provinces throughout the Mekong Delta. Characteristics of the 2-phase farming technology model includes a nursery phase (phase 1) and a commercial farming phase (phase 2). In the first phase, shrimp are typically reared in net-covered houses for 20 - 30 days to protect them from adverse weather conditions and other external factors. The pond environment is strictly controlled to minimize shrimp mortality. Characteristics of the 3-phase farming technology model consist of two nursery phases (nursery phase 1 and nursery phase 2), followed by a commercial farming phase. All ponds are covered with tarpaulins during hot weather to help maintain a stable water temperature of approximately 30°C, which is optimal for shrimp growth.

Semi-Biofloc microbiological farming technology in intensive shrimp farming involves cultivating beneficial bacteria outside the pond (also known as microbial incubation) using carbon sources such as molasses and sugarcane molasses. The bacterial strains used are beneficial species of Bacillus. The cultivated bacteria are then introduced to the culture ponds to create a favorable rearing environment (Mangott et al., 2020). This environment can process excess nutrients before they are discharged into the external environment, thereby improving feed efficiency, reducing disease outbreaks, and enhancing biosecurity for the farmed shrimp.

Super-intensive shrimp farming technology in greenhouses is a modern, closed-loop aquaculture model. The farming system is housed within a greenhouse structure, which is covered with durable glass that withstands prolonged exposure to sunlight and rain while allowing sufficient light transmission for shrimp culture. Shrimp are stocked at high densities, typically 300 to 500 individuals per square meter, optimizing space and yield. The water recirculation and waste treatment systems are strictly controlled to minimize environmental pollution and improve resource use efficiency.

Different shrimp farming technologies exhibit distinct strengths and limitations in terms of productivity, biosecurity, investment cost, and operational complexity. Multi-stage shrimp farming technology enables very high stocking densities, typically ranging from 250 to 300 individuals per square meter, which results in high yields of approximately 35-40 tons per hectare and a relatively short and stable culture cycle of 70-85 days per crop. This system also achieves high survival rates, often exceeding 90%, and demonstrates reduced vulnerability to environmental fluctuations and external pathogens. However, these advantages are accompanied by substantial initial and operational costs, particularly for feed, seed stock, and electricity, and the requirement for extensive auxiliary infrastructure, which limits the effective farming area to only 20-25% of the total site.

Semi-biofloc microbiological farming technology applied in intensive shrimp culture offers effective control of excess nutrients, improves feed conversion efficiency, and enhances biosecurity. When combined with other technological innovations, this approach improves pond environmental conditions and promotes the formation of natural bioflocs, thereby reducing feed consumption and simplifying farm operations. In addition, the use of limited external water exchange reduces the risk of pathogen intrusion. Nevertheless, this system requires strict control of multiple operational parameters, including adequate aeration, appropriate water circulation, and precise adjustment of the carbon-to-nitrogen ratio. Maintaining stable and balanced microbial communities across large ponds, typically ranging from 1,500 to 3,000 m^2, remains challenging, and continuous aeration is necessary to sustain sufficient dissolved oxygen levels. Consequently, successful operation depends heavily on experienced personnel and advanced management skills.

Super-intensive shrimp farming in greenhouse systems relies on high-level technological integration to improve traceability of shrimp seed and feed sources, thereby ensuring food hygiene and safety. The incorporation of microbiological approaches without the use of antibiotics contributes to high and stable productivity while significantly reducing land requirements. However, the implementation of greenhouse structures and membrane-based systems results in investment costs that are considerably higher than those of conventional intensive farming models. Moreover, this farming approach demands skilled operators with strong technical and managerial capabilities.

Recirculating shrimp farming systems with minimal water exchange provide effective control of environmental conditions and disease outbreaks, while significantly reducing water consumption and increasing shrimp survival rates. These systems typically operate without antibiotics or chemical additives, thereby minimizing environmental impacts and creating a safer culture environment. High stocking densities, ranging from 150 to 300 individuals per square meter, can be achieved, with reported yields of approximately 7.6-7.8 tons per 1,000 m^2. Despite these advantages, recirculating systems require high capital investment, estimated to be 45-60% greater than that of conventional farming systems, and necessitate operators with appropriate professional training and technical expertise.

Winter shrimp farming in tarpaulin-covered systems enables off-season production and can deliver high productivity and economic value. However, this approach involves substantial investment and extended culture durations. Environmental and disease control during winter farming is generally more complex than in the main production season, and improper management of individual crops may increase the risk of environmental pollution and disease outbreaks. Recirculating aquaculture system (RAS) for shrimp farming with minimal water exchange features filtration systems (mechanical and biological filters), culture ponds, and water supply and drainage channels operating under a mechanism that ensures the reuse of farming water (Halim et al., 2025; Nugraha et al., 2023). Wastewater is treated through sedimentation tanks, biological filtration, and disinfection before being returned to the culture ponds (Arun et al., 2023). The model helps maintain stable water quality, minimizes water exchange, and reduces the risks of disease outbreaks and environmental pollution. With effective environmental control, shrimp exhibit faster growth, higher survival rates, and improved economic efficiency. Winter shrimp farming in tarpaulin-covered systems is an intensive farming model conducted within tarpaulin-covered structures, that helps maintain stable temperatures during colder seasons. The tarpaulin cover provides insulation, blocks wind and rain, and creates a favorable environment for shrimp growth under adverse weather conditions (Kashem et al., 2023).

There are two standard farming methods: (i) Single-Stage Farming, in which shrimp are directly stocked into ponds and reared for 3-4 months before harvest; and (ii) Multi-Stage Farming, which includes 2 phases (Phase 1: Shrimp are reared in indoor nursery tanks for 20-30 days. Phase 2: Once the shrimp reach a size of 3 - 4 cm each, they are transferred to commercial ponds at an average density of 100 shrimp per square meter. After two months, shrimp grow to a size of 50 - 60 individuals/kg and are ready for harvest.

It can be concluded that the shrimp farming industry is increasingly adopting various advanced technologies to improve productivity and minimize risks. Each technological model exhibits characteristics suitable for specific environmental conditions and farming scales. The multi-stage shrimp farming system is appropriate for regions with well-developed infrastructure. By separating each rearing phase, this model improves disease control; however, it requires advanced technical expertise and significant capital investment. In contrast, semi-biofloc technology, which employs beneficial microorganisms for water treatment and improved feed conversion, is commonly applied in small- and medium-scale operations. Despite its advantages in cost reduction, this method poses challenges in managing water quality at high stocking densities. Winter shrimp farming in tarpaulin-covered houses is suitable for northern provinces or areas with distinct cold seasons. This approach allows for the extension of the farming season and supports shrimp survival under adverse climatic conditions. Nonetheless, it remains seasonal in nature and limited in production scale. Super-intensive greenhouse shrimp farming represents a modern, closed farming model characterized by high productivity and strong environmental control. It is particularly suitable for large-scale farms or enterprises due to its high initial investment requirement. Among the technologies, the RAS with minimal water exchange is currently regarded as the most effective and broadly applicable model (Liu et al., 2024). RAS enables water reuse, reduces environmental discharge, enhances control over water quality parameters, conserves water resources, and increases shrimp survival rates (Samui et al., 2024). Compared to other farming systems, RAS offers superior environmental and disease control, resulting in greater productivity and economic efficiency. This model aligns well with the principles of sustainable aquaculture and is expected to play a central role in the industry's future growth.

Water is the primary living medium, directly influencing shrimp growth, physiological health, nutrient metabolism, and disease resistance. Effective water quality management is a fundamental prerequisite for maintaining productivity, optimizing economic performance, and ensuring the long-term sustainability of shrimp farming systems. Shrimp farming, particularly in intensive and super-intensive systems, requires substantial water. The total water consumption during a production cycle can amount to several thousand cubic meters per hectare. During the culture period, periodic water exchange is necessary to maintain a stable pond environment, dilute organic pollutants, and mitigate the accumulation of toxic gases. Modern aquaculture systems like RAS, are increasingly being adopted to reduce water usage and significantly minimize environmental discharge. Shrimp farming infrastructures are typically designed with distinct functional ponds, including sedimentation ponds, treatment ponds, grow-out ponds, and effluent holding ponds, to ensure strict control over water quality, thereby minimizing the risks of disease transmission and cross-contamination. The quality of water supplied to shrimp ponds must conform to the standards specified in the national technical regulation on brackish water shrimp culture farm - Conditions for veterinary hygiene, environmental protection and food safety (QCVN 02-19:2014/BNNPTNT), which is summarized in Table 2.

3.1.3 Characteristics of wastewater generation in shrimp farmings

Shrimp excrete organic and metabolic wastes and uneaten feed during growth and development. These substances accumulate and decompose, resulting in water quality deterioration and the formation of wastewater containing high concentrations of pollutants such as ammonia (NH_3/NH_4^+), nitrite (NO_2^-), nitrate (NO_3^-), phosphate (PO_4^{3-}), organic matter and pathogenic microorganisms (Aquino et al., 2019; Vu et al., 2021). Poor water management can result in disease outbreaks, causing shrimp mortality. The prolonged presence of these pollutants in water can lead to oxygen depletion and contamination. Chemicals and pharmaceuticals have been widely applied in shrimp farming due to their critical roles in enhancing productivity, promoting growth, and disease control. These substances include antibiotics, antifouling agents, pesticides, polychlorinated biphenyls (PCBs), polybrominated biphenyl ethers, and disinfectants (Silerio Vázquez et al., 2024). Chemicals discharged into water bodies negatively impact environmental health and human safety (Ahmad et al., 2022; Do et al., 2019). Reports indicate that intensive and semi-intensive shrimp farming uses over 8.2 tons of chemicals. These compounds persist in the aquatic environment for extended periods after discharge (Phuong et al., 2023). To maintain water quality, periodic water exchange is essential for removing accumulated waste within ponds. This practice generates substantial volumes of wastewater, especially when pond water shows signs of contamination or during disease outbreaks (Ayalew, 2022). The discharged water typically contains elevated suspended solids, organic matter, and bacteria levels. Activities such as bottom sludge dredging, pond washing, disinfection, and sediment conditioning produce wastewater during pond preparation. This wastewater may contain residual chemicals (lime, disinfectants, bactericides), sludge deposits, and accumulated debris from previous farming cycles (Do et al., 2018).

Wastewater from shrimp farming is compositionally complex, typically containing high concentrations of pollutants and microorganisms, particularly pathogenic agents (Krishnani et al., 2018). The composition and characteristics of shrimp farming wastewater vary depending on the culture stage, stocking density, feed type, feeding strategies, water exchange regimes, and pond management practices (Chuaicham et al., 2023). Major constituents include uneaten feed, shrimp excretory products, and decomposing organic matter from dead flora and fauna (Tien Nguyen et al., 2024). These organic compounds contribute to elevated BOD and COD levels. Nitrogen- and phosphorus-containing compounds, such as NH_3/NH_4^+, NO_2^-, NO_3^-, PO_4^{3-} are also commonly present. Elevated ammonia and nitrite concentrations are toxic to shrimp and the surrounding ecosystem. In addition, heavy metals and residual chemicals may be present due to improper use of lime, pharmaceuticals, and other chemical agents (Do et al., 2022). Wastewater also harbors heterotrophic bacteria and organic-degrading microorganisms, including pathogenic strains such as Vibrio spp. Algae and plankton can proliferate excessively in nutrient-rich conditions, altering pH levels and dissolved oxygen concentrations in the water (Álvarez & Otero, 2020). The characteristic composition of shrimp pond wastewater is summarized in Table 3. Key

TABLE 2: Quality of water supplied to and present in ponds for black tiger shrimp and whiteleg shrimp (QCVN 02-19:2014).

No.	Parameters	Unit	Permissible Value
1	Dissolved Oxygen (DO)	mg/l	≥ 3.5
2	pH		7-9, daily fluctuations < 0.5
3	Salinity	mg/l	5-35
4	Alkalinity	mg/l	60-180
5	Water Transparency	cm	20-50
6	NH_3	mg/l	< 0,3
7	H_2S	mg/l	< 0.05
8	Temperature	°C	18

TABLE 3: Characteristic parameters of shrimp farming wastewater.

