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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

THE INTENTION-BEHAVIOR GAP AND THE ROLE OF PSYCHOLOGY IN THE TRANSITION TO A CIRCULAR ECONOMY

Why do people resist adopting a different lifestyle or changing their habits? How can we spur positive change that leads to a more sustainable and equitable society? Answering these questions is crucial to building a circular economy and reducing waste. Engaging citizens and understanding why they might resist to change is essential to making progress efficiently and without delay.

In this regard, psychology can offer valuable insights. For example, one issue that psychological research has extensively examined is the intention-behavior gap (Sheeran & Webb, 2016) - that is, people's difficulty in translating intentions into actual behavior. This is something many of us have experienced at some point, such as when we intended to start a diet, exercise more, or quit smoking.

To understand why the intention-behavior gap exists, it helps to look briefly at dual-process theories (Kahneman, 2011). Psychologists identify two main thinking systems: the intuitive system and the analytical system. The intuitive system is fast, based on feelings and associative mechanisms, and does not require much effort. The analytical system is slower, relies on conscious reasoning, uses learned rules, and requires cognitive effort in terms of attention and memory. While the intuitive system generates quick, rough solutions, the analytical system is supposed to vet and, if necessary, override them. However, this vetting process is cognitively demanding. As a result, the analytical system often functions as a permissive controller, allowing the intuitive system to dominate in order to conserve energy.

From this perspective, we see that forming good intentions-such as eating less meat, recycling, or buying more sustainable products-is relatively easy. Acting on those intentions, however, can feel burdensome. We may enjoy meat, recycling demands attentiveness, and sustainable products are often more expensive. Without strong motivation, our intuitive system generates justifications to avoid these tasks (sometimes even embracing blatantly false information), and our permissive analytical system accepts or even bolsters these rationalizations-a process known as motivated reasoning.

Here, motivation is key. A young person who is deeply concerned about environmental degradation may walk to work under the summer sun, buy second-hand clothes, and meticulously sort their waste. Others may do none of these things. Most people fall somewhere in between, acting sustainably when it's meaningful or convenient-for example, biking to work but only when the weather is pleasant.

These justifications are often driven by affective reactions-automatic, emotional responses that guide our perceptions of risks and benefits (the affect heuristic; Slovic et al., 2007). One telling example is public skepticism toward green chemistry. Many people associate synthetic substances with negative emotions (a phenomenon called chemophobia; Saleh et al., 2019), viewing them as risky and unnatural. In contrast, natural substances evoke positive feelings and are seen as safer and healthier. For instance, people are more accepting of the same level of risk when it comes from traditional meat than from cultured meat, simply because the latter is perceived as more artificial.

Research also shows that additions to natural products reduce perceived naturalness more than removals. For example, adding pulp to orange juice makes it seem less natural than removing it. Similarly, saying a gene was added to an organism (versus removed) reduces perceived naturalness more sharply.

These insights have important implications for the transition to a circular economy. When we introduce sustainable alternatives to traditional products, we must consider these psychological dynamics. For example, producing recycled textiles for the fashion industry often involves chemical additives. This can trigger resistance, as consumers may believe unsubstantiated claims (e.g., "these chemicals will irritate the skin")-beliefs that can be exploited by those seeking to preserve the status quo.

To prevent such resistance, we must harness psychology to understand public perceptions and design effective communication strategies-strategies that reassure consumers without concealing information or potential risks. These can include emotionally positive labeling, effective framing, incentives, and clear, transparent messaging that counters irrational beliefs.

Another crucial factor is context. People's behavior is heavily influenced by the environment in which they make decisions. Take the fashion industry: it's increasingly difficult to resist buying new clothes. Many consumers receive frequent promotional emails from favorite brands, and a single click leads them straight to an online shop. From there, it's easy to select a size, add items to the cart, and pay-sometimes with a stored payment method that streamlines the process. Some enjoy in-store shopping, but for many, the convenience and low cost of online fashion are

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irresistible. Over time, repeated visits to vendor websites reinforce the urge to purchase-especially during sales.

Some interventions have targeted these contextual cues, such as encouraging people to unsubscribe from marketing emails or making second-hand purchases and clothing rental options more convenient-for example, by offering these alternatives alongside new clothing options and highlighting favorable cost comparisons. New technologies like on-demand clothes may also help reduce overproduction. However, public acceptance of these solutions remains uncertain. Some individuals may feel uncomfortable with second-hand clothing due to hygiene concerns. Likewise, on-demand clothes could raise privacy issues or significantly alter the shopping experience in ways some may find off-putting.

In this editorial, I have emphasized the importance of understanding the psychological roots of resistance to sustainability-oriented innovations. Doing so can accelerate the transition to a circular economy and a more sustainable society-but only if done ethically. It must not become a way to impose lifestyles that people are unwilling to adopt. We have already seen how top-down initiatives can backfire. Citizens have the right to voice concerns and reject proposed solutions. Policymakers must listen, explain clearly why certain approaches are supported by science, and engage in participatory decision-making wherever possible.

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IMPROVING WASTE SEPARATION IN PUBLIC SPACES – A FIELD STUDY FROM AUSTRIAN CITIES

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ABSTRACT

Improving waste separation is fundamental to promoting a more sustainable and circular economy. While waste separation in private households is already widely established, it is often neglected in public spaces such as parks or public squares despite high recovery potential (e.g. of single-use packaging from to-go consumption). Hence, particularly with respect to the public sphere, there is a lack of specific knowledge about separation behaviour and separation performance. In order to fill this knowledge gap, field trials were designed and carried out in an interdisciplinary collaboration effort (cooperation of industrial design, social sciences, waste management) to investigate public separation behaviour and resource potential. Additionally, a novel improvement measure was tested in the form of a "recyclables guidance system". The test setups were implemented at four public test locations in two Austrian cities. The results showed that by installing a centralized waste separation station, about 17% of public waste was collected separately and 20% of recyclables were correctly disposed of in the test areas. The implementation of a guidance system resulted in a slight overall improvement in separation performance (total recyclables collection rate +4.6%) and thus shows potential as a cost-effective measure for future applications. The results of this study contribute to a better understanding of waste separation behaviour and have practical implications for promoting more sustainable waste management practices in public spaces.

1. INTRODUCTION

1.1 Waste collection in public spaces

Separate waste collection is fundamental to enabling high-quality material recycling and is one of the key priorities in the EU's circular economy strategy. By progressively increasing the targets for the reuse and recycling of municipal waste, the EU aims to bring about a transformation towards circular material utilisation. Recycling quotes for plastic packaging of 50% by 2025 and 55% by 2030 must be met (directive 94/62/EG, Article 6), and a separate collection target of 90% for beverage packaging must be achieved by 2029 (EU directive 2019/904, Article 9). While in the EU waste separation schemes are widely implemented in private households and some privately managed semi-public spaces, such as public transport stations, airports, and shopping malls, they are often overlooked in public areas like parks, pedestrian zones, and streets, where the primary focus is on preventing littering. A survey among Austrian municipalities in 2024, for example, revealed that only 1% of public waste containers are intended for separate waste collection (Egger, 2024).

Although public waste represents a relatively small waste stream, approx. 2 to 5% of the municipal solid waste in Austria (MSW) (BMK, 2023; Kladnik et al., 2024; TBH, 2021), the few published studies on this waste stream indicate that its resource potential is high. For example, in the city of Krems (Austria), over 50% of the public waste was found to be recyclables (Kladnik et al., 2024) and waste analysis from other regions (Germany, Vietnam, Belgium) have shown similarly high percentages (Gellenbeck and Reuter, 2020; Pham Phu et al., 2019; Verstegen et al., 2022). Especially at urban hot spots, including places in the proximity of eating establishments (high generation of recyclables) or at places with a high pedestrian frequency (high proportion of recyclables), such as shopping streets, the potential for resource recovery is high (Gangl et al., 2022). If correctly disposed of and collected, these materials could be reintroduced into a recycling scheme and contribute to a circular economy. However, waste in public spaces plays a crucial role not only because of the valuable recyclable materials it contains, but also because of its high visibility and its potential to act as a "role model" and driver of social change, encouraging sustainable behaviour by setting a positive example in public.

A practical reason for the current lack of waste separation in public spaces may be the already high operational

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costs associated with public waste management, particularly in the collection process. When roughly compared to household waste collection costs (Province Lower Austria, 2022; Rechnungshof, 2014; Reh et al., 2014), the costs of managing public waste (KPLUSV, 2020; TBH, 2021; Wilts et al., 2022), could be up to seven times higher per tonne. Additional efforts for introducing separation schemes, including costs for container acquisition, extra storage space and waste transport, potentially act as further cost drivers.

Beyond operational factors, the success of collection schemes heavily relies on citizen engagement. Studies from Austria show that separate collection of waste has not yet become a social norm in public spaces and is considered a lower priority compared to households (ARA, 2023; Gök, 2023; Gök et al.; Hartl et al., n.d.), which presents greater challenges for the implementation.

1.2 Factors influencing waste separation behaviour

Effective recycling programmes rely on a well-designed collection infrastructure. Factors such as bin colour, shape and size, which influence visibility and attractiveness, may play an influential role in driving participation. As findings from experimental studies suggest, changing the appearance of waste bins by covering them with pleasant brightly coloured nature designs (Gangl et al., 2022; Lin et al., 2016), using bright green compared to grey bins (Montazeri et al., 2012) or using compost bins with the highest design preference scores (Leeabai et al., 2022) positively enhanced waste separation under certain conditions. However, it is not a general rule that container designs with high consumer preference (e.g. preferred colours and opening shapes or fun design) are able to trigger a positive behavioural response, as shown by Jiang et al. (2019), Leeabai et al. (2021) and Supakata (2018). The effect may also depend on the context and vary from location to location (Gangl et al., 2022). In any case, unclean-looking containers and surroundings can discourage consumers from using containers and should be avoided (Gangl et al., 2022; Hartl & Hofmann, 2024; Supakata, 2018).

In addition, it is important to incorporate design features that clearly communicate recycling information, as knowing the rules of correct waste disposal is essential (Rousta et al., 2017; Uehara et al., 2022). The provision of recycling information directly on containers, for example applied in the form of clear and/or encouraging signs and stickers, showed a positive effect on waste separation in some studies (Austin et al., 1993; Jiang et al., 2019; Rousta et al., 2015; Sussman et al., 2013). Interventions that provided information indirectly, such as through educational lectures or the distribution of information leaflets or displays, have shown mixed results, highlighting the gap between people's intentions and their actual behaviour (Abbasi et al., 2020; Árnadóttir et al., 2019; Moreland & Melsop, 2014; Sadeghi et al., 2020; Tangwanichagapong et al., 2017). Rousta et al. (2017) emphasized that, in addition to information design, the way of conveying information is crucial and that it should be presented recurrently in a way that engages users. The use of recurrent and consistent container and signage design and established colour coding is also highlighted as beneficial in other studies (Ahmed et al., 2016; European Commission et al., 2024; Lee & Manfredi, 2021; Wu et al., 2018).

While studies on improving waste separation use different strategies and reach different conclusions, they generally agree that making separation easy and convenient for consumers is essential. Therefore, the setting conditions - encompassing the distance to waste bins, their arrangement, placement and noticeability - play a predominant role (Andrews et al., 2013; DiGiacomo et al., 2018; Gangl et al., 2022; Kalatzi et al., Leeabai et al., 2019; 2015; McCoy et al., 2018). More convenient setting conditions have shown to be especially effective if coupled with other incentive programs or improvements in information (Miller et al., 2016; Moreland and Melsop, 2014; Rousta et al., 2015; Struk, 2017). Waste bins positioned within shorter distances are more effective in capturing recyclables (González-Torre and Adenso-Díaz, 2005; Rousta et al., 2015). However, there is no universal distance level that individuals are willing to walk for the purposes of recycling, as this depends on the situation and setting conditions. For example, Leebai et al. (2019) suggest thresholds between 8 and 410m in which waste disposal behaviour may be affected, depending substantially on the walking path direction. Concerning the arrangement of the separation containers, studies suggest that it is critical that these be placed side by side, as short distances may already be a barrier to performing waste separation and may increase contaminations and decrease separation efficiencies (Andrews et al., 2013; Jiang et al., 2019; Leeabai et al., 2019).

Overall, findings from experimental studies suggest that the key factors to ensure participation in separate waste collection are: (1) the availability of appropriate recycling infrastructure (bin design), (2) convenience, encompassing setting conditions (e.g. waste bin distance and arrangement), and (3) clear information on waste separation. Considering the regional context in infrastructure design is, in any case, critical since preferences and associations towards container design and waste types vary depending on the region (Jiang et al., 2021; Keramitsoglou and Tsagarakis, 2018; Schloss et al., 2018).

1.3 Objectives of the present study

Although numerous studies have examined waste separation behaviour, particularly in a semi-public context such as universities (Abbasi et al., 2020; Ahmed et al., 2016; Andrews et al., 2013; Austin et al., 1993; Cheung et al., 2018; Jiang et al., 2019, 2021a; Kalatzi et al., 2015; Lee and Manfredi, 2021; Leeabai et al., 2019, 2022; McCoy et al., 2018; Miller et al., 2016; Moreland and Melsop, 2014; Supakata, 2018; Tangwanichagapong et al., 2017), research on recycling in other public spaces remains limited. This context poses unique challenges, such as high collection efforts, a lack of separation infrastructure and separation norms, which need to be addressed for successful implementation.

This research pioneers a systematic examination of waste separation behaviour in public settings through a novel, empirically-based field test design. The study aims to:

1. Assess the impact of introducing waste separation in public spaces on separation performance (collection, capture and contamination) across different waste types, and identify opportunities to optimise resource recovery.
2. Explore whether waste separation can be enhanced by implementing an improvement measure using a "recyclables guidance system" based on wayfinding principles.

As an essential part of the field study, centralized separation stations were introduced in multiple public locations and a novel guidance system for recyclables was developed and tested under real field conditions. The field tests were accompanied by comprehensive waste audits, which are the focus of this paper, as well as behavioural observations, which are part of a separate publication (Hartl et al., n.d.).

2. METHODS

The field tests were developed by an interdisciplinary project team combining the research areas of social science, industrial design and waste management and were carried out in spring/ summer 2023 at four public test locations identified as "waste hotspots" in two Austrian cities. At these locations, first, a central station for waste separation (SS) was installed, followed by the installation of a "recyclables guidance system" on the surrounding residual waste containers (RWC) as a potential measure of improvement. Detailed waste analyses were performed to evaluate the effects of these interventions and their overall impact. The specific elements of the study are detailed below.

2.1 Field tests

The field test setup includes the following steps: 1. Installation/ modification of the central separation station (SS), 2. Stabilisation period I, 3. Baseline waste audit (base), 4. Intervention (guidance system) 5. Stabilisation period II, 6. Post waste audit (post), as shown schematically in Figure 1 and described below. Further details on the test setup and locations can be found in Supplementary Material (SM) (see chapters 1.1 to 1.6).

2.1.1 Test locations and installation of separation stations

As it is known that the level of urbanisation influences participation in separate collection (Edjabou et al., 2014; Feil et al., 2017; Schuch et al., 2023), two cities with different urbanisation levels, Vienna (2 million inhabitants) and Krems an der Donau (50,000 inhabitants), were included. Both cities have similar household waste collection systems in place, which separate paper (packaging and non-packaging), biowaste (bio-waste), glass (packaging glass) and lightweight packaging. In Austria, lightweight packaging collection recently started to be harmonized in January 2023 to include the collection of beverage bottles, composite packaging, metal and all types of plastic packaging (films, trays, cups, etc.) in one collection fraction. In public places of the two cities, mainly residual waste is currently collected, with the exception of public transport areas, where separation bins are often installed. Suitable test locations were selected by identifying public "hot spots" with a high potential for implementing waste separation and a guidance system (high pedestrian traffic, high density of public containers and high consumption in the area). In Vienna, a publicly utilized outdoor area at a university campus (UC) and a frequented forecourt of a subway station entrance (S) were chosen. In Krems, the square in front of the train station (TS) and the pedestrian zone in the old town (PZ) were chosen. At these four locations, a new waste separation station (SS) was introduced (or modified) in addition to several existing public containers for residual waste (RWC). The included RWC containers and catchment areas were defined in such a way that RWCs are located within a reasonable walking radius and along the pedestrian route around the SS to result in comparable container densities at the different locations (between 32 to 41 containers per ha). The number or ratio of SSs to RWCs that were included varied depending on the location conditions, ranging from 1 to 13 to 1 to 6. The approach of introducing one centralized SS instead of a comprehensive replacement of all existing RWCs was chosen to min-

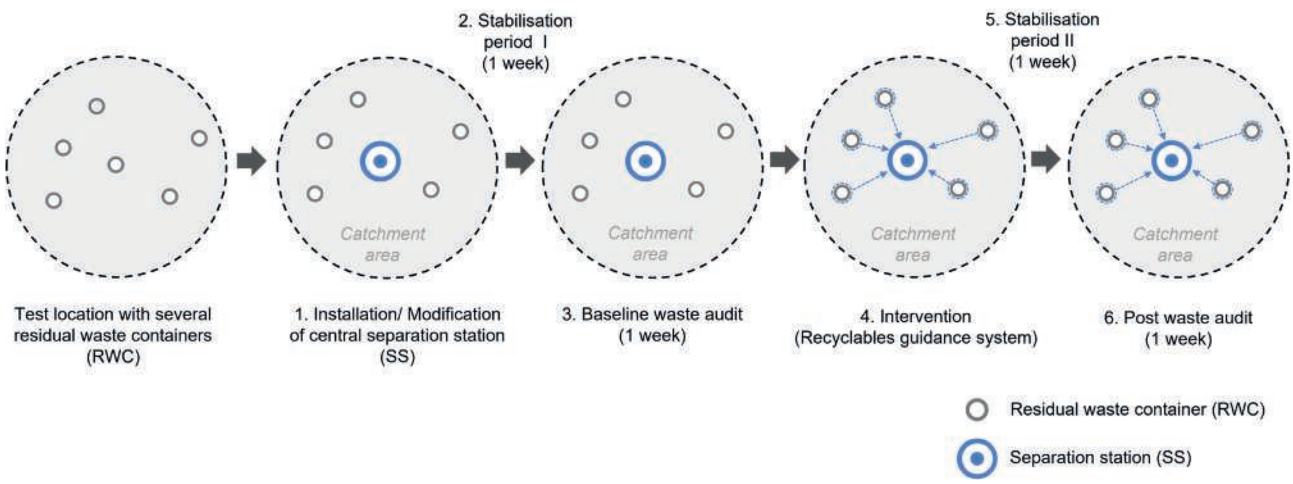


FIGURE 1: Scheme of the field test setup.

imize the additional efforts in disposal logistics and, thus, to present a more realistic implementation scenario. The positioning and design of the SS was done in consultation with the local authorities and as joint effort of the interdisciplinary project team, taking into account the findings on critical factors for separation behaviour (as mentioned in the introduction) and local conditions. A location analysis was carried out beforehand to determine the optimal central and visible positioning of the SS and the number of included surrounding RWCs. The walking distance from an RWC to the SS ranged between 7m and 135m in the locations (total average of 38m). More information on the test locations is provided in the SM (see chapter 1.1).

The SS comprised separation containers (SC) for coloured and white glass (GL), lightweight packaging (LWP), including composite, metal and plastic packaging, and paper (PAP), which were installed next to an existing residual waste container (SSRWC). The SCs used were of the same design as the containers already installed in the area and were clearly labelled with signage stickers using the locally established colour coding (yellow - lightweight packaging, green or white - glass, red - paper, grey or orange - residual waste) and displaying photographs of commonly disposed of waste items (see further details on signage in SM chapter 1.4). A separate collection of biogenic waste was not considered due to the impracticality (vermin, spoilage, emptying). Therefore, biogenic waste in the study is not a target for recoverable waste, but a target for residual waste. At the University Campus (UC), a separate collection for metal, plastic, coloured glass (GLc) and white glass (GLw) was already in place prior to the study. Hence, only modifications were necessary to fit the purpose of this study (see further details in SM chapter 1.1.4.).

FIGURE 2: a) Field test setting at pedestrian zone in Krems. b) Guidance sticker with text (translated): Residual waste, no recyclables please! Waste separation 25 seconds. c) Overhead signs with text (translated): Waste separation, here!

2.1.2 Stabilisation period

A stabilisation period of at least one week was arranged to mitigate any disruption or adaption effects of the initial implementation of an intervention and to observe whether any unintended consequences occurred. During this time, no waste audit was conducted.

2.1.3 Intervention - Recyclables guidance system

The guidance system was designed in the form of stickers that were applied to RWCS and aimed at propagating waste separation behaviour by generating attention via signal colours (red) and format (Stop sign) and by providing information in the form of clear separation instructions (Figure 2, a) and b)). The instructions are displayed as a verbal prompt ("Residual waste, no recyclables please!"), include illustrations of waste items and are enforced through colour coding (red = wrong, green = correct) and icons (cross = wrong, check mark = correct). The size of the guidance stickers varied between 42x47cm and 31x35cm depending on the location and container size. The illustrations were chosen in photographic style as these are often preferred over icons (Gangl et al., 2022; YaHan, 2020) and were based upon frequent public waste found in prior waste analysis (Kladnik et al., 2024). The guidance stickers further included information on the walking distance as duration (in seconds and minutes) and direction (arrow) to the next separation station. Duration was chosen as people have a tendency to overestimate walking distances, especially when given in metric units of length, making them potentially less willing to walk (Ralph et al., 2020). In addition, clearly visible overhead signs were placed above the separation station to mark the destination (Figure 2 c).

2.1.4 Waste audit

To evaluate the waste separation behaviour, two waste audits per test location were conducted: one audit as a baseline (base) during one week after installation of the central SS and one audit as a post audit (post) during one week after the intervention. The waste from the test locations was collected daily within a consistent time interval of 24 hours. The containers were emptied into bags, labelled (date, fraction, location) and weighted individually. Bags from RWCs were pooled into one sample and bags from the SCs were treated as individual samples. At the UC, white glass and coloured glass, and plastic and metal were later combined in one fraction in the analysis (GL and LWP) to allow comparison with the other test locations.

The samples were sorted by manual picking analysis separately for each location, for each collection fraction (RWC, SSRWC, GL, PAP, LWP) and for each collection day. The sorting catalogue was mainly based on official separation recommendations for consumers as specified and communicated by the Austrian federal ministry as well as by the municipalities of Vienna and Krems (BMNT, 2019; City of Vienna, 2024; Municipal association Krems, 2024). The waste was sorted into 25 subfractions corresponding to the target fraction of collection (Table 1). There are certain problematic waste items which in previous studies have been found to be commonly confusing to consumers for correct disposal, for example napkins, coffee-to-go cups, coated cardboard packaging and composite packaging, while other waste items, such as plastic bottles, tend to be more easily understood (Andrews et al., 2013; Gangl et al., 2022; Hartl and Hofmann, 2024; Jiang et al., 2021; YaHan, 2020). These items were regarded as separate fractions in the sorting catalogue and some were depicted on the separation signage (coffee-to-go cup, hygienic paper). A detailed sorting catalogue with further specifications on classification and examples of sorting fractions is provided in the SM (see chapter 1.6).

The data were recorded as wet packaging weight, including product residues and moisture. After sorting, the mass of the sorted fractions was documented and cross-checked with the initial sample mass to ensure accuracy. The maximum allowed deviation was set at 3%.

2.2 Performance Indicators (SCR, CR, CL)

In the present study, a comprehensive set of performance indicators was used to evaluate waste separation efficiency, quality and recovery potential.

The separate collection rate (SCR) reflects the share of waste collected in a certain waste container and represents a rough measure for participation in separate collection, as waste composition and contamination are not considered. It is a typical indicator used in official reporting and was therefore included for comparisons and is calculated according to Equation 1.

$$SCR = \frac{\text{weight of waste collected in container A}}{\text{weight of waste collected in all containers in the test area}} \text{ x } 100\ \% \quad (1)$$

The capture rate (CR) refers to a specific target waste and is defined as the share of waste correctly disposed of in the target container in relation to the total waste of that type generated (Equation 2). It represents a measure for the separation efficiency of a specific waste type.

$$CR = \frac{\text{weight of correctly disposed of target waste a in target container A}}{\text{weight of all target waste collected in all containers}} \text{ x } 100\ \% \quad (2)$$

The contamination level (CL) refers to a certain waste container, where it indicates the share of unwanted materials disposed of in the container (Equation 3). It represents a measure for separation quality in the case of separation fractions (GL, PAP, LWP) and a measure for the recovery potential of recyclables in the case of residual waste (con-

TABLE 1: Sorting catalogue for waste audits.

Waste sorting fraction		Subfraction		Abbreviation
1	Residual waste (rw)	1.1	Biogenic waste - unavoidable food waste and organics	ufw
		1.2	Biogenic waste - avoidable food waste - unpackaged	fwu
		1.3	Biogenic waste - avoidable food waste and beverages - packaged (incl. packaging)	fwp
		1.4	Hygienic paper and sanitary articles	hyg
		1.5	Dog feces	dog
		1.6	Other waste	otw
		1.7	Paper non-packaging contaminants	pco
2	Paper, cardboard, corrugated board (PCC) (pap)	2.1	PCC packaging[1]	ppa
		2.2	PCC non-packaging	pnp
3	Lightweight packaging (lwp)	3.1	Plastic beverage bottles	pbb
		3.2	Other plastic packaging	opp
		3.3	Metal beverage packaging	mbp
		3.4	Other metal packaging	omp
		3.5	Composite packaging - beverage carton	cbc
		3.6	Composite packaging - PCC composite packaging and coated PCC packaging	cpa
		3.7	Composite packaging - coated cardboard cups for liquid food and beverages	ccc
		3.8	Composite packaging - plastic-metal composites	cpm
		3.9	Other lightweight packaging	olw
4	Glass packaging (gl)	4.1	Coloured glass packaging	cgl
		4.2	White glass packaging	wgl
5	Other collection points (o)	5.1	Problem waste	prw
		5.2	WEEE, batteries and lamps	wbl
		5.3	Metals non-packaging	mnp
		5.4	Textiles	tex
6	Sorting residue (sr)	6	Sorting residue	sor

Remark: rw and sr are considered non-recyclables; pap, lwp, gl and o are considered recyclables in the context of the field study taminant in RWC = recyclable material other collection points target factions).

$$CL = \frac{\text{weight of incorrectly disposed of waste a in container A}}{\text{weight of all waste collected in container A*}} \times 100\,\% \quad (3)$$

The CL and CR generally refer to the sum of subfractions classified as target waste or incorrectly disposed of waste, but can also refer to the specific subfractions a_x (e.g., hygienic paper) in a container A (e.g. PAP), hereinafter referred to as the specific contamination level ($CL_{sp}(a_x)$ A) and specific capture rate ($CR_{sp}(a_x)A$).

In the test setup, a change in indicators (e.g. +/- ΔSCR) before and after the intervention was analysed to evaluate the effect of the guidance system.

2.3 Data treatment and statistical methods

The amount of waste generated and waste separation performance varied considerably over the course of the week among the different test locations. To counteract daily and location fluctuations and obtain weighted results, the main results are presented based on the absolute changes in weekly waste amounts cumulated from all four test locations (total). To identify potential statistically significant effects of the intervention, a paired t-test was applied to compare the means of performance indicators during base and post-audit based on individual daily values. For each test location, and in total (cumulated waste from all test locations), daily performance indicators were assessed, resulting in n=7 observations per collection fraction (RWC, SSRWC, LWP, PAP, GL) per audit week. Hence, seven values of the baseline week are compared with seven values of the post-week.

Prior to the significance tests, the gaussian normality of the data was assessed using a Shapiro-Wilk test to determine whether parametric or non-parametric tests are appropriate. As normality was violated in some cases, a non-parametric two-sample permutation t-test was performed in addition to the regular student's t-test using the Software R. and the function "perm.t.test" (package MKinfer). This test generates the sampling distribution from the observed data rather than relying on the assumption of an existing sampling distribution and is suitable for small sample sizes (Christensen & Zabriskie, 2022; Menke & Martinez, 2004). Significance test results are reported in the main article if the rejection of the null hypothesis is true (confidence level 0.95) and in full in the SM (see SM chapter 2.3).

During the waste sorting analyses, it became evident that waste which was not generated in public space but rather originated from households, shops or restaurants (in this study specified as "unauthorized waste") was consistently disposed of into the bins. As this potentially skews the results, outliers were eliminated from the data analysis if possible (see SM chapter 1.7).

3. RESULTS AND DISCUSSION

The following results are based on extensive waste sorting analysis. In the course of the analyses, a total of 1,665 kg of waste was collected for the analysis (base: 795 kg, post: 870 kg). The quantities varied greatly between the different test locations and over the course of the week, which is reflected in high standard deviations of the average daily quantities (see collection quantities in SM chapter 2.1).

3.1 Waste separation in public spaces

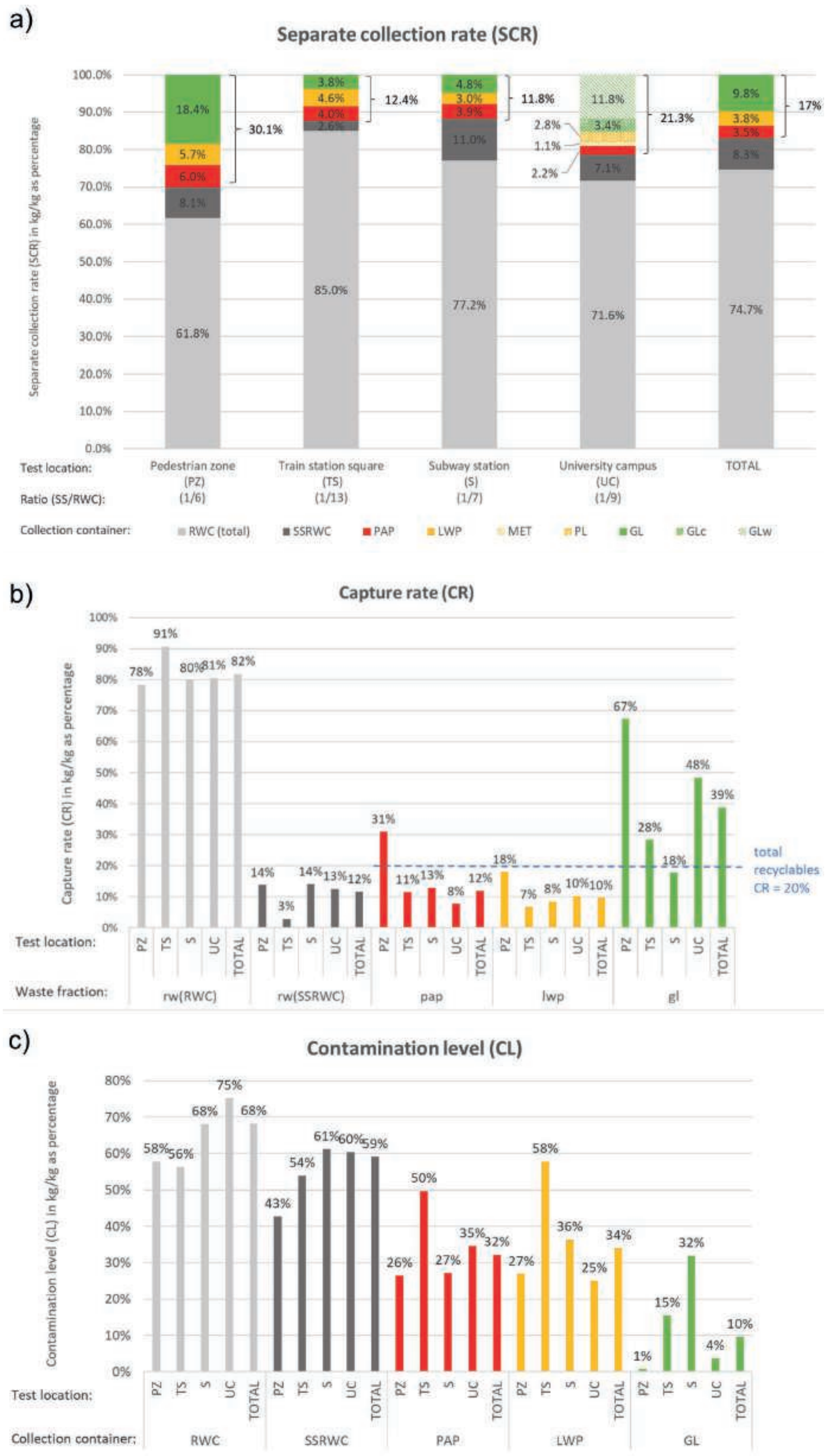
The following results of introducing waste separation are discussed based on the total weekly cumulative waste from all four test locations across both waste audits (baseline + post-intervention week) and are summarized in Figure 3. The overall performance after implementation of the waste separation station is presented independently of the improvement measure (recyclables guidance system), as the impact of the intervention was limited (overall effect < 5%; see chapter 3.2, which details the impact of the guidance system). More detailed results by waste type are presented in Table 2. The results per analysis week, as well as implications of the results on the differences between the test locations, are presented and discussed in the SM (see chapters 2.1-2.6).