No.	Parameters	Unit	Value Range	QCVN 02 - 19:2014/BNNPTNT
1	Salinity	‰	12-30	-
2	COD	mg/l	65-180	150
3	BOD_5 (20°C)	mg/l	20-100	50
4	NH_4^+	mg/l	1-10	-
5	NO_3^-	mg/l	0.4-3	-
6	NO_2^-	mg/l	0.1-5	-
7	TN	mg/l	5-20	-
8	TP	mg/l	0.1-12	-
9	TSS	mg/l	50-200	100

pollution indicators such as COD, BOD_5, and TSS exceed the permissible limits defined by QCVN 02-19:2014/BNNPTNT. Therefore, appropriate treatment measures must be implemented to treat shrimp farming wastewater before it is discharged into the environment or reused.

The quality of shrimp pond wastewater at Hai Dong Commune, Hai Hau District, Nam Dinh Province indicates that most of the measured parameters exceed the permissible limits. Specifically, TSS exceed the regulatory limit by a factor of 20.8, while COD and BOD_5 exceed the limits by 8.73 and 7.88 times, respectively. These results indicate that shrimp farming activities significantly impact the quality of local water bodies. Analytical results also reveal that the receiving canals are contaminated with elevated concentrations of organic matter.

The characteristics of wastewater from black tiger shrimp (Penaeus monodon) ponds in Cu Lai village (Phu Hai commune, Phu Vang district, Thua Thien Hue province) and from white-leg shrimp (Litopenaeus vannamei) farms on sandy soils in Dien Loc (Phong Dien district, Thua Thien Hue province) show that wastewater from shrimp farming on sandy soils exhibits a pollution profile similar to that of traditional black tiger shrimp ponds. Most parameters are within the permissible discharge limits specified in QCVN 24:2009/BTNMT (Column B); however, COD exceeds the standard by approximately 1.3 to 2.0 times. Compared to the standards for surface water quality (QCVN 08:2008/BTNMT) and coastal seawater quality (QCVN 10:2008/BTNMT), additional treatment is required to reduce TSS, COD, NH_4^+, NO_3^-, and NO_2^- to protect aquatic life.

The pH values of shrimp farming wastewater in Bac Lieu province fall within the permissible range specified by QCVN and are suitable for white-leg shrimp (Litopenaeus vannamei) culture (optimal pH 7.5-8.5) (Table 4). Meanwhile, COD and BOD_5 concentrations in wastewater from super-intensive shrimp farming are 1.5 times higher than those in intensive shrimp farming wastewater, and both exceed the permissible limits by a significant margin. The aggregated results reveal that pollutant concentrations vary considerably across shrimp farming models.

Specifically, intensive and super-intensive farming systems exhibit markedly higher pollutant levels than sand-based farming, black tiger shrimp, and white-leg shrimp models. Parameters such as BOD_5, COD, TSS, total nitrogen (TN), and total phosphorus (TP) in wastewater from intensive and super-intensive shrimp farming exceed the QCVN 40:2011/BTNMT Column B standards, in some cases by multiple folds, reflecting substantial organic matter, suspended solids, and excess nutrients. Additionally, NH_4^+ concentrations and total coliform levels are also considerably elevated. Conversely, shrimp farming on sandy soils and black tiger shrimp and white-leg shrimp systems exhibit significantly lower COD, TSS, and total nitrogen, with most parameters remaining within or near the regulatory limits (Goswami et al., 2022).

3.1.4 Environmental impacts of shrimp farming wastewater

When effectively managed, shrimp farming wastewater can help enhance nutrient concentrations in culture ponds to increase aquaculture productivity. In certain situations, supplementary feeding is not required, which helps reduce production costs. Shrimp farmers can integrate crop cultivation with shrimp farming by establishing adjacent pond sections where nutrient-rich wastewater is used for irrigation. Shrimp farming wastewater can be reused to mitigate environmental degradation and conserve water, enabling more rational use of natural water resources and preventing wastage (Mishra et al., 2018). Additionally, this wastewater is beneficial for restoring nutrient-poor sandy soils, which are known to lack sufficient nutrients for crops. However, if shrimp farming wastewater is not effectively and promptly treated, it can cause negative impacts on water quality, soil health, and human health.

This wastewater contains high levels of organic compounds such as uneaten feed, shrimp feces, and decomposed shrimp carcasses, which increase BOD and COD, significantly reducing DO levels. This leads to oxygen depletion, adversely affecting aquatic organisms. Furthermore, wastewater may contain pathogens such as viruses, bacteria, and parasites. When discharged into rivers, canals, or seas, these pathogens can spread to natural aquatic species or nearby aquaculture areas, increasing the risk of widespread disease outbreaks. Wastewater can cause long-term soil impacts when used for irrigation and agriculture. Crops grown in soils with excessive nitrogen and phosphorus tend to exhibit excessive vegetative growth, which is undesirable for productivity. Moreover, heavy metals absorbed by plants can enter the food chain, potentially reaching humans (Do & Tran, 2023). Soil salinity is elevated near shrimp farms; specifically, for every one-meter de-

TABLE 4: Characteristics of wastewater from intensive and super-intensive shrimp farming in bac lieu province.

No.	Parameters	Unit	Intensive Shrimp Farming Wastewater (n = 20)	Super-Intensive Shrimp Farming Wastewater (n = 20)	QCVN 40:2011/BTNMT Column B
1	pH	-	7.55±0.24	7.87±0.18	5.5-9
2	BOD_5	mg/l	268±41	403±95	50
3	COD	mg/l	291±37	466±92	150
4	TSS	mg/l	492.5±129.5	698.6±350.7	100
5	Total N	mg/l	52.75±23.01	9.63±10.93	40
6	Total P	mg/l	5.63±2.34	17.32±12.05	6
7	N-NHA_4^+	mg/l	8.461±4.36	29.841±24.807	10
8	Total Coliform	MPN/100ml	27585±19558	27105±11800	5000

crease in distance from the shrimp pond to the surrounding land, salinity increases by 0.14% (Amoako Johnson et al., 2016). Another study indicated that shrimp wastewater significantly increases concentrations of total organic carbon (TOC), TN, and TP in coastal soils up to a depth of 10 cm. This wastewater accounts for 30% - 33.6% of TOC in coastal soils and alters carbon and nutrient dynamics in receiving areas.

3.2 Current technologies for shrimp aquaculture wastewater treatment

Various technologies have been applied to treat shrimp aquaculture wastewater depending on pollutant composition and operational conditions. Table 5 summarizes the principal treatment technologies reported for shrimp aquaculture wastewater, highlighting their treatment mechanisms, pollutant removal performance, and major practical constraints.

The following sections present a more detailed description of each technology to illustrate their mechanisms and performance in treating shrimp aquaculture wastewater.

3.2.1 Constructed wetlands

Constructed wetlands (CWs) are treatment systems that mimic natural wetlands but are designed and controlled to improve water quality (Huang et al., 2019). CWs are considered a cost-effective system for treating aquaculture wastewater, especially shrimp farming wastewater (Dinesh Kumar et al., 2020). CWs carry out nitrification, denitrification, and demineralization processes through plants and microorganisms (Yang et al., 2023). The effectiveness depends on design factors (substrate, plants, microorganisms), operational factors (hydraulic retention time, hydraulic loading rate, groundwater depth, flow regime), and environmental conditions (temperature, pH, salinity, moisture, nutrient levels, specific carbon sources).

In Vietnam, studies have shown that constructed wetlands can effectively treat shrimp farming wastewater. One study in Bac Lieu evaluated a 400 m^2 wetland system using native salt-tolerant plants such as Sesbania, Eleocharis, and saltgrass. The system combined biological ponds and wetlands to reuse water from black tiger shrimp ponds – the same source of wastewater (Hiep et al., 2023). Results showed that COD, BOD_5, NH_4^+, and TP removal rates exceeded 50%. The NH_3 concentration in the effluent was low (<0.1 mg/L), making the water suitable for reuse. Internationally, studies have also used constructed wetland models to treat aquaculture wastewater (Kashem et al., 2023). A system using Canna indica combined with 20 mg/L Fe^{2+} showed very high treatment efficiency, with removal rates of TN, TP, and COD reaching 95%, 75%, and 62%, respectively (Zhimiao et al., 2019). Another study investigated the impact of plant physiological characteristics on the treatment efficiency of CWs (de Paula et al., 2024). Results indicated that CWs planted with a mixture of multiple plant species had higher treatment efficiency compared to systems with only one species. Besides removing conventional pollutants, this system could also treat antibiotics in the water. Specifically, removal efficiencies for antibiotics SMX, SMM, SMZ, SDZ, and TMP were 29.8%-76.3%, 20%, 20%, 12%, and 89%, respectively.

The use of constructed wetlands for shrimp wastewater treatment offers several notable advantages. One of the main benefits is their relatively low construction and operating costs compared with conventional treatment technologies. Constructed wetlands rely primarily on natural processes involving aquatic plants and microbial communities to remove pollutants, resulting in low energy consumption and minimal maintenance requirements. Previous studies have shown that these systems are effective in removing organic matter, nitrogen, phosphorus, and, in some cases, residual antibiotics commonly found in shrimp farming effluents. In addition, constructed wetlands can be integrated directly into shrimp farms, contributing to water reuse and promoting more sustainable resource management practices.

However, constructed wetlands also present several limitations. A major constraint is the relatively large land area required for their implementation, which may restrict their applicability in regions with limited space. Treatment efficiency can vary depending on environmental conditions

TABLE 5: Overview of major treatment technologies for shrimp aquaculture wastewater.

Technology	Treatment characteristics	Advantages and limitations
Aerobic/anoxic biological treatment	Based on microbial activity for organic matter degradation and nitrogen conversion; effective removal of COD, BOD, and NH_4^+	Low operating cost and easy implementation, but sensitive to organic loading fluctuations and environmental conditions
Biofloc Technology	Heterotrophic microorganisms assimilate inorganic nitrogen and form biological flocs, contributing to water quality stabilization	Water-saving and nutrient recycling, but difficult to control floc density
Constructed wetland	Combines sedimentation, adsorption, and biodegradation by plants and microorganisms; effective for TSS, nitrogen, and phosphorus removal	Low cost and environmentally friendly, but requires large land area
Recirculating Aquaculture System (RAS)	Integrates mechanical filtration, biological treatment, and water recirculation to maintain stable water quality	Reduces water exchange and improves environmental control, but requires high initial investment
Polymer membrane-based MBR	Combines biological treatment with membrane separation, achieving high removal of COD, NH_4^+, and TSS	Produces high-quality effluent, but membrane fouling remains significant
Nano TiO_2 modified ceramic membrane	Integrates membrane filtration and photocatalysis, enhancing removal of COD, TSS, microorganisms, and refractory pollutants	Good fouling resistance and chemical durability, but requires high investment cost and UV irradiation

such as temperature, pH, and salinity, leading to fluctuations in performance. Moreover, constructed wetlands typically require a long start-up period before reaching stable and optimal treatment efficiency. If not properly designed and managed, these systems may also create favorable conditions for mosquito breeding. Furthermore, constructed wetlands are generally less effective in treating wastewater with very high pollutant concentrations or toxic compounds, and therefore may require pre-treatment or combination with other treatment technologies.

3.2.2 Biofloc technology

Biofloc technology is a new biological approach that is effective in aquaculture, based on the principle of suspended activated sludge (Banu et al., 2011). In Vietnam, this technology has been applied in several localities with promising results, supporting further development and broader adoption. Microorganisms in the biofloc system compete with pathogens in the water, helping reduce disease and improve yields. When an external carbon source is added, heterotrophic bacteria combine with excess suspended organic matter and algae to form floc. These floc particles are rich in protein and serve as a preferred metabolic food source for shrimp (Ahmed & Ambinakudige, 2024). Various factors, such as the C:N ratio, TSS, DO, pH, stocking density, biofloc dosage, and light, affect the efficiency and sustainability of biofloc technology. This method is effective, cost-saving, and easy to operate. However, it also has some limitations: High initial investment cost: farmers need to have a good understanding of the technology; the aeration system must operate continuously, otherwise, dissolved oxygen levels in the pond drop rapidly, leading to shrimp mortality or biofloc die-off, which endangers shrimp health; at high stocking densities, especially in the late stages of shrimp growth, waste accumulation can exceed assimilation capacity. This reduces biofloc efficiency, degrades water quality, and increases risk.

3.2.3 Microalgae and HRAP systems

Microalgae are tiny photosynthetic organisms capable of assimilating nutrients in aquaculture environments (Huang et al., 2022). They offer a cost-effective and practical biological method for aquaculture wastewater, including that from shrimp farms. Microalgae are used not only for wastewater purification but also to synthesize increased amounts of protein, lipids, and natural pigments to replace aquaculture feed and enhance animal immunity (Dinesh Kumar et al., 2016). However, selecting suitable microalgae species requires careful consideration, as pollutant removal efficiency depends heavily on species and environmental conditions. Microalgae technology is an advanced, eco-friendly technology that offers multiple benefits (Zhao et al., 2025). It helps absorb excess nutrients such as nitrogen and phosphorus while releasing dissolved oxygen via photosynthesis, improving water quality and pond stability. Some microalgae species secrete substances that inhibit pathogenic bacteria, helping reduce disease risk. The biomass after treatment can be used as fertilizer, animal feed, or bioproducts, increasing the economic value of the farming system. However, the efficiency depends on light and temperature conditions, that treatment efficiency may decrease during bad weather. Farmers require basic technical knowledge, and initial investment costs in ponds, aeration, and lighting can be relatively high.

Managing shrimp farm wastewater by algal pond systems is effective, profitable, and a green technology (Razaviarani et al., 2023). Algae are maintained at high densities and harvested to process valuable products such as biofuel. Algal growth helps absorb excess nutrients in polluted water, which contributes to water purification before reusing or discharging it into the environment (Rodríguez Leal et al., 2023). A study by Soka University, Japan, using simulated aquaculture wastewater, showed that HRAP could remove 100% of ammonium, nitrate, phosphate, and over 80% of organic matter. Another report found Arthrospira sp. Similarly, Arthrospira sp. was also reported to PCC7413 is effective, removing 84.9% ± 1.9% ammonia by Arthrospira sp. Concentrations drop to as low as 4.9 mg/L during treatment by Nostoc sp. and PCC7413, achieved within 24 hours. In an integrated farming study involving shrimp, clams, and aquatic plants in Romania, algae demonstrated a higher efficiency in removing pollutants. In an integrated farming study involving shrimp, clams, and aquatic plants in Romania, algal-based treatment systems achieved pollutant removal efficiencies of 29%, 79%, 76%, and 99% for COD, suspended solids, total nitrogen, and total phosphorus, respectively; however, the original study did not specify the exact algal species used.

3.2.4 Recirculating aquaculture systems (RAS)

In RAS systems, shrimp are cultured in ponds or tanks equipped with agitators and aerators suited to their growth. Shrimp ponds or tanks collect waste, which is pumped into external mechanical and biological filtration systems for treatment (Chen et al., 2024). The system continuously filters solids like feces, uneaten feed, molted shrimp shells, dead algae, and suspended organic matter in pond water, which are continuously filtered and treated separately in the recirculation tanks. After removing harmful substances, water is biologically treated and recirculated to the shrimp ponds. Continuous waste removal, combined with beneficial microbes, keeps pond water clean. Toxic gases (NH_3, NO_2^-, and H_2S) remain within safe limits, reducing disease, allowing higher stocking densities, and improving yield. The typical operating principle of the RAS farming system is illustrated in Figure 1. The RAS consists of supplementary processes that allow wastewater to be reused for the culture tanks). It is divided into two types: partial water exchange systems (10%-70% water recirculated per day) and full water recirculation systems (less than 10% water replaced per day). RAS includes shrimp culture tanks, settling and mechanical filtration tanks, biological filtration tanks, disinfection equipment, and water supply, drainage, and aeration piping systems. Initially, wastewater is transferred from culture tanks to filtration units. Solid particles settle into a sludge collection pit. Water is then filtered through materials such as sand, gravel, fabric, and mesh (Duong et al., 2019). Large particles are retained and moved to the sludge tank. After this stage, water still contains high concentrations of dissolved ammonia (NH_3) and remains un-

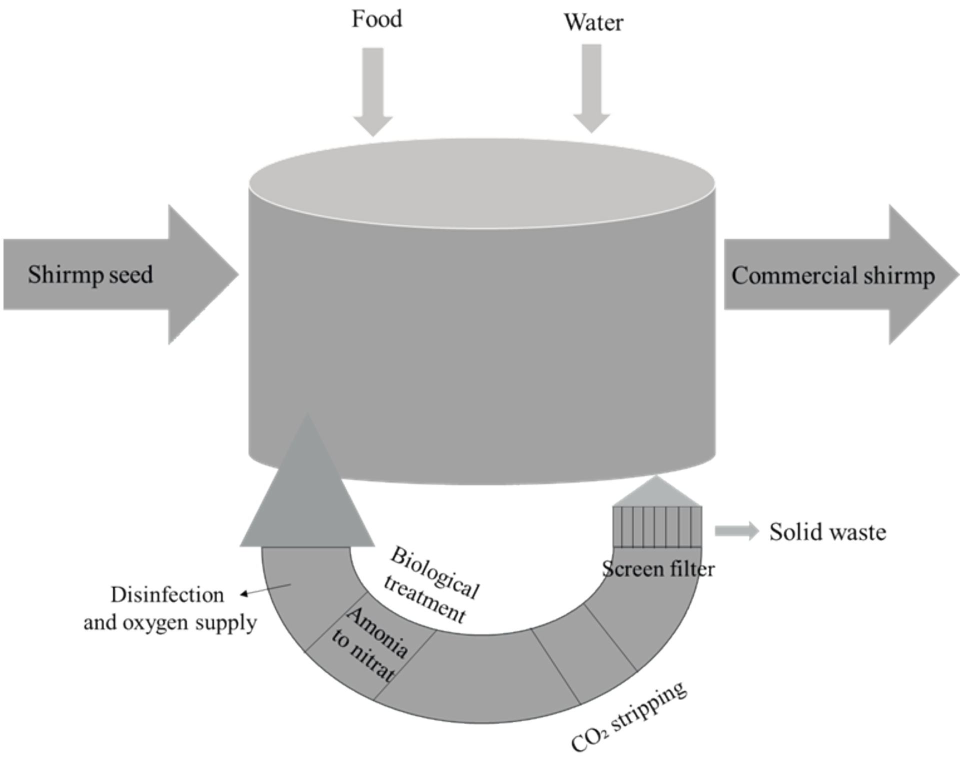

FIGURE 1: Diagram of the RAS system.

treated (Mohammadi et al., 2016). Aerobic, facultative, and anaerobic bacteria in biological filters perform nitrification and denitrification. These bacterial groups convert Nitrogen- and carbon-based compounds into non-toxic forms (Vu et al., 2023). The treated water is pumped back to the culture tanks. Aeration operates continuously to supply sufficient oxygen for bacterial degradation. Disinfection is crucial for eliminating pathogens and controlling microbes to prevent disease in culture ponds. UV light or ozone can be used during this stage.

Throughout the culture period, water circulates in a closed system with no replacement, with only a small amount of fresh water added to compensate for evaporation losses (Hung et al., 2017). The filtration system must operate continuously throughout the culture cycle (3-5 months), and aeration must be maintained daily; therefore, a stable power supply for the water pumps is essential. Among aquaculture wastewater treatment methods, RAS is considered a superior solution due to its integration of multiple outstanding advantages. Therefore, researching and improving the RAS technology process to suit wastewater from whiteleg shrimp farming, while adapting to Vietnam's technical and economic conditions, is essential (Viet Do et al., 2022).

Recirculating aquaculture system (RAS) technology with low water exchange is currently applied on a limited scale and is mainly implemented in research projects and pilot models rather than in widespread commercial shrimp farming. The main advantage of this technology lies in its high treatment efficiency, allowing effective control of water quality under intensive culture conditions. RAS operates without the use of antibiotics or chemical additives, thereby minimizing negative environmental impacts, creating a safe growth environment for shrimp, and significantly reducing the risk of disease outbreaks.

Despite these advantages, RAS technology also presents notable limitations. The most significant drawback is the high initial investment cost, which is approximately 45-60% higher than that of conventional shrimp farming systems. In addition, the operation of RAS requires skilled personnel with professional expertise and appropriate training to ensure stable system performance and effective management. These factors currently limit the large-scale adoption of RAS in shrimp farming practices.

In RAS, treated wastewater is not completely discharged but is reused repeatedly within the same system. This requires the effluent quality to achieve a high standard, not only ensuring the removal of organic matter, toxic compounds, and pathogenic agents, but also maintaining long-term stability to prevent pollutant accumulation during recirculation.

To overcome these limitations, membrane-based treatment technologies have attracted increasing attention because of their ability to provide effective solid–liquid separation and improve effluent quality under recirculating conditions. Among available membrane materials, ceramic membrane is considered particularly suitable for aquaculture applications due to its high mechanical strength, chemical resistance, thermal stability, and tolerance to harsh cleaning procedures, allowing stable long-term operation in complex wastewater environments. In addition, ceramic membranes exhibit superior durability compared with polymeric membranes, making them more appropriate for intensive and continuous operation in RAS.

To further enhance treatment efficiency, recent studies have focused on surface modification of ceramic membranes using nano-Titanium dioxide. Under Ultraviolet light irradiation, TiO_2 coated ceramic membranes can effectively degrade various organic compounds, proteins, and antibiotics resistant to biodegradation, which are characteristic pollutants in shrimp aquaculture wastewater. Moreover, TiO_2 coating improves membrane hydrophilicity, thereby reducing foulant accumulation and microbial attachment on the membrane surface, which helps mitigate membrane fouling one of the major operational challenges in recirculating systems. With these combined advantages, TiO_2 modified ceramic membranes not only improve pollutant removal efficiency but also extend operational cycles, reduce maintenance requirements, and enhance the overall sustainability of RAS operation.

3.3 Advanced membrane based treatment for shrimp wastewater

3.3.1 Ceramic membrane technology in wastewater treatment

In recent years, several innovative technologies have been increasingly applied to mitigate the impact of pollution caused by shrimp farming on surface water bodies, including the RAS. Among these, membrane filtration techniques have shown significant promise in enhancing treatment efficiency and enabling water reuse (Do, Bui, & Vu, 2023; Duong et al., 2020). In particular, ceramic membranes have attracted attention due to their superior properties compared to conventional polymer membranes, such as greater mechanical, thermal, and chemical stability, resulting in extended lifespan and improved fouling resistance (Ayode Otitoju et al., 2020). However, membrane fouling remains a significant challenge (Do & Chu, 2022). To address this, modifying ceramic membranes with photocatalytic nanomaterials has attracted considerable interest, aimed at enhancing both pollutant removal efficiency and antifouling performance (Pereira et al., 2011). Titanium dioxide (TiO_2), owing to its high quantum yield, chemical stability, and cost-effectiveness, is widely used as a coating to enhance photocatalytic activity (Dharma et al., 2022; Radeka et al., 2014).

3.3.2 Nano TiO_2 modified ceramic membranes

In the context of increasing water pollution, TiO_2 photocatalysis has emerged as an effective solution due to its ability to generate highly oxidative hydroxyl (•OH) and superoxide (O_2^-•) radicals, capable of degrading recalcitrant organic pollutants (Hassaan et al., 2023).