3.1.1 Separate collection performance

The separate collection rate (SCR) is determined by the distribution of quantities in the different containers and is, therefore, strongly dependent on the generated waste and the number or ratio of SS/RWC in the test areas. The introduction of separate collection led to total SCR ranging between 30.1% in the pedestrian zone PZ ("best case scenario" with the lowest ratio SS/ RWC 1 to 6) and 11.8% at the subway station entrance S (ratio SS/RWC 1 to 7). Overall, a total SCR of 17% was measured, which was the highest for glass (9.8%) followed by LWP (3.8%) and PAP (3.5%) (Figure 3 a).

3.1.2 Separation efficiency

The separation efficiency (measured by the capture rate CR) indicates which waste types have been better "understood" and are better separated compared to others. In total, the waste separated most efficiently in the public test locations is glass (CR 39%), followed by paper (CR 12%) and lightweight packaging (CR 10%) (Figure 3 b). Specific separation efficiencies (measured by CR_{sp}) for recyclables are presented in Table 2 and more detailed for all waste types and differentiated audit weeks in the SM (see chapter 2.2). Results show that separation commitment varies considerably depending on the specific waste type. Recyclables with higher ranging separation efficiency (CR_{sp} > 10%) include glass packaging (particularly white glass), paper packaging and paper non-packaging (mainly newspapers), plastic beverage bottles and metal beverage packaging, while recyclables with particularly low separation efficiency (< 5%) include paper composite packaging (including coated paper packaging), other lightweight packaging (mainly wooden cutlery), beverage carton and coated cardboard cups (Table 2). These differences may partly be attributed to the fact that certain waste items were depicted on the separation station (e.g. newspapers, beverage bottle; see SM chapter 1.4), acting as an important source of information. Some consumers have been observed comparing their own waste to the separation



Collection fractions: RWC – residual waste, SSRWC – residual waste at separation station, PAP – paper waste, LWP – lightweight packaging (total), MET – metal packaging waste, PL – plastic packaging, GL – glass waste (total), GLw – glass waste white, GLc – glass waste coloured

Waste fractions: rw – residual waste, pap – paper, lwp – lightweight packaging, gl - glass

FIGURE 3: Results of field test based on total amount of waste for each test location and cumulated (total). a) Separate collection rate (SCR), b) Capture rate (CR), c) Contamination level (CL).

TABLE 2: Waste-type specific results on separation efficiency, contaminations and recovery potential based on total amount of waste (base + post) and combined test locations (total).

Collection fraction	Subfraction (a_x)	Indicator
Separation efficiency (CR_{sp})		
		$CR_{sp}(a_x)PAP$
Paper	PCC non-packaging (pnp)	13.8%
	PCC packaging (ppa)	10.0%
		$CR_{sp}(a_x)LWP$
Lightweight packaging	Plastic beverage bottles (pbb)	19.9%
	Metal beverage packaging (mbp)	13.5%
	Composite packaging - plastic-metal composites (cpm)	9.9%
	Other metal packaging (omp) Other plastic packaging (opp)	9.9% 7.9%
	Composite packaging - coated cardboard cups for liquid food and beverages (ccc)	4.1%
	Composite packaging - beverage carton (cbc)	3.7%
	Other lightweight packaging (olw)	2.6%
	Composite packaging - PCC composite packaging and coated PCC packaging (cpa)	1.7%
		$CR_{sp}(a_x)GL$
Glass	White glass packaging (wgl)	48.4%
	Coloured glass packaging (cgl)	26.8%
Contaminations (CL_{sp})		
		$CL_{sp}(a_x)PAP$
Paper top 3	hygienic paper and sanitary articles (hyg)	5.9%
	Composite packaging - PCC composite packaging and coated PCC packaging (cpa)	4.1%
	Paper non-packaging contaminants (pco)	4.0%
		$CL_{sp}(a_x)LWP$
Lightweight packaging top 3	avoidable food waste and beverages - packaged (incl. packaging) (fwp)	13.7%
	PCC packaging (ppa)	4.1%
	hygienic paper and sanitary articles (hyg)	4.1%
		$CL_{sp}(a_x)GL$
Glass top 3	avoidable food waste and beverages - packaged (incl. packaging) (fwp)	2.8%
	metal beverage packaging (mbp)	1.8%
	plastic beverage bottles (pbb)	1.0%
Recovery potential from residual waste		
		$CL_{sp}(a_x)RWC+SSRWC$
Residual waste	**PCC packaging (ppa)**	**10.6%**
	PCC non-packaging (pnp)	**10.3%**
	Avoidable food waste and beverages - packaged (incl. packaging) (fwp)	9.9%
	Coloured glass packaging (cgl)	**8.9%**
	White glass packaging (wgl)	**7.9%**
	Unavoidable food waste and organics (ufw)	7.7%
	Hygienic paper and sanitary articles (hyg)	7.4%
	Other plastic packaging (opp)	**7.0%**
	Metal beverage packaging (mbp)	**5.1%**
	Plastic beverage bottles (pbb)	**4.7%**
	Avoidable food waste - unpackaged (fwu)	4.7%
	Composite packaging - PCC composite packaging and coated PCC packaging (cpa)	**4.2%**
	Composite packaging - coated cardboard cups for liquid food and beverages (ccc)	**3.2%**
	Composite packaging - beverage carton (cbc)	**1.5%**

** Recyclables marked in bold*

signs in accompanying observation studies (Hartl et al., n.d.). However, the differences in the specific separation efficiencies of waste types are expected to be influenced by other factors as well, such as the fact that certain materials are easier to identify or perceived as having a higher value, for example glass (Langley et al., 2011). In addition, separation norms for certain waste materials may be better established as a result of previous sustained awareness campaigns. For composites and coated paper, official separation recommendations are often ambiguous, and for some materials, such as other plastic packaging (e.g. foils, trays and cups), separate collection has only recently been introduced in Vienna and Krems as part of the national harmonisation of the LWP collection (in January 2023) (VVO - BGBl. II No. 184/2014). The findings are consistent with other studies which found particular composites and cardboard cups among frequently misunderstood waste items (Andrews et al., 2013; Gangl et al., 2022; Hartl & Hofmann, 2024; YaHan, 2020).

Compared to separation performance in households, in particular, a higher efficiency for paper separation would have been expected in the present study (CR 12%) as paper is typically separated with rather high efficiency compared to other waste (separation efficiencies in Viennese households: Paper total: 62%, Glass total: 56%, LWP plastic bottle collection: 23%) (MA48 & Huber, 2024).

3.1.3 Separation quality

High levels of contamination in the collection streams can cause problems and increase the costs of further processing and sorting, and should be kept to a minimum (Neubauer et al., 2021). The contamination levels (CL) found in this study are presented in Figure 3 c) and the specific contamination levels for different waste types in Table 2. Waste composition results per container are presented in Figure 4 and in more detail (individual subfractions and audit weeks) in the SM (see chapter 2.5). Highest contamination levels were found in LWP (CL 33.9%), closely followed by PAP (CL 32.2%) and lastly GL (9.6%). Compared to the contamination levels found in household waste, the public CL are generally higher, but most strikingly in PAP (contamination levels reported in households: CL PAP: 3.6% in Vienna; CL LWP: 20-30% in Austria, 21% in Graz; CL GL: 0.4-2.3% in Austria, 0.3-0.7% in Vienna excl. glass colouring contaminations) (Lingitz, 2021; MA48 & Huber, 2024; TBH, 2014). The largest specific contaminations in PAP are hygienic paper and sanitary articles, paper composite packaging and non-packaging paper contaminants (e.g. receipts), all of which are fibre-based. The largest sources of contamination in LWP are packaged food waste, paper packaging and hygienic paper. The highest contaminations found in glass were due to packaged food waste, metal beverage packaging and beverage plastic bottles (Table2). Waste composition and contaminations reflect common types of waste from public activities, including shopping and to-go consumption. This includes items such as coated paper packaging, food waste, napkins, drink bottles and receipts.

3.1.4 Recovery and optimisation potential

To interpret the impact of the field test, it is important to consider results in relation to the available potential of recyclable materials. To illustrate the overall results of waste separation in the prescribed test setups, the total quantities of waste collected and analysed at the four test sites are summarised in Figure 5 by means of material flows.

Looking at the total generated public waste (regardless of collection container), there is a material recovery potential (percentage of all recyclables) of about 69%, with 59% consisting of packaging. With the introduction of a centralized separation station, located on average 38m walking distance in the test areas, a total of 20% of these recyclables were correctly separated, while the remaining 80% were either disposed of in the residual waste (78%) or in an "incorrect" separation fraction (2%) (see total recyclables capture rate CR in Figure 3 b) and waste flows in Figure 5). Despite the presence of a separation station, between 59% of the collected residual waste in SSRWC and 68% in RWCs was recyclable material (see contamination level CL Figure 3 c) and waste composition in Figure 4). In total (RWC + SSRWC), recyclables constitute around 65% of residual waste, while the greatest recovery potential from residual waste lies with paper (packaging and non-packaging 20.9%), glass packaging (white and coloured 16.8%), other plastic packaging (7.0%), metal beverage cans (5.1%) and plastic bottles (4.7%) (see Table 2 for details). The share of recyclables in the public residual waste was, in any case, higher than in households, where about 21% to 31% can be expected (if biogenic waste and other collection points target factions are not considered) (Beigl, 2020; MA48 & Huber, 2024) and compared to previous studies, where about 52% was measured in public waste (Kladnik et al., 2024). This may be due to the fact that hotspot locations were analysed.

To reduce the total amount of residual waste, efforts to optimise waste separation should focus on those wastes that are currently separated with low efficiency (indicated by low CR), while simultaneously showing a high recovery potential in terms of mass (indicated by high CL in residual waste). This applies in particular to other plastic packaging (incl. film, trays, cups, etc.), constituting almost 7% of residual waste, with only 7.9% being correctly disposed of (see Table 2). With the introduction of a deposit return system in Austria in 2025 (AWG 2002, BGBl. I Nr. 102/2002), this waste category will become particularly important as the new main collection target (plastic bottles and metal cans will no longer be targeted in LWP). Similarly, paper composite packaging (ccc, cbc, cpa) make up 8.9% (in sum) of total residual waste, but only 1.7% (cpa) to 4.1% (ccc) are correctly disposed of. Paper packaging and non-packaging, which each account for more than 10% of residual waste, show significant potential for improvement as it is typically much better separated in households in relation to other waste fractions (see also chapter 3.1.2).

Overall, the results suggest that clear container labelling and the provision of adequate separation infrastructure alone may not lead to sufficient separation quality and efficiency in busy public spaces, where waste separation

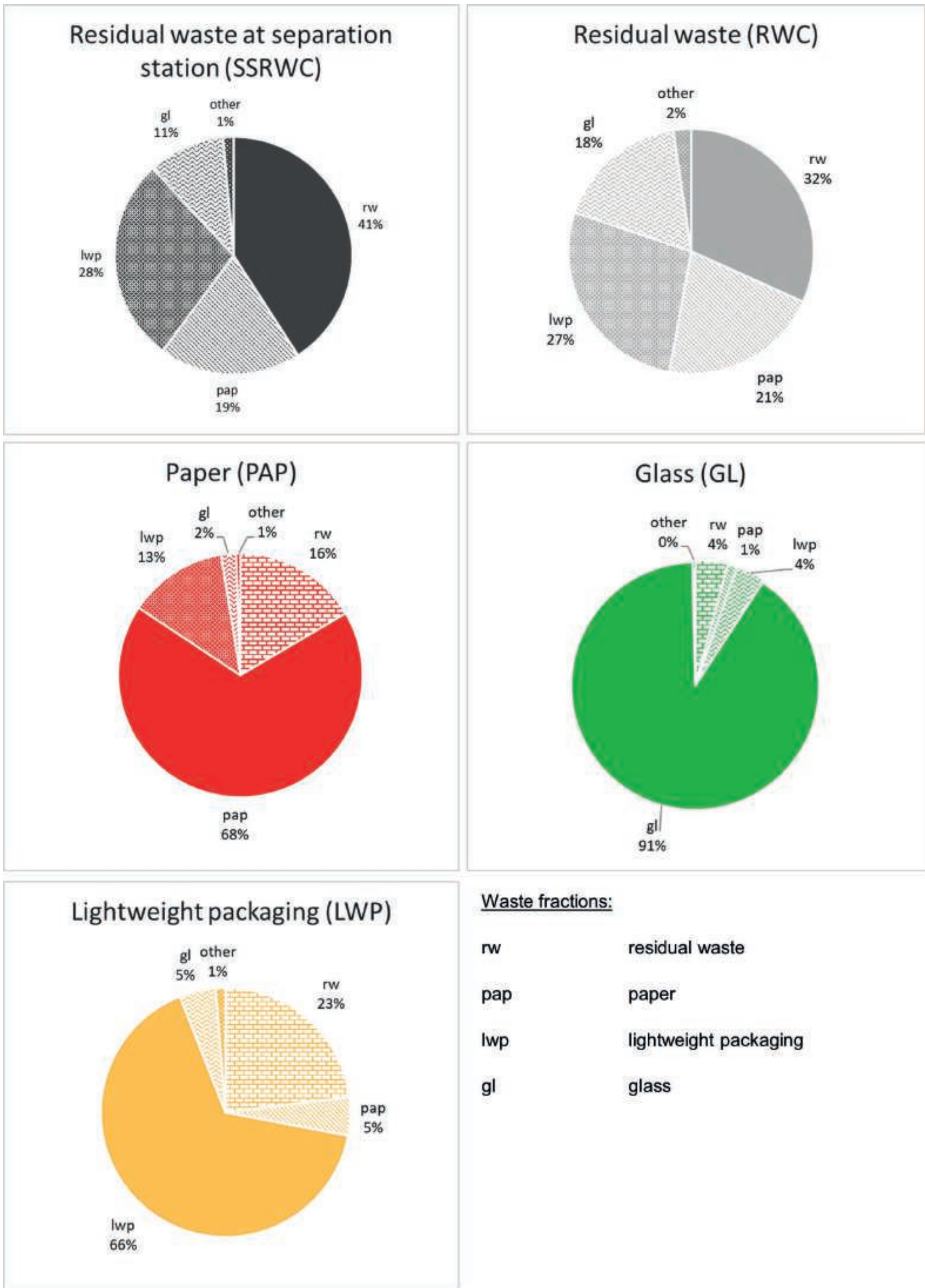


FIGURE 4: Composition of public waste (excluding sorting residues) per collection container based on the total amount of waste cumulated from all test locations (total).

is not yet perceived as a social norm (Gök et al.; Hartl and Hofmann, 2024). Communicating the purpose of separate collection and the material transformation behind recycling (Hartl and Hofmann, 2024; Winterich et al., 2019), as well as broader awareness campaigns or age-targeted initiatives that integrate digital tools (Concari, 2023), could be further measures to promote waste separation.

While the results highlight the high recovery potential of public waste, the extent to which separated fractions can be effectively utilized or marketed depends on regional recycling infrastructure and market demand. Austria has a well-established recycling system for glass, metal and paper. However, lightweight packaging, especially composite and mixed plastic fractions, often face significant challenges due to contamination, as well as fluctuating demand and marketability (ARA, 2022; Neubauer et al., 2021). The effectiveness of separate collection in public spaces, therefore, relies not only on improving consumer behaviour but also on ensuring viable processing and end markets for recyclables.

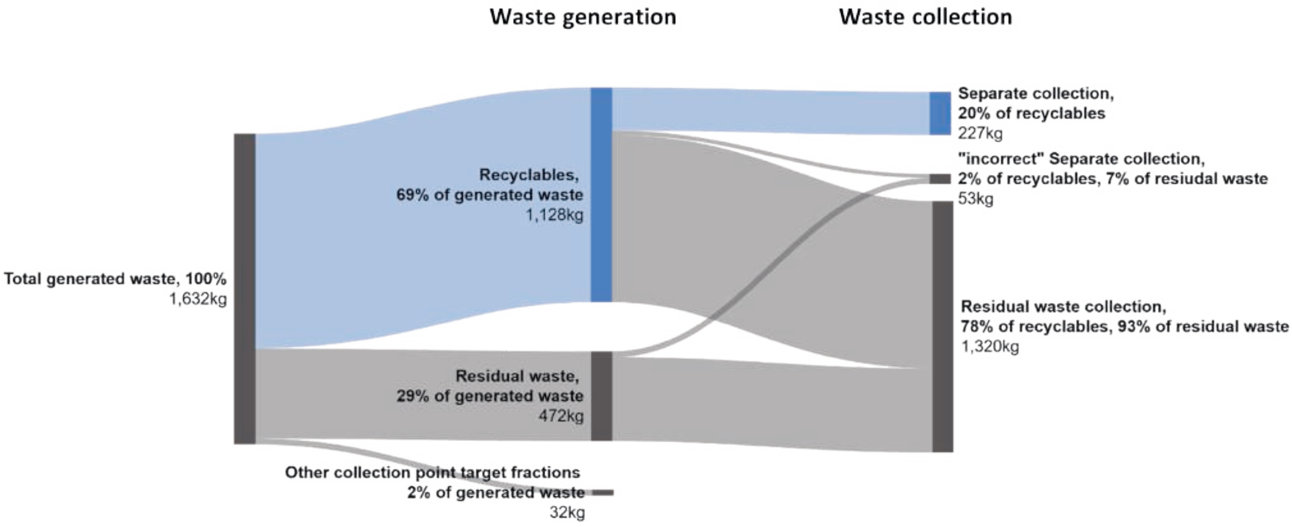


FIGURE 5: Waste material flows illustrating recovery potential and overall separation performance in the test areas, based on total analysed waste (excl. sorting residues). Values were rounded for illustrative purposes.

3.2 Effects of the guidance system

The effects of the guidance intervention are discussed based on the absolute differences in weekly performance indicators before and after the intervention for total waste (cumulated from all test locations). In addition, results were tested for significance based on the mean difference in daily performance indicator values (n=7) between the two audit weeks. Significant test results (p-value < 0.05) are reported below and detailed results are reported in the SM (see chapter 2.3).

In total, the intervention showed a positive effect on the separation of glass, as more waste was collected in the glass container (change in separate collection rate ΔSCR + 1.93%, result significant based on mean difference: +2.17%, p-value = 0.0469), glass waste was properly separated to a greater extent (change in capture rate ΔCR +9.03%), and it was less contaminated (change in contamination level ΔCL –4.38%). The effect was also positive on lightweight packaging, as more waste was collected in the LWP (ΔSCR + 2.11%), lwp waste was properly separated to a greater extent (ΔCR +4.98%, result significant based on mean difference: +4.65%, perm. p-value = 0.0234) and it was less contaminated (ΔCL –1.10%). Residual waste collection was influenced positively in the SSRWC as the separation efficiency and quality improved (ΔSCR –0.17%, ΔCR +2.36%, result significant based on mean difference: +2.44%; perm. p-value = 0.01562, ΔCL –6.91%). However, a negative effect was observed for paper waste, as less waste was collected in PAP (ΔSCR –0.11%), less paper waste was properly separated (ΔCR –1.02%) and the container was more heavily contaminated (ΔCL +5.74%) after the intervention. Overall, however, there was an improvement in the separation efficiency of total recyclables ("total recyclables capture rate" ΔCR +4.56%, result significant based on mean difference: +4.76%, perm. p-value = 0.03125). The fact that the overall effect was modest (< 5%) is supported by observations in which, in general, few interactions with the guidance stickers were observed (Hartl et al., n.d.). A detailed examination of the specific effects associated with individual waste fractions, which is provided in the SM (see chapter 2.4), allows more nuanced conclusions to be drawn regarding waste-specific behaviour and the design of guidance signage. For example, the negative separation effect for paper waste was due to more non-packaging paper (e.g., newspapers) being disposed of as residual waste after the intervention. This effect may be related to the use of red-coloured guidance stickers (Figure 2 b), which are associated with waste paper in Austria and may have caused confusion. Using attention-grabbing colours with neutral waste associations instead (e.g., pink in Austria) or minimal accents (e.g., a red exclamation mark) could prevent unwanted triggering of specific waste associations.

3.3 Limitations

Waste amounts typically vary significantly throughout the week (Edjabou et al., 2015; Leeabai et al., 2021), as was the case in this study. To avoid variations and evaluate long-term impacts, longer test periods and using average weekly data would be beneficial. The analysis period was limited due to resource constraints and to minimise possible seasonal variations, which should be taken into account when interpreting the results. In general, waste sorting analyses on wet waste, as performed in this study, can give a distorted picture of separation behaviour, as it does not analyse the number and quality of individual "tosses" and is affected by humidity fluctuations among waste fractions. Uncertainties also exist in relation to different moisture contents of different collection fractions, e.g. a typically higher moisture content of paper in residual waste compared to paper in the waste paper container. Waste audits further revealed that in some test locations, owners of local shops and snack bars used public bins to dispose of larger quantities of their commercial waste (unauthorized waste), potentially skewing the results.

Several factors, including the bin design, setting conditions (distance, placement, arrangement of waste bins), and external influences such as weather, the level of greening, car traffic, pedestrian traffic, clientele (e.g., socio-demographic differences), consumption and stay patterns are likely to influence waste disposal and separation behaviour. For example, in busy public places with short stay durations, diffuse pedestrian flows, or cold and rainy weather conditions, attention to waste disposal and separation may be reduced. Conversely, low vehicle traffic, favourable weather and ample resting areas could create a calmer environment, potentially increasing awareness and improving waste separation at the site. This study recorded weather and setting conditions, which are mentioned in terms of differences between the test locations in SM Chapter 2.6, and provides a qualitative description of the test locations in SM chapter 1.1. Beyond that, external factors were not systematically recorded, which is a potential limitation to the comparability of the study results.

4. CONCLUSIONS

In order to gain insight into the public's waste separation behaviour and to test the effectiveness of a guidance system for recyclables, field tests were conducted in public places in Austrian cities. The results of comprehensive waste audits show that the resource potential at public waste hotspots is high (69% recyclables, 59% packaging), making these areas well-suited for the introduction of waste separation. The introduction of central separation containers has resulted in 17% of the waste in the catchment area of the test locations being collected separately and 20% of the recyclables being captured for recycling. Although these results would fall short of the ambitious collection and recycling targets (e.g. 80% collection target for plastic packaging according to ARA (2022)), they represent a substantial improvement over the current situation where public waste separation is currently very limited in Austria (Egger, 2024;) and other European Countries (European Commission, 2021). In terms of collection quality, the results showed the highest contamination levels in lightweight packaging (CL 33.9%), closely followed by paper (CL 32.2%) and glass waste (9.6%), which exceed the contamination rates in Austrian households.

Beyond the specific focus on the public context, the results also provide valuable insights into waste separation behaviour across different waste types. It appears that some waste types are already much better understood and separated than others. To improve resource recovery, the separation of already "well-understood" waste types, such as plastic and glass bottles, should be continuously promoted. However, specific optimisation potential exists for improving the separation of other plastic packaging (cups, trays, films), paper composite packaging (including coated paper and cardboard) and paper in general (packaging and non-packaging) as these are not yet well separated. To reduce contaminations, measures specifically targeting the identified problematic contaminants such as hygienic paper and packaged food waste (e.g. additional instructions "please no used tissues or food leftovers") could be effective.

The pilot introduction of a recyclables guidance system, which was tested as a low-cost improvement measure to increase waste separation in the test areas, showed an overall positive effect. The collection of total recyclables increased by about 4.6%. However, the results are more differentiated for different types of waste and further research on wayfinding interventions is recommended to substantiate the results, as also accompanying behavioural studies did not provide clear evidence of consumer interaction with the guidance signage (Hartl et al., n.d.). While the results provide an overall picture of public hot spot areas, the location conditions and results varied greatly in individual situations. Future studies could include the assessment and analysis of external factors such as clientele, landscaping, pedestrian traffic, and length of stay to better understand their impact on separation behaviour and improve study comparability.

Although the implementation of waste separation in public spaces is challenging, it can contribute to waste reduction and establish waste separation as a societal standard. This study provides valuable insights into waste separation behaviour and has important implications for the design and implementation of waste separation schemes.

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IMPACT OF MUNICIPAL HOUSEHOLD PAY-AS-YOU-THROW ON CONSUMER FOOD WASTE BEHAVIORS AND ATTITUDES IN JAPAN

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ABSTRACT

In Japan, half of the avoidable food waste is generated at home, and municipal household Pay-As-You-Throw (PAYT) policies are expected to reduce it. However, few studies have examined how PAYT influences household food waste, specifically the types of food waste-related behaviors and attitudes affected, the number of people influenced, and those impacted by PAYT. This study uses a questionnaire survey to examine these aspects by targeting residents of cities implementing PAYT. The results revealed that 13-21% of residents perceived a significant influence of PAYT and showed a lower frequency of waste of homemade meals and plate leftovers. They showed a higher frequency of food waste reduction behaviors, such as storing vegetables properly and prioritizing the consumption of near-expiry food. The perceived effect of PAYT was slightly greater for individuals who prefer to consume homemade meals. The results indicated that the overall impact of PAYT was limited and that additional interventions were required. Efforts should target behaviors that were not sufficiently promoted by PAYT, such as checking stock before shopping and planning purchases and meals carefully, as well as developing strategies that reach individuals with low homemade meal orientation. As the study uses self-reported data, findings should be interpreted cautiously. Behavioral changes should be further examined through pre- and post-PAYT longitudinal studies.

1. INTRODUCTION

The issue of food waste is gaining importance because of its impact on global warming and food security. According to FAO's report, food waste from households is a serious problem in Europe, North America, Oceania and East Asia (Gustavsson et al., 2011). Even in Japan, because half of the total avoidable food waste (food that was edible prior to disposal) is generated at home, it is imperative to reduce household avoidable food waste.

As discussed in review papers by Aschemann-Witzel et al. (2015), Nonomura (2018), Schanes et al. (2018), and Vittuari et al. (2023), there has been a lot of research on the factors and consumer behaviors that influence household avoidable food waste. Avoidable food waste relates to a range of behaviors in the home consumption process: purchasing, storing, managing, cooking, eating, and disposing. These behaviors are promoted or restricted by individual attitudes, social norms, knowledge and skills related to food, lifestyle, and the environment surrounding food-related housework. To reduce household avoidable food waste, it is important to propose specific measures to change consumer behavior while considering these factors and verifying the effects of these measures. More studies are focusing on interventions to reduce food waste (Reynolds et al., 2019; Stöckli et al., 2018). A major intervention measure is to provide consumers with information, tools and tips to help them reduce food waste and improve their behavior. Stöckli et al. (2018) point out that information provision alone is ineffective.

Local governments have multiple intervention options and they are expected to play an important role in reducing household food waste. According to Wunder et al. (2019), policy options for household food waste reduction can be categorized as follows: 1) information and awareness-raising campaigns; 2) regulation of food sales and food disposal methods; 3) economic instruments, such as fees and taxes; 4) nudges and organization of choice architecture; and 5) strategies and guidelines that present voluntary agreements and action frameworks, such as public-private

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partnerships. The household pay-as-you-throw scheme (PAYT), which is included in (3), is a system in which the local government charges a fee based on the amount of household waste produced. It has been introduced in various countries as local government waste disposal systems (Chalak et al., 2016). In Japan, 62% of the 1,741 cities, towns, and villages have introduced PAYT (MoE, 2024).

PAYT is an economic incentive for consumers to prevent waste. Many studies have demonstrated that PAYT reduces household waste. This is also expected to reduce avoidable food waste (Wunder et al., 2019). Yorimoto et al. (1998) conducted a household waste composition analysis in Yono City before and after the introduction of PAYT and reported that food waste decreased after its introduction. Wheeler & Gregg (2025) report that consumers recognize that economic incentives including PAYT are more effective at reducing food waste than providing information or education. However, Chalak et al.'s (2016) cross-country analysis found that economic measures like PAYT have an impact on the generation of household food waste, but that the impact is small. van der Werf et al. (2020), who measured the amount of food waste in households in Toronto that have implemented PAYT, suggest that Toronto's PAYT did not reduce the amount of food waste, although it did promote recycling of food waste.

For local governments to develop effective policies to reduce household avoidable food waste, it is important to understand the potential and limitations of PAYT. To do this, it is necessary to understand 1) what kinds of behaviors and attitudes are affected by PAYT among the various behaviors and attitudes related to avoidable food waste, 2) how many people are affected by PAYT, and 3) who is affected by PAYT. However, despite the large number of studies on household food waste, few studies focus on the impact of PAYT. The limited existing studies focus on whether PAYT reduces food waste but do not discuss how PAYT influences household food waste. Therefore, this study examines the above three issues regarding PAYT.

2. METHOD

To clarify what kinds of behaviors and attitudes PAYT affects, we compared the behaviors and attitudes related to household avoidable food waste of two groups of people: residents of municipalities that introduced PAYT (intervention group) and residents of municipalities that did not introduce PAYT (control group). To be specific, after selecting municipalities that introduced PAYT (explained in section 2.1), we selected residents of those municipalities as the intervention group through an online survey (explained in 2.2). The control group was selected from residents of municipalities nationwide that did not introduce PAYT through an online survey (explained in 2.2). The behaviors and attitudes to be compared were asked in the online survey and are explained in 2.3. We compared behaviors and attitudes by t-test and an analysis of covariance (explained in 2.4). The selection of the covariates for the analysis of covariance is explained in 2.3 and 2.4.

The intervention group was also asked about their self-perception of the impact of PAYT (explained in 2.3). Based on their responses, we divided the participants into three groups: those who greatly reduced avoidable food waste, those who somewhat reduced it, and those who did not reduce it. We then compared behaviors and attitudes among these groups by one-way analysis of variance. Based on these results, we further discussed the impact of PAYT and how many people are affected by PAYT. In addition, we analyzed the correlation between the respondents' perceived impact and their characteristics to discuss who is affected by PAYT.

2.1 Selection of local governments

We define PAYT as a system that charges citizen fees based on the amount of household waste produced. We selected three local governments that introduced this system: Chigasaki City in Kanagawa Prefecture, Handa City in Aichi Prefecture, and Hatsukaichi City in Hiroshima Prefecture. The selection criteria were as follows: 1) cities with a population of over 100,000 to ensure a sufficient sample size for an online survey; 2) cities that started PAYT after 2020 as it was expected that the effect of the introduction of the system would be relatively clearly observable; 3) cities where separate collection of food waste was not being implemented as we could focus on the effects of PAYT and excluded the effects of food waste collection that can potentially promote food waste reduction behavior (Cardew, 2019; Morgan et al., 2024); and 4) cities where we could not find campaigns to reduce household avoidable food waste on their websites to exclude the effects of campaigns.

Chigasaki City, Handa City, and Hatsukaichi City have populations of 242,447, 119,590, and 117,045, respectively. PAYT was introduced in Chigasaki in 2022, in Handa in 2021, and in Hatsukaichi in 2020. They collect fees that are included in the price of the designated garbage bags and collect combustible waste, including food waste, twice a week. The fee in Chigasaki is two yen per liter, which is twice as high as that in the other two cities. There was no designated bag system prior to its introduction in Chigasaki.

2.2 Survey of residents

An online questionnaire survey was conducted in February 2024 by a research company, targeting residents of the 3 selected cities and citizens nationwide as a control group. The respondents, aged between 20 and 79 years, lived in their city for at least 2 years, and were mainly responsible for cooking and food management at home. The respondents from the three selected cities were aware of the implementation of each scheme. The numbers of respondents are listed in Table 1.

We selected 141 respondents who answered that their municipality had not introduced PAYT as the control group. The respondents subjectively judged whether PAYT was being implemented. This judgment may not necessarily match our definition, but we considered whether people were aware of PAYT to be important when considering its impact on behaviors and attitudes. We did not exclude the residents of municipalities which implemented food waste collection or campaigns to reduce household avoidable food waste from the control group. This is because only

TABLE 1: Number and attributes of respondents.

Total		Age						Gender		Household size				Policy cooperation
		20~	30~	40~	50~	60~	70~	M	F	1	2	3	4~	
Chigasaki City	252	9	24	49	71	61	38	94	158	81	86	43	42	248
		4%	10%	19%	28%	24%	15%	37%	63%	32%	34%	17%	17%	98%
Handa City	160	1	22	39	44	38	16	48	112	41	51	31	36	158
		1%	14%	24%	28%	24%	10%	30%	70%	26%	32%	19%	23%	99%
Hatsukaichi City	134	7	15	24	32	38	18	32	102	27	51	26	30	134
		5%	11%	18%	24%	28%	13%	24%	76%	20%	38%	19%	22%	100%
Control	141	20	17	29	25	20	30	49	92	61	45	17	18	-
		14%	12%	21%	18%	14%	21%	35%	65%	43%	32%	12%	13%	-

M, male; F, female. Policy cooperation: Respondents who answered that they use designated garbage bags of their municipalities

8% of municipalities have implemented food waste collection (MoE, 2024) and most of them are small (Nakamura & Wada, 2003), and because we estimated that few residents are aware of the campaigns of their municipalities based on National Network Council Against Food Loss and Waste (2021).