Analysis of 4,500 scientific publications from 2019-2024 using VOSviewer indicates two concurrent research trends: improving photocatalytic materials and integrating them with physical treatment platforms, particularly membrane technology (Figure 2). Doping TiO_2 with metal or non-metal elements can improve its adsorption capacity and thus enhance water treatment efficiency. However, recovering dispersed TiO_2 powders from the reaction medium is challenging, limiting reusability and increasing operating costs. To overcome this, various support materials have been used to immobilize TiO_2, facilitating catalyst recovery (Cruz Moreno et al., 2025). Effective substrates include ceramics, activated carbon, glass, composite, stainless steel, and zeolites. Among them, ceramics stand out due to their low cost, natural abundance of clay, tunable porosity, and excellent thermal, chemical, and mechanical

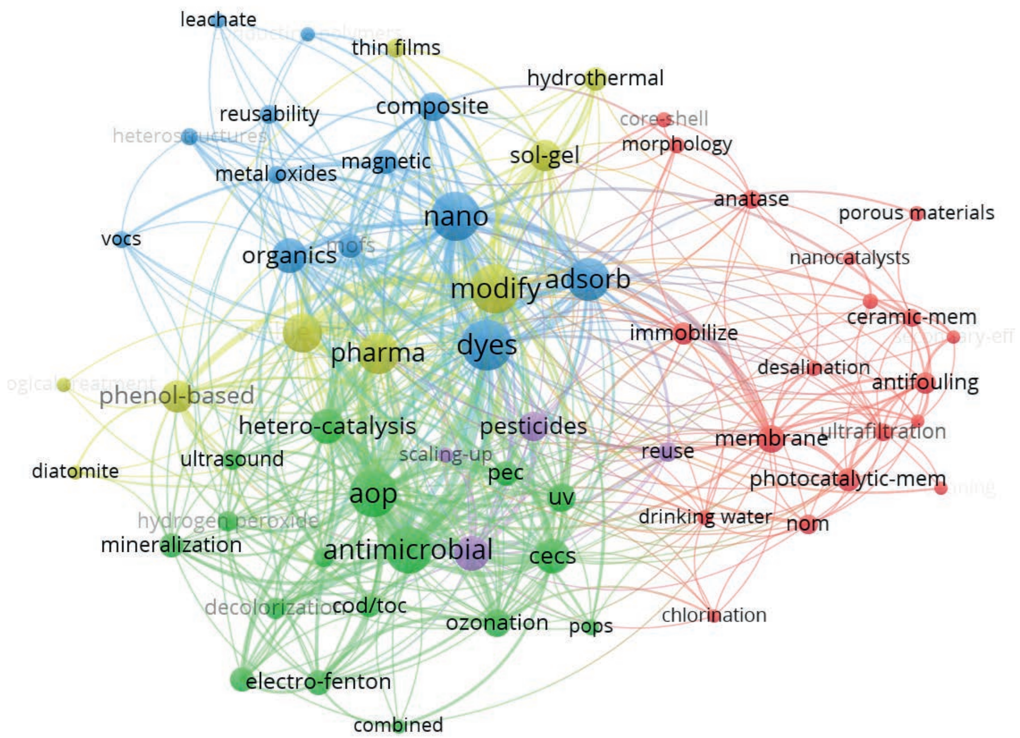

FIGURE 2: Research trends on TiO_2 photocatalysis in water and wastewater treatment.

stability (Morjène et al., 2020; Zendehzaban et al., 2013). Nano TiO_2 coated ceramic membranes have proven effective in degrading pollutants present in shrimp farm wastewater, including organic compounds, antibiotics, and nitrogenous substances (2023; Shi et al., 2013).

Incorporating or coating TiO_2 onto ceramic membranes allows simultaneous physical filtration and photocatalytic oxidation, forming photocatalytic membrane reactors (PMRs). Under UV or visible light irradiation, the generated electron-hole pairs (e^-/h^+) trigger free radical reactions that degrade organic compounds on the membrane surface, reduce fouling, and extend operational lifespan.

The effectiveness of TiO_2 modified ceramic membranes in removing various pollutants has been demonstrated in numerous studies. Table 6 summarizes representative research on the performance of nano TiO_2-coated ceramic membranes for water and wastewater treatment.

From the table, it can be seen that TiO_2 modified ceramic membranes have demonstrated broad applicability in treating a variety of wastewater pollutants, including azo dyes, proteins, oils, and recalcitrant organics. Their effectiveness arises from the synergy between mechanical filtration and photocatalytic degradation: physical retention captures larger contaminants, while photocatalytic activity generates hydroxyl and superoxide radicals under UV or visible light, decomposing smaller or recalcitrant molecules. This dual function not only enhances removal efficiency but also mitigates membrane fouling and prolongs operational lifespan.

Optimal performance depends on pore size, membrane structure, and light exposure. Nano and ultrafiltration membranes (1-50 nm) balance retention and photocatalytic efficiency for dyes and proteins, whereas microfiltration membranes handle larger particles and emulsified oils. Doping TiO_2 with metals or non metals (Ag, Ni, N) further improves antimicrobial activity, broadens light absorption, and enhances pollutant degradation. Reported removal efficiencies are high..., >90% for dyes and proteins, 90-98.5% for oils, and 99.9% bacterial inactivation.

Despite these advantages, challenges remain. Photocatalytic efficiency can be limited by high turbidity or surface fouling, and thick TiO_2 coatings may reduce water flux. Therefore, careful optimization of layer thickness, pore size, and light accessibility is essential for practical applications. Overall, TiO_2 modified ceramic membranes offer a promising, versatile solution for advanced wastewater treatment, effectively combining filtration and photocatalysis for high removal efficiency and reduced fouling.

3.3.3 Integration of membrane bioreactor (MBR) systems TiO_2 modified

In conventional shrimp farming, water is typically sourced and pretreated before being supplied to the culture ponds. In contrast, the proposed system (Figure 3) integrates the shrimp pond with a wastewater treatment unit designed to treat and recirculate the water, thus forming a closed-loop system. The technological layout for the recirculating wastewater treatment system using MBR and nano TiO_2-modified ceramic membranes is illustrated in Figure 4.

Initially, wastewater from the shrimp pond is pumped through a coarse screen to remove solid waste such as shrimp remains and other debris (Figure 4). It then flows into an equalization tank to regulate flow rate and homogenize water quality prior to treatment. The pretreated water is sent to the primary treatment units using physicochemical and biological methods. In the biological treatment stage, the water passes through aerobic and anoxic tanks to remove organic matter and nutrients. Following biological treatment, activated sludge is separated by the TiO_2-modified ceramic membranes (Mozia et al., 2015). To maximize photocatalytic performance, place the mem-

TABLE 6: Studies on TiO_2 nanoparticle modified ceramic membranes for wastewater treatment.

Membrane type	Functionalization method	Target pollutants	Operating conditions	Removal efficiency / Key results
Ceramic membrane coated with TiO_2 nanofibers	Doping, coating, functionalization	Azo dyes (MB, RB5, CR, DR80, AO, CYX)	pH ~8, UVA 365 nm	MB: from 40.84% (retention) to 97.74% with UVA irradiation; optimal pore size 10-50 nm
Ceramic ultrafiltration (UF) TiO_2 membrane	–	Proteins (BSA)	Pore size 6-14 nm, UVA irradiation	Retention 98–100% BSA; TiO_2-Ag composite achieves ~100% under visible light
Ceramic microfiltration (MF) TiO_2 membrane	–	Proteins (BSA)	Pore size 530 nm, UV-A irradiation	Removal 70% BSA, high water flux 3000 LMH.bar $^{-1}$
Ceramic TiO_2 membrane	Ag/TiO_2 nanofiber coating	Bacteria, MB, TOC	UV 100 mW/cm², 98 min	E. coli 99.9%, MB 88%, TOC 99%; flux ~5 L/m².bar
Al_2O_3 tubular membrane coated with TiO_2	Coating	Organic compounds, ink, dyes (humic acid, methyl orange)	UV light 1 W/m²	Fouling-induced flux decline reduced to 27% (vs. 67% without irradiation)
Al_2O_3 / Ti substrate coated with TiO_2 nanostructures	Coating / rod-like	Pesticides (Diuron, Chlorfenvinphos)	UV 10-300 W/m²	Removal: Diuron 78%, Chlorfenvinphos 68%; flux ~15 L/m².bar
Al_2O_3 membrane coated with N-doped TiO_2 (N-TiO_2)	Nitrogen doping	Organic compounds	Pore size 200-800 nm, visible light	Flux decline 12-50%, enhanced organic degradation
Al_2O_3 membrane coated with TiO_2/Ag/HAP	Combined coating	Bacteria (E. coli)	Light intensity 0.3 mW/cm², 60 min	6-log removal (LRV 6) of E. coli; flux decreased 20-25%

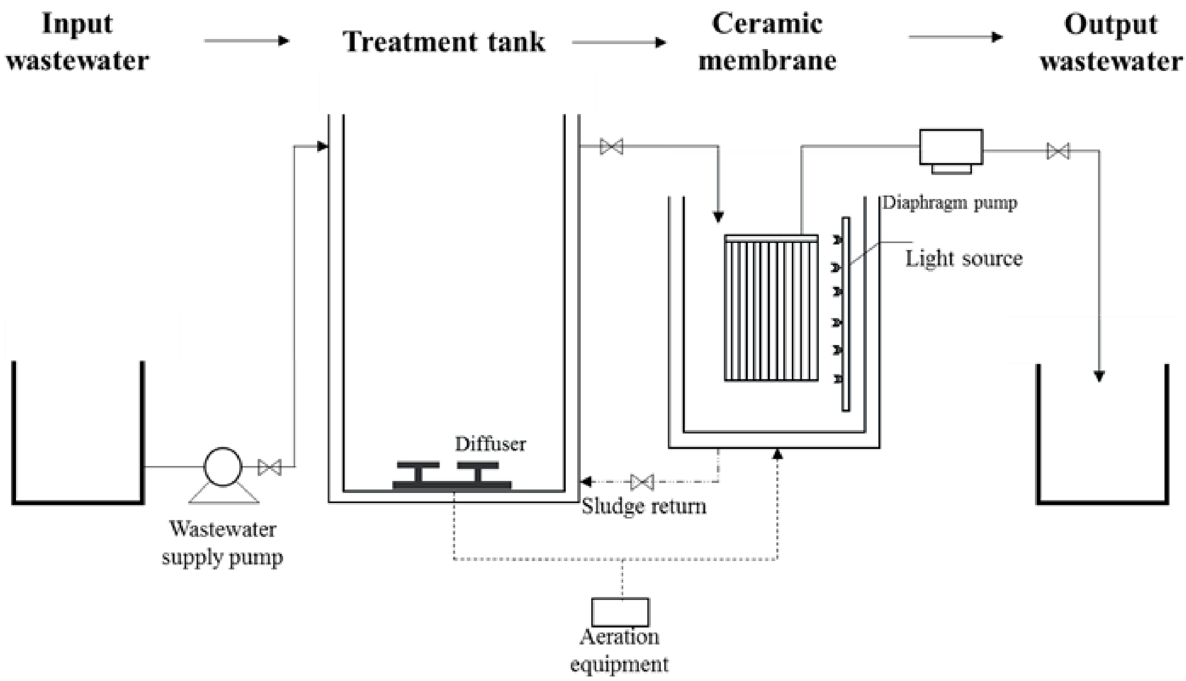

FIGURE 3: Proposed process for the integrated physico-chemical and biological.

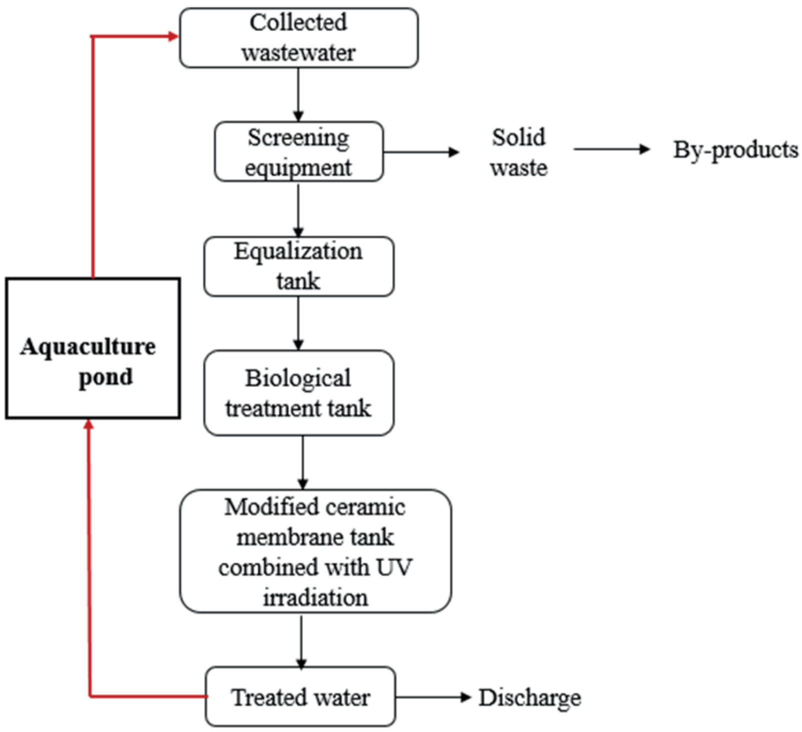

FIGURE 4: Process flow diagram of the recirculating wastewater treatment system for shrimp farming using MBR technology with a modified ceramic membrane.

brane module outside the biological reactor (Loddo et al., 2025; Zheng et al., 2017).

Under UV light, the TiO_2 coating performs physical filtration and degrades refractory organic compounds such as antibiotics used during shrimp farming and residual organics entirely removed in the bioreactor (Kabir et al., 2020). Additionally, UV light also acts as a disinfectant. With the integration of multiple treatment processes, the treated water can be recycled back to the shrimp pond via an intermediate tank or discharged into the environment if regulatory standards are met (Kruse et al., 2020). Furthermore, a supplementary step may be included in reintroducing essential minerals before reusing (Xie et al., 2022). The system - including pumps, aerators, mixers, sensors, and other control equipment - is managed by an automated panel. This setup conserves water, reduces discharge volumes, and maintains water quality suitable for shrimp farming.

3.3.4 Limitations and operational challenges TiO_2 modified

Despite their potential, TiO_2-modified ceramic membranes still face several limitations. Ceramic membranes cost significantly more than conventional polymer membranes.

Though resistant to corrosion and heat, eramic membranes are brittle and prone to cracking. Damaged membranes cannot be repaired and must be entirely replaced, raising costs and causing system downtime. Thus, strict mechanical safety protocols are required during transport, installation, and operation to avoid impact and vibrations. Although nano TiO_2 coatings enhance fouling resistance, membrane clogging remains challenging, particularly in shrimp farm wastewater rich in proteins and polysaccharides (Nannou et al., 2025). A study integrating TiO_2 photocatalysis with ceramic membrane filtration showed promising results in reducing organic pollutants (El Sharkawy et al., 2023). However, regular cleaning was still required to maintain filtration performance. Variations in influent flow and pollutant load can destabilize the microbial community, leading to shock loads and incomplete treatment, accelerating membrane fouling and reducing lifespan. Therefore, stable system performance requires precise influent control, microbial support (through aeration, nutrients, or probiotics), and regular membrane cleaning. TiO_2-modified ceramic membranes are mainly limited to laboratory or small-scale pilot models. High investment and maintenance costs make it unsuitable for smallholder farmers without technical or financial support.

3.3.5 Economic and operational feasibility of nano TiO_2 modified ceramic membrane systems

Economic feasibility is an important factor influencing the practical adoption of advanced wastewater treatment technologies in shrimp aquaculture because treatment costs directly affect production efficiency and long-term operational sustainability. Ceramic membrane systems have attracted considerable attention because of their high chemical resistance, thermal stability, and long operational lifespan compared with polymeric membranes. However, their initial investment cost remains relatively high due to the expensive raw materials and manufacturing processes involved. In general, ceramic membranes may cost approximately 3-5 times more than conventional polymeric membranes. While polymer membranes cost around 200-1.000 US$/m^2, ceramic membranes (unmodified) range from 1,000-5,000 US$/m^2, representing a fivefold increase. Additionally, the nano TiO_2 material and the surface modification process incur further costs (Davari et al., 2025; Szymański et al., 2018).. To harness the photocatalytic capability of TiO_2, the system must be equipped with UV light sources, increasing capital, energy, and maintenance costs .although their service life can be significantly longer under harsh wastewater conditions. Membrane fouling remains one of the major operational challenges, particularly when treating shrimp wastewater containing suspended solids, organic matter, proteins, and microbial residues. Fouling leads to permeate flux decline and increases the frequency of chemical cleaning, thereby raising operational costs. In membrane bioreactor systems, aeration is commonly applied to control fouling accumulation and may account for a substantial proportion of total energy consumption.

For nano TiO_2 modified ceramic membranes, photocatalytic activity under ultraviolet irradiation improves membrane surface hydrophilicity and promotes degradation of organic pollutants, thereby reducing fouling intensity. However, ultraviolet irradiation also introduces additional energy demand. Depending on irradiation intensity and operating duration, UV related energy consumption may significantly increase total operating cost, particularly in continuous treatment processes.

Compared with conventional biological treatment technologies such as constructed wetlands or biofloc systems, membrane-based systems generally require higher capital investment but provide superior effluent quality and greater potential for water reuse. This advantage is particularly important because water reuse can reduce freshwater demand and improve biosecurity in shrimp farming operations.

To improve economic applicability, hybrid treatment systems combining biological pretreatment with membrane separation have been increasingly recommended. Biological pretreatment reduces pollutant loading before membrane filtration, thereby extending membrane lifespan and lowering cleaning frequency. Although the initial installation cost remains relatively high, long-term benefits such as stable treatment efficiency, reduced environmental discharge, and improved water reuse potential may partially offset the initial investment under practical production conditions.

4. CONCLUSIONS

Vietnam's shrimp farming sector has significantly increased productivity and economic value. However, it also exerts considerable pressure on the environment due to increasing pollution from pond effluents. Shrimp pond wastewater contains high and variable loads of organic matter, nutrients, and pathogenic microorganisms, necessitating more efficient and stable treatment solutions. Combining MBR technology with nano TiO_2-modified ceramic membranes has shown great potential in addressing these challenges. Its advantages, high pollutant removal efficiency, antifouling properties, antibacterial action, and extended membrane life, are well documented in worldwide studies. Integrating biological treatment and advanced membrane technology offers a promising pathway for shrimp wastewater treatment. It builds on current technologies and supports effective practices in shrimp aquaculture. This provides both a scientific and practical basis for the subsequent phases of this research. Developing and evaluating an MBR system using nano TiO_2-modified ceramic membranes for shrimp wastewater would be helpful to design a model that integrates biological treatment with advanced membrane filtration. TiO_2-modified ceramic membranes aim to enhance antibacterial properties, reduce fouling, and extend system longevity.. Future studies should focus on optimizing hydraulic retention time, mixed liquor suspended solids, and membrane operating pressure under practical shrimp farming conditions to improve long-term treatment efficiency and economic feasibility.

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Extra contents

COLUMNS AND SPECIAL CONTENTS

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Environmental Forensics, Law and Policy

ENVIRONMENTAL LIABILITY ALLOCATION - PRACTICES

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1. INTRODUCTION

Environmental liability allocation, although grounded in sound and progressive legal principles capable of responding to evolving environmental challenges, remains ineffective unless those principles are meaningfully translated into practice without losing their purpose and intent. While our last column examined the foundational doctrines governing environmental liability—such as the polluter pays principle, precautionary principle, strict and absolute liability, and various civil liability allocation models—the practical application of these principles is discussed in this column. Environmental harm frequently involves multiple actors, historical contamination, scientific uncertainty, cross-border impacts, and evolving regulatory frameworks, all of which add to the complexity of identifying responsible parties and apportioning liability. Against this backdrop, we try to explore the practical approaches, mechanisms, and challenges involved in implementing environmental liability allocation in real-world environmental disputes and remediation processes.

By liability allocation practices, we mean the practical methods and mechanisms used to determine who should bear responsibility for environmental damage, to what extent, and in what manner such responsibility should be enforced. It may involve identifying responsible actors, establishing causation, apportioning liability among multiple contributors, determining remediation obligations, and enforcing compensation and restoration measures. While liability allocation principles provide the legal foundation for environmental accountability, liability allocation practices concern their operational application in real-world situations. Consequently, liability allocation practices represent the interface between legal theory and practical enforceability, translating environmental liability principles into workable mechanisms capable of ensuring effective remediation, environmental justice, and long-term environmental protection. These practices become particularly important in cases involving multiple polluters, historical contamination, scientific uncertainty, and long-term ecological harm, where even identifying the responsible party itself may be a complex exercise. The process is often shaped not only by legal rules but also by scientific evidence, regulatory policies, economic considerations, contractual arrangements, and institutional capacity.

2. CHALLENGES IN LIABILITY ALLOCATION

While undertaking liability allocation, it is important to be mindful of the challenges involved in translating the principles of environmental liability allocation into practice. Recognizing these challenges in advance helps in anticipating potential issues and carrying out the allocation process in the most appropriate and equitable manner. The major challenges likely to be encountered during liability allocation include:

- *Difficulty in identifying responsible parties*: Environmental harm often results from the cumulative activities of multiple actors over long periods, making the identification of responsible parties a complex exercise (Petrisor, 2014). Determining who caused the damage, to what extent, and during which period becomes particularly difficult in cases of historical contamination or diffuse pollution, where environmental harm may arise gradually from multiple sources rather than from a single identifiable polluter.
- *Problems of causation and scientific uncertainty*: Establishing a clear causal link between a particular activity and environmental harm is often one of the most difficult aspects of environmental liability allocation. Scientific uncertainty, cumulative pollution from multiple sources, and the delayed manifestation of environmental damage frequently complicate efforts to identify the precise source and extent of harm. In many cases, environmental impacts become evident only years or decades after the polluting activity occurred, making causation difficult to prove with certainty (Kruge et al., 2020).
- *Apportionment of liability among multiple polluters*: Even where responsible parties are identified, allocating liability proportionately remains a significant challenge. Determining the appropriate basis for differentiating liability among multiple responsible parties—whether based on the degree of contribution, duration of in-

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volvement, nature of activity, level of fault, or extent of environmental harm caused—is often a complex exercise (Reddy, 2010). Once such individual responsibilities are assessed, courts and regulators may decide whether liability should be imposed through joint and several liability, proportionate liability, or equitable allocation methods.

- *Quantification of environmental damage*: Environmental harm frequently involves ecological degradation, biodiversity loss, and long-term public health impacts that are not easily quantifiable in monetary terms (Pfennigstorf, 1979). Unlike conventional property damage, environmental injury may affect ecosystems, natural resources, and future generations in ways that are difficult to measure precisely. Consequently, assessing the appropriate cost of remediation, restoration, and compensation often becomes contentious, particularly where scientific uncertainty and competing valuation methods are involved.
- *Insolvency or disappearance of polluters*: In many cases, the entities responsible for environmental harm may become insolvent, dissolved, defunct, or otherwise untraceable by the time contamination is discovered or remediation is required. This creates significant practical difficulties in enforcing environmental liability, particularly in cases involving historical pollution or long-term environmental damage. As a result, governments or affected communities are often compelled to bear the financial burden of cleanup and restoration, undermining the effectiveness of the polluter pays principle and shifting environmental costs to the public.
- *Regulatory and institutional limitations*: The effective implementation of environmental liability regimes is often constrained by institutional and administrative limitations. Weak enforcement mechanisms, lack of technical expertise, inadequate monitoring and data collection systems, and bureaucratic delays can significantly hinder timely investigation, assessment, and remediation of environmental harm. In many jurisdictions, regulatory authorities may also face shortages of financial resources and scientific capacity, reducing their ability to enforce liability effectively and consistently.
- *Balancing environmental protection with economic development*: Governments may sometimes hesitate to impose stringent environmental liability on industries due to concerns about economic growth, industrial development, employment generation, and investment inflows. Fear of discouraging business activity or affecting economic competitiveness can lead to diluted enforcement, regulatory leniency, or delays in imposing remediation obligations, thereby weakening the effectiveness of environmental liability regimes (Becker et al., 2013).
- *Cross-border and transboundary environmental harm*: Environmental pollution frequently extends beyond territorial and jurisdictional boundaries, particularly in cases involving air pollution, transboundary rivers, marine pollution, and climate change. Such situations raise complex questions relating to applicable law, jurisdiction, enforcement authority, and the responsibility of different States or actors. The absence of uniform international standards and the need for effective cross-border cooperation often make the allocation and enforcement of environmental liability particularly challenging.