2.3 Questions

To create the target variable for the analysis, we asked about food waste behavior, food waste reduction behavior, and attitude related to food waste. We asked 5 questions about food waste behavior and 16 questions about food waste reduction behavior. As we focused on the behavior related to avoidable food waste, 15 questions were selected with reference to Nonomura (2018) regarding food waste reduction behavior at each stage of food procurement, cooking, storage, management, eating, and disposal. Food waste behaviors were assessed using a five-point frequency scale: 1 = Never, 2 = Once every two weeks, 3 = 1-2 times a week, 4 = 3-4 times a week, and 5 = 5 or more times a week. Food waste reduction behaviors were assessed using a five-point frequency scale: 1 = Never to 5 = Always. We asked four questions about attitudes related to food waste, and the degree of agreement was answered on a five-point Likert scale: 1 = strongly disagree to 5 = strongly agree.

As covariates to be considered in the analysis, we asked about gender, age, number of household members, whether they lived with children, household income, and type of residence, which Cardew (2019), Chalak et al. (2016), Koivupuro et al. (2012), Ventour (2008), Stancu et al. (2016), and others have identified as having an impact on food waste. We also asked about working hours, food-related behaviors and attitudes (e.g., frequency of cooking, thriftiness, preference for homemade meals, frequency of receiving food gifts, whether they grew vegetables or fruits at home), frequency of participation in local activities and events, and awareness of local activities regarding food waste reduction (e.g., food donation activities and pamphlets). The questions and answers are listed in Table 2. We also asked the intervention group whether they thought their household avoidable food waste had decreased because of PAYT to know their self-perception of the impact of PAYT. It was answered on a five-point scale: 1 = Decreased greatly, 2 = Decreased somewhat, 3 = Not changed, 4 = Increased somewhat, and 5 = Increased greatly.

This survey was approved by the Ethics Review Board of the first author's university. Respondents were informed in writing about anonymization, voluntary participation, and consent to participate was obtained. The participants were compensated through the research company. It was unlikely that the incentive had an effect, as all respondents received an incentive, regardless of the content of their answers.

2.4 Analysis of data

We compared the means of attitudes related to food waste, frequency of food waste behaviors, and frequency of reduction behaviors between residents of the cities with PAYT and the control group. We confirmed a significant difference between groups using an independent-samples t-test (Welch's t-test when unequal variances were assumed) and checked the effect size using Cohen's d. Cohen's d is a standardized difference between the means of two groups. It is used to compare the size of the difference. According to Cohen (1988), effect sizes can be interpreted as small (d = 0.2), medium (d = 0.5), and large (d = 0.8). IBM SPSS Statistics 27 was used for statistical analysis. A post hoc power analysis was conducted using G*Power 3.1 with an alpha error probability of 0.05 (two-tailed). Given the sample sizes of the intervention group (n = 546) and the control group (n = 141), the power for a t-test was 0.56 for a small effect size and over 0.99 for a medium effect size. We adopted the parametric method according to the idea that parametric testing methods are robust to non-normality and do not pose a major problem when used with ordinal data measured by a rating scale (Norman, 2010).

We also conducted an analysis of covariance to analyze the impact of PAYT, considering the characteristics of the respondents. In the analysis of the PAYT, the covariates were seven basic attributes and three items: frequency of receiving food gifts, frequency of participating in local activities and events, and awareness of local food donation activities. These three items were selected from the various covariates that we considered because the absolute value of Cohen's d between residents of the city with PAYT and the control group was 0.2 or more. Dummy variables distinguishing the cities were included. A post hoc power analysis was conducted for the analysis of covariance. Due

TABLE 2: Questions and answers.

Questions			Answer
Food waste behavior	1) Threw away food.		Frequency (5)
	2) Not aware of the food and it went bad.		
	3) Did not finish the meal I made and threw it away.		
	4) Threw away leftovers on plates.		
	5) Threw away food because the expiry date had passed.		
Food waste reduction behavior	Procurement	1) Check stock of food at home prior to shopping.	Frequency (5)
		2) Purchase food after carefully considering whether we can eat it all.	
	Storage	3) Store vegetables in a way that will keep them fresh for longer.	
		4) Store leftover meals in my fridge.	
	Management	5) Eat near-expiry food first if I find it in my fridge.	
		6) Move near-expiry food to a more visible position in my fridge.	
		7) Set a day to use up the food in the fridge.	
		8) Organize the contents of my fridge to easily see what is in there.	
	Cooking	9) Use the skins and ends of vegetables in cooking.	
		10) Cook meals carefully considering whether we can eat it all.	
	Eating	11) Serve food after carefully considering whether we can eat it all.	
	Disposal	12) Throw away the entire vegetable or fruit if it is partly damaged. (R)	
		13) Eat food as far as possible even if its best-before date has passed.	
		14) Have donated food that we could not eat at home.	
		15) Share food that we cannot eat with the people around me.	
	Other	16) Talk with family and friends about how to use up food.	
Food waste attitude	1) Avoiding throwing food away at home is very important to me.		Degree of agreement (5)
	2) The people around me are careful to avoid throwing food away.		
	3) My local government is proactive in reducing waste.		
	4) My local government is proactive in reducing avoidable food waste.		
Basic attribute	Age		Free
	Gender		Male/female
	Household size		Free
	Living with children		Yes/No
	Working hours		(5)
	Household income		(9)
	Type of residence		Detached house/flat
Food-related attitude	Saving money on food is very important to me.		Degree of agreement (5)
	Saving time and effort on meal preparation is very important to me.		
	Cooking my own meals is very important to me.		
Food-related behavior	Shop for food.		Frequency (5)
	Cook using ingredients such as vegetables, meat, fish, and eggs.		
	Someone other than me buys food or cooks at home.		
	Eat out.		
	Eat out unexpectedly.		
	Grow vegetables or fruits at home.		Yes/No
	Receive food gifts.		Frequency (6)
Participation in society	Participate in local activities and events.		Frequency (6)
	Make small talk with people outside the family.		Frequency (5)
Awareness of local activities	Have read a pamphlet about reducing household food waste.		Yes/No
	Have seen awareness-raising activities for reducing food waste at a local store.		
	Have participated in a seminar or cooking class about reducing household food waste.		
	Know about local food donation activities.		
	Have talked with my children or grandchildren about learning about food waste at school.		

(R) denotes a reverse-coded item. (5) means five-point scale. The same applies to the other entries

to missing values in responses to questions of basic attributes, the total sample size was 422. Assuming an alpha error probability of 0.05, the power was 0.54 for a small effect size (f = 0.10) and over 0.99 for a medium effect size (f = 0.25). The interpretation of effect size f is based on Cohen (1988).

Additionally, we divided the intervention group into three groups based on their self-perception of the impact of PAYT on household avoidable food waste and then compared food waste behaviors, food waste reduction behaviors and attitudes related to food waste among the three groups: "decreased greatly," "decreased somewhat," and "not changed." If the probability of significance was less than 0.05 in a one-way analysis of variance, multiple comparisons were used to determine where significant differences existed. Welch's analysis of variance and the Games – Howell test were used when unequal variances are assumed. We checked the effect size of each pair using Cohen's d. A post hoc power analysis was conducted for the one-way analysis of variance. With a total sample size of 540 across three groups and an alpha error probability of 0.05, the statistical power was 0.53 for detecting a small effect size (f = 0.10) and over 0.99 for a medium effect size (f = 0.25).

To examine what type of people was affected by PAYT, we checked the correlation between respondents' evaluation of impact ratings (on three levels: decreased greatly, decreased somewhat, and did not change) and basic attributes, food-related behaviors and attitudes, participation in local activities and events, and awareness of local activities regarding food waste reduction using Spearman's rank correlation coefficient. A post hoc power analysis was conducted for the correlation analysis. With a total sample size of 540 and an alpha error probability of 0.05, the statistical power was 0.64 for detecting a small effect size (ρ = 0.1) and over 0.99 for a medium effect size (ρ = 0.3). The interpretation of effect size ρ is based on Cohen (1988).

3. RESULTS

3.1 Overview of respondents

The numbers of respondents by attribute are listed in Table 1. The proportion of people in each age group in the control group was almost the same as that in the 2020 national census, while the proportion of people in their 20s and 70s was smaller in the 3 cities, and the proportion of people in their 50s and 60s was higher. Compared with the 2020 national census, the proportion of women was higher, and there was a trend of fewer single-person households. This is probably because the respondents were mainly responsible for cooking and food management at home and had lived in the city for more than two years. In the three cities implementing PAYT, almost everyone cooperated with the policy; that is, they used designated garbage bags.

We confirmed the correlation between food waste behaviors and reduction behaviors using Spearman's rank correlation coefficient. The results indicated that 5 reduction behaviors had a significant negative correlation of 0.2 or more with any of the food waste behaviors: 1) check stock of food at home prior to shopping, 2) purchase food after carefully considering whether we can eat it all, 5) eat near-expiry food first if I find it in my fridge, 10) cook meals carefully considering whether we can eat it all, and 12) throw away the entire vegetable or fruit if it is partly damaged (a reversed item).

3.2 Comparison of food waste-related behaviors and attitudes of residents of the cities with PAYT and the control group

The frequency of food waste behavior among residents of cities with PAYT was higher in all five categories than in the control group (Figure 1). The absolute value of the effect size (Cohen's d) of the four behaviors — 1) threw away food, 3) did not finish the meal I made and threw it away, 4) threw away leftovers on plates, and 5) threw away food because the expiry date had passed — was 0.17 to 0.20. The differences in these behaviors between the two groups were small. For behavior 2) not aware of the food and it went bad, the difference was a little larger compared to other food waste behaviors.

The means of frequency of food waste reduction behavior were almost the same for both groups (the absolute value of Cohen's d: |d| = 0.05-0.17), with no significant differences. The attitude "my local government is proactive in reducing waste" was significantly higher among residents of cities with PAYT, with a medium effect size (|d| = 0.52). Other attitudes were almost the same for both groups (|d| = 0.00-0.17).

3.3 Analysis of the impact of PAYT using analysis of covariance

No significant impact of PAYT was observed on any of the five food waste behaviors, whereas household size, frequency of receiving food gifts, and frequency of participation in local activities and events significantly increased the frequency of some food waste behaviors (Table 3). Significantly higher frequencies were observed in Chigasaki and Handa populations. No significant impact of PAYT was observed in food waste attitudes or food waste reduction behaviors (Table 3 and 4). For the attitude "the local government is proactive in waste reduction", the variable "Chigasaki" had a significantly positive impact.

3.4 Respondents' perceived impact of PAYT on their household avoidable food waste

In the 3 cities with PAYT, 13-21% of respondents said that avoidable food waste had "decreased greatly" owing to PAYT, 37-41% said it had "decreased somewhat," and 42-44% said it had "not changed" (Figure 2). In Chigasaki City, more respondents reported that food waste had "decreased greatly" compared to the other two cities.

Although there was no significant difference and the effect size was small, the frequency of food waste behaviors of the "decreased somewhat" group was higher than that of the "not changed" group (Figure 3). In contrast, the "decreased greatly" group discarded less frequently than other groups. The "decreased greatly" group showed significantly lower frequency than the "decreased somewhat" group with effect sizes of 0.3 or greater for two food waste

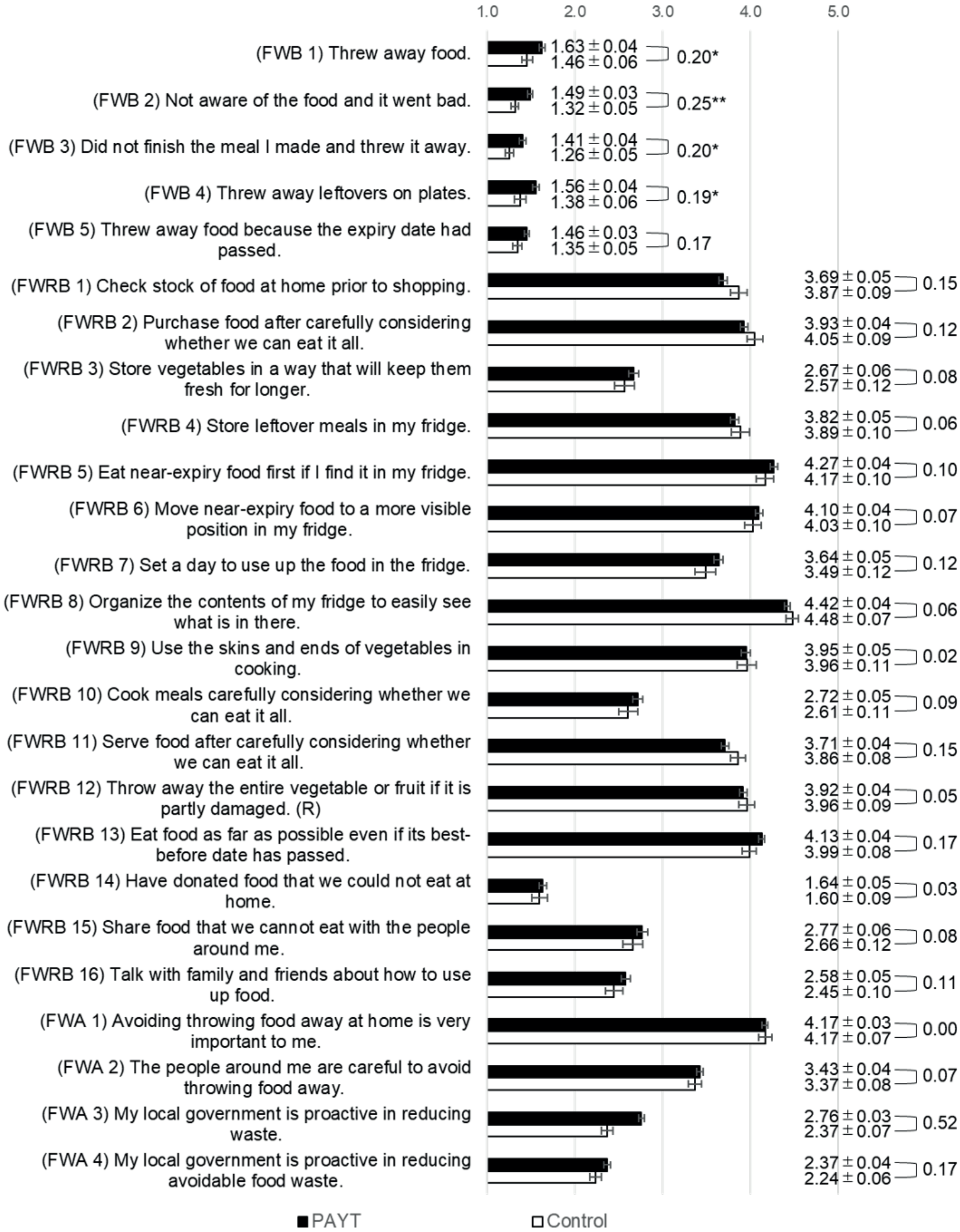

FIGURE 1: Food waste-related behaviors and attitudes of residents of cities with PAYT and the control group. FWB, food waste behavior; FWRB, food waste reduction behavior; FWA, food waste. The scale from 1 to 5 indicates frequency or level of agreement. For FWB: 1 = Never, 2 = Once every two weeks, 3 = 1-2 times a week, 4 = 3-4 times a week, and 5 = 5 or more times a week. For FWRB: 1 = Never to 5 = Always. For FWA: 1 = Strongly disagree to 5 = Strongly agree. Bars represent means. Error bars represent standard errors. Values next to bars are means and standard errors. Values between the means represent the absolute value of Cohen's d. **: p<0.01, *: p<0.05.

TABLE 3: Impact of PAYT on food waste behaviors and reduction behaviors (analysis of covariance).

	FWB					FWRB						
	1) Threw away food.	2) Not aware of the food and it went bad.	3) Did not finish the meal I made and threw it away.	4) Threw away leftovers on plates.	5) Threw away food because the expiry date had passed.	1) Check stock of food at home prior to shopping.	2) Purchase food after carefully considering whether we can eat it all.	3) Store vegetables in a way that will keep them fresh for longer.	4) Store leftover meals in my fridge.	5) Eat near-expiry food first if I find it in my fridge.	6) Move near-expiry food to a more visible position in my fridge.	7) Set a day to use up the food in the fridge.
	β	β	β	β	β	β	β	β	β	β	β	β
PAYT	-0.02	0.04	-0.01	-0.05	0.01	-0.08	-0.04	0.07	-0.02	-0.08	-0.05	0.01
Age	-0.03	0.04	0.00	0.00	-0.04	-0.10	-0.04	0.06	0.01	0.03	0.07	-0.01
Gender (female)	0.06	0.06	0.05	0.03	0.06	-0.04	-0.02	0.09	0.24**	0.09	0.15*	-0.08
Household size	0.03	0.03	0.15*	0.22**	0.01	0.20*	0.10	-0.01	0.03	0.03	0.05	0.16*
Living with children	0.04	0.03	0.05	0.14*	0.04	-0.11	-0.09	-0.07	-0.06	0.01	-0.03	-0.15*
Working hours	0.02	0.10	0.03	-0.05	0.04	-0.04	-0.06	-0.18**	-0.04	-0.05	-0.02	0.02
Household income	0.02	0.03	-0.04	-0.08	-0.04	-0.01	0.03	0.06	0.06	-0.11*	-0.05	-0.07
Type of residence (detached house)	0.01	0.04	-0.02	-0.05	0.01	-0.06	-0.03	0.08	0.07	0.02	0.00	0.04
Awareness of local food donation activities	0.01	-0.02	0.03	0.02	0.00	0.05	0.07	-0.02	-0.01	0.07	0.06	0.02
Frequency of receiving food gifts	0.17**	0.16**	0.03	0.09	0.15**	0.04	-0.02	0.04	-0.01	0.03	0.09	-0.03
Frequency of participating in local activities	0.07	0.07	0.10*	0.07	0.09	0.09	0.00	0.08	0.02	-0.03	0.05	0.19**
Chigasaki City	0.12	0.05	0.12*	0.12*	0.08	-0.03	-0.08	-0.06	0.00	-0.01	-0.04	0.07
Handa City	0.13*	0.05	0.08	0.09	0.09	-0.02	-0.01	-0.09	-0.03	0.02	0.02	0.05

***: p<0.01, *: p<0.05. FWB, food waste behavior; FWRB, food waste reduction behavior.*

behaviors: 3) did not finish the meal I made and threw it away, and 4) threw away leftovers on plates.

Except for behavior 14 (food donation), the frequency of food waste reduction behaviors was highest among the “decreased greatly” group, followed by the “somewhat decreased” group, and lowest among the “not changed” group. Compared to the “not changed” group, the “decreased greatly” group showed significantly higher frequencies in the following behaviors, with medium effect sizes (|d| = 0.31-0.65): 3) store vegetables in a way that will keep them fresh for longer, 5) eat near-expiry food first if I find it in my fridge, 6) move near-expiry food to a more visible position in my fridge, 8) organize the contents of my fridge to easily see what is in there, 9) use the skins and ends of vegetables in cooking, 15) share food that we cannot eat with the people around me, and 16) talk with family and friends about how to use up food. Among these, behaviors 5, 6, and 9 showed only minimal differences between the “decreased somewhat” and “not changed” groups (|d| = 0.04-0.10), indicating that the frequency of these behaviors are high only in the “decreased greatly” group. Behaviors 3, 8, 15, and 16 showed medium size differences (|d| = 0.24-0.41) between the “decreased somewhat” and “not changed” groups. That is, these four behaviors were more frequent in both the “decreased greatly” and “decreased somewhat” groups than in the “not changed” group.

Among the behaviors that showed significant differences between groups, only behavior 5 was a food waste reduction behavior that had a significant negative correlation of 0.2 or greater with food waste behaviors (see Section 3.1). Other behaviors — namely behaviors 1, 2, 10, and 12 — which also showed significant negative correlations of 0.2 or greater with food waste behaviors, did not differ significantly between groups and had small effect sizes.

Food waste-related attitudes were higher in the order of the “decreased greatly” group, the “decreased somewhat” group, and the “not changed” group. The differences between the “decreased greatly” and “not changed” groups were significant and showed medium to large effect sizes (|d| = 0.52-0.83). For 2) the people around me are careful to avoid throwing food away, 3) my local government is proactive in reducing waste, and 4) my local government is proactive in reducing avoidable food waste, the differences between the “decreased somewhat” and “not changed” groups were not small (|d| = 0.24-0.47). That is, these attitudes were higher in both the “decreased greatly” and “decreased somewhat” groups.

3.5 Correlation between respondents’ perceived impact and characteristics

Respondents’ perceived impact of PAYT was weakly and significantly correlated with homemade orientation measured by “cooking my own meals is very important to me” (Table 5). The second highly and significantly correlated factor was frugality, measured by “saving money on food is very important to me”, although the correlation

TABLE 4: Impact of PAYT on food waste reduction behaviors and attitudes (analysis of covariance).

	FWRB									FWA			
	8) Organize the contents of my fridge to easily see what is in there.	9 Use the skins and ends of vegetables in cooking.	10) Cook meals carefully considering whether we can eat it all.	11) Serve food after carefully considering whether we can eat it all.	12) Throw away the entire vegetable or fruit if it is partly damaged. (R)	13) Eat food as far as possible even if its best-before date has passed.	14) Have donated food that we could not eat at home.	15) Share food that we cannot eat with the people around me.	16) Talk with family and friends about how to use up food.	1) Avoiding throwing food away at home is very important to me.	2) The people around me are careful to avoid throwing food away.	3) My local government is proactive in reducing waste.	4) My local government is proactive in reducing avoidable food waste.
	β	β	β	β	β	β	β	β	β	β	β	β	β
PAYT	-0.02	0.05	-0.02	0.01	-0.01	0.00	-0.06	-0.08	-0.02	-0.01	-0.02	0.09	0.08
Age	0.04	0.08	0.03	0.03	0.17**	-0.05	-0.05	-0.04	0.01	0.03	-0.12*	0.12*	0.01
Gender (female)	0.03	0.05	0.01	0.04	0.16**	0.02	0.01	0.05	0.00	0.05	0.03	-0.01	-0.06
Household size	0.03	0.09	0.10	0.06	0.01	0.07	0.04	-0.04	0.12	0.04	-0.03	-0.15*	-0.02
Living with children	0.08	-0.07	-0.12	-0.05	-0.01	0.02	-0.10	0.10	-0.02	0.05	0.05	0.16*	0.03
Working hours	-0.04	0.02	-0.09	-0.12*	-0.03	0.05	-0.05	-0.02	-0.08	-0.09	-0.17**	-0.05	0.04
Household income	-0.05	-0.04	0.08	0.06	0.02	0.07	0.11*	-0.01	0.02	-0.12*	-0.08	-0.08	-0.16**
Type of residence (detached house)	0.01	0.01	0.03	-0.01	0.01	0.04	0.04	0.13*	0.05	0.04	0.07	0.02	-0.08
Awareness of local food donation activities	0.03	0.00	0.03	0.01	0.01	0.08	0.15**	0.09*	0.08	0.04	-0.03	0.14**	0.18**
Frequency of receiving food gifts	0.01	0.04	0.06	0.04	-0.03	-0.01	-0.04	0.21**	0.15*	-0.01	0.02	0.06	0.05
Frequency of participating in local activities	0.08	0.14**	0.06	0.07	-0.09	0.01	0.32**	0.16**	0.18**	0.01	0.12*	0.07	0.09
Chigasaki City	-0.10	0.02	-0.03	-0.04	-0.02	0.05	0.09	0.05	0.07	-0.03	0.01	0.22**	0.09
Handa City	-0.13*	-0.13*	-0.07	-0.06	-0.02	-0.01	-0.02	0.00	0.04	-0.08	0.00	0.01	-0.05

***: p<0.01, *: p<0.05. FWRB, food waste reduction behavior; FWA, food waste attitude.*

coefficient was small at 0.18. Age, type of residence, frequency of receiving food gifts, participation in local activities, and experience of hearing about children's food waste learning also showed significant correlations, but the correlation coefficients were even smaller.

4. DISCUSSION

4.1 How many people were affected by PAYT?

Between 54% and 57% of the intervention group perceived that they reduced their avoidable food waste somewhat or greatly owning to PAYT, which aligns with the observation by Wheeler and Gregg (2025) that economic incentives are perceived as effective. It should be noted that there may be a gap between respondents' perceived effects and actual effects. Therefore, by comparing behaviors across groups with different levels of perceived impact, we discuss the influence more objectively. Those who thought that their avoidable food waste had "decreased somewhat" owing to PAYT exhibited a higher frequency of food waste behaviors than those who thought that their food waste had "not changed." Considering that Ventour (2008) and Jörissen et al. (2015) pointed out that consum-

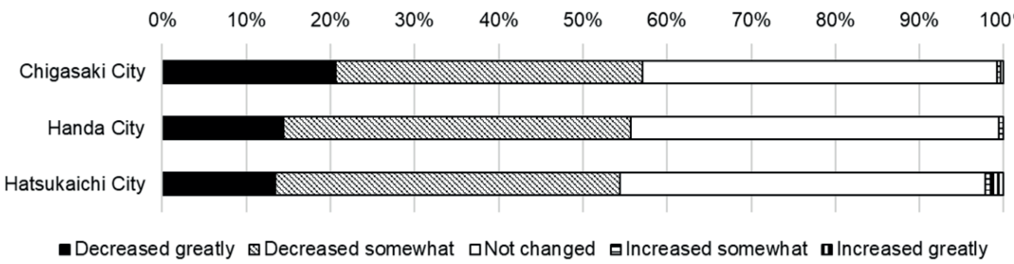

FIGURE 2: Respondents' evaluation of the impact of PAYT on their household avoidable food waste.

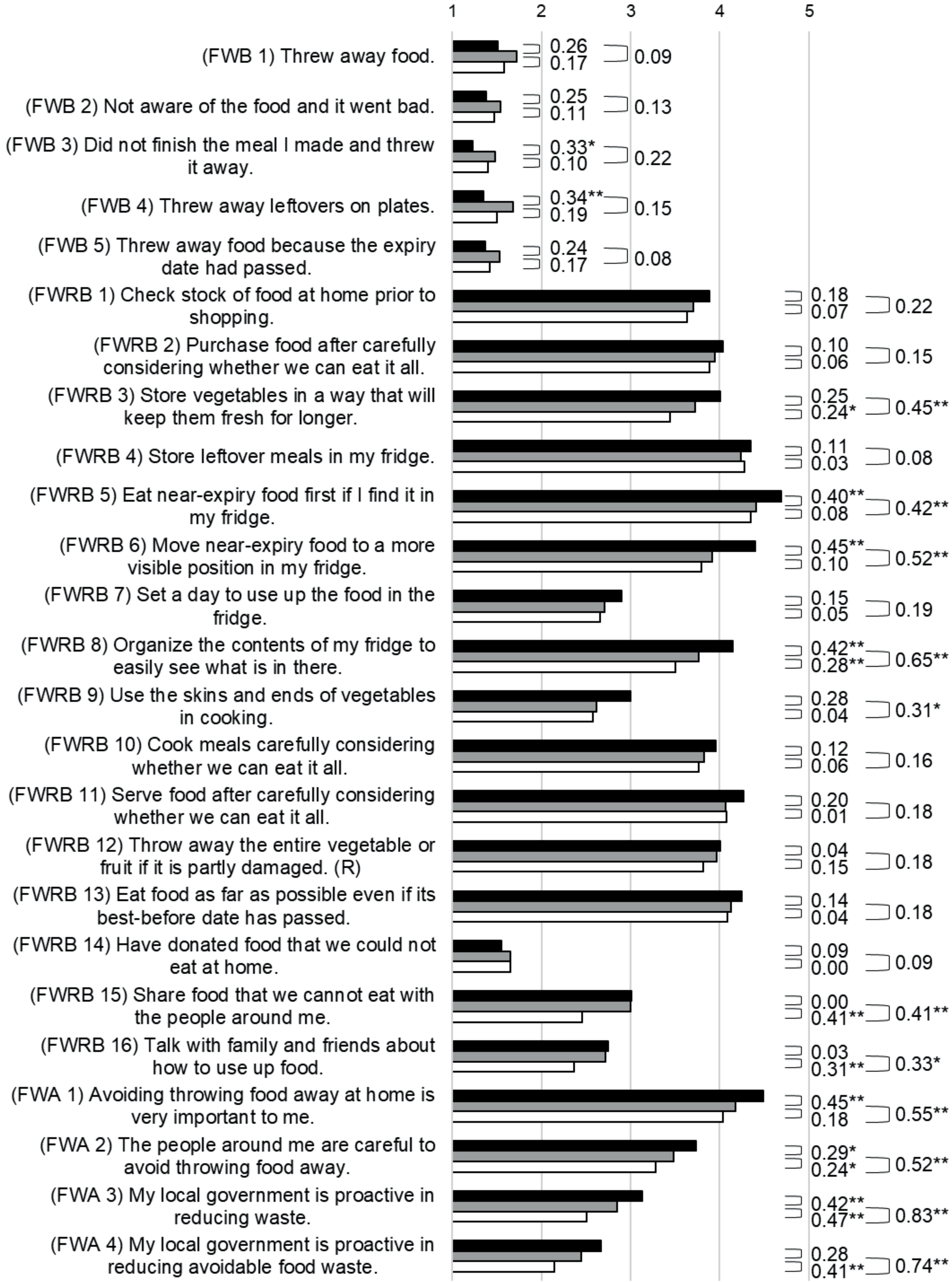

FIGURE 3: Food waste-related behaviors and attitudes based on respondents' evaluation of PAYT's impact. FWB, food waste behavior; FWRB, food waste reduction behavior; FWA, food waste. The scale from 1 to 5 indicates frequency or level of agreement. For FWB: 1 = Never, 2 = Once every two weeks, 3 = 1–2 times a week, 4 = 3–4 times a week, and 5 = 5 or more times a week. For FWRB: 1 = Never to 5 = Always. For FWA: 1 = Strongly disagree to 5 = Strongly agree. Bars represent means. Error bars represent standard errors. Values between the means represent the absolute value of Cohen's d. **: p<0.01, *: p<0.05.

TABLE 5: Corellations between perceived impact of PAYT and basic attributes, food-related behaviors and attitudes.

Variables		Correlation coefficient
Basic attribute	Age	-0.05
	Gender (female)	-0.13**
	Household size	-0.04
	Living with children	-0.06
	Working hours	0.07
	Household income	0.06
	Type of residence (detached house)	0.09*
Food-related attitude	Saving money on food is very important to me.	0.18**
	Saving time and effort on meal preparation is very important to me.	0.07
	Cooking my own meals is very important to me.	0.26**
Food-related behavior	Shop for food.	-0.08
	Cook using ingredients such as vegetables, meat, fish, and eggs.	0.04
	Someone other than me buys food or cooks at home.	-0.01
	Eat out.	-0.01
	Eat out unexpectedly.	-0.01
	Grow vegetables or fruits at home.	0.08
	Receive food gifts.	0.15**
Participation in society	Participate in local activities and events.	0.13**
	Make small talk with people outside the family.	0.11**
Awareness of local activities	Have read a pamphlet about reducing household food waste.	0.13**
	Have seen awareness-raising activities for reducing food waste at a local store.	0.07
	Have participated in a seminar or cooking class about reducing household food waste.	0.05
	Know about local food donation activities.	0.06
	Have talked with my children or grandchildren about learning about food waste at school.	0.12**

***: p<0.01, *: p<0.05.*

ers underestimate avoidable food waste, these results are possibly due to increased awareness of household avoidable food waste that they produce because of PAYT. In contrast, those who thought that their food waste had "decreased greatly" showed a lower frequency of food waste behaviors than those who thought that their food waste had "decreased somewhat" or "not changed." These results were obtained even though the "decreased greatly" group should also have been more aware of food waste similar to the "decreased somewhat" group. This means that the "decreased greatly" group did reduce their food waste owing to PAYT, as they perceived. The "decreased greatly" group accounted for 13-21% of the intervention group.

The "decreased somewhat" group, which accounted for 37-41% of the intervention group, is also expected to have reduced their food waste as perceived, due to increased awareness of household food waste. This is because Reynolds et al. (2019) pointed out that simply becoming aware of one's food waste can lead to a reduction in food waste. However, we could not confirm this effect. In summary, 13-21% of residents in municipalities with PAYT were considered to have reduced their food waste, while 37-41% increased awareness of their food waste but did not necessarily reduce waste.

4.2 What kinds of behaviors and attitudes were affected by PAYT?

As mentioned in Section 4.1, the "decreased greatly" group was considered to have reduced avoidable food waste and this reduction was particularly evident in the waste of homemade meals and leftovers on plates. The frequency of reduction behaviors such as storing vegetables properly, prioritizing near-expiry food, organizing the fridge, using vegetable skins, sharing food, and talking with family about using up food was higher in the "decreased greatly" group than in the "not changed" group. This suggests that these behaviors were encouraged by the introduction of PAYT. Behaviors such as storing vegetables properly, organizing the fridge, sharing food, and talking about using up food were also more frequent in the "decreased somewhat" group than in the "not changed" group, indicating that these are behaviors that a relatively large number of people are likely to change. Prioritizing near-expiry food and using vegetable skins were more frequent only in the "decreased greatly" group, suggesting that these behaviors were promoted among a smaller group of individuals.