These challenges present a persistent gap between legal theory and practical enforceability in environmental liability allocation. While environmental law has developed sophisticated principles to ensure accountability, prevention, and remediation, their effective implementation often encounters scientific uncertainty, evidentiary difficulties, institutional limitations, economic pressures, and complex factual situations involving multiple actors and long-term environmental harm. As a result, the true effectiveness of environmental liability regimes depends not merely on the existence of sound legal principles but on the capacity of legal and regulatory systems to apply them consistently, fairly, and effectively in practice.

Liability allocation practices adopted across different jurisdictions have attempted to address these challenges, although with varying degrees of success. Nevertheless, environmental liability allocation procedures continue to evolve, supported by ongoing legal, regulatory, and scientific research.

3. LIABILITY ALLOCATION—SELECTED EXAMPLES

One of the major areas in which environmental liability has been extensively applied is the remediation of contaminated sites. Consequently, remediation liability provides valuable examples for understanding the existing practices of environmental liability allocation.

3.1 Liability allocation under CERCLA

The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of the United States is widely regarded as one of the earliest and most influential civil liability statutes specifically addressing environmental remediation liability. Enacted in 1980, the legislation is more commonly known as the Superfund Act. Under CERCLA, the liability allocation process for contaminated site remediation follows a systematic procedure involving site assessment, identification of responsible parties, remediation planning, and cost recovery. The process generally begins with the identification of a contaminated site by the United States Environmental Protection Agency (US EPA) or state environmental agencies. Preliminary assessments and detailed site investigations are then conducted to determine the nature and extent of contamination, identify hazardous substances present, evaluate environmental and human health risks, and assess the urgency of remedial action.

Following site characterization, the EPA identifies Potentially Responsible Parties (PRPs), which may include current and former owners or operators of the site, hazardous waste generators, and transporters involved in the disposal of hazardous substances. CERCLA imposes strict, joint, several, and retroactive liability, meaning that any

PRP may potentially be held responsible for the full cost of remediation regardless of fault or the timing of the activity. Once PRPs are identified, the EPA generally encourages negotiated settlements under which the responsible parties voluntarily undertake or finance cleanup activities in accordance with EPA-approved remediation plans.

In situations involving multiple PRPs, liability allocation becomes necessary to equitably distribute remediation costs among the parties. Such allocation may occur through negotiations, mediation, non-binding allocation procedures, or contribution litigation before courts. During this process, several equitable considerations are taken into account to determine the relative responsibility of each PRP. The widely applied Gore Factors and Torres Factors provide important guiding principles for such allocation and are discussed separately. If negotiated allocation is unsuccessful, courts may determine the proportionate liability of each party based on site-specific circumstances and equitable considerations.

Once liability allocation is completed, remediation activities are implemented either directly by the PRPs or by the EPA using Superfund resources. Where the EPA undertakes cleanup itself, it may subsequently recover remediation costs from responsible parties through administrative or judicial proceedings.

3.2 Liability allocation examples from European Union

The Environmental Liability Directive (Directive 2004/35/EC) provides the overarching framework for environmental liability across the member states of the European Union (EU). However, the Directive functions as a minimum harmonization framework and is implemented through national legislation in each member state. Consequently, while the broad principles and objectives established by the Directive are common across the EU, the specific procedures and approaches for liability allocation may vary among member states depending on their legal systems and implementing legislation. Nevertheless, these national frameworks are generally aligned with the overarching requirements and guiding principles of the EU Directive.

3.2.1 Sweden

In Sweden, the allocation of liability is carried out under the Swedish Environmental Code (SEC), which is founded on several core principles: the polluter pays principle, strict liability, and shared and retroactive responsibility for environmental damage. The fundamental premise is that the party responsible for pollution should also bear the costs of preventing and remedying any resulting harm.

Under the Code's general rules of consideration, anyone who pursues or intends to pursue an activity must take the protective measures, observe the restrictions, and adopt the precautions necessary to prevent, hinder, or counteract damage or nuisance to human health or the environment (Ch. 2, s. 3 SEC). Where damage nevertheless occurs, the party who, through an activity or measure, has caused such damage is required to restore the environment or compensate for the harm caused. This responsibility persists "until the damage or nuisance has ceased" (Ch. 2, s. 8 SEC). These general rules apply broadly to virtually all activities affecting land, water, air, and ecosystems.

More specific provisions governing liability for environmental damage are set out in Chapter 10 SEC. Since 2007, these rules have been aligned with the EU Environmental Liability Directive and focus on three categories of serious environmental damage: damage to protected species and natural habitats, damage to water, and land contamination (Ch. 10, s. 1 SEC). The primary liable party is the person or legal entity that conducts or has conducted the activity that caused the pollution (the "operator"). Liability is strict, meaning that it does not depend on negligence or fault, and it applies to both current and former operators. Swedish law thus recognises retroactive liability, allowing responsibility to be imposed even for activities that have ceased. In practice, however, liability is generally limited to activities conducted after 30 June 1969, when modern environmental regulation emerged with the Environmental Protection Act. Retroactivity is particularly significant in cases involving contaminated land, such as abandoned industrial sites. Liability is not confined to completed activities; it may also arise in relation to ongoing operations where pollution damage or serious environmental damage can be established.

Where several parties have contributed to the pollution, they may be held jointly and severally liable. This allows the supervisory authority to require any one of them to bear the full cost of remediation. That party may subsequently seek recourse against the others in proportion to their respective contributions. Regardless of who is identified as the operator, the scope of remedial obligations is subject to a case-by-case assessment of reasonableness. In remediation cases, the reasonableness assessment balances, on the one hand, the general duty to take necessary preventive measures and, on the other hand, factors such as the time elapsed since the pollution occurred, whether the activity was lawful at the time, and the extent to which the party contributed to the damage (Ch. 10, s. 4 SEC). Consequently, even where an operator is formally responsible for historical pollution, the reasonableness assessment may reduce liability in practice, potentially to zero.

Under certain conditions, liability may also extend to landowners. This liability is subsidiary and arises only where no responsible operator can be identified or held accountable. It further requires that the property was acquired after the contamination occurred and that the acquirer knew, or ought to have known, of the pollution at the time of acquisition. The purpose of the landowner liability is to push for thorough investigations in land acquisitions, thereby enforcing the precautionary part of the regulatory framework.

3.2.2 Austria

In Austria, liability allocation for environmental damage was introduced in 2009 and amended in 2018 through the Federal Environmental Liability Act (BGBl. I Nr. 55/2009), which transposed the European Environmental Liability Directive into national law. Consistent with the EU Directive, the Austrian framework is based on the polluter pays principle and relies on a combination of strict public law enforcement and civil liability mechanisms.

Similar to Swedish legislation, operators engaged in specified hazardous activities are subject to strict liability, irrespective of fault, for the prevention and remediation of environmental damage affecting soil, water bodies, and biodiversity. The Act defines operators as persons or entities carrying out professional activities and excludes private individuals from its scope.

Unlike the Swedish framework, however, liability under the Austrian Environmental Liability Act is limited to environmental damage occurring after the Act entered into force on 20 June 2009 and therefore does not have retroactive effect. For contamination predating the Act, or in situations where the polluter cannot be identified, other legislative instruments may apply, most notably the Contaminated Sites Remediation Act, which has been in force since 1989. This Act is intended to address legacy pollution and orphan contaminated sites. Remediation activities under the Contaminated Sites Remediation Act are financed through a dedicated environmental levy imposed on landfilling, long-term waste storage, waste incineration, and certain waste transport activities. In addition to remediation measures, the fund also supports site investigations, monitoring programmes, and research on innovative remediation technologies. In certain circumstances, the provisions of the Federal Environmental Liability Act may be superseded by more specific legislation, such as the Water Rights Act or the Waste Management Act.

The costs of preventive and remedial measures must be borne by the operator responsible for the environmental damage, including costs incurred by third parties acting on the operator's behalf. Where such costs cannot be recovered from the liable operator, the owner or co-owner of the property from which the damage originates may be required to bear the costs, provided that the owner consented to or knowingly tolerated the installations or activities that caused the damage and failed to take reasonable preventive measures.

The allocation of costs under the Austrian framework is intended to incentivize operators to adopt preventive measures and sound environmental management practices while also recognizing the responsibilities of property owners in preventing environmental harm.

3.3 Liability allocation in India

India does not yet have a dedicated and comprehensive environmental liability allocation framework comparable to the detailed allocation mechanisms established under CERCLA or the Environmental Liability Directive. However, liability allocation principles are increasingly reflected through a combination of statutory provisions, judicial decisions, and regulatory guidelines. One notable guideline is the 'Guidelines on Implementing Liabilities for Environmental Damages due to Handling and Disposal of Hazardous Waste and Penalty' prepared by the Central Pollution Control Board (CPCB). It is based on the principles of strict liability and joint and several liability, under which the responsible party—whether occupier, transporter, operator, or importer of hazardous waste—is held liable irrespective of negligence. In the event of spills, leakages, fires, illegal dumping, or other hazardous waste incidents, the responsible party must immediately undertake emergency response measures to contain and control the release, protect human health and the environment, and report the incident to the concerned authorities. The responsible party is further required to carry out an environmental site assessment, including Phase I and Phase II Environmental Site Assessments (ESA I and ESA II), to determine the extent of contamination, identify contaminants of concern, assess exposure pathways and receptors, and evaluate risks to human health and the environment. Based on these assessments, remediation plans with site-specific target levels must be prepared and implemented following approval by the State Pollution Control Boards (SPCB) or Pollution Control Committees (PCC). The framework also imposes compensation liability for damages such as loss of property, crop damage, reduced agricultural productivity, health impacts, hospitalization costs, ecological damage, and loss of life.

The guidelines prescribe indicative financial liabilities for different stages of environmental response and remediation. Upon identification of an incident, an immediate response liability is imposed to cover emergency response actions and Phase I assessment. If the SPCB/PCC itself undertakes the emergency response due to non-compliance by the responsible party, the liable amount may increase to twice the immediate response liability along with applicable interest. In addition, a minimum site assessment liability is also imposed, which can increase depending on the extent and nature of contamination. Remediation liabilities vary depending on factors such as contaminant type, impacted environmental media, groundwater contamination, and ecological sensitivity. The responsible party may also be required to furnish bank guarantees equivalent to the estimated assessment and remediation liabilities.

The guidelines further state that when the responsible party is not traceable, the SPCBs/PCCs may themselves undertake emergency response, environmental assessment, and remediation activities directly or through third-party agencies, and may seek financial assistance from the State/UT Government if necessary. In such situations, the SPCBs/PCCs are empowered to file an FIR under the Code of Criminal Procedure (CrPC) for investigation and identification of the responsible party, and subsequently recover liabilities equivalent to three times the actual costs incurred, along with applicable interest.

4. GENERALIZED PROCEDURE OF LIABILITY ALLOCATION

A closer examination of the examples discussed above reveals that, although the specific details may vary across jurisdictions and cases, the underlying liability allocation procedure remains broadly similar. This general framework may be summarized as illustrated in Figure 1. Table 1 briefly explain these stages.

5. DETERMINANTS OF LIABILITY

A frequent challenge in environmental liability allocation is determining the relative contribution of individual polluters in situations involving multiple responsible par-

TABLE 1: Liability allocation procedure.

Step	Stage	Key Activities	Key Output
1	Identification of Damage or Contamination	Detection through inspection, monitoring, self-reporting, or complaints; preliminary inquiry by competent authority	Damage or environmental threat identified
2	Emergency Response and Immediate Measures	Contain, control, and mitigate immediate risks; protect human health and environment; authority intervention if responsible party fails to act	Immediate risks reduced or controlled
3	Site Assessment and Damage Characterization	Assess extent and nature of contamination; identify pollutants, affected media, receptors, and pathways; conduct risk assessment and causal analysis	Site assessment and risk characterization completed
4	Identification of Responsible Parties	Identify owners, operators, generators, transporters, importers, and other contributors using records, permits, manifests, and forensic analysis	List of potentially responsible parties prepared
5	Determination of Applicable Liability Standard	Determine applicable legal regime such as strict liability, fault-based liability, absolute liability, joint and several liability, or proportional liability	Applicable liability principles established
6	Development of Remediation/Restoration Plan	Prepare remediation and restoration strategy; include primary, complementary, and compensatory measures where necessary; obtain regulatory approval	Approved remediation or restoration plan
7	Allocation of Liability Among Multiple Parties	Allocate liability through negotiation, mediation, administrative process, or court proceedings; consider contribution, toxicity, duration, compliance, causation, and benefit derived	Allocation decision and share of liability for each party
8	Imposition of Financial Liability and Cost Recovery	Impose liabilities for response, assessment, remediation, compensation, monitoring, and administrative costs; require financial assurance mechanisms	Financial liabilities imposed and secured
9	Implementation of Remediation Measures	Responsible parties implement approved remediation plan under authority supervision and compliance monitoring	Remediation measures implemented and compliance achieved
10	Government Intervention (if Non-Compliance or Unidentified Parties)	Authority undertakes remediation where parties fail, are insolvent, or unidentified; recover costs, penalties, and interest through legal action	Government action and cost recovery initiated

FIGURE 1: Stages of environmental liability allocation.

ties. To address this issue, courts in the United States have often relied on equitable allocation approaches such as the Gore Factors and Torres Factors. In addition, recent research has increasingly focused on developing methodologies for differential responsibility allocation, incorporating scientific, legal, and risk-based approaches to achieve more equitable distribution of environmental liabilities.

5.1 Gore factors

The Gore Factors originated from legislative discussions led by former U.S. Congressman Albert Gore Jr. during the development of CERCLA. Although they were never formally incorporated into the statute, over time, the Gore Factors (H.R. 7020, 96th Cong., 2d Sess. (1980)) have become widely accepted in contribution actions, settlement negotiations, and non-binding allocation procedures as practical tools for equitable apportionment of cleanup costs among responsible parties.

The Gore Factors generally consider six major aspects while allocating liability: (i) the ability to distinguish the contribution of each party to the contamination; (ii) the quantity of hazardous waste contributed by each party; (iii) the degree of toxicity of the hazardous substances involved; (iv) the degree of involvement of each party in the generation, transportation, treatment, storage, or disposal of hazardous waste; (v) the degree of care exercised by the parties with respect to the hazardous substances; and (vi) the degree of cooperation demonstrated by the parties with regulatory authorities during investigation and remediation.

Although the Gore Factors are non-binding and do not override CERCLA's strict, joint, and several liability framework, they play an important role in promoting fairness and facilitating negotiated settlements among PRPs. Courts, allocators, and regulatory agencies frequently rely on these factors, along with site-specific considerations, to distribute remediation costs in a more equitable manner. The Gore Factors have also influenced environmental liability allocation practices in several other jurisdictions and continue to serve as one of the most recognized frameworks for equitable allocation of environmental remediation liabilities.

5.2 Torres factors

The Torres Factors are additional equitable considerations used in the United States to assist in the allocation of environmental remediation liability among multiple PRPs under CERCLA. Unlike the more widely recognized Gore Factors, the Torres Factors (United States v. Davis, 31F. Supp.2d 45 (D.R.I.1998)), emerged primarily through judicial interpretations and case-specific allocation exercises in complex contamination disputes. They are generally applied as supplementary criteria to achieve a more equitable and practical distribution of remediation costs, particularly in situations where strict application of statutory liability may produce disproportionate outcomes.

The Torres Factors expand the scope of liability allocation beyond direct contaminant contribution by incorporating broader equitable and socioeconomic considerations. These factors may include the economic benefit derived from the polluting activity, the degree of knowledge regarding the hazardous nature of the waste, the financial capability of the responsible party, the extent of negligence or misconduct, efforts taken to prevent environmental harm, and the willingness of parties to participate in remediation and cooperate with regulatory authorities. In some cases, courts may also consider the relative fairness of imposing liability, including whether excessive financial burden on a party would undermine equitable cost distribution. Consequently, the Torres Factors provide flexibility in liability allocation and allow courts and allocators to account for site-specific circumstances that may not be fully addressed through traditional contaminant-based allocation approaches alone.

6. RECENT DEVELOPMENTS

The Gore and Torres factors provide a strong foundation for liability allocation in situations involving multiple parties contributing to environmental pollution. In addition, the Environmental Liability Directive and guidelines adopted in several other countries have proposed various factors relevant to different contamination scenarios and regulatory contexts. Numerous court decisions across jurisdictions have also relied on case-specific considerations for proportionate liability allocation. Building upon these developments, Priya et al. (2022) conducted a comprehensive analysis of the various determinants used in environmental liability allocation and proposed a structured framework that integrates scientific assessment with legal and equitable considerations in cases involving multiple polluters contributing to a common environmental damage. Recognizing the limitations of the current approaches to liability apportionment, the authors proposed a two-stage allocation procedure consisting of technical liability allocation followed by legal liability allocation. The framework is intended to improve transparency, consistency, and scientific defensibility in assigning remediation responsibilities among polluters.

The first stage, termed technical liability allocation, focuses on scientifically quantifiable characteristics of pollution and pollutants. According to the authors, technical liability represents the proportion of responsibility attributable to each polluter based on measurable environmental attributes determined through environmental forensic investigations. The proposed technical factors include pollutant quantity, toxicity, mobility, persistence, spread within environmental media, duration of pollutant release, and remediability of the contaminant within the affected environmental matrix. To operationalize these factors, the framework proposes the use of indices such as an "Impact Index" and a "Remediation Index," which collectively reflect the extent of environmental harm and the complexity of remediation attributable to each polluter. This stage therefore attempts to establish a scientifically derived proportional contribution of each responsible party.

The second stage involves legal liability allocation, wherein the technically derived shares are further adjusted using legal, regulatory, and equitable considerations. These may include negligence, regulatory non-compliance, economic benefit derived from the polluting activity, cooperation with authorities, and other jurisdiction-specific legal principles. In this manner, the framework combines objective scientific assessment with broader legal and policy considerations to arrive at a more balanced and equitable liability allocation. The proposal by Priya et al. is particularly significant because it allows technical experts to undertake the scientific component of liability determination while enabling the judiciary and regulatory authorities to focus primarily on legal and equitable considerations within their domain of expertise (Priya et al., 2025).

7. CONCLUDING REMARKS

Environmental liability allocation is an inherently complex and challenging task, particularly in situations involving multiple polluters, long-term contamination, and uncertainties in causation and environmental damage assessment. The principles underlying liability allocation reflect broader societal priorities regarding environmental protection, ecological restoration, public health, fairness, and accountability. Consequently, liability allocation practices must not only ensure effective recovery of remediation costs but also uphold the fundamental spirit of environmental justice and the polluter-pays principle.

The effectiveness of environmental liability systems depends significantly on the robustness, transparency, and scientific defensibility of the allocation procedures adopted. Well-defined allocation methodologies are essential for translating broad legal principles into practical, equitable, and implementable outcomes. In this context, liability allocation should not remain purely a legal exercise, as environmental contamination often involves highly technical issues related to pollutant behaviour, contaminant transport, ecological risk, environmental fate, and remediation complexity. Therefore, the involvement of technical experts, particularly environmental forensic experts, is essential for establishing scientifically sound and defensible allocation decisions. Integrating technical expertise with legal and regulatory considerations can substantially improve the accuracy, transparency, consistency, and acceptability of liability allocation outcomes, thereby contributing to more effective environmental remediation, environmental justice, and overall environmental governance.

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Grassroots Innovations in Solid Waste Management

SOCIAL AND CIRCULAR INNOVATIONS FROM BELOW: INSIGHTS FROM BINNERS INDIVIDUAL EXPERIENCES IN VICTORIA

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1. INTRODUCTION

This column presents preliminary results from an ongoing research project with waste pickers in Canada, where they are commonly called binners, exploring different forms of grassroots social innovation identified during fieldwork.

The project started in October 2025 and involved binners from Victoria and Vancouver, both in British Columbia, with a focus on understanding their educational background, needs, wishes, and dreams. Activities included: i) conversations and connections with non-profit organizations working with people experiencing social vulnerability; ii) visits to Bottle Depots, where binners deliver beverage containers, for observations and informal conversations; iii) short interviews with those interested in participating in the project; iv) and one workshop.

Although the project initially focused on education, this immersion into the daily realities of binners also provided broader insights into their experiences. Binners contribute to resource recovery and circular economy systems by collecting bottles discarded in public spaces, or recovering recyclables incorrectly disposed of in waste bins, and helping to keep refund money circulating within the local economy. In this sense, they simultaneously resist social exclusion while generating environmental benefits for society.

One of the main differences observed between the two cities is that, in Vancouver, many binners are connected through the Binners' Project (Binners' Project, 2025), while in Victoria they work mainly individually.

Our last research project conducted in this region in 2024 explored the role of grassroots organizations in the circular economy, showing examples of their social innovation, but was not able to explore the individual experiences of binners (Castro et al., 2026). For this reason, this column will focus on the case of Victoria, presenting the experience of three binners working individually, emphasizing their informal environmental stewardship and contributions to the circular economy.

Our argument is that social innovation also emerges among waste pickers working individually, even though the literature and our previous work often focused on organized groups such as cooperatives as case studies (Campos et al., 2022; Castro & Gutberlet, 2025; Gutberlet, 2021; Gutberlet et al., 2020, 2023).

2. CONTEXTUALIZING WASTE PICKERS IN CANADA

Waste picking activities in Canada are closely connected to Deposit Return Systems (DRS), also known as bottle bills (Container Recycling Institute, n.d.). In these systems, consumers pay a deposit when purchasing beverages and receive the money back when containers are returned to designated collection points. Since many containers are never returned by consumers, this creates an opportunity for people in need of income to collect and redeem them (Talbott, 2021). Different from many Global South contexts, where waste pickers usually sell different recyclable materials (Morais et al., 2022), in Canada, binners mainly return beverage containers and receive the deposit refund, as shown in Figure 1.

Some people question the relevance of this activity, since Canada already has separate collection and recycling systems in place. However, many beverage containers still end up littered in public spaces such as beaches and parks, or mixed with waste in incorrect bins, as showed in Figure 2. In this sense, binners help reduce pollution and increase recycling rates by recovering these materials. They also collect containers previously separated by residents for recycling. In these cases, the material would likely be recycled anyway, but the refund money would remain within the private recycling system. When collected by waste pickers, this money instead circulates within the local economy and can contribute, even in a limited way, to poverty reduction.

In Vancouver, waste pickers are commonly called binners; in Victoria, binners or diverters; and in Montreal, valoristes. In Vancouver and Montreal, grassroots waste picker organizations advocate for workers' rights and recognition while also creating better work opportunities (Castro et al., 2026). In Victoria, British Columbia, an organization called The Diverters' Foundation (DF) operated between 2020 and 2025, but the organization eventually ended its activities.