As shown in previous studies (Jörissen et al., 2015; Mallinson et al., 2016; Stefan et al., 2013; Williams et al., 2012), the food waste reduction behaviors that observed to be related to food waste behaviors in this study included checking stock before shopping, purchasing food after careful consideration, prioritizing near-expiry food, cooking after careful consideration, and eating partly damaged food. Except for prioritizing near-expiry food, the differences between the groups were negligible, suggesting that these behaviors were not promoted.

The attitudes that the local government is proactive in waste reduction, that the local government is proactive in reducing avoidable food waste, and that people around me are conscious of reducing avoidable food waste were higher in both the "decreased greatly" group and the "decreased somewhat" group compared to the "not changed" group. This suggests that these attitudes were promoted among a relatively large number of people by PAYT. The attitude that the local government is proactive in waste reduction was higher in the intervention group compared to the control group. An analysis of covariance indicated that the variable "Chigasaki City" had a positive effect on this attitude. Chigasaki City had a higher fee compared to the other two cities. Additionally, the introduction of PAYT may mark a significant change in Chigasaki City because there was no designated garbage bag scheme prior to this. These suggest that the effects of PAYT on the attitude were observed in Chigasaki City.

The attitude that avoiding food waste is important was higher in the "decreased greatly" group, but there was little difference between the "decreased somewhat" and "not changed" groups. This suggests that such an attitude may be promoted only among a limited segment of residents. However, when interpreting the effects on food waste-related attitudes, it is important to consider the possibility of reverse causality — that individuals who were already highly conscious of avoidable food waste may have been more susceptible to the intervention's influence.

4.3 Who was affected by PAYT?

The results suggest that the effect of PAYT is slightly greater for those who are more inclined to consume homemade meals. We predicted that frugal individuals would be more affected as households that generate less waste pay less under PAYT. However, the correlation between frugality and perceived impact was small. Highly frugal individuals may already be minimizing avoidable food waste (Stancu et al., 2022), leaving little room for further change.

4.4 Implications for future interventions

The means of frequency of food waste behavior among respondents in cities with PAYT — including those who did not recognize the influence of PAYT — were not lower than that of the control group. The means of frequency of food waste reduction behavior were not higher either. This is probably because only a small number of respondents changed their behaviors. This is in line with the claim by Chalak et al. (2016) that the impact of PAYT is limited. This underscores the need for additional interventions. Specifically, it is necessary to implement interventions targeting behaviors that contribute to food waste reduction but are not sufficiently promoted by PAYT, such as checking stock before shopping, purchasing food after careful consideration, cooking after careful consideration, and making use of partly damaged food. Although PAYT may broadly influence individuals regardless of basic attributes, food-related attitudes and behaviors, or social involvement, it was somewhat less effective for people with low homemade-orientation — those who are not averse to eating processed foods. Therefore, additional interventions could be targeted at this group.

5. CONCLUSIONS

Although there is a significant amount of research on household food waste, few studies examine the impact of PAYT. The existing research focuses on whether PAYT reduces food waste but does not explore how PAYT influences it. Therefore, we conducted an online survey and examined how PAYT influenced food waste-related behaviors and attitudes among Japanese residents, including what kinds of behaviors and attitudes were affected, how many people were influenced, and who was impacted by PAYT.

The results suggest that 13-21% of residents in municipalities with PAYT likely reduced their avoidable food waste, while 37-41% increased their awareness of their avoidable food waste but did not necessarily reduce it. The 13-21% of residents particularly reduced waste of homemade meals and plate leftovers. PAYT was thought to promote their food waste reduction behaviors such as storing vegetables properly, prioritizing near-expiry food, organizing the fridge, using vegetable skins, sharing food, and talking with family about food usage. It also promoted attitudes that others around them care about food waste, that avoiding food waste is important, and that local governments are proactive in waste reduction and food waste reduction.

However, the means of frequency of food waste behaviors among respondents in cities with PAYT were not lower than that of the control group. The means of frequency of food waste reduction behaviors were not higher either. The attitude that avoiding food waste is important was almost the same in municipalities with and without PAYT. These results imply that the overall impact of PAYT is limited and that additional interventions are needed to reduce food waste more effectively. Specifically, efforts should target reduction behaviors such as checking stock before shopping, planning purchases and meals carefully, and making use of slightly damaged food. It is also important to develop strategies that reach individuals with low homemade meal orientation, who are less affected by PAYT.

In this study, we examined the impact of PAYT considering various resident characteristics. However, because we compared residents of specific cities and the control group, we were unable to completely rule out the impact of regional characteristics. It is also possible that the people who were already active in reducing food waste before the introduction of PAYT answered "decreased greatly." A longitudinal study that tracks changes in food waste behaviors before and after the introduction of PAYT would provide a clearer picture of the true impact of these policies. Future research should also explore the effectiveness of additional measures, such as awareness campaigns and nudges.

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ENVIRONMENTAL SUSTAINABILITY: FROM TRASH TO FASHION ADORNMENT - GREEN INNOVATION POSSIBILITIES

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ABSTRACT

The purpose of this study is to explore the crafting of fashionable accessories from waste fabric. This aims to equip small scale garment manufacturers with the potential of transforming their waste into valuable fashion adornment. It is based on findings reveled in relation to waste generated by Ghanaian small scale fashion industries and manufacturers and their waste disposal practices. The green innovation and green practice possibilities were adopted to create environmentally sustainable fashion product giving new life to fabric waste. In achieving this green practice, the practice-based-research was employed for the study, this afforded the researchers a practical approach to help create value added green artistic products. The concept of material collaborations was also adopted. The main material that was used for the projects was scraps from African prints. These scraps are pieces of African prints off cuts that are found at garment manufacturers shops. The findings from the studio practice revealed that the fabric off cuts depending on their colour and sizes can be fabricated into green innovated fashion adornments. It was also brought to bear that the supposed trash from the small-scale garment industries could be given new life by transforming them into brooches, flower bouquet, flower accents and other possibilities. The success of the study provided opportunities for small scale garment manufacturers to explore fabric waste materials found on their workshop floor, intend to reduce the amount of waste in the environment.

1. INTRODUCTION

The fashion industry stands out as one of the most thriving sectors globally. As indicated by Lund et al. (2020), its global value reaches into the trillions, providing employment opportunities for over nine hundred trillion individuals. Over recent decades, the industry has consistently expanded, emerging as a foundational pillar of numerous economies. This growth has engendered adverse repercussions on the environment (Opoku, Amankwah & Assibey, 2022). The production of a single kilogram of cotton necessitates a staggering 10,000 liters of water, or roughly 3,000 liters for a single cotton shirt (Mohammed, Shiyani & Ardeshna, 2018). The dyeing of textiles involves the use of hazardous chemicals that subsequently find their way into our oceans, contributing to approximately 20% of global wastewater (Le, 2020). Further compounding the issue, the fashion industry has been designated by the United Nations as the second most polluting sector, accounting for 8% of all carbon emissions and 20% of global wastewater and it bears responsibility for a significant proportion of carbon emissions (Bailey, Basu & Sharma, 2022). In 2015 alone, the global fashion waste reached a staggering 92 million metric tons, with projections pointing towards a 56 million metric tons increase by 2030 (Stanescu, 2021). The environmental challenges arising from this expanding industry is of paramount importance. The fashion industry has made several actions, such as adopting green design, eco-design, and sustainability-focused design practices to help ease the impact of the industry on the environment, however substantial progress remains elusive. This has led to criticisms from discerning consumers and environmentally-conscious organizations (Opoku et al., 2022).

In the context of the waste generated by Ghanaian small scale fashion industries Safo-Ankama, Sawyerr and Wiredu (2023) notes that the predominant type of waste generated by manufacturers was fabric waste, constituting a substantial majority (82%) of the waste produced. An overwhelming 90% of the fabric waste was comprised of cotton, with a significant proportion being African print fabrics. This trend could be attributed to the popularity of African prints within the Ghanaian market due to their affordability and widespread use for various occasions such as weddings, funerals, and naming ceremonies (Acquaye, Sawyerr & Kusi, 2022). Additionally, studies by Jones-Quartey (2023) revealed that a considerable portion of the

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fabric waste, approximately 60%, was either discarded through disposal methods like throwing away or burning. However, many manufacturers also engage in recycling or upcycling practices of their fabric waste into the creation of diverse items, including pillow filling, “asasawa” fabric through the incorporation of fabric pieces, crafting cover buttons, and combining the fabric waste with other materials to manufacture garments (Safo-Ankama et al., 2023). The practice of producing fashion accessories from waste fabric remained unexplored among small scale garment manufacturers in Ghana.

The purpose of this study explores the crafting of fashionable accessories from waste fabric, aiming to equip small scale garment manufacturers with the potential of transforming their waste into valuable products. This approach of converting fabric waste into useful products not only holds the promise of generating additional revenue for manufacturers but also contributes to environmental sustainability by encouraging waste recycling. Outcomes will also help address SDG’s (1 -No poverty), (8- Decent work and Economic growth) and (12 – Responsible consumption and production).

1.1 Everyday fabric economy of Ghanaian small scale garment industries

Textiles and cloth are an important part of the Ghanaian fashion economy. Cotton is the most common material used in the sub-sector, however man-made fibres are also seldomly used. African Prints and home fabrics are the most common cotton-based textiles produced by the industry (Adeloye, Akinbogun & Ogunduyile, 2023). Large and small textile plants produce the colourful ‘fancy prints’ and ‘wax prints’ and contribute to the economy through employment and sales. These prints are produced locally while others are imported into the country (Howard, 2016). It is revealing to share that the majority of the fabric economy of the Ghanaian small scale garment industries manifested great use of African prints. African prints are identifiably traditional to the Ghanaian culture and also customarily referred to as “Ankara fabrics” (Adeloye, 2022). They are cotton fabrics that were initially manufactured in Europe to be sold in West and Central Africa but are now produced in various factories across the African continent. The use of African print in the Ghanaian small scale fabric economy cannot be overstated, they are used for women, men, kids wear and other household items. The African prints can be classified into two types: wax prints and fancy prints, which differ in their manufacturing processes. Wax prints are produced by applying a resin paste on both sides of the cloth, treating it mechanically to create cracking effects, and dyeing it in indigo (Jurkowitsch & Sarlay, 2010). The design concepts and fabric names materialise the philosophies of the culture area, giving it visual communicator character. Comparatively the fancy prints are only printed on one side, using the same design procedure as wax prints, but without resin.

Various scholarly accounts indicate the origin of African prints in West Africa. Acquaye, Sawyerr and Kusi (2022), Ankersmit (2010) and Nielsen (1979) traced the history of the prints to the late 1800s. They found that a Scottish merchant called Brown Fleming introduced HKM wax prints to the Gold Coast, a former British colony (now known as Ghana), to meet the local demand for high-quality textiles. These prints quickly became popular and spread to other West African countries. It is noteworthy that Indian textiles, which included woven and printed fabrics, were already well-received in West Africa, particularly chintz fabrics that featured small floral motifs that were hand-blocked.

1.2 Characteristics (Visual) of African Prints

African print fabrics involve using wax resins and dyes to machine-print batik-like patterns onto clothing (Akinwumi, 2008). These fabrics are prevalent across Africa and other regions and come in a variety of vivid colours and patterns. According to Nielsen (1979), African print fabrics are available in various designs and styles including tribal prints, geometric shapes, animal prints, flowers, and plants. African printed fabrics also evoke stunning patterns and colour schemes, but these fabrics carry a complex story woven into each “ntoma”(meaning “cloth” in “Twi” a Ghanaian Language) through themes and historical cultural values (Omatseye & Emeriewen, 2012). Jurkowitsch and Sarlay (2010) note that besides having the same pattern on each side, there are further elements in wax fabrics that make each piece unique. The colours, intricate patterns, and distinctive aesthetics are defining features of African Prints. These fabrics’ designs, motifs, and hues are carefully chosen to represent the cultural dressing styles and traditions of African people, conveying their cultural values across generations. Dereje, Liu and Zhou (2013) highlight the use of specific techniques to transmit cultural knowledge through the fabrics’ patterns. Halls and Martino (2018) stress that motifs and colours used in African prints are not solely intended for visual pleasure, but also serve as a means of communication for conveying spiritual values and beliefs inherited from ancestors in African societies. The significance of these patterns and colours is deeply ingrained in African culture and often draws inspiration from poems, proverbs, traditional fables, and tales. Colours are also used to symbolize age, marital status, social status, and tribe. In contemporary African prints, Western objects and symbols such as umbrellas, phones, electric fans, cameras, and radios are increasingly incorporated into backgrounds with lines and geometric shapes, as shown in the work of Amankwah and Howard (2013) and Chichi, Howard and Baines (2016).

The meanings of colours are significant in societies as they can be linked with history and possess their own implications. The colours communicate information about happenings, time of day, temperature, and season. Kansanba et al. (2021) note that colours hold philosophical meaning in the African context, representing social status, age, tribal affiliation, and marital status, as well as the stories portrayed in the prints’ patterns that are pertinent to the wearer, such as proverbs, poems, and traditional African fables. Colours are imbued with significant meaning in the African context, and their meanings differ across various ethnic groups, countries etc. (Acquaye et al., 2022). Dereje et al. (2013) state that the choice of fabric is influenced by the occasion and the dominant colour, making it essential to comprehend the significance of colours in African culture to grasp the deeper aesthetic meanings conveyed through clothing. These characteristics make it a suitable choice for many manufacturers when it comes to the production of garments and other fashion accessories such as brooches, headbands, bracelets.

1.3 Properties of African Prints that makes it suitable to be manipulated into textile products

African Prints are mostly made from cotton fibre, a natural fibre that has been a cornerstone of the textile industry for centuries (Ajila,2016). Its widespread use is attributed to a unique combination of physical, chemical, and mechanical properties that make it highly suitable for manipulation during textile production (Ismail & Azha, 2018). From spinning and weaving to dyeing and finishing, cotton's versatility allows it to be transformed into a wide range of fabrics, from lightweight apparel to heavy-duty industrial textiles. Below are properties that makes cotton easy to be manipulated into textile products and its selection for the study.

Fibre Length and Strength: One of the most critical properties of cotton is its fibre length, or staple length, which typically ranges from 10 to 65 millimetres. Longer fibres, such as those found in Egyptian or Pima cotton, are particularly prized for their ability to produce smooth, strong, and uniform yarns (Khan et al., 2023). The strength of cotton fibres further enhances their suitability for spinning, as they can withstand the mechanical stresses involved in yarn formation without breaking (Chakraborty, 2012). This combination of length and strength makes it apporiate for the project in that the manipulation processes requires the textile material to be resilent lengthwise and widthwise in other to create the decorative fabric adornment.

Flexibility and Elasticity: Cotton fibres exhibit a moderate degree of flexibility and elasticity, which allows them to be twisted, stretched, and shaped during the manipulation proceses to the decortive fabric adornment (Carr et al., 2008). This property is particularly important in ensuring that cotton fabrics retain their structural integrity while being manipulated (Manju, Divakara & Somashekar, 2020).

Smooth Surface: The relatively smooth surface of cotton fibres contributes to their ease of manipulation during adornment creative processes (Manju et al., 2020). It also imparts on the lustre of the finished product.

Softness and Comfort: The inherent softness of cotton fibres contributes to their ease of handling during the manipulative process and ensures that the final product is comfortable for end-users (Khanzada, Khan & Kayani, 2020).

Sustainability and Biodegradability: In an era of increasing environmental awareness, cotton's biodegradability and renewability are significant advantages. As a natural fibre, cotton is biodegradable and can be processed using sustainable methods, such as organic farming and eco-friendly dyes (Fletcher, 2014). This aligns with the growing demand for environmentally responsible textiles and enhances cotton's appeal as a material for manipulation in sustainable textile production.

These unique properties of cotton make it exceptionally suitable for manipulation in textile production. These properties enable cotton to be manipulated into diverse functional and aesthetic requirements. As the textile industry continues to evolve, cotton's versatility and sustainability ensure its enduring relevance as a material of choice for both manufacturers and consumers.

1.4 Profiles of Artist upcycling African print textiles using different techniques

There are some textile artistes who are making intentional efforts to upcycle textile waste into useful artifacts for interior and outdoor functional spaces. The following are targeted at making statements focusing on sustainability, green innovation with fabric waste and resourcefulness.

1.4.1 Yinka Shonibare

Yinka Shonibare, MBE, an artist based in London, is renowned for his investigation of cultural and national identity, notably within the intricate dynamics between England and Nigeria. Having been brought up in Nigeria subsequent to its attainment of independence, Shonibare characterizes himself as a "postcolonial hybrid," and his artistic portfolio encompasses a diverse array of mediums, including photography, sculpture, film, installation, and performance. His most prominent pieces prominently feature headless mannequins adorned in vibrant attire crafted from Dutch wax fabrics, which, despite their colonial lineage, are frequently interpreted as emblematic of African heritage. Originating from Southeast Asia and disseminated by the Netherlands on a large scale, these textiles captivate Shonibare due to their representation of both manufactured and genuine African cultural elements (Shonibare, 2025).

Style and technique: Renowned for his technical and visual adaptability, Shonibare employs Dutch wax textiles in paintings, sculptures, and intricate costumes designed for performers. Examples of his notable works include "Scramble for Africa" (2003), Wind Sculptures (2013) and Earth Kids (2020)." The utilization of Dutch wax fabric in Shonibare's artistic pieces symbolically captures the multifaceted aspects of globalization, authenticity, and cultural interchange within a rapidly evolving global landscape. Some works of Shonibare as presented in Figure 1.

1.4.2 Eva Sonaike

Eva Sonaike is a London-based interior designer and entrepreneur who specializes in luxurious textiles and home décor with a vibrant West-African aesthetic. She was born in Germany to Nigerian parents, Sonaike's passion for interior design stems from her multicultural upbringing and her desire to infuse homes with colour and vibrancy. After working as a journalist, Sonaike embarked on her entrepreneurial journey, starting with designing fabric for cushions in her own home. Encouraged by the positive response from friends, she launched her business in 2009, facing challenges but persevering to secure prestigious stockists like Selfridges, Liberty, and Fenwick (Sonaike, 2024).


FIGURE 1: Yinka Shonibare and his work.

Style and technique: Sonaike's brand has since expanded internationally, offering a range of products including cushions, rugs, wallpaper, and fabrics, all reflecting her unique blend of African heritage and European craftsmanship. Sonaike's dedication and creative vision have solidified her position in the luxury interiors market, contributing to the growing global interest in African design and textiles. Some of the works of Sonaike are shown in Figure 2.

1.4.3 Simone Post

Simone Post is a Dutch textile and product designer based in Rotterdam, known for her innovative approach to materials and processes. With a background in textiles and a penchant for experimentation, Post explores the boundaries of design by collaborating with companies and pushing the limits of the industry. Her creations exude optimism while also provoking thoughtful questions about materiality and craftsmanship. She collaborated with esteemed companies like Adidas, Kvadrat, and Hermès, Post is driven by her intrinsic passion to create unique and highly sought-after objects. Her work has garnered international acclaim, with exhibitions held worldwide and pieces acquired by prestigious museums such as the Vitra Design Museum and the Cooper Hewitt. Post's ability to transform ordinary materials into extraordinary works of art demonstrates her dedication to the craft and her relentless pursuit of innovation (Post, 2024).

Style and technique: She repurposed waste material from Vlisco into new textiles, showcasing her commitment to sustainability and resourcefulness. Post's work spans a wide range of mediums, from refurbished furniture to pleated ceramics, all characterized by bold use of colour, texture, and print. Figure 3 showcase some works of Simone Post.

1.5 Theoretical Basis

The study adopted the green innovation conceptas expressed by Kemp and Pearson (2007). Globalization has profoundly reshaped the global landscape and business practices. Over recent decades, production and consumption patterns have undergone substantial changes (Kneipp


FIGURE 2: Eva Sonaike and her work.

FIGURE 3: Simone Post and her work.

et al., 2019). This transformation has led to significant challenges, including climate change, overexploitation of natural resources, and biodiversity loss, compromising planetary life (Elimam, 2017; Li, Wang & Wu., 2019). Consequently, various industries, including fashion and textiles, are increasingly focused on mitigating their environmental impact. Evidence suggests that environmental concerns have influenced consumer behavior (Colvin, Witt & Lacey, 2020). While some individuals remain unaware of environmental issues (Afonso et al., 2018), Dyck and Silvestre (2018) contend that societal awareness has generally increased, with more consumers making environmentally conscious choices. Thus, organizations are responding to environmental constraints and consumer demands by enhancing corporate performance and maintaining market competitiveness. Many companies are adopting practices to minimize pollution and utilize resources more efficiently (Bolis, Morioka & Sznelwar, 2017; Mubarak et al., 2021). One such practice is green innovation.

Kemp and Pearson (2007) define green innovation as a novel product, production process, service, or management method that, throughout its lifecycle, reduces environmental risk, pollution, and other adverse impacts compared to traditional alternatives. Similarly, Eiadat et al. (2008) describe green innovations as initiatives aimed at pollution prevention, waste reduction, and the implementation of environmental management systems within organizations. To navigate these challenges and successfully implement green innovation, businesses engage in activities that either incorporate external knowledge to drive innovation or leverage internal knowledge in external markets for profit (Takalo & Tooranloo, 2021). Firms that adopt green innovation strategies are anticipated to command premium prices for eco-friendly products, improve their brand image, market sustainable goods and services, and access new markets (DeBoer, Panwar & Rivera, 2017; Kneipp et al., 2019; Mubarak et al., 2021).

In this study, the green innovation concept was adopted to add value to fabric pieces that are usually a waste product from the tailors and dressmaker's shops. These fabric pieces were transformed into fashion accessories and adornments. Thus, fabric pieces which could have landed in landfills were given new possibilities and new life through green innovative strategies and this could significantly reduce pollution in the environment. The innovative strategy also served as an avenue to create decent work and employment for the youth in achieving economic growth.

2. MATERIALS AND METHODS

In the adoption of green innovation and green practices to create value with waste, the researchers employed a practical-based-research approach to help create value added green artistic products. Practice-based-research is a method, whose result is an artefact created by the researcher (Winter, 2010). Studio based activities were used to execute the projects. Studio activity requires the use of techniques, tools, materials (Mills, 2009) as well as aesthetic analysis to gain new ideas or knowledge through practice to achieve the result of that practice (Candy &Edmonds, 2018). The creative techniques adopted for the execution of the projects included hand stitching, interfacing usage, gluing, pinning, use of templates, stuffing, fixing of fasteners, pressing and starching. The study adopted the concept of material collaborations for some of the green artistic products (Yang, 2013), however the main material that was used for the projects was scraps from African prints. These scraps are pieces of fabric waste which are African prints off cuts and are found at garment manufacturers' shops. The criteria for the selection of fabric pieces were colour, sizes, pattern arrangement, fabric weight among others. Other materials included glue, thread, starch, and fabric stiffeners. The tools used included scissors, tape measure, ruler, pencil, tailors chalk, pressing iron, brush and punch.

The researchers adopted the aesthetico-action research model developed by Marshall (2010) which uses observation, reflection, planning and creation were adapted for the creative studio approach for the project. However, the researchers introduced the concept of green innovation in the development of a new adapted model. The green innovative concept offered the researchers the avenue to introduce new variables that helped in the transformation of the fabric waste. The adoption of the four (4) new phases of the model, green creativity coupled with green value creation and green artistic practices to produce green textile art products facilitated the attainment of the set objectives. This conceptual frame work as shown in Figure 4 is geared towards the concept of sustainability within the textile and garment small scale industries.

The new variables made it possible to make use of fabric wastes in the studio settings with an operational foundation of the aesthetico-action model, which also provides the platform for artistic creation. The operational foundational model provides an extensive platform to observe, reflect, plan and create. However, the green innovation introduced the new variables which includes green creativity, green value creation, green artistic practices which resulted in the green textile art products. These variables are discussed below.

"Green Creativity" refers to the creative process of generating sustainable and innovative ideas, solutions, or products that are ethical, environmentally sustainable and eco-friendly (Chen et al., 2016). It focuses on reducing environmental impact, conserving resources, and on promoting sustainability. Green creativity was adopted as an artistic practice in creating the textile art product to address environmental challenges and contribute to a more sustainable future. "Green Value Creation" denotes the process of producing economic, social and environmental value through eco-friendly and sustainable practices (Brozović, D'Auria & Tregua, 2020). It comprises creating artistic products that contribute positively to the environment and society. This concept aligns with the principles of the circular economy. "Green Artistic Practices" represent creative artistic processes that prioritize, eco- friendliness, eco-consciousness, and ethical responsibility (Stoltz, 2023). These artistic practices are targeted at minimizing harm to the environment while fostering awareness of ecological issues through art. Green artistic practices reduce the environmental footprint of art and communicates the urgency of sustainability and inspire positive change. "Green Textile Art Products" are eco-friendly textile artworks that prioritize sustainability, ethical production, and environmental friendliness. Their production processes adopt sustainable materials, low-impact processes, and focuses on themes like nature, conservation, or recycling. A sustainable textile product is designed, made, and disposed of with minimal environmental and social harm, while balancing economic, ecological, and social concerns throughout its life cycle (Kumar, 2020).

2.1 Observation

The observation activities were underpinned by green value creation towards the reliazation of green textile art products.the obersveation practices being guided by the green value creation afforeded the researchers to leverage on internal and external knowledge in green artistic pratices and strategies to adopte eco-friendly possiblities. The possibility of using fabric waste to create fashion accessories was assessed based on observing existing accessories produced from malleable materials and other fabric pieces. Observation afforded the researchers to critically through a non-obstructive assess the foundational material to be employed for the creative process. A check was developed by the researchers to aid observation for example selection of fabric off cut, the colours based on the knowledge of colour psychology, sizes of off cuts, pattern arrangement of designs in off cuts, with preference to the concept of engineered designs and fabric weight because the concept of composite creation was considered in the design thinking. This check list was important for the study because the focus was on fashion accessories, majority being accents (brooches, hair pieces, pendants, wrist bands etc.). Accents are small pieces of fashion acces-

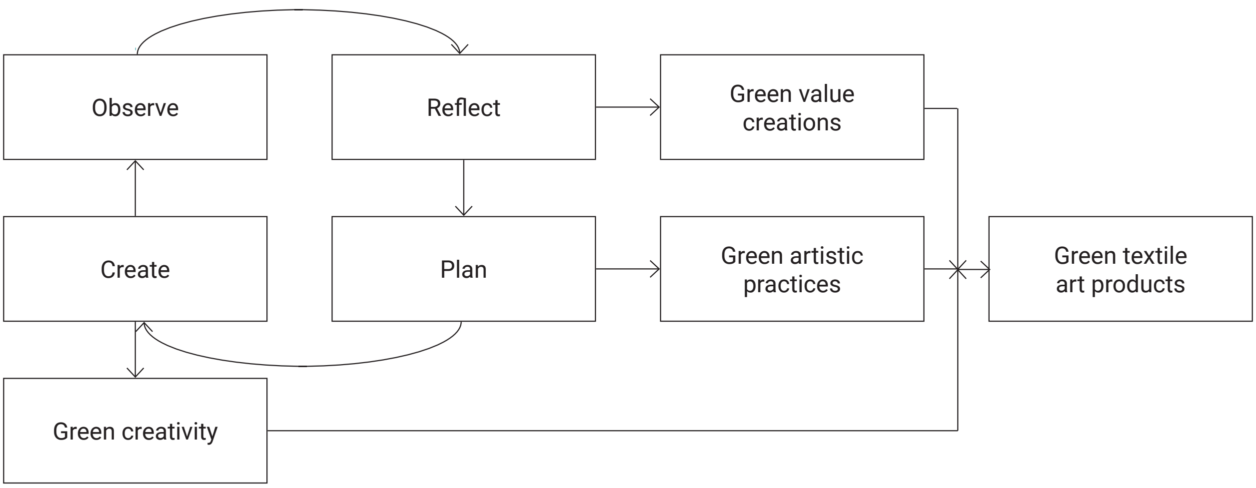

FIGURE 4: Researcher's construct adapted from the Aesthetico-Action Model (2024).

sories that adds colour to the overall outlook of a person. Observation helped greatly; small pieces of fabric were selected because they were to be used to produce accent and therefore should not be large. Light weight fabrics were also selected to make it easy to manipulate. In the fabric selection process, fabric with motif arrangement in all over pattern and abstract motifs were preferred. It was also to be ensured that motifs in engineered designs would not be cut through or distorted during the creation of the accessories. The sizes of motifs and textures in fabrics for specific end uses were also considered. Colour psychology was also considered at this stage because the accessories were not going to be stand-alone items, colour binds, facial complexions etc. were considered. Thus, fabric pieces with colours which could match a lot of colour ranges were considered for selection.

2.2 Reflection

Various ideas and possibilities were generated at this stage having in mind green valve creation and green textile artistic practices and ultimately the green textile art product. Reflective creative thinking was carried out, incubating possible fabric manipulative process like pleats and folds, decorative box pleats, decorative gathering, applied gathering, direct smocking, pleating, tucks and tucks variations, ruffles and frills, hand-tied quilting, trapunto and other creative techniques. The creative thinking also reflected on useful hand stitching techniques like back stiches, blankets, running, blanket and other stay-stitching techniques and fasteners. During the reflection process consideration was given to prints having names with philosophies ramifications to aid the creation of specific accessories. A mood board was created to show the inspiration for the collection, the mood board for the collection was titled “Nhwiren” meaning “flowers” in the Ghanaian ‘Twi’ language. Accents as fashion accessories are to interplay with the environment (and perceived source of light) to produce the intended enhancement. Based on this the researchers considered fabric pieces that could produce good colour relationships when exposed to light. These lights perceived colour illusions and effect that were preferred includes metamerism, bezold effects.

2.3 Planning

The planning stage presented the extensive platform for diverse element to be harmoniously put together as units. The concept of recycling green textile arts product was high on the thinking board for the purpose of environmental sustainability. A material board was created to bring to reality the abstract thinking of the researchers. The planning stage presents illustrations and specifications on how fabrics would be used, its durability and cost effectiveness of the intended green textile products. At this stage the life cycle of the product the fabric pieces were going to be used for were also well-thought-out, this is because the concept of composite material collaborations was to be adopted by using fabric pieces of different weight, texture and different levels of possible degradation. The planning stage placed high emphasis on reproducibility of the accents to be created, this was high on the researchers’ design thinking for the accents produced to be reproduced easily following the systematic steps discussed. The ease with which the end products could be recycled was also an important factor to consider due to environmentally sustainability. Based on the above, sketches of the various ideas and concepts of different end products were made with details of fabrics and techniques to be used to produced them.

2.4 Creation

Prototypes of the end products thus fashions accessories were produced. They were evaluated to ensure that they met basic quality check such as functionality, easy to wear and remove, size, easy maintenance, safety etc. Where the end product fell short of the specifications after the evaluation, new ideas and changes were made and this was carried out in the final sketches. Finally, a report of all studio practice activities was made to ensure reproducibility. The study adopted the Ghanaian ‘Twi’ language for the titles of the artworks produced. The studio practice activities, material and design notes are captured from Fashion Adornment 1-7.

2.4.1 ‘BanbƆ’ (Protector)

To produce ‘BanbƆ’ (meaning Protector in ‘Twi’ language), fabric piece that could measure 6cm by 6cm was selected. Using a writing tool, ruler, and scissors, twelve (12) fabric squares measuring 6cm by 6cm were precisely cut. Each square was then folded diagonally to form a triangular shape. With the help of a threaded needle, the frayed edges of the triangular fabric pieces were securely stitched together. This stitching process was repeated for all the triangles, creating a continuous chain of fabric pieces resembling suggestive petals. The stitching was intentionally loose to allow for easy manipulation of the petals, forming folds as desired. The chain of continuous triangular fabric pieces was then pulled to create circular loops. Each fabric piece was meticulously arranged, ensuring a seamless connection, and the ends were firmly secured. To complement the design, a plain matching fabric measuring 10cm by 10cm was cut and stitched around its square perimeter using a threaded needle. The resulting square was then filled with latex wool. By pulling the thread tightly, a ball shape was formed. Glue was applied to the uneven surface of the ball and affixed within the space created by the petals. To complete the accessory, latex stiffeners were utilized to cover the base of the rosette. For convenient usage, a brooch pin was attached to the base. The procedure for making fashion adornment one (1) is presented in Figure 5.

2.4.2 ‘Odehye3’ (Royalty)

To produce ‘Odehye3’ (meaning Royalty in ‘Twi’ language) a metallic wire with a length of 12cm was cut and manipulated to create a loop in a form of an oval shape by bending and coiling one side of the wire. This process was repeated until a total of ten (10) metallic wire loop pieces were obtained. The loops were deliberately crafted in various sizes (small, big, and medium) to introduce diversity and prevent monotony in the final piece. To attach the fabric to the loops, glue was applied along the edges and

FIGURE 5: Procedure for making 'BanbƆ' (Protector).

then affixed onto fabric pieces. The fabric and the glued metal loops were allowed to dry for proper bonding. Subsequently, any excess fabric extending beyond the loops was trimmed away,. In order to complete the flower, florist tape was wrapped around the stem, which refers to the section of wire that did not form the loop. By bringing together the ten individual petals created through this process, a cohesive flower structure was achieved. The processes involved in making fashion adornment two (2) is illustrated in Figure 6.

2.4.3 'Ahofɛ́' (Beautiful)

To produce 'Ahofɛ́' (meaning Beautiful in 'Twi' language), a medium-sized circular object of 4cm diameter was placed on fabric pieces as template guide to trace the circular shapes. Careful cutting was done to extract these circular pieces from various fabric ends. Each circular piece was then folded in half, creating a semi-circle. This semi-circle was subsequently folded again to form a cone-like shape. This folding process was repeated multiple times, generating several cone-like fabric pieces to achieve

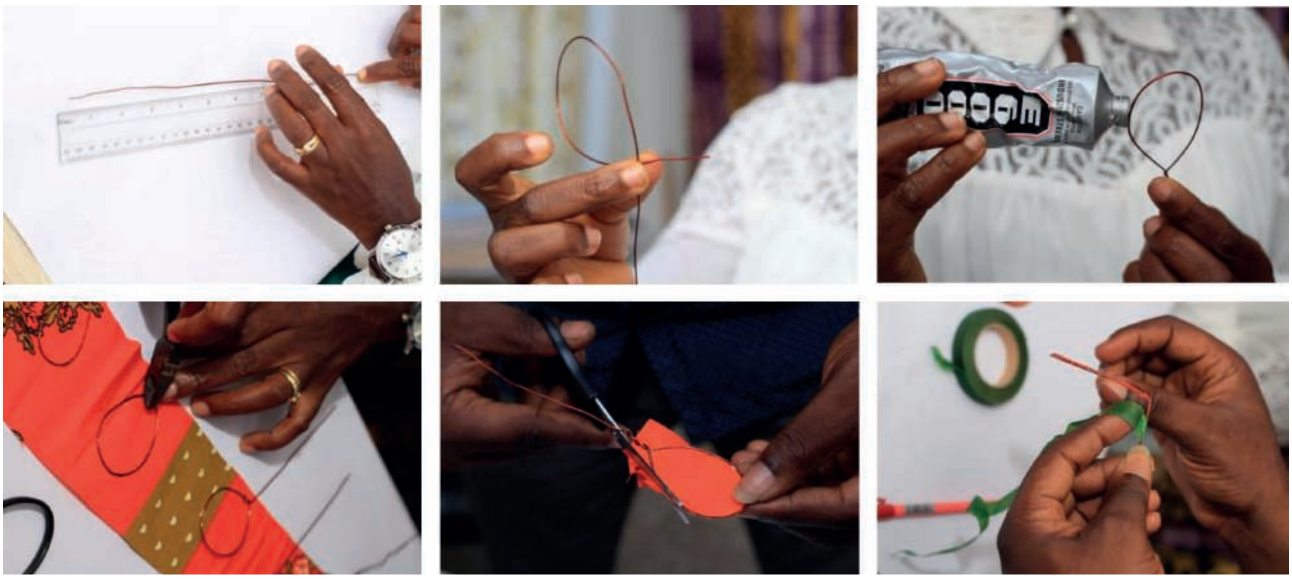

FIGURE 6: Researcher's construct adapted from the Aesthetico-Action Model (2024).

the desired quantities for the final product. To assemble the fabric pieces, felt-base was used as support forming the foundational structure to carry the pile. Fabric glue was employed to secure the cone-like shapes in place. The pieces were strategically arranged in layers, providing a sense of fullness. An accessory was positioned at the center to cover the tips of the fabric pieces. To serve its function as a brooch, a brooch pin was attached to the back of the fabric base. The processes ised in making fashion adornment three (3) is presented in Figure 7.

2.4.4 'Nsroma' (Star)

To produce 'Nsroma' (meaning Star in 'Twi' language) a circular cardboard with a radius of 5cm was marked and cut out, serving as a template. This template was then used to mark and cut out six (6) circular fabric pieces from a chosen material. Each circular piece was folded in half. To join the folded pieces together, a threaded needle was used. Ensure that the stitches were secure yet loose enough to allow the thread to pass through easily. By carefully pulling the thread from one end, a sense of fullness was created through the folds. The threads' ends were brought together and continuously pulled until the inner tops of the fabric pieces became taut, resulting in petal shapes with a round space in the center. To enhance the appearance, a suitable accessory was added to embellish the middle. The procedure for making fashion adornment four (4) is shown in Figure 8.

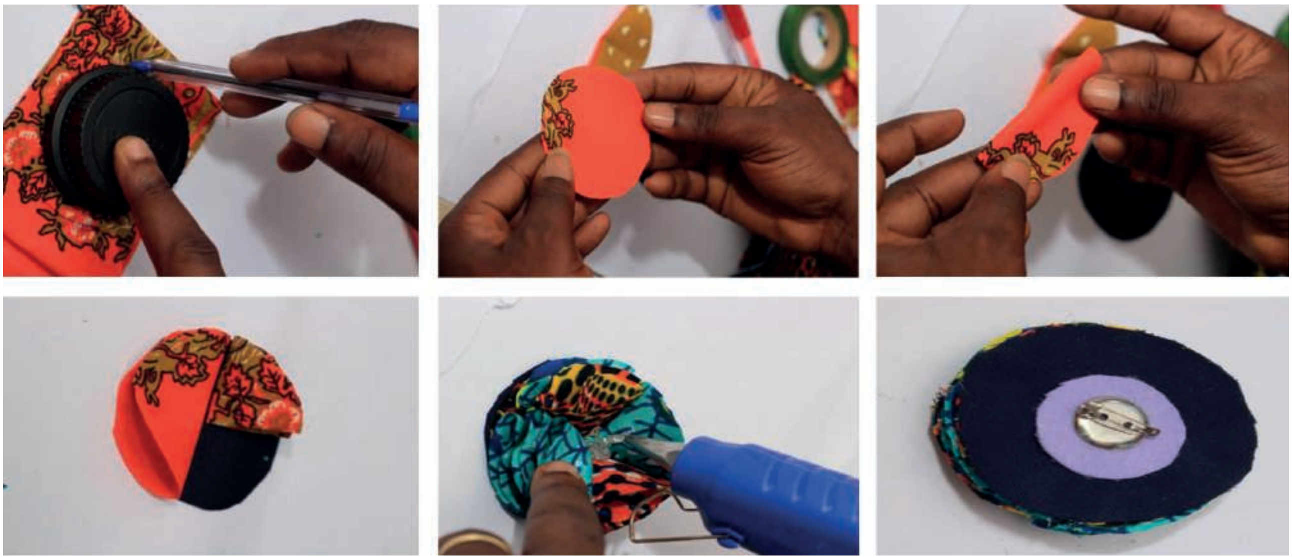

FIGURE 7: Procedure for making 'Ahofɛ́' (Beautiful).

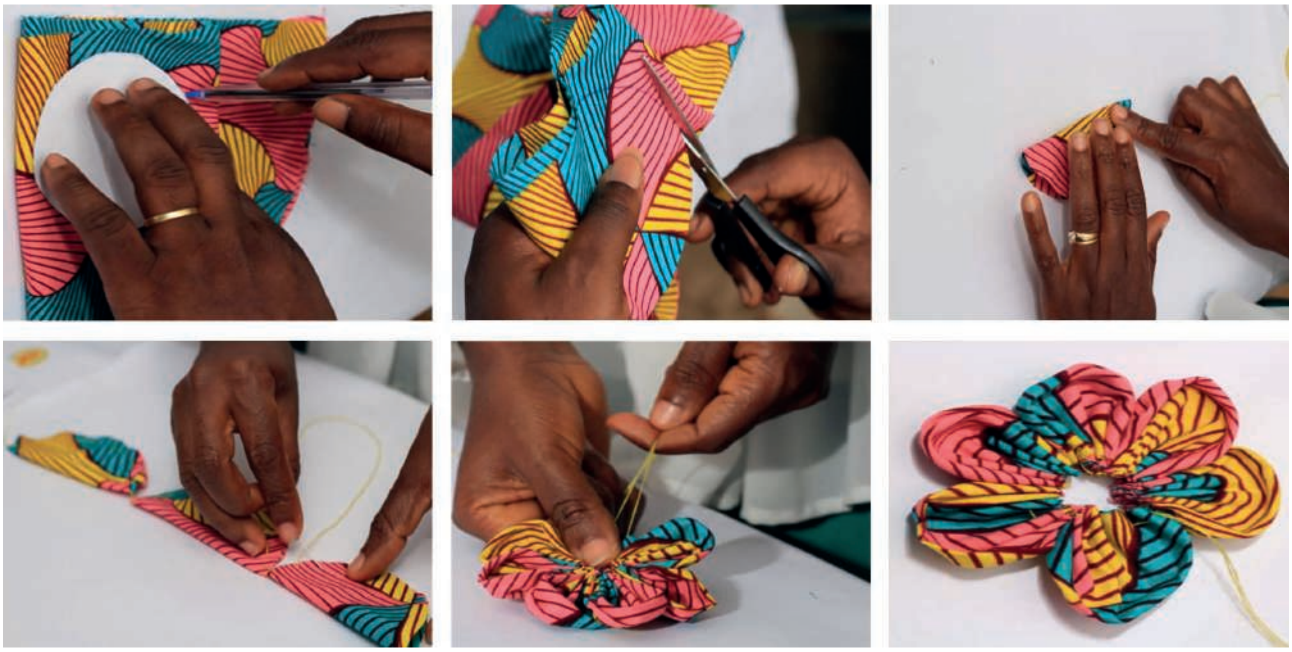

FIGURE 8: Procedure for making 'Nsroma' (Star).

2.4.5 'Anidado' (Hope)

For the construction of 'Anidado' (meaning Hope in 'Twi' language), eight circular pieces were cut out. Each piece was then folded into quarters, creating four sections. These sections were securely joined together by stitching. The ends of the thread were brought together and continuously pulled until the inner tops of the fabric pieces became taut. This process resulted in folds that added a sense of fullness, forming the "petals" of the flowers. To complete the flower, a decorative accessory with a harmonious colour scheme was fixed with the aid of fabric glue to seal the hole created in the center by the pulling process. The process of making fashion adornment five (5) is illustrated in Figure 9.

2.4.6 'Anigye' (Happiness)

'Anigye' (meaning Happiness in 'Twi' language) presents a simple heart shape chosen for the flower petal design. In the construction process, a simple heart shape was drawn on a piece of paper and carefully cut out. This heart template was then placed on a fabric pieces, traced, and cut out. This process was repeated until a total number of 10 heart-shaped fabric pieces of the same shape, were created. Using a threaded needle, the edges of a paired set of heart-shaped fabric pieces were stitched, leaving an approximate 2cm opening. The next step involved filling the interior of the fabric heart with shredded fabrics in the form of linters, creating a padded effect. To secure the structure, a 10cm copper wire was cut and a hook was fashioned at one end. The hooked end was carefully inserted into the padded heart piece, and the filling opening was sealed by sewing to close up the opening end that aided the filling process. To achieve a neat finish, florist tape was wrapped around the copper wire, covering it completely. This process was repeated until the desired number of heart-shaped pieces were obtained. Figure 10 presents the process of making fashion adornment six (6).

2.4.7 'Nkabom' (Unity)

The construction of 'Nkabom' (Unity) demanded using a fabric piece measuring 2 by 4 inches as a guide, twenty (20) rectangular fabric pieces were cut out. These rectangular pieces were then transformed into triangular shapes by folding the side tips inward and securing them with glue, resulting in the form. Next, a hard stiffener was measured to create a circle with a diameter of 6 inches, which was then cut out. The triangular fabric pieces were coated with glue and affixed onto the stiff base. The pieces were arranged in an overlapping manner to create a star-like pattern. This arrangement continued until the entire surface of the stiff base was covered. To complete the flower, a decorative piece was positioned at the center, providing a finishing touch. Figure 11 shows the procdure for making fashion adornment seven (7).

3. FINDINGS AND DISCUSSION

The study revealed interesting creations as a result of green value creation, green creativity, green artistic practices coupled with manipulation and altering of fabrics through different technique. These creations fall under fashion accessories, accents and brooches. They can be used as standalone accessories or combined with other

FIGURE 9: Procedure for making 'Anidado' (Hope).

FIGURE 10: Procedure for making 'Anigye' (Happiness).

accents to enhance aesthetic sensibilities. The final products were given names that were familiar with Ghanaian fashion consumers so they could relate with them.

3.1 'BanbↃ' (Protector)

'BanbↃ' (Protector)is a fabric rose as shown in Figure 12a which is a suggestive representation of the natural rose flower. It was made out of medium sized fabric pieces (6cm x 6cm). It represents the intricate overlaps of the rose flower. With the use of colourful ankara fabric a simulated rose flower wasachieved. Ankara fabric was use because it could easily adapt to the manipulation of the folds associated with the rose flower. The rosette produced has multiple uses, it can be used as a hair piece when a comb is fixed at the base or a brooch when a safety/brooch pin is attached to it.

Based on its design concept and usage the researchers named and refer to it as 'BanbↃ' meaning protector, a suggestive visual analysis presents an artistic description of the fabric rose, depicting the way the petals of the rose flower are arranged revealing a portion of the golden fabric ball in the middle. This name also suggests care and enhancement.

'BanbↃ' relates to safeguarding and defending in the context of environmental sustainability. The concept for the creation of this adornment is hinged on preserving and restoring the natural eco system (Stoltz, 2023). Reducing pollution and advocating for practices that do not deplete resources (Eiadat et al., 2008). 'BanbↃ' (protector) concept looks at the ability to protect the resources for future generation. 'BanbↃ' radiates restoring the depleted habitats and maintaining biodiversity, conservational efforts and advocacy (Elimam, 2017; Li, Wang & Wu., 2019).

3.2 'Odehye3' (Royalty)

This is a result of fabric pieces manipulated to create decorative petals of different sizes. As seen in Figure 12b, this piece is a suggestive description of the flamboyant flower. It has similar characteristics to the flame tree flower and represents the glow and brightness of the flamboyant flower. Using attractive and luminous ankara fabric pieces through creative manipulations, the fabric-flambo flower was created. Typically, the flamboyant flower petal is support by a stalk, thus a florist tapped copper wire was used to represent the suggestive stalk of the fabric-flambo flower. It was named and referred to as 'Odehye3' a word in the 'Twi'language of Ghana which means royalty. In African culture, the word "royalty" carries significant meaning and is often associated with power, leadership, and prestige. Royalty is symbolized by individuals who possess regal qualities and are seen as the embodiment of authority and dignity within their communities.

'Odehyde3' flower bouquet can be seen as a symbol of pride and beauty, reminiscing the majestic and colorful regalia worn by African royals. Just as African royals would adorn themselves in ornate garments and accessories, this bouquet becomes a visual representation of the opulence and regal nature associated with African traditions. This flower bouquet, which is made from different Ankara fabrics, depicts the concept of flamboyancy which can be related to the rich African culture by the vibrant and bold colours often seen in traditional African textiles and artistic expressions.

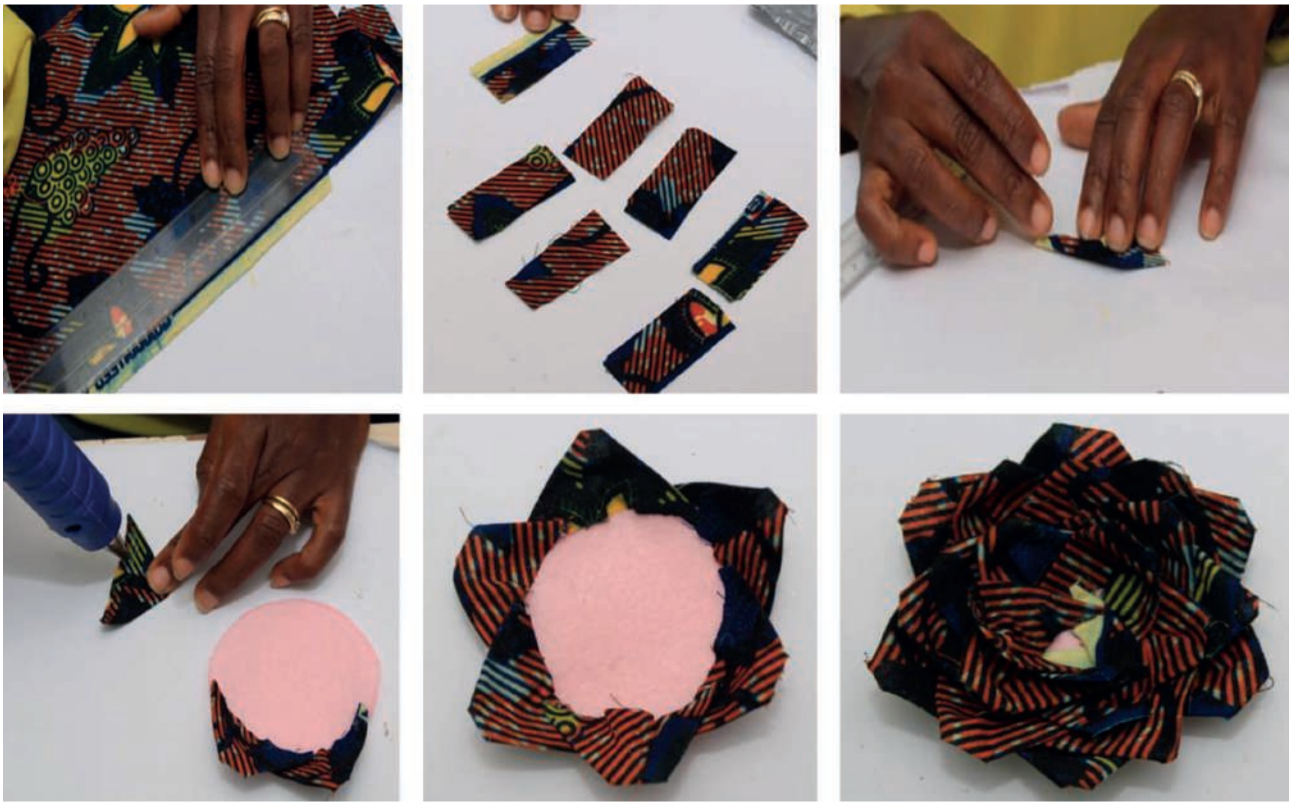

FIGURE 11: Procedure for making Nkabom' (Unity).

'Odehyde3' radiates pride and beauty which interweaves beautifully with environmental sustainability in several graceful ways. 'Odehyde3' advocate as an inspiring motivator for cultural area and communities to care for the environment and practice sustainable activities (Kumar, 2020). Individuals and communities that take pride and beauty as a cherished concepts engage in activities that preserve and enhance the local environment. Beautiful and sustainable environment promotes fascinating aesthetic sceneries and values with eco- friendly designs with aesthetic values (Brozović et al., 2020). This promotesclean air and green spaces with pride.

3.3 'Ahofɛ́' (Beautiful)

The researchers named and referred to the brooch as 'Ahofɛ́' which means 'beautiful' in the 'Twi' language in Ghana. 'Ahofɛ́' as seen in Figure 12c, is a decorative clothing enhancer used as a fashion accessory. It was made from Ankara. The word "beautiful" is closely linked to this fabric accessory looking at its aesthetic appeal, decorative nature, attention to detail, versatility, and ability to enhance the self-confidence of the user. As visual representations of beauty, craftsmanship, and personal style, the 'Ahofɛ́' is an integral part of fashion sensibilities, self-expression and radiates elegance and charm.

'Ahofɛ́' offers a unique opportunity for personalization and individual style as it can be worn in various ways, allowing the wearer to express their personality and taste. Whether pinned to a lapel, attached to a hat or used as a belt buckle, this accessory contributes to the overall aesthetic of an outfit, adding a touch of beauty that is distinct and personal. The choice of fabrics, colours, and embellishments are dependent on aura intended to be ignited.

'Ahofɛ́' is a visual representation of beauty and a powerful way to communicate environmental sustainability in a way of preserving our natural local environments, inspiring actions that raise awareness of stunning aesthetics of the environment (Chen et al., 2016). 'Ahofɛ́' hinges on enhancement, focusing on improving and optimising natural and manmade systems to arrive at better environmental outcomes (Kneipp et al., 2019). 'Ahofɛ́' (beautiful) capitalises on concepts like restoration, renewable, sustainable, green approaches circular economy and innovation (Kemp & Pearson, 2007). 'Ahofɛ́' highlights on collection of critical sustainable initiatives to create an enhanced environment.

3.4 'Nsroma' (Star)

The researchers named and referred to the fabric flower as 'Nsroma' which means a star, in the 'Twi' language. This simple flower mimics the phlox flower which is star-shaped, thus the name 'Nsroma' seems appropriate. Stars are a symbol of the cycle of life, representing growth, renewal, and the passage of time. In the African setting, the Phlox flower can be associated with these themes. As the Phlox blooms and blossoms, it represents the growth and renewal of life, echoing the celestial cycles observed in the stars. It is presented in Figure 12d.

The 'Nsroma' adornment can be likened to the concept of blooms and blossoms. This suggestively aligns with

FIGURE 12: Final Products produced from fabric waste: (a) 'BanbƆ' (Protector); (b) 'Odehye3' (Royalty); (c) 'Ahofɛ́' (Beautiful); (d) 'Nsroma' (Star); (e) Anidaso' (Hope); (f) 'Anigye' (Happiness); (g) Nkabom' (Unity).

achieving the environmental sustainability agenda. Blooms relate to creative solutions and initiatives in relation to environmentally sustainable practices (Chen et al., 2016). It manifests a clear understanding of issues of environmentally sustainable practices. 'Nsroma' as a concept is contextualised to focus on habit transformation and renewal from traditional practices. It radiates the awareness of embracing sustainable lifestyles (Dyck & Silvestre ,2018).

3.5 'Anidaso' (Hope)

This piece is a simple sunflower and the researchers named it 'Anidaso' which is a 'Twi' word that means 'Hope'. Sunflowers can be associated with positive emotions, including hope and fulfillments. The morning spread of the vibrant yellow petals, and sun-facing behavior symbolize optimism, positivity, and a hopeful outlook. 'Anidaso' is a seven-petal brooch with a glittery stud in the centre of the flower. Displayed as a brooch on the bust area of a figure radiates fullness and illusionary creates a fuller bust. Its therapeutic effects psychologically create a feel of convergence and divergent energies that takes the eye away from any figure flaws. 'Anidaso' fabric flower as seen in Figure 12e represents the belief that even in difficult circumstances, there is the potential for growth, renewal, and brighter days ahead.

This concept inspires action. It is powerful and promotes resilience in the actions to achieve sustainable development. 'Anidaso' is a bridging gap between our aspiration for a sustainable environment and the motivation for a better sustainable future (Takalo & Tooranloo, 2021). 'Anidaso' preaches concepts like empowering, resilience, collaboration, shared responsibility, collective impact, maintaining determination and possible coexistence between human needs and ecological limit (Brozović et al, 2020).

3.6 'Anigye' (Happiness)

The researchers named the heart patterned flower bouquet as seen in Figure 12f. 'Anigye' (happiness)is a Ghanaian 'Twi' word that means happiness. Flowers have long been associated with beauty, and their presence can bring joy and happiness to people. The vibrant patterns and colours of Ankara fabrics leave this bouquet to be visually striking and captivating. The combination of natural beauty and the artistic appeal of Ankara fabrics can evoke positive emotions, uplift spirits, and enhance feelings of happiness. The array of colours manifested by the Ankara adopted resonates the freedom from waste. The fabrics suggestively display a cry out from bondage, embracing a new life of new opportunities, with padded and puffy representation at the top which usually represent the head, the seat of wisdom. The suggestive stem area manifest series of independent stakes being held together by a band to radiate the felling of togetherness and unity. This description connotes the 'Anigye 'concept.

'Anigye'(Happiness) as a concept interconnect seamlessly with environmental sustainability. Radiating wellbeing and quality lifestyle which is premised on quality ecological life and alignment of human lifestyles with ecological balance (Kumar, 2020). A clean environment reduces positive energy, reduces diseases, reduces stress, thereby addressing environmental inequalities and promoting sense of belongingness (Dyck & Silvestre, 2018). 'Anigye'(Happiness) promotes sustainable lifestyle and fosters long term wellbeing for individuals and their environment (Mubarak et al., 2021).

3.7 'Nkabom' (Unity)

The researchers named this artefact 'Nkabom'. It is a Ghanaian 'Twi' word that means unity an ingredient which is essential in the family, community, nation, and race. In designing this Ankara fabric flower, the individual fabric pieces are intricately intertwined producing layered manifestation to form a cohesive whole as shown in Figure 12g. This interconnectedness can symbolize unity, as each fabric piece represents a different part, yet they come together to create a unified and complete flower. The Ankara fabric flower serves as a visual representation of the interconnected nature of individuals within a community, highlighting how unity can be achieved by embracing and appreciating the unique contributions of each person.

This concept talks about partnership and collaboration, referencing SDG 17. It radiates collective action and shared responsibility. The 'Nkabom' (Unity) concept stands for collaboration and cooperation at all levels, design interconnectivity and a dependable eco system (Kumar, 2020). Unity is a crucial ingredient for the attainment of environmental sustainability because it basic focus is on shared goal, collaboration and interconnectedness to bring a harmonious environment of equal balance of energy (Bolis et al., 2017).

4. CONCLUSIONS

This project has demonstrated how fabric waste from the small-scale garment industries can be reused to help solve the problem of waste management in Ghana. It was revealed that most fabric waste find their ways in the landfill or burnt in the open which causes environmental pollution and are hazardous to humans and the eco system in general. From the study it was also brought to bear that there are opportunities and several possibilities for artists, fashion designers and garment manufacturers to explore knowledge and skills to create useful decorative accents and fashion accessories to enhance garments and create psychological and therapeutic perfect fashion figures and imagery by using recycled and upclyed textile waste materials. The success of this project promotes environmental sustainability and green innovation. Manipulation of materials were made simple to promote replication. Materials employed were basic waste from the small-scale dress maker's shop. It is envisaged that the project outcomes result in skills for alternative employment and job creation. The findings of this research not only create an extensive platform for generating additional revenue for manufacturers but also contributes to environmental sustainability by encouraging waste recycling. Outcomes also help address SDG's (1- No poverty), (8- Decent work and Economic growth) and (12- Responsible consumption and production).

The research explores the potential of material waste management through the creation of innovative textile art pieces, such as brooches, bouquets, fabric flower pins, and floral arrangements. By analyzing the environmental repercussions of incineration and landfilling, the study proposes actionable strategies to mitigate hazards linked to improper fabric waste disposal. Textile artists, Mastercraft persons and their apprentices from the small-scale garment industries can adopt the techniques demonstrated to upskill their green competencies to reduce waste in the environment. Governments and non-governmental organizations can also explore other innovative green innovation approaches to help upcoming garment apprentices and early career garment makers to develop green competencies by adopting green practices to reduce waste in their garment industries.

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THE USE OF AGRO-INDUSTRIAL WASTE TOWARDS A SUSTAINABLE CIRCULAR ECONOMY: A SYSTEMATIC REVIEW

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ABSTRACT
The agribusiness production model follows the linear economy model and generates waste, which, if not properly managed, causes economic, environmental, and social challenges. In this context, a substantial body of research indicates that there are sustainable alternative solutions that transform waste materials into raw materials, thereby reducing the amount of pollution. This article presents a systematic review of the use of agro-industrial waste as a sustainable solution, with a particular focus on its role in the transition to a circular economy. The significance of this work lies in identifying trends and opportunities for the use of agro-industrial waste, which contributes to sustainability through alternative uses that minimize environmental impact. In addition, it provides ideas for the development of value-added business units. The results are useful for policymakers, entrepreneurs, and researchers interested in implementing sustainable practices. A systematic analysis of 100 research articles published between 2017 and 2024 was conducted using the PRISMA tool to identify trends, progress, and benefits associated with the circular economy in relation to agro-industrial waste. The findings demonstrate the potential for repurposing these by-products, with applications in the production of bioenergy, the development of materials, and the extraction of compounds with utility across a range of industries, including agriculture, cosmetics, pharmaceuticals, and food production. In conclusion, the use of agro-industrial waste materials encourages the adoption of responsible practices and makes a substantial contribution to a sustainable future.

1. INTRODUCTION

The global production model follows the linear economy model, which is characterized by the extraction, manufacturing, consumption, and discarding of resources. This model has been used by the agroindustrial sector in its various activities, resulting in negative economic, social, and environmental impacts (Cury et al., 2017). The generation of waste occurs at all stages of the production process, including the transformation and commercialization of products. In the absence of an effective management plan, this waste presents significant challenges in its final disposal. It is imperative to transition from a linear economy model to a circular one that is based on the principles of reduction, reuse, recycling, repurposing, remanufacturing, and redesign (Romero-Sáez, 2022; García, 2022; Afteni et al., 2021), becoming a global priority as a strategy to dynamize territories (Khanna et al., 2022; Zheng et al., 2025).

Agro-industry is the set of activities aimed at the industrialization and commercialization of value-added products produced from waste converted into raw materials derived from food production processes (Peñaranda et al., 2017; Aguiar et al., 2022a; 2021b). It is estimated that approximately one-third of the world's food for human consumption is discarded, resulting in the generation of waste throughout the entire supply chain, from the cultivation of raw material to its commercialization. However, the amount and type of waste are influenced by a few factors, including GDP, average income, and population consumption. In some countries like Colombia, India, Ecuador, Mexico, and Paraguay, waste originates in agriculture, given that their economies are primarily based on this sector and the activities that comprise it (Peñaranda et al., 2017).

Aware of these issues, the appropriate management of waste is imperative to mitigate environmental damage (Alazaiza, 2025). It is necessary to reassess the linear economy model and consider more sustainable alternatives (Özkan & Yücel, 2020). The circular economy model offers a transformative approach to natural resource and waste management, aiming to ensure long-term sustaina-

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bility. It involves designing products for multiple life cycles, efficient resource utilization, and minimizing the generation of hazardous waste that could harm the planet (Silva y Oliveira, 2021).

Due to the above, research is being conducted with the aim of identifying sustainable solutions to minimize the problem. Potential solutions include the recovery and use of waste generated in the sector, where the production of biofuels (Golato et al., 2017; Delgado et al., 2023), bioplastic (Azmin et al., 2020; Henao and Salazar, 2018), compost (Moises et al., 2022; Chia et al., 2020), and renewable energy (Torres and Quintero, 2019) are examples of how to transform waste into valuable resources, representing a promising path for reducing environmental pollution.

A systematic review was conducted to demonstrate the productive utilization of agro-industrial residues as a sustainable solution. The objective of this study was to analyze existing research on the use of fruit and vegetable waste as raw material, identify trends and advances, and assess environmental, social, and economic benefits associated with this practice. The search focused on the use of agro-industrial residues for the development of new products, including fuels, animal feed, biomass, construction materials, compost, among others.

The results show the existence of productive initiatives that are moving toward a sustainable circular economy. Likewise, alternative uses for agroindustrial waste were identified, including the generation of bioenergy, the development of materials, and the extraction of compounds with potential applications in various industries such as agriculture, cosmetics, pharmaceuticals, and food. In conclusion, the use of agroindustrial waste promotes responsible practices and contributes significantly to a more sustainable world, especially in countries that rely on this sector for their economies.

The document targets those interested in the transformation of raw materials, including waste at technological and agricultural levels. It is also intended for professionals in industrial engineering, chemistry, construction (cement companies), and anyone focused on environmental quality and climate change improvement through agro-industrial consumption.

2. MATERIALS AND METHODS

2.1 Methodology

The objective of the research was to investigate the feasibility of contributing to sustainability and pollution abatement by transitioning from a linear to a circular economy model. The research employs an exploratory mixed approach, utilizing the systematic analysis method (Jeong et al., 2024; Codina, 2024; Castillo et al., 2024). The review encompassed 1,785 articles, which were subjected to a process of refinement based on pre-defined exclusion and inclusion criteria. The study period comprises articles published during the years 2017 and 2024. The analysis is conducted from a theoretical and documentary perspective, identifying trends, advances, and the utilization of agroindustrial waste. This evidence advances in this field, particularly regarding the practices and productive bets from a circular economy that allows contributions to environmental, social, and economic sustainability.

The search strategy was structured according to four main axes: topic, approach, context, and applications (Table 1). For each axis, key terms were defined and linked using Boolean operators (AND, OR, and NOT) since their use produces better results when searching for information (Aliyu, 2017; Bramer et al., 2018; Villegas, 2023). To begin, the search equation included either subjects such as agro-industrial residues, wastes, and by-products: ("agro-industrial residues") OR ("agro-industrial wastes") OR ("agro-industrial by-products"). Subsequently, the search was refined by defining the approach, which incorporated concepts such as recovery, valorization, reuse, and the circular economy: ("utilization") OR ("valorization") OR ("reuse") OR ("transformation") OR ("circular economy") OR ("sustainability"). As the literature on this subject is vast, it was necessary to establish a comprehensive context for the studies, with a particular focus on the agro-industrial, food, cosmetic, and pharmaceutical sectors: ("agro-industry*") OR ("agricultural sector") OR ("food industry") OR ("cosmetics industry") OR ("pharmaceutical industry"). Finally, to refine the search, applications were limited to bioenergy, materials development, and sustainable practices: ("bioenergy") OR ("materials development") OR ("compound extraction") OR ("responsible practices") OR ("sustainable solutions").