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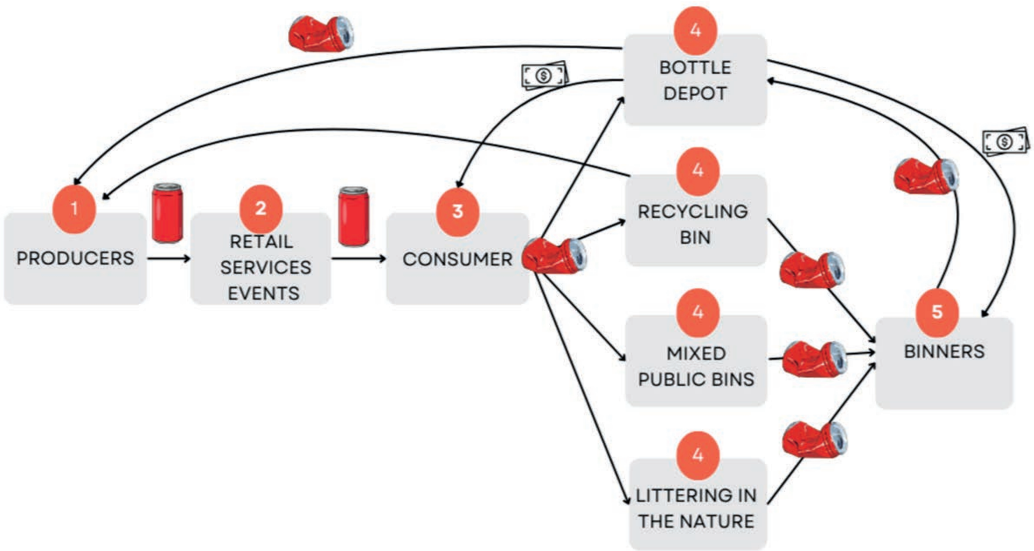

FIGURE 1: Flow of beverage containers with refunds in Victoria, highlighting where binners operate (Source: Authors).

3. BINNERS' SOCIAL AND CIRCULAR INNOVATIONS IN VICTORIA

Currently, there is no grassroots organization bringing binners together in Victoria to organize work or promote collective action. As a result, most binners work independently, with only a few collecting alongside a partner or friend, and the activity remains completely informal. Participants were approached and invited to join the research in front of a Bottle Depot in the downtown area, where many binners regularly deliver the beverage containers they collect.

FIGURE 2: A public waste bin located on Dallas Road in Victoria, BC, in April 2026. The bin did not allow for waste segregation, resulting in mixed waste disposal. Once full, recyclables such as beverage containers overflowed onto the ground, illustrating the role of binners in preventing pollution and diverting recyclable materials from landfill (Source: Authors).

Across interviews and informal conversations, broader issues such as housing insecurity, mental health challenges, stigma, and the ongoing drug crisis in British Columbia frequently emerged, reflecting some of the social vulnerabilities that shape the daily realities of many binners in the region.

This section discusses experiences and perspectives shared by three male participants who have been engaged in binning for several years: i) Binner 1, Ryan Thomas, a former member of The Diverters' Foundation (DF), who expressed pride in having his name included in the study and participated in both an interview and a workshop (Figure 3); ii) Binner 2, who participated in an interview but preferred to remain anonymous; and iii) Binner 3, who did not wish to participate formally in the interview process, but with whom informal conversations were conducted on two occasions near the depot.

Ryan expressed pride in being a binner and highlighted several positive aspects of the activity, including physical exercise, environmental contribution, and the possibility of earning daily cash income. He also demonstrated genuine concern for the environment, society, and his local community.

"I love this planet and I don't know why we're being so hazardous to it. It's disgusting… I just keep doing what's right, what I believe is right (…). There's so many positives that I've been mentioning that come from it (being a binner), like the exercise, the helping in the environment, the cash daily, so many positives for how could I not be proud of it?" (Ryan Thomas, April 10, 2026).

According to Ryan, binning in Victoria remains largely an individual activity, despite the existence of some sense of community among workers. He explained that working collectively can sometimes become distracting, reduce earnings, and limit autonomy regarding when, where, and how to work. He also mentioned that unequal levels of effort may create tensions when income needs to be shared.

FIGURE 3: From left to right, Julia, Ryan, and Ana, during the workshop held on April 10, 2026, at the public library in Downtown Victoria (Source: Authors).

These perspectives resemble reasons often identified in the literature for why some independent waste pickers do not want to join cooperatives (Rosaldo, 2022; Sekhwela & Samson, 2020).

When he was a member of the DF, Ryan participated in activities such as providing waste sorting and awareness services at events, organizing Bottle Drive initiatives where community members could donate containers and interact with binners, and contributing to the filming of a documentary about binners. At the same time, he continued collecting containers independently on the streets, which he still does today.

The contribution of binners to the circular economy extends beyond recycling. Besides recovering beverage containers, they also recover and recirculate reusable goods that would otherwise be discarded. Both Ryan and Binner 2 mentioned the large quantity of usable items disposed of by society and how binners intervene in this process. For example, Binner 2 regularly collects discarded materials to resell:

"*What introduced me to it (to become a binner) was… I was in Vancouver when they had a significant garbage strike and garbage just started piling up in the alleys and such and I was living in a low income neighborhood. There was just so many products in the driveway. VCRs, bikes, furniture, TVs, and you know, you can look at some of it and you say, well, that's garbage, that's garbage, but it's like 'oh, somebody will give me two bucks for this, and this here is 10 bucks'. So it was through that, that really, 'cause you walk by and you think 'I can't, I can't walk. I'll take a chance*". (Binner 2, March 10, 2026).

"*Christmas in the dumpsters are like hilarious man, like people's whole living rooms get thrown out because they get new stuff. Like you open up a bin and you're like 'oh I know this person's room is in here' (…) it's like perfectly good electronics, they still work and stuff like that (…). Its brutal how wasteful this society is.*" (Ryan Thomas, April 10, 2026).

Despite the contribution of binners to reuse and repurpose, this activity faces significant stigmatization. Ryan argues that it is essential for the community to understand that it is important work and to recognize how creative and talented these people are:

"*That's the cool thing, is how the bottle collectors will find stuff in garbages, and they make something out of it, like a trailer to bring with them or something, they make out of scraps. and some of these things are amazing what they come up with (…). I think that's a part of the stigma that needs to be exposed about these people. A lot of the stigma is that people that do that kind of work are pretty much useless to society. A lot of people view them like that, and some of the stuff they come up with will blow you away, man. And that means they're working too, like they make things*". (Ryan Thomas, April 10, 2026).

Binner 3 provides a clear example of this type of innovation through reuse, as he built his own adapted bicycle for collecting beverage containers, allowing him to transport and store larger quantities of materials while facilitating mobility, which may help explain his high productivity (Figure 4). Ryan also demonstrates high productivity and relies on a particular mode of transportation, using roller blades to move more quickly between collection points. In contrast, Binner 2 collects materials on foot and transports them to the depot by bus (this is only feasible because it's not a large quantity, since binners with big bags and a cart usually can't use public transport with them).

These three collection and transportation methods generate little or no pollution when compared to conventional waste collection systems that rely on trucks. In this sense, binners contribute not only through material recovery, but also through relatively low-impact collection practices.

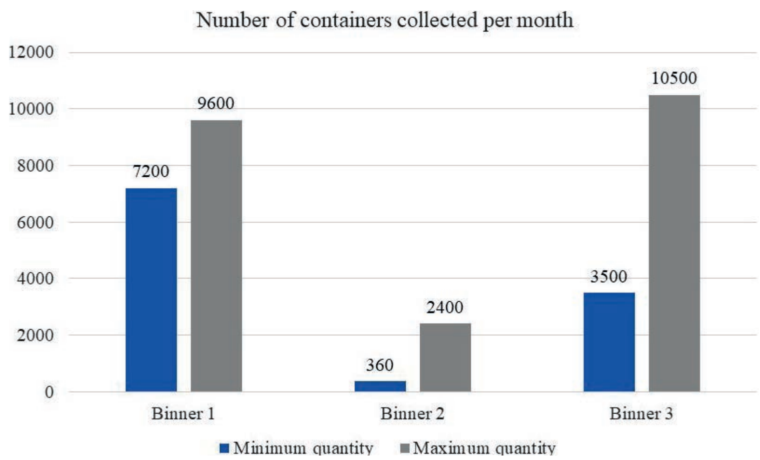

FIGURE 4: Estimated minimum and maximum number of containers collected by each binner per month. Source: Authors' calculations based on estimates provided by binners during fieldwork conducted in Victoria in 2026.

4. FINAL CONSIDERATIONS

This column presented an ongoing research project and some initial reflections on grassroots social innovations identified during fieldwork with binners in Victoria. The experiences discussed here illustrate how binners contribute to circular economy practices through reuse, repurposing, resale, and recycling activities, acting as informal environmental stewards despite persistent stigma and social vulnerability.

Based on our experiences conducting research in these regions, we recognize that grassroots organizations can strengthen the impacts generated by binners and improve their living conditions, by increasing visibility, creating more income opportunities, and supporting better working conditions. In this context, our intention is not to suggest that working individually is preferable. Rather, this column seeks to show that even with limited resources and support, binners working independently continue to develop adaptive practices and make environmental and social contributions to their communities.

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DETRITUS & ART / A personal point of view on Environment and Art

by Rainer Stegmann

Diedel Kloever, an artist that brings scrap to life

I met Diedel Kloever in his beautiful garden in Varel, Germany. He is a very hospitable and friendly person, deeply connected to his homeland. He sent me the following text, which is part of his biography written by Laava Royal (www.laavaroyal.com). To me, it characterizes Diedel Kloever`s work perfectly:

Sculptor, musician, and festival producer, Diedel Kloever has spent the past two decades turning discarded metal into living works of art. He describes himself as a "scrap artist." Known for his Yard Art sculpture garden, Kloever welds old tools, car parts, and other unwanted metal into strikingly lifelike figures—animal and human forms that seem alive with energy.

Kloever was always drawn to painting, tinkering, and creating. However, it wasn't until the early 2000s, after he taught himself to weld, that he discovered his authentic artistic voice. Unlike many sculptors who start with a sketch, Kloever begins with the raw material itself. The scraps decide what story they want to tell. Each piece evolves organically, guided by the metal's shapes and his intuitive sense of form. The results are strikingly realistic, two of his most impressive pieces being a massive silverback gorilla head that seems to return your gaze, and a rhino that stands sentinel as the garden's "watchman". He not only sculpts realistic-looking animals but also gives them an expression and brings them to life.

Diedel Kloever showed me his impressive workshop, where he creates his sculptures like a locksmith, using a variety of tools, including welding equipment. It is often forgotten that when we admire sculptures and statues, there is the hard work of the manufacturing process and the craftsmanship that the artist must possess. I think the examples presented here speak for themselves. I am always pleasantly surprised by the enthusiasm Diedel Kloever shows in creating his work. It reminds me of scientists who are as devoted to their work as artists like him are. They want to solve a problem that makes them think about it "all the time". Only when you are really devoted to your work outstanding results can be reached.

Diedel Kloever receives his metal scrap from a local manufacturer and has no trouble obtaining adequate material. In general, scrap metals are recycled. Recycling pure iron and steel is standard practice, but alloy steel, which accounts for about 20% of total iron and steel, cannot be recycled in the same way because it produces inferior steel; therefore, alloy steel must be separated from delivered steel scrap upfront in a complex process. Recycling involves separating alloying metals during thermal recycling, as different metals melt at different temperatures; this process does not achieve 100% separation. Diedel Kloever opens our eyes to the beauty that hides in scrap, as well as to its material value.

More information about the artist can be found on his website at www.yard-art.de.

In the next issue of DETRITUS, I will discuss with you whether the image presented is art or waste

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