2.1.1 Data acquisition

The search for articles was conducted using databases that covered visualization in different contexts, including Scopus, SciELO, DOAJ, and Latindex. The selection of databases was based on their coverage of scientific literature in the fields of agroindustry and waste management. It should be noted that the databases consulted have blind peer review, which ensures the quality of the documents, in addition to having search tools that allow users to find relevant information based on specific keywords.

A search engine was used to generate keywords related to the purpose of the study, which were then classified into six blocks: agricultural waste utilization, animal feed pro-

TABLE 1: Search equation.

Topic	Search terms
Subject	("agro-industrial residues") OR ("agro-industrial wastes") OR ("agro-industrial by-products")
Approach	("utilization") OR ("valorization") OR ("reuse") OR ("transformation") OR ("circular economy") OR ("sustainability")
Context	("agro-industry*") OR ("agricultural sector") OR ("food industry") OR ("cosmetics industry") OR ("pharmaceutical industry")
Applications	("bioenergy") OR ("materials development") OR ("compound extraction") OR ("responsible practices") OR ("sustainable solutions")

TABLE 2: Inclusion and exclusion criteria.

Inclusion criteria	Exclusion criteria
Articles published between 2017 and 2024	Articles published before 2017 or after 2024
Studies on the use of agro-industrial wastes	Studies that do not focus on agro-industrial wastes
Research demonstrating practical applications such as bioenergy, materials development, compound extraction	Research that only mentions the waste problem without proposing solutions
Studies that relate the use of waste to the circular economy and sustainability	Studies that focus exclusively on waste generation without addressing waste utilization
Publications in peer-reviewed scientific journals	Research that does not provide clear methodological details
Studies published either in English or Spanish	Publications in languages other than English or Spanish
Open Access studies	Paid studies (Not Open Access)

duction, bioenergy production, extraction of compounds, materials processing, and organic fertilizers, as well as other related topics.

Inclusion and exclusion criteria (Table 2) were established to ensure the relevance and quality of the selected studies. Articles were included if they were published in the defined period between 2017 and 2024 and were included in the four axes. Moreover, they should specifically address the use of waste from agro-industrial processes, with practical applications and a focus on circular economy or sustainability. Priority was also given to Open Access publications in English or Spanish. Studies that did not focus on agro-industrial process waste or that only mentioned the problem without proposing solutions were excluded, as were articles without clear methodological data and articles published in restricted access journals.

2.1.2 Systematic review

A bibliographic matrix was constructed according to category, thus allowing the texts to be documented for analysis and discrimination. This allowed for the identification of trends, the number of publications per year, authors, citations, journals, topics addressed, advances, and practices related to the use of residues derived from agroindustrial processes. Figure 1 illustrates the process flow.

The figure illustrates how the equation and search engines were used to identify 1,785 articles. Following the implementation of the exclusion and inclusion criteria, a

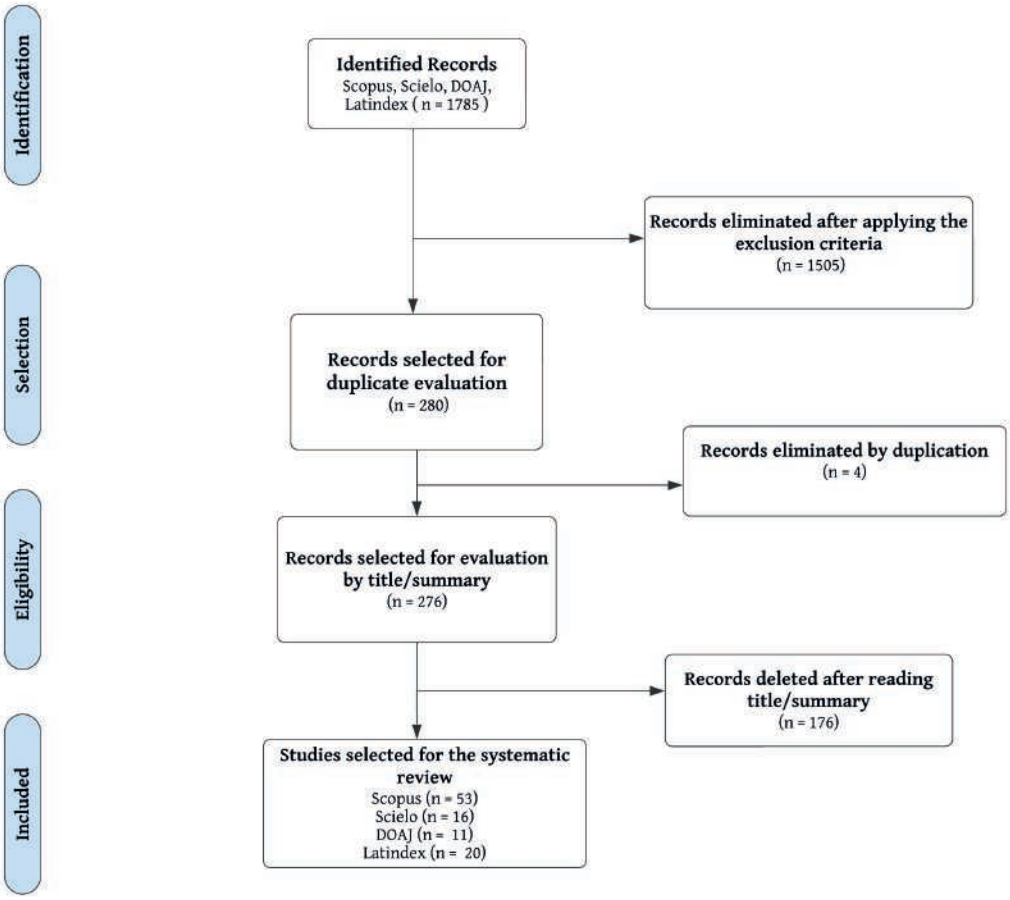

FIGURE 1: Selection process flowchart.

total of 1,505 records were deemed to be non-pertinent and were subsequently eliminated from the analysis. The inclusion criteria included: articles published between 2017 and 2024, studies focusing on the utilization of agro-industrial byproducts, research that elucidates practical applications such as bioenergy, material development, and compound extraction, studies that delineate the utilization of waste in relation to the circular economy and sustainability, publications in peer-reviewed scientific journals, and studies published in either English or Spanish, along with open access studies. Then, records were examined for duplicity, resulting in the removal of 4 duplicates. The remaining 276 records were evaluated by reviewing their titles and abstracts to verify their relevance, resulting in 100 articles, and were classified into the following areas: agricultural waste utilization, animal feed production, bioenergy production, extraction of compounds, materials processing, and organic fertilizers, as well as other related topics. The database of origin for each article is as follows: 53 articles from Scopus, 16 articles from Scielo, 11 articles from Doaj, and 20 articles from Latindex.

3. RESULTS AND DISCUSSIONS

The first stage of analysis identifies all published research studies during the specified period. Figure 2 shows that most publications (52%) occurred in 2020, 2021, and 2023. 2024 only encompasses the first quarter, indicating a promising trend in publication activity, except in 2022.

Secondly, the journals that disseminate the research are analyzed, as well as the number of publications and citations during the period of study. The results indicate that the topic is of interest with a growing trend and diversity of research. A total of 3960 citations were found, with 60% concentrated in the first ten journals shown in Table 3.

Regarding the assessment of recurrent terminology across the articles, Figure 3 provides a representation of the thematic interconnections network, with two focal points: sustainability and fuels. Three clusters were identified: the first (red) pertains to animal feed, food waste, and fermentation; the second (green) is concerned with biofuels, biomass, and fossil fuels; and the third (blue) is centered on agriculture. The connecting lines between nodes represent the strength of bibliometric relationships. It was found that there is a close relationship between "biofuels-biomass" and "food waste-fermentation." Also, the "sustainable development" node acts as a central point of convergence, connecting aspects of agricultural waste management with bioenergy production.

Likewise, Figure 4 offers a visual representation of the articles consulted, classified by country of study origin during the period of study. This figure illustrates the geographical distribution of consulted articles, indicating a concentration of publications in countries with a productive economy based on agricultural products. The analysis is focused on the nine countries that account for 60% of the total number of publications.

The most frequently cited articles on this topic during the period of study were also identified. Three of the most frequently cited articles were identified in the Scopus database. 1. The article "Agro-industrial wastes and their utilization using solid-state fermentation: a review" in Bioresources and Bioprocessing (2018) has been referenced 807 times, while the article "Towards transparent valorization of food surplus, waste, and loss: clarifying definitions, food waste hierarchy, and role in the circular economy," published in the journal Science of The Total Environment (2020), has been cited 257 times. The third article, "Biofuels and their sources of production: A review on cleaner, sustainable alternatives against conventional fuel in the framework of the food and energy nexus" published in the journal Energy Nexus (2021), has been referenced 113 times.

Furthermore, additional articles were identified in other databases, including Latindex, which yielded the article "Use of Agro-Industrial Waste to Improve Environmental

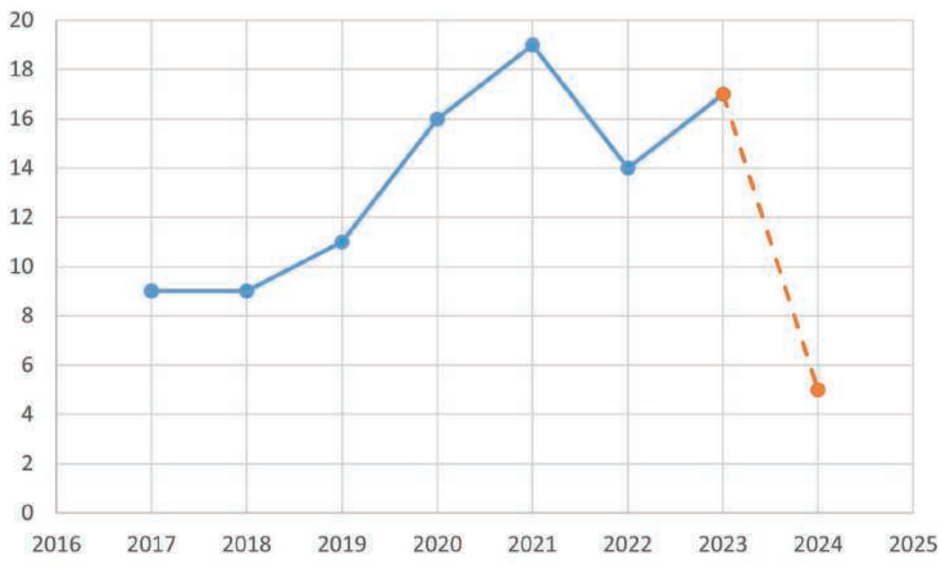

FIGURE 2: Number of articles published per year.

TABLE 3: Journal and citations.

Journal	Number of articles	Publications %	Total citation	Average number of citations
Bioresources and Bioprocessing	1	1%	804	804
Revista Facultad de Ciencias Básicas, Universidad Militar Nueva Granada	2	2%	382	191
Science of The Total Environment	2	2%	257	129
Revista De Investigación Agraria Y Ambiental	1	1%	194	194
Revista Colombiana de Ciencia Animal	1	1%	171	171
Energy Nexus	1	1%	158	158
Journal of Bioresources and Bioproducts	1	1%	140	140
Environmental Pollution	1	1%	103	103
Fuel	3	3%	102	34
Foods	1	1%	95	95
Orinoquia	1	1%	88	88
Dominio de las Ciencias	1	1%	83	83
Journal of Environmental Chemical Engineering	1	1%	81	81
PLOS ONE	1	1%	79	79
Ain Shams Engineering Journal	1	1%	78	78
Revista Ingeniería Industrial	1	1%	69	69
Annals of Agricultural Sciences	1	1%	68	68
Journal of Materials Research and Technology	1	1%	51	51
Bioresource Technology	1	1%	45	45
Heliyon	2	2%	45	23
Molecules	2	2%	45	23
CIENCIA ergo-sum	1	1%	44	44
Agriculture	1	1%	39	39
Materials Science for Energy Technologies	1	1%	37	37
Biomass Conversion and Biorefinery	1	1%	33	33
Scientia et Technica	1	1%	32	32
Animals	2	2%	31	16
Ingenierías USBMed	1	1%	31	31
Avances en Ciencias e Ingeniería	1	1%	27	27
Industrial Crops and Products	1	1%	27	27
Revista Mexicana de Ciencias Agrícolas	1	1%	24	24
Investigación e Innovación en Ingenierías	1	1%	23	23
Sustainable Energy Technologies and Assessments	1	1%	23	23
Revista Cubana de Quimica	1	1%	21	21
TecnoLógicas	1	1%	21	21
Polo del Conocimiento	1	1%	20	20
Axioma	1	1%	18	18
Case Studies in Chemical and Environmental Engineering	1	1%	18	18
Biomass and Bioenergy	2	2%	17	9
Journal of Thermoplastic Composite Materials	1	1%	17	17
Energies	1	1%	16	16
Meat Science	1	1%	16	16
Revista Iberoamericana de Tecnología Postcosecha	1	1%	15	15
Archives of Microbiology	1	1%	14	14
Cuadernos del Tomás	1	1%	14	14
RIINN - Revista Ingeniería e Innovación	2	2%	14	7

Journal	Number of articles	Publications %	Total citation	Average number of citations
Sustainable Production and Consumption	1	1%	14	14
Prospectiva	3	3%	13	4
Revista Colombiana de Investigaciones Agroindustriales	1	1%	13	13
Revista Tecnología en Marcha	1	1%	13	13
Revista industrial y agrícola de Tucumán	1	1%	12	12
ALFA	1	1%	11	11
Enfoque UTE	1	1%	10	10
FIGEMPA: Investigación y Desarrollo	1	1%	10	10
Rivar	1	1%	10	10
International Journal of Biological Macromolecules	1	1%	9	9
Designia	1	1%	8	8
Journal of Environmental Management	1	1%	8	8
Resources, Conservation and Recycling	1	1%	8	8
Revista Ingeniería Agrícola	1	1%	8	8
Energy for Sustainable Development	1	1%	7	7
Journal Of Academia	1	1%	7	7
Saudi Journal of Biological Sciences	1	1%	7	7
Gestión y Ambiente	1	1%	6	6
Food Packaging and Shelf Life	1	1%	5	5
Revista Colón Ciencias, Tecnología y Negocios	1	1%	5	5
Revista Kawsaypacha: Sociedad y Medio Ambiente	1	1%	5	5
Scientia Agropecuaria	1	1%	5	5
South African Journal of Animal Sciences	1	1%	5	5
Cuadernos de Investigación UNED	1	1%	4	4
Materials Today: Proceedings	2	2%	4	2
Ciencia del suelo	1	1%	3	3
En Computer-aided chemical engineering	1	1%	3	3
Pertinencia Académica	1	1%	3	3
Química Hoy	1	1%	3	3
Chemical Engineering Research and Design	1	1%	2	2
Ciencia Latina Revista Científica Multidisciplinar	1	1%	2	2
Journal of Analytical and Applied Pyrolysis	1	1%	2	2
Minerva	1	1%	2	2
Acta Nova	1	1%	1	1
Agro Productividad	1	1%	1	1
Digital Ciencia@ UAQRO	1	1%	1	1
Agro UNS	1	1%	0	0
Anales Científicos	1	1%	0	0
Fuel Processing Technology	1	1%	0	0
LOGINN Investigación Científica Y Tecnológica	1	1%	0	0
Revista de la Facultad de Agronomia	1	1%	0	0
Revista Teinnova	1	1%	0	0
Total	100	100%	3960	

Quality" from the journal Revista Facultad de Ciencias Basicas, Universidad Militar Nueva Granada (2018). This article has received a total of 370 citations. DOAJ lists the article "Use of Agro-industrial Waste in Colombia" in the Revista De Investigación Agraria Y Ambiental (2017) with 194 citations, while CIELO lists the article "Agro-industrial

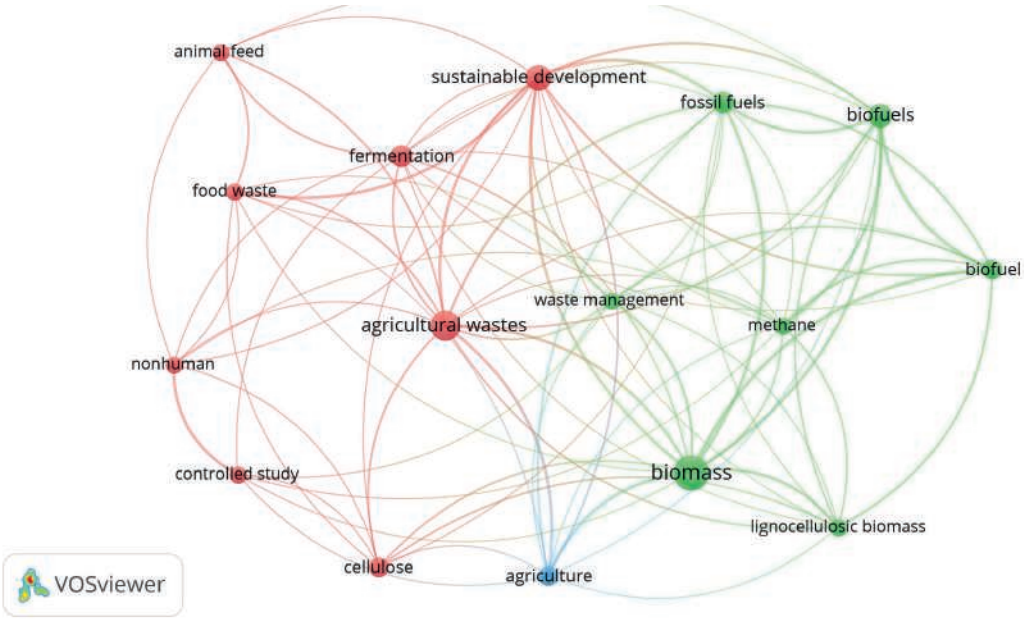

FIGURE 3: Thematic interconnections network.

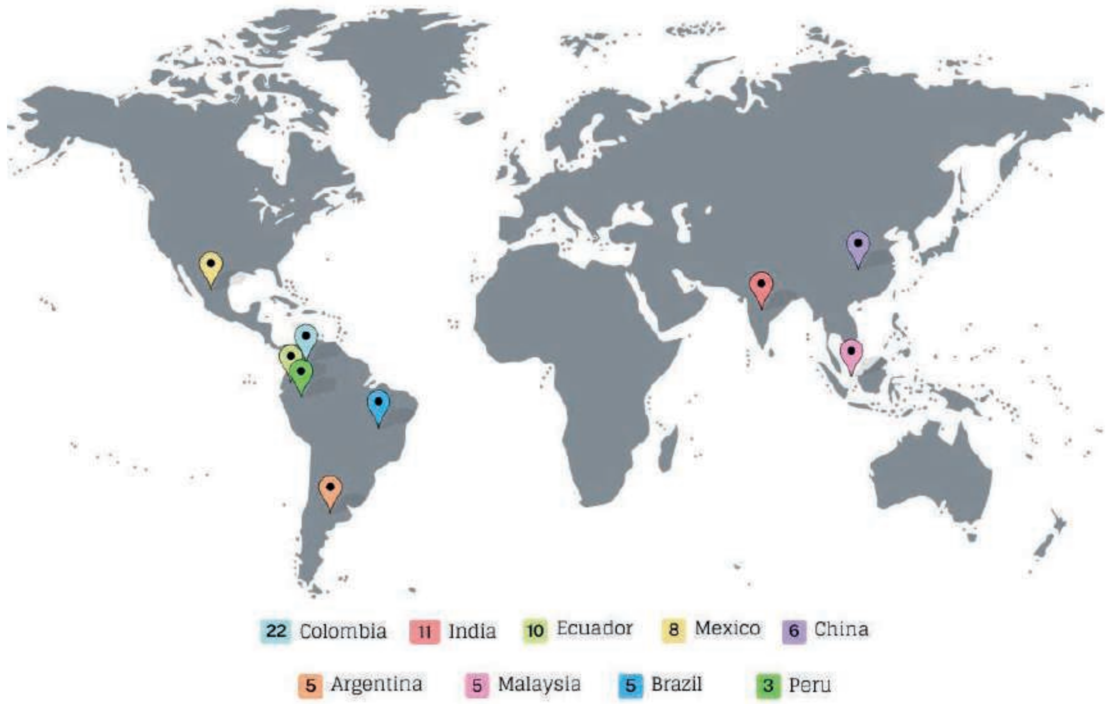

FIGURE 4: Country of study origin.

Waste Impact, Management and Utilization" in the Revista Colombiana de Ciencia Animal (2017) with 171 citations.

It can be stated with a reasonable degree of certainty that there is now sufficient evidence to affirm that in the world there is an increased awareness of change towards a circular economy production model. This is evidenced by the fact that productive bets are being generated using agroindustrial waste on different fronts that were classified in six categories, and the participation is as follows: production of animal feed with 14%; generation of bioenergy with 27%; elaboration of materials with 14%; extraction of valuable compounds with 16%; production of fertilizers with 10%; and other applications with 18%.

The objective of this article was to identify productive practices that involve the use of agroindustrial wastes as part of the transition from a linear to a circular economy model, with a view to contributing to sustainability. Through a systematic review, the state of the art was obtained, with particular attention paid to trends in the use of agroindustrial wastes. This revealed the production of animal feed, bioenergy, materials and extraction compounds, materials, fertilizers, and other applications such as food for human consumption and cosmetics.

3.1 Animal Feed

It is possible to produce animal feed (for ruminants, pigs, and poultry) from agro-industrial residues. For example, the stems and leaves have a high fiber content but a low protein content. In contrast, husks, seeds, and bran of grains, such as wheat, are rich in protein but have less fiber. Combining and blending is necessary to formulate compound feeds that provide animals with the nutritional value necessary for their development (Yang et al., 2021).

However, it should be noted that some residues contain toxic elements tolerated by ruminants but not by other species. This makes it necessary to subject the residues to physical, chemical, or biological treatment processes to degrade or eliminate the toxic factors, guaranteeing food safety (Yafetto et al., 2023). Furthermore, it is evident that this type of research is being pursued in a multitude of geographical contexts. For example, in Ghana, the lack of feed supply for the livestock industry has led most farmers to use agricultural residues derived from groundnut, cassava, pigeon pea, yam, corncob, and rice in their raw state as livestock feed. In order to achieve an effective valorization of these residues, Yafetto et al. (2023) suggest the biological processing of these residues, taking full advantage of their nutritional potential.

In Mexico, Alarcón-Rojo et al. (2019) conducted a study that demonstrated that the inclusion of fermented apple pomace in lamb diets resulted in improved meat quality. Similarly, the study by Mizael et al. (2020) in Brazil indicated that the introduction of fermented tomato pomace in the diet of lactating goats resulted in remarkable improvements in both milk production and milk composition. These findings underscore the beneficial effects of incorporating agro-industrial residues in animal feed.

Likewise, the implementation of standards for the use of agro-industrial residues is required. In fact, the environmental and economic benefits are well-documented; however, the necessity of implementing regulations aimed at sustainable practices is a matter of debate. The establishment of treatment protocols and quality certifications would ensure food safety and promote confidence in these inputs, thereby encouraging their adoption by producers and promoting a more sustainable model in the livestock industry (Table 4).

3.2 Bioenergy

Another potential application of agro-industrial waste is its use in bioenergy generation as an alternative and a new commitment to sustainability. Lignocellulosic biomass, such as rice husks, coffee husks, banana leaves, and corn straw, can be converted into biofuels through biochemical and thermochemical processes (Alves et al., 2023; Cherwoo et al., 2023; Wang et al., 2023). These processes produce bio-oil, biochar, biodiesel, bioethanol, and biogas, contributing to cleaner energy alternatives.

The manufacture of bio-oil utilizes a variety of agricultural by-products, including rice husk residues, coffee husk, banana leaves, and oat and corn straw (AlMallahi et al., 2023; Bieniek et al., 2023; Ma et al., 2024). Husk, fiber, and residual leaves from coconut processing are promising sources for obtaining biochar (Duangkham and Thuadaij, 2023; Ighalo et al., 2023). Also, in bioethanol production, orange peel, seed and pulp residues, as well as coffee pulp residues, can be used as feedstock (Acevedo et al., 2021; Manrique, 2018). Furthermore, rice straw, sunflower stalk and head, together with sugarcane bagasse, are viable sources for obtaining biogas (Hashemi et al., 2019; Zhou et al., 2017; Zhurka et al., 2019). The use of these residues for biofuel production not only contributes to reducing greenhouse gas emissions, but also offers sustainable energy solutions (Sharmila et al., 2024; Mahapatra et al., 2021; Coello et al., 2021).

Taking advantage of agricultural residues in the production of bioenergy not only contributes to solving environmental problems related to waste management and the use of highly polluting fuels but also allows obtaining high

TABLE 4: Animal feed.

Authors	Usable waste / Recoverable waste	Country	Year of publication
Yafetto et al. (2023)	General (agricultural waste)	Alemania	2023
Sun et al. (2024)	General (agricultural waste)	Colombia	2024
Quintero-Herrera et al. (2023)	General (agricultural waste)	Países bajos	2023
Mizael et al. (2020)	Residual tomato pulp	Reino unido	2020
Alarcon-Rojo et al. (2019)	Apple pulp waste	Países bajos	2019
de Evan et al. (2020)	Cauliflower stems	Países bajos	2020
Aruna et al. (2017)	Yam peel	Reino unido	2017
Jais et al. (2017)	Banana peel	Reino unido	2017
Yang et al. (2021)	General (agricultural waste)	Reino unido	2021
Camacho Villa & Grande Tovar (2021)	Malt bagasse	Países bajos	2021
Aguiar et al. (2021)	Agro-industrial waste	Ecuador	2021
Nobre et al. (2020)	Guava agro-industrial waste	Brasil	2020
Romero-Sáez (2022)	Agro-industrial waste	Colombia	2022

value-added products from residues (Casoni et al., 2018; Fit, 2025; Rashid & Malik, 2023).

A fundamental aspect of the production of bioenergy, derived from agroindustrial waste, is the need to enhance the efficiency and profitability of conversion processes. Technologies are crucial in achieving this, as they can lead to cost reductions. From a public policy perspective, it is necessary to establish incentives for the utilization of bioenergy in the industrial and transport sectors in order to mitigate climate change (Table 5).

3.3 Material and extraction compounds

The recovery of bioactive compounds and materials, including the extraction of valuable compounds from agro-industrial waste, presents a promising opportunity. For example, lignocellulose biomass, an agro-industrial and forestry waste, when dissolved with ionic liquids, yields cellulose, lignin, and hemicellulose, which are compounds used as biofuel feedstock, biochemicals, and bioplastics (Norfarhana et al. 2024). Likewise, cellulose, a component of plants,

TABLE 5: Bionergy.

Authors	Usable waste / Recoverable waste	Country	Year of publication
Khan et al. (2023)	General (agricultural waste)	Malasia	2023
Sharmila et al. (2024)	General (agricultural waste)	Colombia	2024
Duangkham & Thuadaij (2023)	Rice straw and banana peel	Argentina	2023
Aruwajoye et al. (2020)	Mixed starchy agricultural waste	México	2020
Acevedo et al. (2021)	Coffee waste	Argentina	2021
Gómez-Castro et al. (2022)	Fruit and vegetable waste	Chile	2023
Gómez Manrique (2018)	Citrus waste	Colombia	2018
Golato et al. (2017)	Sugarcane waste	Colombia	2017
Delgado Alvarado et al. (2023)	General (agricultural waste)	Colombia	2022
Gil Aguilar et al. (2022)	General (agricultural waste)	Ecuador	2022
Vargas Corredor & Peréz Pérez (2018)	General (agricultural waste)	Bolivia	2018
Reyes Suárez et al. (2020)	Tomato waste	Ecuador	2020
Ighalo et al. (2023)	Coconut waste	México	2023
Torres Pérez & Quintero Lopez (2019)	African palm waste	México	2019
Sadh et al. (2018)	General (agricultural waste)	India	2018
Mahapatra et al. (2021)	Algae, biomasses	Colombia	2021
Rojas-González & López-Rodríguez	Agro-industrial waste - Fruits - Pineapple	Colombia	2019
Morales Apaza et al. (2021)	Pineapple waste	Bolivia	2021
Ginni et al. (2021)	Agro-industrial waste	India	2021
Anvari et al. (2024)	Agro-industrial waste	Tunisia	2024
Zhang et al. (2023)	Agro-industrial waste	China	2023
Kabir Ahmad et al. (2022)	Coconut waste	Malasia	2022
Bot et al. (2023)	Banana peels, rattan waste, coconut shells, and sugarcane bagasse	Camerún	2021
Zinla et al. (2021)	Rice straw, rice husk, coffee husk, and cocoa pod husk	Costa de Marfil	2021
Aristizábal-Marulanda et al. (2022)	Cut coffee stems	Colombia	2022
Teigiserova et al. (2020)	Food waste	Dinamarca	2020
Alves et al. (2023)	African palm waste	Brasil	2023
Cherwoo et al. (2023)	General (agricultural waste)	India	2023
AlMallahi et al. (2023)	Biochar and bio-oil	Emiratos Árabes Unidos	2023
Bieniek et al. (2023)	Oats and corn straw	Polonia	2023
Ma et al. (2024)	Biochar and bio-oil	China	2024
Sajad Hashemi et al. (2019)	Sugarcane waste	Iran	2019
Zhou et al. (2017)	Rice straw	China	2017
Zhurka et al. (2019)	Sunflower seeds	Grecia	2019
Casoni et al. (2018)	Sunflower seed shell	Argentina	2018
Gallipoli et al. (2021)	Citrus fruit waste		2021

has a variety of applications, including the reinforcement of composite materials and the production of biomaterials. It can be extracted from residues such as straws, husks, and stems, as well as from pineapple residues, by enzymatic hydrolysis or advanced chemical treatments (Presenda-Geronimo et al., 2020).

However, the use of agro-industrial waste to obtain bioactive compounds not only promotes sustainability but also fosters innovation across diverse industry sectors, thereby reducing the reliance on conventional sources and minimizing environmental impact. Moreover, this approach generates economic opportunities for the agro-industrial sector.

The food, cosmetic, and pharmaceutical industries are interested in bioactive compounds such as bromelain, as well as phenolic compounds, due to their biological properties, antioxidant, anticancer, and antimicrobial capacity. These valuable compounds can be extracted from pineapple peel, which highlights the importance of utilizing available resources for various industrial applications (Campos et al., 2020; Paz Arteaga, S. 2022).

Nevertheless, advanced techniques such as enzymatic hydrolysis, fermentation, and extraction allow for the production of premium-quality compounds with a multitude of applications across diverse sectors, including food, pharmaceuticals, energy, and materials. Consequently, the recovery of valuable compounds from agro-industrial waste represents a promising path for fostering a sustainable and efficient future, particularly in terms of waste management, which represents a shift to a regenerative circular economy (Pal, 2024).

The development of materials such as bioplastics and biorefinery from agro-industrial waste represents a cutting-edge approach in the pursuit of sustainable solutions (Table 6).

3.4 Materials

By employing innovative processes, a range of agricultural residues, including cucumber peels, tubers, pineapple, cocoa, orange peels, straw, and crop residues, are subjected to controlled degradation treatments or fermentation processes to extract valuable compounds, an eco-friendly alternative to conventional plastics derived from non-renewable resources (Caliskan, 2025). In the case of bioplastics, the cellulose obtained from these residues can be transformed into biodegradable polymers, offering an environmentally friendly alternative to conventional plastics derived from non-renewable resources.

TABLE 6: Material and extraction compounds.

Authors	Usable waste / Recoverable waste	Country	Year of publication
Norfarhana et al. (2024)	General (lignocellulosic biomass)		2024
Paul et al. (2023)	Coconut fiber		2023
Nurika et al. (2020)	Rice straw		2020
Pattnaik et al. (2022)	Sugarcane waste		2022
Camacho-Oviedo et al. (2020)	Potato peel		2020
Presenda-Gerónimo et al. (2020)	Pineapple waste		2020
Valle Alvarez et al. (2019)	Waste from palm oil production	Ecuador	2019
Zambrano Zambrano et al. (2021)	Rice husk		2021
Montoya-Pérez et al. (2017)	Pineapple waste		2017
Cabascango et al. (2021)	General (agricultural waste)		2021
Del Rio Osorio & Grande-Tovar (2021)	Cassava waste	Colombia	2021
Diaz-Uribe et al. (2020)	Waste from the peel of Vaccinium meridionale fruit (antioxidant)	Colombia	2020
Matiacevich et al. (2023)	General (agricultural waste)	Chile	2023
Aguiar Novillo et al. (2022)	Agro-industrial waste	Ecuador	2022
Vargas y Vargas et al. (2019)	Fruit peel	México	2019
Flórez Montes & Rojas González (2018)	Agro-industrial waste	Colombia	2019
Campos et al. (2020)	Pineapple waste	Portugal	2020
Coello-Pisco et al. (2021)	Coffee waste	Colombia	2021
Sudarsan et al. (2023)	Rice straw	China	2023
Ilangovan et al. (2019)	Coffee husk	India	2019
Penkhrue et al. (2020)	Pineapple waste	Tailandia	2020
Azmin et al. (2020)	Cocoa husk and sugarcane bagasse	Malasia	2020
Kharb & Saharan (2023)	Cucumber peel	India	2023
Santos et al. (2023)	Orange peel and pulp residues	Brasil	2023
Yaradoddi et al. (2022)	Orange peel	India	2022

In addition, biorefining also harnesses the diversity of compounds in agro-industrial waste to produce biofuels, chemicals, and advanced materials. This integrated approach not only reduces dependence on fossil resources but also helps to mitigate the environmental impacts associated with inefficient waste management. Ultimately, the transformation of agro-industrial waste into advanced materials highlights the potential of the circular economy and demonstrates how innovation and sustainability can converge to effectively address today's challenges (Kharb and Sahara, 2023; Santos et al., 2023; Lema, 2021; Azmin, 2020) (Table 7).

3.5 Fertilizers

Agro-industrial waste composting is a sustainable practice that contributes to reducing the environmental impact of agricultural and food production. This process transforms organic waste into compost, a nutrient-rich product that can be used as fertilizer. The benefits of composting include reducing the use of chemical fertilizers, improving soil quality, and helping to reduce greenhouse gas emissions. Composting is also an effective way to treat agricultural waste and produce organic fertilizer, achieving waste minimization and stabilization. Internal and external parameters, such as moisture content, temperature, pH, ventilation, and external additives, are some of the factors that influence the composting process (Xie et al., 2023; Vargas-Pineda, 2019) (Table 8).

Finally, there are other applications, such as in construction, where rice straw is presented as a substitute for additives in concrete, promoting cost-effective and environmentally friendly construction practices while reducing dependence on traditional materials (Sudarsan et al., 2023b). Similarly, in the cosmetics industry, passion fruit seeds provide a source for oil extraction and the production of beneficial exfoliants for skin care (Proaño et al., 2020). Mango seeds can be used to produce wholemeal flour, which diversifies the supply of nutritional products and efficiently uses food resources (Velasco & Cuesta González, 2019). However, implementation requires advances in waste processing technologies, regulatory support, and industry collaboration. To maximize the efficiency and scalability of agro-industrial waste utilization, the use of innovative biotechnological approaches such as enzymatic hydrolysis, microbial fermentation, and biorefining processes is essential.

3.6 Food for human consumption

Mango seeds have the potential to be used to produce wholemeal flour, diversifying the supply of nutritional products and making efficient use of food resources (Velasco & Cuesta González, 2019). However, its implementation requires advances in waste treatment technologies, regulatory support, and industry collaboration. To achieve maximum efficiency and scalability in the utilization of agro-industrial waste, there is a need for innovative bio-

TABLE 7: Materials.

Authors	Usable waste / Recoverable waste	Country	Year of publication
Haro-Velasteguí et al. (2017)	Banana waste	Ecuador	2017
Lema Vera (2021)	Cocoa shell and sugarcane bagasse	Colombia	2021
Hernández Chaverri & Prado Barragán (2018)	Banana waste	Costa Rica	2018
Henao Díaz & Salazar Perdomo (2017)	General (agricultural waste)	Colombia	2018
Marlon Fernando et al. (2021)	Banana waste	Colombia	2021
Riera et al. (2018)	General (agricultural waste)	Ecuador	2018
Buraglia Osorio (2021)	General (agricultural waste)	Colombia	2021
Peñaranda Gonzalez et al. (2017)	Fruit peel	Colombia	2017
Cury R et al. (2017)	Agro-industrial waste	Colombia	2017

TABLE 8: Fertilizers.

Authors	Usable waste / Recoverable waste	Country	Year of publication
Xie et al. (2023)	General (organic waste)	China	2023
Chia et al. (2020)	General (organic waste)	Malasia	2020
Vargas-Pineda et al. (2019)	Food waste	México	2019
Duval et al. (2019)	Soybean oil waste	Argentina	2019
Méndez-Matías et al. (2018)	General (organic waste)	México	2018
Moisés et al. (1983)	General (organic waste)	Argentina	2022
Vargas Corredor & Peréz Pérez (2018)	General (organic waste)	Colombia	2018
Romero-Sáez (2022)	Agro-industrial waste	Colombia	2022
Alvarado Dávila & Rangel Zambrano (2020)	Agro-industrial waste	Colombia	2020
Oliveira Vieira et al. (2022)	Agro-industrial waste	Brasil	2022

technological approaches such as enzymatic hydrolysis, microbial fermentation, and biorefining processes.

Similarly, coconut fiber, rice straw, and sugarcane bagasse are agroindustrial residues that can be employed in the manufacture of biovanilla, an alternative aromatic compound to the synthetic vanilla that is commonly utilized in the food and cosmetic industries (Paul et al., 2023; Nurika et al., 2020; Pattnaik et al., 2022).

Furthermore, the design and development of policies that encourage waste recovery and circular economy initiatives is critical to foster a sustainable industrial ecosystem (Paul et al., 2023; Nurika et al., 2020; Pattnaik et al., 2022) (Table 9).

3.7 Cosmetics

Similarly, in the cosmetics industry, passion fruit seeds provide a source for oil extraction and the production of beneficial exfoliants for skin care (Proaño et al., 2020) (Table 10).

4. CONCLUSIONS

These days, there are still businesses that persist in operating within the limits of the linear economy model, thus resulting in the generation of waste without taking advantage of it or the mitigation of adverse environmental impacts. This review attempts to identify which are the most common uses of agro-industrial waste as a sustainable solution. In order to achieve this, a systematic review was conducted to identify trends and opportunities in the utilization of agroindustrial waste that contributes to sustainability. This review comprised blind peer review articles from indexed open access journals, aiming to classify the by-products, with applications in the production of bioenergy, the development of materials, and the extraction of compounds with utility across a range of industries, including agriculture, cosmetics, pharmaceuticals, and food production.

The use of agro-industrial waste represents an opportunity to move towards a circular economy model, with implications for different sectors and economic activities. In the food sector, the use of waste, once transformed, generates nutrients and minerals for human and animal consumption. Similarly, the production of bioenergy from lignocellulosic biomass (bioethanol and biogas) reduces greenhouse gas emissions and becomes a sustainable alternative to fossil fuels (Silva and Oliveira, 2021; Kharb and Sahara, 2023; Santos et al., 2023; Lema, 2021; and Azmin, 2020). This transition is emerging as a global priority as a strategy to promote dynamism in territories (Bag et al., 2021; Khanna et al., 2022; Zheng et al., 2025). It is important to note production sectors such as animal feed, bioenergy, bioplastics, and specialty composites can achieve both economic and environmental benefits through the transformation and integration of waste. Sustainable agro-industrial waste management contributes to reducing waste accumulation and environmental degradation and promotes the efficient use of natural resources.

On the other hand, the recovery of bioactive compounds and the development of materials indicate the potential for the generation of value-added products applicable in the food, pharmaceutical, and cosmetic industries. Likewise, the extraction of compounds such as phenols and bromelain, as well as biomass for the creation of bioplastics and biomaterials, demonstrates the impact of technological innovation on the comprehensive utilization of these resources. Furthermore, it underscores the potential for utilization as fertilizers in crops, thereby facilitating the implementation of balanced and environmentally conscious agricultural practices (Paul et al., 2023; Nurika et al., 2020; Pattnaik et al., 2022). These applications reinforce the principles of

TABLE 9: Food for human consumption.

Authors	Usable waste / Recoverable waste	Country	Year of publication
Coral Velasco & Cuesta González (2019)	Mango seed	Cuba	2019
López Ráez et al. (2021)	Mango waste	Colombia	2021
Camacho Villa & Grande Tovar (2021)	Malt bagasse	Colombia	2021
Duval et al. (2019)	Soybean waste	Argentina	2019
Sanz M. et al. (2021)	Mango seed	Colombia	2021
Preciado-Saldaña et al. (2022)	General (agricultural waste)	Mexico	2022

TABLE 10: Cosmetics.

Authors	Usable waste / Recoverable waste	Country	Year of publication
Proaño et al. (2020)	Passion fruit waste	India	2020
Presenda-Gerónimo et al. (2020)	Pineapple waste	México	2020
Mejia (2018)	General (agricultural waste)	Colombia	2018
Filippín et al. (2017)	Olive and oilseed residues	Colombia	2017
Vera Raza et al. (2022)	Lignocellulosic waste		2017
Suárez Ramos & Ubillus Ascarza (2022)	Lucuma waste	México	2022
Soto-Regalado et al. (2021)	Soybean waste	Argentina	2022
Rojas Romaní et al. (2021)	Seeds and shell of Passiflora tripartita fruit	Venezuela	2021

sustainability by minimizing reliance on fossil fuels, synthetic chemicals, and environmentally harmful materials.

From a broader perspective, the comprehensive utilization of agro-industrial waste is presented as a fundamental element in the development of a sustainable future. This integrated approach not only aims to ensure responsible waste management practices but also promotes environmentally sustainable activities that contribute to the advancement of communities and industrial sectors.

In turn, the use of agro-industrial waste fosters innovation, mitigates climate change impacts, and enhances economic resilience by creating new value chains and promoting sustainable business models. In order to optimize the potential of these resources, it is crucial to address the issues associated with waste management through the implentation of policy frameworks and research.

Ultimately, the continued development of innovative strategies for the use of agro-industrial waste is essential to shape a more sustainable and resource-efficient future, ensuring environmental management while fostering economic growth and social welfare.

This study illustrates how the topic has gained prominence and generated awareness globally, offering sustainable solutions through the utilization of agro-industrial waste, underscoring its role in the transition to a circular and sustainable economy (Kharb and Sahara, 2023; Santos et al., 2023; Lema, 2021; Azmin, 2020). This research demonstrates the development of strategies that address challenges such as waste management and climate change while simultaneously fostering innovation and sustainability. As a result, agro-industrial waste has emerged as a crucial resource in the transition to a more sustainable future.

It is recommended that future research should focus on the optimization of transformation processes, the assessment of the economic feasibility of large-scale implementation, and the consolidation of interdisciplinary collaborations between academia, industry, and policymakers.

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BMP TEST TO MONITOR SEASONAL EFFICIENCY OF DRY ANAEROBIC DIGESTION PLANT

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ABSTRACT
The lack of specific monitoring tools is a hurdle for dry anaerobic digestion plant performance studies. The work aims to suggest a solid-state BMP protocol to monitor the full-scale dry anaerobic digestion process of the organic fraction of municipal solid waste. Physicochemical analyses, biomethane potential, and biodegradability data of different seasonal mixes fed in the reactor are provided. The data collected showed the effectiveness of the dry BMP test to analyse the process efficiency and to estimate the potential methane production of the biowaste. The process efficiency (expressed as % of methane production) was estimated combining the experimental data (BMP) and the plant parameters (organic loading rate and specific methane production) in four different seasons (Autumn, Winter, Spring, and Summer). The methane production (MP) of the plant ranged from 70 to 90 % of the potential biomethane production measured at lab scale. From the data collected, the seasonal differences were due to input biowaste (organic fraction of municipal solid waste and lignocellulosic materials used as bulking agent in dry AD) and their biodegradability, which results in different volatile solids removal in industrial reactor. The approach provided may be useful to better manage the process in a dry anaerobic digestion full-scale plant.

1. INTRODUCTION

The European Member States produce about 88 million tons of bio-waste every year (Papa et al; 2022); improvements in the collection and treatment of municipal waste across Europe are advocated to achieve the EU recycling target of 65 % by 2035 (EEA, 2020). The biowaste treatment through anaerobic digestion (AD) is promising, and in the year 2022, Europe's biogases production (combined biogas and biomethane) amounted to 21 bcm (European Biogas Association, Statistical Report 2023).

Compared to wet anaerobic digestion, dry anaerobic digestion (AD) has a low energy requirement for heating and pumping, less effluent production requiring dewatering, higher volumetric methane yield, and it has been employed using various technologies in smaller reactors, single or multistage operations (Rocamora et al., 2020; Wang et al., 2023). However, the main critical issues regard the process stability; the higher organic loading rate could generate an accumulation of potential inhibitors (such as ammonia and volatile fatty acids), and the higher total solids could lead to a decrease in the methane yield (Wang et al., 2020; Wang et al., 2023).

The Kompogas' system originated in Switzerland in the 1980s; it is a modified horizontal plug flow system with a slowly rotating internal axial mixer. The adopted mixing system increases the contact between microorganisms and organic substrate and degases the digestate (DG) before removal; the total solids in the reactor are held in the range of 23-28% to facilitate the flow. Most of the existing Kompogas plants (about 70) are operative in Europe. From the literature data, the expected biogas yield of the reactor is about 100-150 Nm^3/ton of the feed material (Hayyat et al., 2024).

The monitored plant is located in Trentino province (Northern Italy), and treats organic fraction of municipal solid waste (OFMSW) and lignocellulosic green waste. The thermophilic dry AD process is carried out in two horizontal continuously stirred and mixed tank reactors (CSTR; D1 and D2; length 32 m) with a constant feed system (mixture of OFMSW and lignocellulosic material used as a bulking agent) for 21 days at 51°C (Bona et al., 2020). Part of the DG is recirculated back to the head of the system as inoculum, while the remaining part goes to the subsequent aerobic composting section, after addition with yard waste

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to balance the C/N ratio of the starting mix. The intensive bio-oxidation phase of the composting process occurs in eight aerated bioreactors, followed by the maturation phase in aerated static piles. Aerobic treatment of DG lasts about 24 days.

Process stability is a crucial operational challenge to ensure plant productivity and efficiency (Cruz et al., 2021). Several recent works have focused on developing a proper monitoring plan (Cruz et al., 2021) with many parameters considered as stability indicators (pH, alkalinity, volatile fatty acid concentrations, biogas composition, methane yield, concentration of CO_2, H_2, aromatic compounds, enzymatic activity, and microbial community (Awhangbo et al., 2020). These parameters are useful to plan operational practices and to manage the reactors correctly. Moreover, the evaluation of the efficiency of the process is important to verify that a reactor is operating at its maximum potential. In a nutshell, monitoring of full-scale plants is strongly recommended to ensure proper management, energy optimisation, and biological stability, but with some challenges.

Firstly, the biomethane potential (BMP) assessment is a valuable tool in AD studies but, as previously detected, there is a lack of standardized protocol and data reporting in performing BMP tests (Hollinger et al., 2016; Oheneng-Ntiamoah and Datta, 2019; Filer et al., 2019). Furthermore, AD monitoring tools are mainly configured for the liquid and gaseous phases (Andrè et al., 2017). Therefore, data from BMP tests conducted under dry conditions, similar to those in industrial plants, could be used as practical indicators of process performance (Li et al., 2017). Some studies have investigated the scaling effect of methane production on specific substrates, and the comparison of bench-scale dry BMP results with full-scale biogas production seems promising (Schievano et al., 2011; Li et al., 2017). Moreover, the OFMSW is very heterogeneous along space and time: its composition in terms of biodegradable compounds (carbohydrates, proteins, and lipids) depends on several aspects, such as social and economic factors related to the food availability, seasonality, consumer customs, generating sources, collection time, and presence of touristic areas (Kobayashi et al., 2012). The work by Fisgativa et al. (2016) demonstrates that the geographical origin, the type of collection source, and the season might explain about 24% of the food waste variations, while more recent studies have shown the quantitative and qualitative seasonal effects of organic waste on the AD process (Edwiges et al., 2018; Mozhiarasi et al., 2019; Arhoun et al., 2019; Trujillo-Reyes et al., 2022).

This work aims to use a dry BMP test protocol at a bench-scale level to monitor the seasonal performance of a dry AD plant of OFMSW.

2. MATERIALS AND METHODS

2.1 BMP tests and seasonal biodegradability of the feedstock

The BMP test was assessed for the samples collected in the four seasons (Autumn 2017-Winter 2017-Spring 2018-Summer 2018). The tests were done in three 20-L experimental reactors modified to sustain a dry AD process with the biowaste mix used in the full-scale AD Kompogas plant. The protocol adopted was the same as described in Bona et al. (2020), by modifying the protocol described in Angelidaki et al (2011) and the German guideline VDI 4630 (2016). In a nutshell, a perforated stainless-steel basket was used in each reactor to guarantee proper gas exchange through the contained sample. The lab-reactors were heated at 51°C, the same operating temperature as the full-scale plant. The (net) biogas production is derived from the pressure changes measurement inside the reactor over time after the subtraction of the production ascribed to the inoculum, and expressed in (Nm^3CH_4/kg_{VS}) referring to the substrate VS.

The feeding mix was prepared with digestate as inoculum (stored and aged until stable production lower than <50 $NLCH_4/kg_{VS}$), screening green lignocellulosic material (SM) separated downstream the anaerobic and aerobic processes and used as a bulking agent (20% v/v), and OFMSW. The used materials were sampled in the plant at each season monitored. The VS ratio of fresh matter and inoculum was about 0.5 (inoculum to substrate ratio, ISR = 2). The measure of the biogas and biomethane production has been made with manometric approach. The methane produced has been measured by sampling 6 L of the produced biogas and analysing the biogas quality (CO_2, CH_4, O_2 and H_2S) by using a portable gas analyser (OPTIMA 7 BIOGAS, MRU Air Fair Gmbh).

The elemental composition (CHNO content) analysis has been assessed to calculate the theoretical stoichiometric biomethane potential (BMP_{th}), following the Buswell and Simons' equation to calculate the theoretical BMP_{th} (Symons & Buswell, 1933). The ratio between BMP_{th} and experimental BMP (BMP_{exp}) provides information about the % of biodegradability (α) of the organic matter content of the biomass considered. The % of biodegradability (α) was calculated for OFMSW each season, as in the following Equation 1.

$$\alpha = (BMP_{th}/BMP_{exp}) \cdot 100 \tag{1}$$

The BMP results have been modelled as first-order kinetics for calculating the hydrolysis constant, using the following equation (2), in agreement with Gunaseelan (2004),

$$ln\ (BMP_{\infty}/BMP_{t}) = k_h \cdot t \tag{2}$$

where the hydrolysis constant k_h (expressed in $days^{-1}$) depends on time t (here equal to the first 5 days considered for the calculation) and the natural logarithm of the ratio between the maximum value BMP_{∞} and the value measured after t days BMP_t (Gunaseelan, 2004).

The data were analysed by one-way ANOVA and multiple pairwise comparisons with Tukey formulation (level of significance α*=0.05). The BMP test results from different seasons were compared.

2.2 Seasonal monitoring plan of the full-scale AD plant

The full-scale plant was monitored yearly, from the Autumn 2017 until the Summer of 2018, considering five seasons: First Summer (June-July-August), Autumn

(September-October-November), Winter (December-January-February), Spring (March-April-May), Second Summer (June-July-August).

For each season, the data collected focused on (a) plant performance, (b) feedstock properties used for feeding digesters, and (c) the BMP of the mixes feeding in the reactors.

The feedstocks considered were OFMSW, recirculated DG as inoculum in the plant, and SM. The feedstock ratio feed in the plant was 60% OFMSW, 10% SM, and 30% recirculated DG on a mass basis. Each feedstock was analysed regularly (monthly), in pH, total solid content (TS), and volatile solids content (VS). The two stirred and mixed Kompogas-reactors were continuously heated at 51°C (+/- 1°C).

The biogas production, methane content in the biogas, and organic loading data of the plant were measured daily. Organic loading rate (OLR), Hydraulic Retention Time (HRT), and Specific Methane production (SMP) have been calculated both monthly and seasonally, related to the inflow VS mass of OFMSW and SM, indicated as VS_{in}, and to the working volume V of the reactor. The equations used were the following Equations (3-5).

$$OLR= VS_{in}/(V\cdot day) \quad (3)$$

$$HRT= V/ VS_{in}/(V\cdot day) \quad (4)$$

$$SMP=Nm^3CH_4/VS_{in} \quad (5)$$

The Methane production potential (MP) of the real plant expected after the BMPs and the efficiency of VS removal (η) were assessed by applying the following equations 6-7 (modified from Hollinger et al., 2017), referring to the mass streams Q of VS related to OFMSW, SM, and DG, respectively (using the total volatile content indicated as $\%TVS_{OFMSW}$, $\%TVS_{SM}$, and $\%TVS_{DG}$, respectively).

$$MP\ (Nm^3CH_4) = Q_{VS}\cdot BMP \quad (6)$$

The efficiency of the process has been calculated as the percentage of the MP compared to total Methane production.

$$\eta=\frac{[(Q_{OFMSW}\cdot\%TVS_{OFMSW})+(Q_{SM}\cdot\%TVS_{SM})+(Q_{DG^*}\cdot\%TVS_{DG})]_{IN}-[(Q_{DG}\cdot\%TVS_{DG})]_{OUT}}{[(Q_{OFMSW}\cdot\%TVS_{OFMSW})+(Q_{SM}\cdot\%TVS_{SM})+(Q_{DG^*}\cdot\%TVS_{DG})]_{IN}} \quad (7)$$

Where the Q_{OFMSW} corresponds to the incoming flow of OFMSW, Q_{SM} corresponds to the lignocellulosic materials used in the feeding mix, and Q_{DG} corresponds to the digestate obtained downstream of the plant. The Q_{DG^*} refers to the digestate fraction recirculated in the plant, in the feeding mix.

The proposed monitoring protocol for a dry-AD industrial plant, starting from lab scale development of dry BMP test, is shown in the following Figure 1.

3. RESULTS AND DISCUSSION

3.1 BMP results and biodegradability of the feedstock

The protocol adopted allowed the measurement of the BMP of OFMSW by simulating the conditions of the Kompogas reactors. The BMP data are in Table 1, and the cumulative BMP results are in Figure 2.

The BMP tests performed on dry conditions are challenging due to the lack of representative protocols and guidelines for very heterogeneous samples (Hollinger et al., 2016). The key issues concern the sampling methods, the inoculum origin concentration, storage and duration, and the different degradability of the lignocellulosic feedstock used as a bulking agent (Andrè et al., 2018). The obtained value (Table 1; Figure 2) agreed with the results of previous works on seasonal organic waste (Edwiges et al., 2018; Trujillo-Reyes et al., 2022) and dry AD tests (Sun et al., 2019).

As recommended, the inoculum came from an active AD plant to provide a stable, active, and diversified microbi-

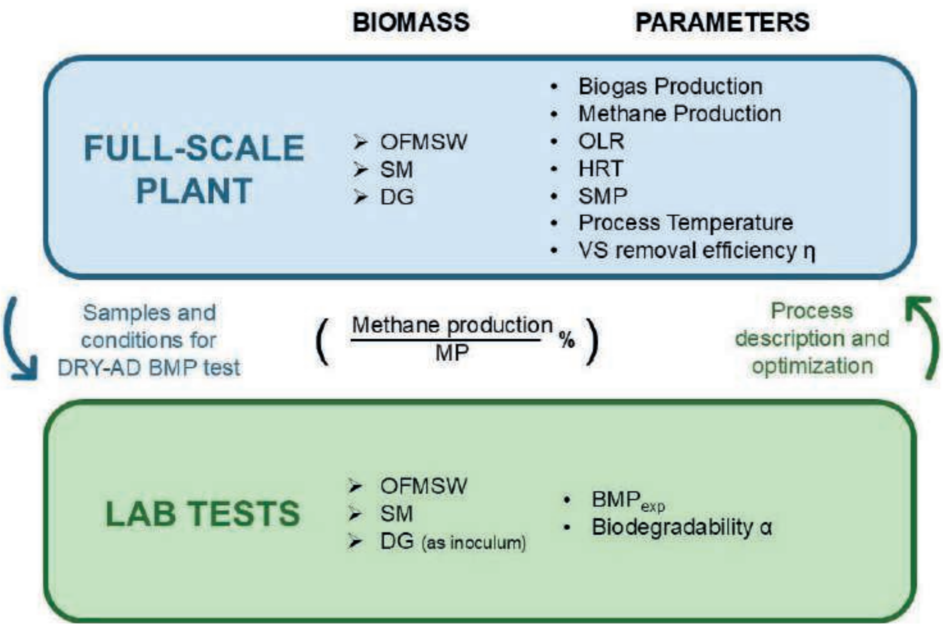

FIGURE 1: Scheme of the proposed monitoring protocol based on the development of a dry BMP test.

TABLE 1: Biogas production, BMP results, biodegradability (α), and hydrolysis constant (kh) for each monitored season (from Autumn 2017 to Summer 2018).

		Autumn	Winter	Spring	Summer
Specific Biogas Production	[Nm^3/kg_{VS}]	0.51 ± 0.09	0.57 ± 0.13	0.56 ± 0.02	0.59 ± 0.06
BMP	[Nm^3CH_4/kg_{VS}]	0.27 ± 0.05	0.31 ± 0.09	0.33 ± 0.01	0.30 ± 0.04
α	[%]	62 ± 12	73 ± 22	76 ± 2	71 ± 11
k_h	[1/days]	0.14	0.07	0.08	0.16

al community, taking care to maintain the same conditions of the plant (mainly temperature) with a very low endogenous methane production (<50 $NLCH_4/kg_{VS}$) (Hollinger et al., 2016). The choice of an adapted inoculum plays a crucial role in duration and methane rate measurement (Koch et al., 2017). The BMP duration was defined considering the validation criteria of previous works (1% of the ultimate methane production for 3 days) (Holliger et al., 2016; Hafner et al., 2020). Differently from wet BMP tests, in our protocol, the sample was not ground and shredded, because the sample's pretreatment could have altered the representativeness of the samples in dry conditions. Each sample was a result of the mixing of four different samples (collected in the plant) to achieve more reliability, and a greater volume of laboratory reactors have ensured the possibility of treating the inhomogeneous feeding mix (Ohemeng-Ntiamoah and Datta, 2019). The substrate concentration and inoculum to substrate ratio (ISR) was set up about 2 for each test; the value is also suitable for dry conditions to avoid a VFA accumulation and pH increase, hence biogas production affecting (Holliger et al., 2016; Ohemeng-Ntiamoah and Datta, 2019; Filer et al., 2019). The protocol adopted was useful to monitor the seasonal difference of the feedstock processed at the industrial plant. The data showed very slight variations among seasons; some differences between Autumn and Spring regarding biogas production, BMP and biodegradability are registered (even if not significant) (Table 1).

The ratio between easily degradable compounds and slowly degradable organics in the OFMSW could affect the BMP (Alibardi and Cossu, 2015). The composition and quantity of OFMSW have changed over seasons, and the presence of fruit and vegetable waste seems to be the main issue (Fisgativa et al., 2016). A recent study showed higher methane potential of OFMSW collected in Spring and confirmed the presence of a greater content of fruit and vegetables (Trujillo-Reyes et al., 2022). Similar results to those obtained in our work (which refers to the monitoring of seasons 2017/2018) were also achieved in this work, confirming the seasonal variability of waste composition and hence in AD performances (Trujillo-Reyes et al., 2022; Trujillo-Reyes et al., 2025).

Moreover, the concentration of lignocellulosic biomass in the dry process may result in the enrichment of hydrolytic and acidogenic microbes in the preliminary stages of the digestion, thus leading to high VS destruction and, subsequently, to a more apparent peak of biogas production than for wet AD (Brown et al., 2012).

The BMP was also performed on the SM of the plant to determine the degradability of the feedstock used as bulking agent in the mix feeding preparation. The RBP of SM was 0.034 Nm^3CH_4/kg_{VS} (degradability 8.88%) (data not

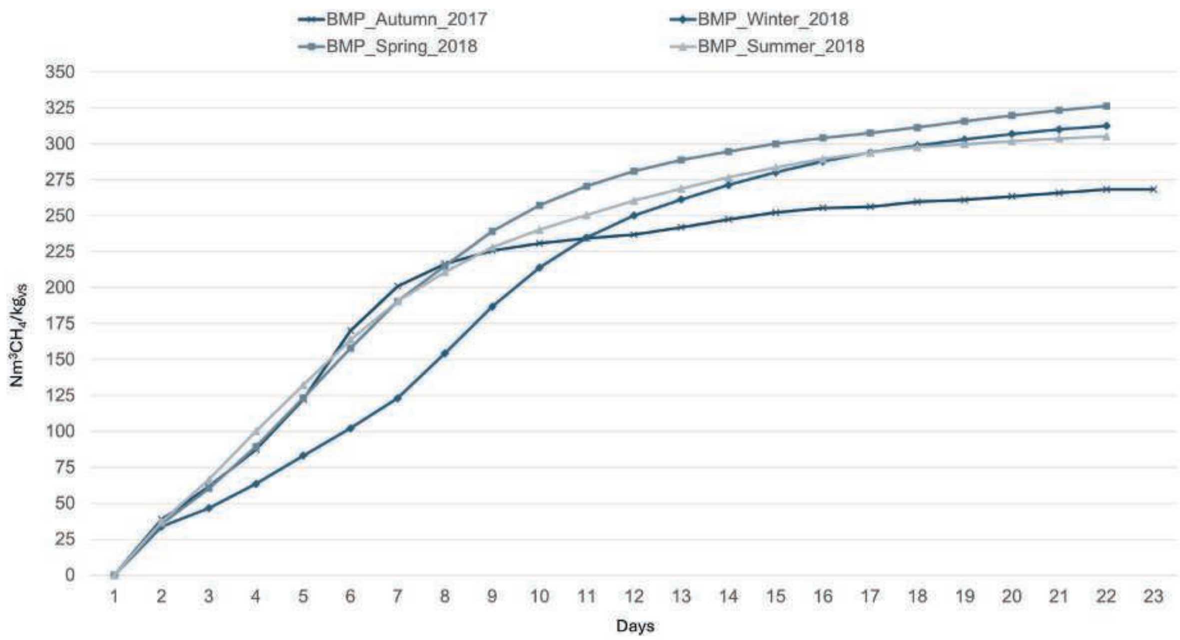

FIGURE 2: BMP cumulative results for OFMSW for each monitored season (from Summer 2017 to Summer 2018).

shown). The lignin content of SM can be a critical point in AD, since feedstock with high energy density compounds (such as lipids or easily degradable components of fruits and vegetables) have a higher BMP value and a higher biodegradability than compounds with high content of fibers (Li et al., 2013).

The first-order model used for modelling the methane production and at the same time the hydrolysis rate (k_h) of the feedstock can be linearized in agreement with Equation 2 (values shown in Table 1). The hydrolysis constant calculated for each seasonal BMP exhibits the same results of OFMSW degradability degree: the lowest hydrolysis constant value was in Autumn, while the highest was in Summer with slightly different kinetics among seasons. The calculated k_h values were inside the range of values reported in previous studies for thermophilic temperature, where methane productions occur faster than in mesophilic AD (Fernandez-Rodriguez et al., 2013). The difference between the Summer and Winter seasons on the k_h was probably related to the organic waste composition. According to previous results, first order kinetic constant of lignocellulosic biomass ranged from 0.08 to 0.09 1/d, fruit wastes ranged from 0.02 to 0.12 1/d, and vegetable wastes ranged from 0.05 to 0.13 1/d (Brown et al., 2012; Gunaseelan et al., 2004).

The feasibility of using BMP as a tool to analyses the process performances in the full-scale plant has been recently assessed, because it provides a good analysis of the anaerobic biodegradation potential of the organic matter in the prevailing reactor conditions (Li et al., 2017; Filler et al., 2019). Similarly, our work aims preliminarily to carry out an informative test, which allows us to consider the main dry AD issues, such as the different degradability of the lignocellulosic feedstock used as a bulking agent, the higher inhomogeneity of the feeding mix, and the mixing resistance (Wang et al., 2016; Ohemeng-Ntiamoah and Datta, 2019).

Holliger et al. (2016) and the subsequent work of Hafner et al. (2020) have defined some validation criteria for BMP data acceptance and evaluation (Hollinger et al., 2016; Hafner et al., 2020). According to these studies, even if the correlation with the cellulose BMP is moderate, the BMP data included in the range 340-395 NmLCH_4/gVS can be accepted, thus making the "proposed dry BMP test" a reliable measurement and monitoring tool, which can be widely used (Hafner et al., 2020). Our BMP protocol considered some of these criteria, however, future work will provide tests to validate the BMP data in dry conditions, i.e., with positive control with cellulose.

3.2 Performance of the full-scale plant during monitoring seasons

The data about the performance of the full-scale plant samples are shown in Table 2 and the monthly data of SMP and OLR are shown in Figure 3.

The HRT values measured for each season ranged from 22 days in Autumn to 21 days in Summer (Table 2). The yearly mean value was 21.98 days. The VS removal efficiency (η) calculated for each season was higher in Spring and Summer than in Autumn and was about 70%. These differences are due to the composition and properties of organic waste. As seen before, the OFMSW of Autumn has lower BMP and biodegradability, which agreed with the lower VS removal as the full-scale plant monitoring showed. The higher content of lignocellulosic compounds in waste made the organic matter less degradable. The SM differed in terms of VS content among seasons (Table 2) and the VS degradability was very low as well as for DG (Table 1). Lignin is the most recalcitrant fraction of lignocellulosic biomass, and it can significantly inhibit the hydrolysis of holocellulose (Li et al., 2021).

In Summer, the VS (expressed in Mg) of OFMSW and SM were higher compared to Autumn and Winter, highlighting the seasonal differences of both quantitative and qualitative organic waste collected (Table 2), in agreement with similar study (Le Pera et al., 2021)

The SMP of the plant was higher in the Autumn and Winter (about 0.36 Nm^3CH_4/kg_{VS}) compared to Summer (about 0.30 Nm^3CH_4/kg_{VS}) as in Figure 3. The OLR (of OFMSW) calculated for each month was higher in the Winter and Sum-

TABLE 2: Data of dry AD full-scale plant monitoring (from Autumn 2017 to Summer 2018).

			Autumn	Winter	Spring	Summer
OFMSW	DM	[%]	31.5 ± 1.4	33.8 ± 1.4	37 ± 3	37 ± 6
	VS	[$\%_{DM}$]	73 ± 7	72 ± 7	65 ± 7	74 ± 5
	pH	[-]	4.72 ± 0.06	5.7 ± 0.4	5.4 ± 0.4	5.1 ± 0.7
SM	DM	[%]	68 ± 3	68.07 ± 0.05	68 ± 3	70 ± 6
	VS	[$\%_{DM}$]	60 ± 7	56 ± 3	67 ± 7	73 ± 5
	pH	[-]	8.85 ± 0.25	8.94 ± 0.16	8.74 ± 0.18	8.93 ± 0.02
DG	DM	[%]	31 ± 7	28.6 ± 1.2	26 ± 3	27 ± 0.8
	VS	[$\%_{DM}$]	51 ± 7	52 ± 3	55 ± 3	56 ± 5
	pH	[-]	8.40 ± 0.15	8.61 ± 0.03	8.61 ± 0.28	8.33 ± 0.15
VS_{OFMSW} IN		[Mg]	530 ± 80	610 ± 80	600 ± 30	680 ± 60
VS_{SM} IN		[Mg]	170± 40	170 ± 40	200 ± 30	220 ± 60
HRT		[day]	22 ± 1	22 ± 5	22 ± 2	21 ± 3
η - VS removal		[%]	65.78	68.46	72.45	71.25

FIGURE 3: SMP and ORL of full-scale dry AD plant during the monitoring seasons (from Summer 2017 to Summer 2018).

mer months, (particularly in November, December, June, and July) (Figure 3) for both quantitative and qualitative differences. The reported data highlighted the effect of a better SMP and process performance in correspondence to lower OLR (Figure 2) and higher HRT (Table 2). The OLR results were slightly lower than those of other dry mesophilic AD plant (Le Pera et al., 2021).

The BMP results were used to calculate the seasonal MP values. Each MP value was compared to the effective methane production of the plant (data collected monthly from the full-scale plant monitoring). The percentage reported in Table 3 represents the average of the efficiency of methane production calculated for each season.

The efficiency of methane production MP (Equation 6) was better in Autumn; the methane production of the dry full-scale plant was in line with the BMP results (Table 2; Table 3). The reasons are due both to better process performance in full-scale plant and to the lower BMP of the OFMSW in Autumn. The data collected so far suggest that the better performance of the process in Autumn was due to both a the lower seasonal ORL and the lower seasonal BMP, corresponding to an overall lower content of available highly degradable organic matter. On the other hand, in the Spring and Summer, the higher OLR and lower HRT determined lower yields. Still, the higher methane potential and biodegradability of the OFMSW could have affected the process.

In recent years, many works have aimed to improve the knowledge of dry AD and the analysis of the performance of the process at full-scale (Li et al., 2019; Rocamora et al., 2020; Zou et al., 2022). The BMP tests could provide useful information for full-scale process efficiency monitoring; recently it has been assessed that BMP is suitable to estimate the methane production of an industrial AD, which is expected to be about 80-90% of MP (Holliger et al., 2017). In our work, this value ranged from 70% (in Summer) and 90% (In Autumn).

From the data collected, the operational management and good biological process resilience managed the qualitative and quantitative changes in incoming organic waste. Similar studies demonstrated that the redundancy of the microbial groups, which occurs when the communities significantly differ in composition but carry out similar roles, was considered as the best strategy to ensure the stability of methane production (Niu et al., 2015; Andrè et al., 2016; Pasalari et al., 2021).

The BMP-based indicator allowed the analysis of the quantitative and qualitative variability of biowaste, considering its anaerobic degradability, and it has been identified as a reliable monitoring system to assess the full-scale performances, as detected previously in the wet-condition AD plant (Li et al., 2017). Integrating the organic matter removal (based on the analysis of feedstock and digestate), and the theoretical methane yield with the biodegradability assessment allows a better understanding of the anaerobic biodegradation potential of biowaste. The results of the work will be useful developing the dry-BMP as monitoring tool. In a nutshell, the work confirms the importance of

TABLE 3: Percentage of the Methane produced at the full-scale plant over the Methane Potential (MP) for each monitored season (from Autumn 2017 to Summer 2018)

		Autumn	Winter	Spring	Summer
Methane: MP	[%]	94 ± 4	80 ± 3	84 ± 10	69 ± 8

proper knowledge of the feedstock in combination with the knowledge of process operations to ensure a stable dry AD process (Rocamora et al., 2020).

4. CONCLUSIONS

The work suggests an approach to perform a dry batch test to monitor the performance of a full-scale AD plant. The monitoring plan of a dry AD full-scale plant, based on the development of dry BMP test can obtain data on the efficiency of the biological process in the industrial reactor, linking the measure of OLR, SMP, and HRT at plant level, and BMP and biodegradability from lab scale test. The data highlighted slight seasonal differences (in plant performance, biodegradability, and BMP), probably related to the organic waste composition and the different lignocellulosic input and content of the organic mix fed into the plant. The plant operating conditions help in maintaining high performances in terms of biogas production. The BMP results give information about the degradability of the feeding mix and can be used to improve the operational management of the plant.

Combining the knowledge (qualitative and quantitative) of all the input feedstock loaded in the plant with the data of the monitoring plan results in a management method helps to predict the plant performances and to ensure the stability and efficiency of the biological process. Future works and data on the lab scale dry BMP test will strengthen the results obtained and hence can validate the dry BMP as a widespread application protocol.

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CISA

COMPARATIVE ANALYSIS OF BIOGAS AND COMPOST PLANTS FOR SOURCE-SEPARATED BIOWASTE TREATMENT

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ABSTRACT

This study presents a comparative analysis of biogas and compost plants for treating 9,400 tonnes of annually source-separated biowaste. The research evaluates the current semi-closed composting system and explores the feasibility of incorporating an anaerobic digestion (AD) facility with a post-composting process. Through a life cycle assessment (LCA), the environmental impacts of these treatment methods are assessed across several categories, including global warming potential, acidification, eutrophication, and resource use. The results reveal that the existing composting system contributes 19.15 kg CO2-equivalent emissions per tonne of waste, whereas the proposed AD system shows a net reduction of -25.87 kg CO2-equivalent per tonne, indicating a significant reduction in greenhouse gas emissions. However, the AD system also exhibits higher acidification potential (0.34 kg SO2-equivalent) and eutrophication potential (0.06 kg PO4-equivalent) compared to composting. In addition, biogas plants require a substantial initial investment for construction and equipment, and market fluctuations, particularly in energy prices and demand, can affect profitability. Compost plants, on the other hand, are characterized by their lower initial investment and simpler technology, making them easier to operate and maintain.

1. INTRODUCTION

In Germany, the separate collection of biowaste began in 1985. The mandatory separate collection of biowaste was enacted in 2012. Germany employs a dual system for collecting biowaste, utilizing both bio-bins and garden waste collection points to effectively manage organic waste. In 2020, this system resulted in the collection of approximately 5.3 million tonnes of biowaste through bio-bins, equating to 64 kilograms per capita (Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection., 2023). Additionally, around 5.33 million tonnes of garden and park waste were collected separately, also averaging 64 kilograms per capita (Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection., 2023; German Environment Agency, 2019).

There are currently 1,102 biological treatment facilities in Germany. This includes 218 biowaste composting plants, 599 green waste composting plants, 227 anaerobic digestion plants, and 58 facilities that integrate both composting and anaerobic digestion processes (Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection., 2023). These facilities ensure that 97 percent of received biodegradable waste undergoes material recovery. Specifically, the composting process produced approximately 4.8 million tonnes of compost, used as nutrient-rich fertilizers and soil improvers in agriculture, forestry, and landscaping. Anaerobic digestion plays a crucial role in this system, processing around 6.24 million tonnes of biowaste to produce digestate and substantial quantities of biogas (Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection., 2023; German Environment Agency, 2019). This biogas is then utilized for electricity and heat generation, contributing significantly to Germany's renewable energy supply. The Renewable Energy Sources Act (EEG) supports the integration of anaerobic digestion into existing composting facilities, enhancing the overall sustainability and efficiency of biowaste treatment.

This study focuses on the treatment of biowaste in a medium-sized city in Germany (Soroush Nakhaei, 2024). Currently, source-separated organic waste is transported to a compost plant where it is processed using a box system. This setup ensures legally compliant treatment of biowaste waste until 2027. However, due to the impending end of the technical service life of the composting facility, a re-evaluation of the treatment processes and location beyond 2027

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is necessary. In response, a proposal over the next two years to shape the future of organic waste treatment and utilization is required. These proposals will analyze volume developments, site considerations, and potential upgrades to system technology to enhance environmental and socioeconomic outcomes. Among the alternative technologies under consideration is the establishment of a biogas plant with a post-composting system for biowaste.

Numerous studies have examined the environmental impact of biological waste treatment methods such as composting and anaerobic digestion (AD) in European cities (Table 1). Several factors must be considered when assessing the environmental benefits of these technologies, including system boundaries, life cycle inventories, and the selected impact categories (Oviedo-Ocaña et al. 2023). When comparing case studies from different countries, variations in energy mix, feedstock composition, and regulatory frameworks significantly influence the final results. In Germany, government subsidies support AD plants. Mayer et al. (2020) found that AD followed by composting was the most cost-effective and environmentally sustainable option. It had a median levelized energy cost of 27 €ct/kWh, lower than AD with incineration or bio-drying with incineration. While biological treatment demonstrates greater environmental benefits in Germany and Switzerland, in the Czech Republic, where the country remains dependent on fossil fuels, incineration has been shown to provide higher benefits in most impact categories (Edelmann and Schleiss 1999; Mayer et al. 2020; Guillaume et al. 2023).

Regarding the combined effects of feedstock composition and energy mix, (Lewerenz et al., 2023) showed that, among various German case studies, composting with a semipermeable membrane resulted in the lowest emissions when treating waste composed of 40% lignocellulosic material and 60% food waste across all treatment options. However, in a case study conducted in Italy, where household waste constituted 75% of the feedstock and green waste made up the remaining 25%, upgrading an existing composting facility to an integrated AD and composting system handling 40,000 tonnes per year led to an overall reduction in environmental impacts across all categories analyzed (Neri et al. 2018). Notably, GHG emissions fell by more than 20%, fossil resource use decreased by 40%, and human toxicity impacts dropped by 70% (Neri et al. 2018).

Emission management at composting plants and transportation distance are other decisive factors in the overall environmental impact (Söllinger, 2018). Well-managed processes help minimize emissions, improve the efficiency of composting plants, and make them a more favorable option (Essonanawe Edjabou and Scheutz, 2023; Bong et al. 2017). When large amounts of organic waste are available locally, AD becomes more viable, and biomethanization is an effective solution for improving efficiency (Lombardi and Francini 2020). It enhances the global warming potential and non-renewable energy impact categories more effectively than combined heat and power (CHP) systems (Ardolino et al., 2018).

While the literature highlights the relationship between financial and environmental sustainability, it lacks an in-depth analysis of how to choose waste treatment technology for a city/town concerning decisive technological factors and national policies. This article aims to bridge this gap by contextualizing organic waste treatment strategies within real-world urban settings, providing a more practical and policy-relevant perspective. The goal of this research is to analyze and compare the sustainability of different organic waste treatment methods, specifically focusing on composting and AD. The central research question addressed is: " Which organic waste treatment method, composting or AD, is appropriate for treating source-separated biowaste in the context of a medium-sized town?" The analysis will quantify the potential environmental impacts, including CO_2-equivalent emissions per tonne of biowaste, and discuss the pros and cons of developing each technology. The results of this study are intended to provide data-driven insights into the environmental sustainability of biowaste management systems. These findings will inform waste management authorities and stakeholders about the most sustainable and environmentally beneficial practices for treating separately collected organic municipal waste.

2. METHOD

2.1 Biowaste generation and collection

The study area is a city with approximately 200,000 inhabitants located in Germany. In 2022, the city generated about 9,374 tonnes of biowaste, accounting for around 19% of the city's total waste generation (Figure 1). Biowaste is collected using brown bins with capacities of 120 liters and 240 liters, depending on the generation rate. These bins are emptied weekly in the summer and biweekly in the winter, ensuring efficient management of organic waste throughout the year. The collected biowaste contains about 6% contaminants, primarily plastic, glass, metal, and other materials. The city has an ongoing public awareness campaign to reduce impurities, especially plastic, in the collected biowaste.

2.2 Scenario analysis

In the existing biowaste treatment system (S0), biowaste treatment is conducted using a semi-closed, automated composting system (Figure 2). The process begins with shredding and screening the waste to remove contaminants, followed by homogenization (Amuah et al., 2022). The prepared waste undergoes intensive composting in enclosed composting boxes, where the environment is tightly controlled to optimize efficiency and minimize odor emissions and environmental impact. This is followed by a secondary composting phase, using turned windrows. The final stage involves refining the compost to meet quality standards for soil improvement. This semi-closed, automated system ensures a controlled environment and reduced risk of groundwater contamination.

In the future scenario (S1), a biogas facility is evaluated. The treatment process starts with the acceptance and screening of biowaste waste, using a magnetic separator to remove metals and other contaminants (González et al., 2022). This is followed by a 2 to 4-day homogenization phase. The materials are then fed into a dry fermenter for

TABLE 1: Literature analysis on biological waste treatment methods.

Source	Country	Biological treatment system	Assessment methods	Main findings
(Lewerenz et al. 2023)	Germany	Composting (open, semi-closed, semipermeable membrane, closed) AD (with open and closed post-rotting) AD+ open composting AD+ closed composting	LCA (open LCA), and uncertainty analysis.	• Composting with a semipermeable membrane had the lowest total impact score. • Highest impact score was associated with the combined anaerobic digestion and closed composting system at 31 EPG/kg. • low-tech, smaller systems with short transportation distances have more ecological benefits for municipalities over high-tech, larger ones requiring extensive transport.
(Edelmann and Schleiss 1999)	Switzerland	Windrow, Enclosed composting, AD, AD + Enclosed composting, AD+ Windrow	LCA using Eco-indicator 95+, Energy Balance, Economic Assessment, Sensitivity Analysis	• AD has the lowest environmental footprint, outperforming both composting and incineration. • AD is the most energy-efficient, producing significant energy from biogas. • AD and EC, are more cost-effective than incineration.
(Ardolino et al. 2018)	Italy	Biomethane production by AD	LCA (Simapro8), and sensitivity analysis.	• AD of organic waste into biomethane for transport reduces global warming potential by 79% compared to biowaste-to-energy. • Non-renewable energy potential is decreased by 36% when producing biomethane instead of energy from biowaste.
(Neri et al. 2018)	Italy	Windrow, AD + Windrow	LCA (Simapro), Impact assessment (ReCiPe), energy and resource analysis, and avoided landfill benefits.	• AD reduces environmental impacts significantly compared to traditional composting. • AD produces enough electricity to run the plant, with 20% of the heat being reused. • AD + Windrow is more cost-effective and sustainable, reducing fossil fuel depletion and climate change impacts.
(Söllinger 2018)	Austria	Windrow, Enclosed, Enclosed Aerated	LCA (OpenLCA), Impact assessment (ReCiPe), energy analysis, and sensitivity analysis.	• Enclosed aerated pile composting has the lowest global warming potential. • Proper management is crucial to minimize CH_4, N_2O, and NH_3 emissions. • Energy demand and emission control are key factors influencing environmental impacts.
(Lombardi and Francini 2020)	Italy	Five biogas-to-biomethane upgrading technologies	LCA (SimaPro V8), LCC	• Amine Scrubbing showed the best environmental performance. • Larger-scale biogas upgrading plants are more cost-effective. • Electricity consumption is crucial in determining the economic and environmental outcomes of biogas upgrading technologies.
(Oviedo-Ocaña et al. 2023)	Global	Various composting technologies including home composting, centralized systems, etc.	Review of 56 LCA studies	• Definitions of system boundaries and selection of impact categories vary widely, affecting comparability. • Data quality is often inconsistent and poor due to varying local conditions and assumptions. • There is a need for standardized methodologies, comprehensive assessments, and better training in LCA methodologies.
(Guillaume et al. 2023)	Czech	Windrow, and AD (semi-dry process)	LCA (GaBi)	• Incineration is the most sustainable option due to Czech's fossil-fuel-based energy mix, producing 183.55 kWh of electricity and 2741.94 kWh of heat per ton of OFMSW. • Composting can supply up to 40% of the region's nitrogen fertilizer needs and reduce ecotoxicity and the use of mineral resources. • AD combined with composting is the best option for meeting EU biowaste separation targets, balancing lower environmental impacts, and enhancing CE benefits.
(Mayer et al. 2020)	Germany	AD + post-composting, and incineration	LCA (Open LCA), Impact assessment, and levelized costs of energy (LCOE)	• AD followed by composting had the lowest median LCOE at 27 €ct/kWh. • Incineration showed higher GWP (~500 g CO2-Eq/kWh) and FDP (~0.075 kg oil-Eq/kWh) compared to AD. • The cascaded treatment system (anaerobic digestion + incineration) had the highest economic costs at 89 €ct/kWh.

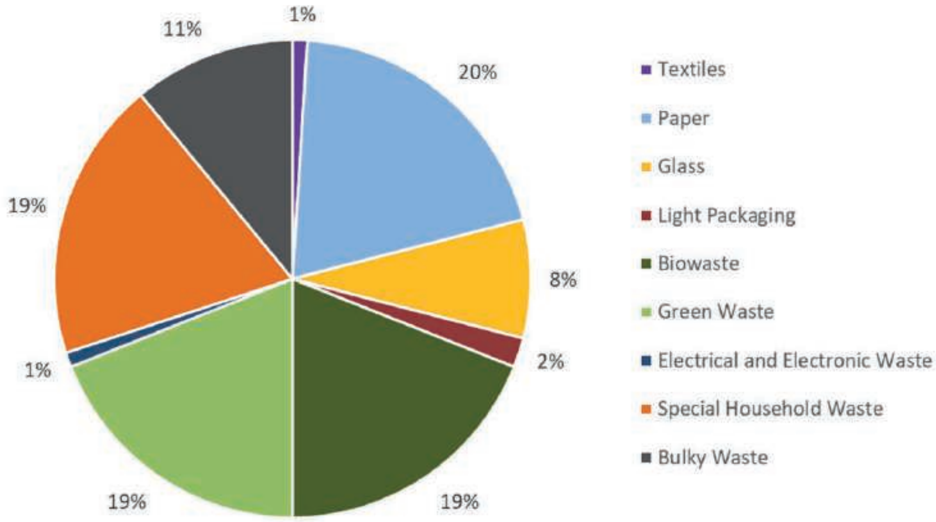

FIGURE 1: Physical composition of solid waste in 2022 (Nakhaei, 2024).

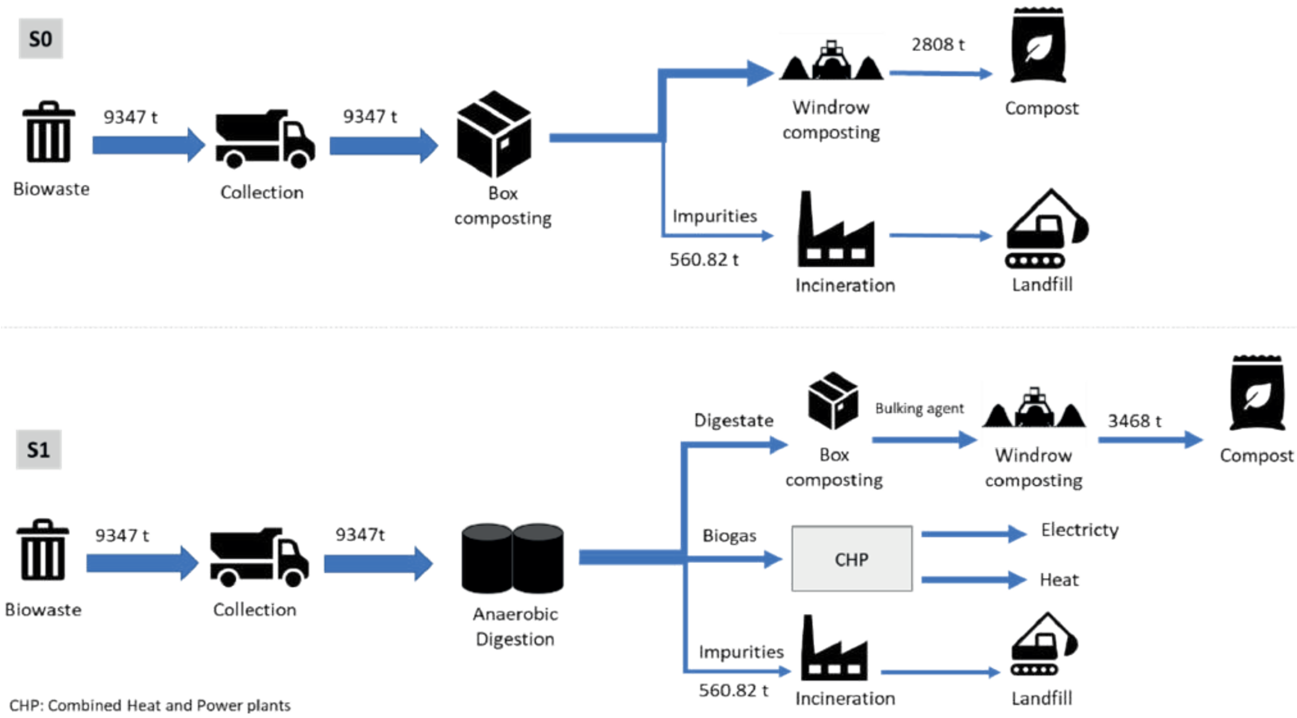

FIGURE 2: Annual biowaste mass flow of the existing system (S0) and future scenario (S1).

anaerobic digestion, which lasts about 21 days. After digestion, the materials are dewatered. The resulting product is mixed with green waste and undergoes a secondary composting phase to produce high-quality compost. The gases generated during the digestion process are utilized in combined heat and power plants to produce heat and electricity (Henriksen et al., 2019).

2.3 Life cycle assessment

2.3.1 Goal and scope definition

Environmental LCA is conducted for both S0 and S1. The system boundary for S0 includes source-separated biowaste storage, collection, transportation, and biological treatment using rotting box composting technology, followed by windrow composting for maturation, and incineration of foreign materials for disposal. For S1, the system boundary involves biological treatment using biogas technology, followed by windrow composting for the maturation of digested biowaste and sending the generated biogas to a CHP plant for the generation of heat and electricity. The functional unit is related to the amount of waste generated in the reference year, 2022. Figure 3 shows the system boundaries for the LCA.

The Lifecycle Analysis was modeled with the "WRATE V4 academic version" software (Castellani et al., 2023).The model contains over 150 standard processes for waste

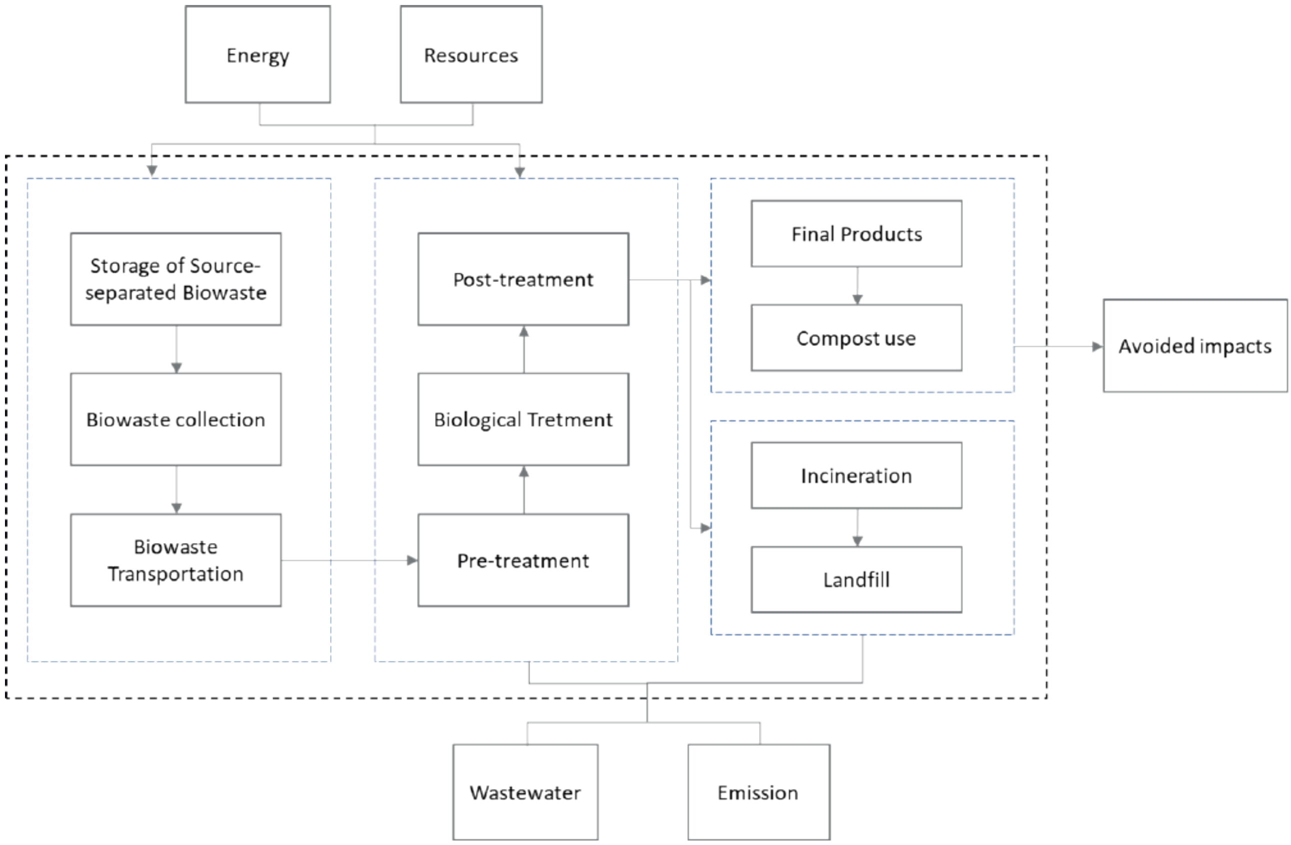

FIGURE 3: LCA system boundary.

management including complex CHP plants, landfills, various vehicles, and numerous recycling. The impact assessment uses the default version provided by the software. However, the software version has limited facilities and vehicles, necessitating the selection of a similar facility and a vehicle with emission class Euro 4.

For the environmental assessment, six categories were defined to show the environmental and human impact, including Climate Change (as global warming), Acidification Potential, Eutrophication Potential, Freshwater Aquatic Ecotoxicity, Human Toxicity, and Resources. To make the data comparable various pollutants are assigned to one or more categories based on their impact potential in equivalent quantities of a reference substance. For the impact assessment, all pollutants are multiplied by an equivalence factor according to their significance (Edelmann and Schleiss, 1999). The impact assessment method of the analysis is related to the CML 2001 database.

2.3.2 Life cycle inventory

The required data for the analysis were collected according to the system boundary of the composting and biogas plants. Primary data including storage bins, and km travel to the biological treatment facility per year were collected from the municipality's report. Secondary data including the characteristics of biological treatment plants were retrieved from the literature and WRATE V4 database. First and secondary data were utilized in the life cycle inventory (Table 2). The electricity mix is considered a low carbon emission, as reported in the WRATE v.4 database (5% fossil fuels, 95% renewable), which is comparable to the German city situation.

In the storage of biowaste, the number of containers employed per year was 14,550. For the collection of biowaste, diesel-powered trucks traveled 675 km per year, covering 50% urban roads, 5% rural roads, and 45% motorways. The treatment of biowaste using semi-closed composting technology had a capacity of 20,000 tonnes per year, with a residence time of 84 days and a lifespan of 25 years. In the treatment of biowaste using AD, three reinforced concrete fermenters with a volume of 880 m³ each and a dwell time of about 3 weeks produced around 500 m³/hour of biogas containing 55% methane.

2.3.3 Interpretation

The comparison of environmental indicators was used to analyze the results, utilizing the normalization approach to convert the outcomes into European person equivalents (EP). This allowed for a comprehensive comparison of S0 and S1, considering all environmental indicators to identify potential reductions or enhancements in impacts when transitioning from the current biowaste treatment system (S0) to the proposed future scenario (S1).

2.4 Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis

In addition to the LCA, a SWOT analysis provides insights for decision-makers considering new system de-

TABLE 2: Life cycle inventory of the processes involved in the research.

Process	Description	Variable introduced	Use of materials	Energy demand
Storage of biowaste	Typical plastic bin containers consist of three parts: the bin, the lid, and the wheels, with a capacity of 120 L. The service life of the product depends on how it is handled by residents and waste collection teams.	Number of containers employed per year was 14550 for both scenarios.	Polyethylene	-
Collection of Biowaste	6 × 4 RCV diesel-powered collection trucks (Euro 6) were used.	675 km travelled per year	-	Diesel
Treatment of Biowaste using composting	Incoming biowaste is unloaded onto a concrete slab and moved by a front-end loader to the shredder. The shredded waste is loaded into the rotting box for stabilization, with controlled air circulation. After composting, the material is matured in windrows, and screened. The final compost is stored in the storage building.	50 % urban road, 5% rural road and 45% motorway.	-	Electricity Water
Treatment of Biowaste using AD	A magnetic separator first removes metals. Biowaste is fermented and then the digitated material is dried, mixed with green waste, and undergoes a post-rotting process to produce compost. The biogas generated is used in a cogeneration plant to produce heat and electricity.	Capacity: 20,000 tonnes year−1. Residence time of 84 days. Life span: 25 years.	-	Electricity water
Disposal of impurities	The process for removing foreign material involves shredding the waste to separate and eliminate contaminants.	Three reinforced concrete fermenters, each with a volume of 880 m³, dwell time of about 3 weeks.	Steel	Electricity

velopments. The analysis highlights the strengths, weaknesses, opportunities, and threats associated with each treatment method, aiding in the selection of the most sustainable and economically viable option for future biowaste management.

3. RESULTS AND DISCUSSION

3.1 Comparative Environmental Assessment of Biowaste Treatment Approaches

This study provides a detailed analysis of the environmental impacts of two biowaste treatment methods: box composting and AD (Figure 4). The results are based on a life cycle inventory and consider specific hypotheses formulated in the goal and scope definition of the life cycle assessment.

The results reveal variable trends in environmental impacts. Scenario 1 shows generally better performance in terms of resource use and climate change impacts compared to Scenario 0. Scenario 1 exhibits significant negative emissions, particularly in the treatment phase, while Scenario 0 has the most significant overall climate impacts. The primary source of GHG emissions is the direct release during the composting process, particularly from the decomposition of organic matter (Bong et al. 2017). The main contributor is methane, with higher emissions recorded in facilities that process the organic fraction of household waste (Essonanawe Edjabou and Scheutz, 2023). HTP is significant in both scenarios, with Scenario 1 having a greater influence during recycling, especially when the product is used in landscaping. Both scenarios demonstrate harmful FATEP, especially when organic waste is disposed of in bins. Scenario 1's recycling impacts in both HTP and FATEP are more significant than those in Scenario 0. In terms of acidification, Scenario 1 has double the impact of Scenario 0. Eutrophication potential is notably higher in Scenario 1 for both treatment and recycling phases.

For each impact category, the total emissions of each scenario are compared. The results indicate that GWP and resource use are the most significant indicators of environmental impacts in both scenarios (Figure 5). Scenario 0 has higher normalized values in acidification potential, eutrophication potential, and freshwater aquatic ecotoxicity, whereas Scenario 1 shows a negative value in climate change impact and resource use, indicating superior performance in these categories.

When comparing the impact assessment for the treatment options per tonne of waste, box composting has the highest greenhouse potential with a value of 19.15 kg CO2-Eq, indicating significant greenhouse gas emissions during the composting process (Table 3). AD, on the other hand, has a negative value of -25.87 CO2-Eq, indicating a net carbon sink effect. This is due to the production of biogas, which can replace fossil fuels and thus reduce greenhouse gas emissions. Additionally, the escaping gas in AD is stored as biogas, unlike in box composting, where it is filtered through biofilters and released into the air. This finding aligns with the study by (Neri et al. 2018), which demonstrates that integrating a biogas plant into a composting facility and expanding its capacity over seven years made fossil fuel depletion the primary environmental impact. Traditional composting is energy-intensive, primarily due to its high oxygen demand for microbial activity, making it dependent on external electricity sources. The electricity produced in AD scenarios exceeded internal energy needs, allowing surplus energy to be fed into the national grid, thereby reducing reliance on conventional power sources.

Box composting has a moderate acidification potential of 0.12 kg SO2-Eq, while AD has a higher acidification potential of 0.34 kg SO2-Eq, likely due to the release of acidic

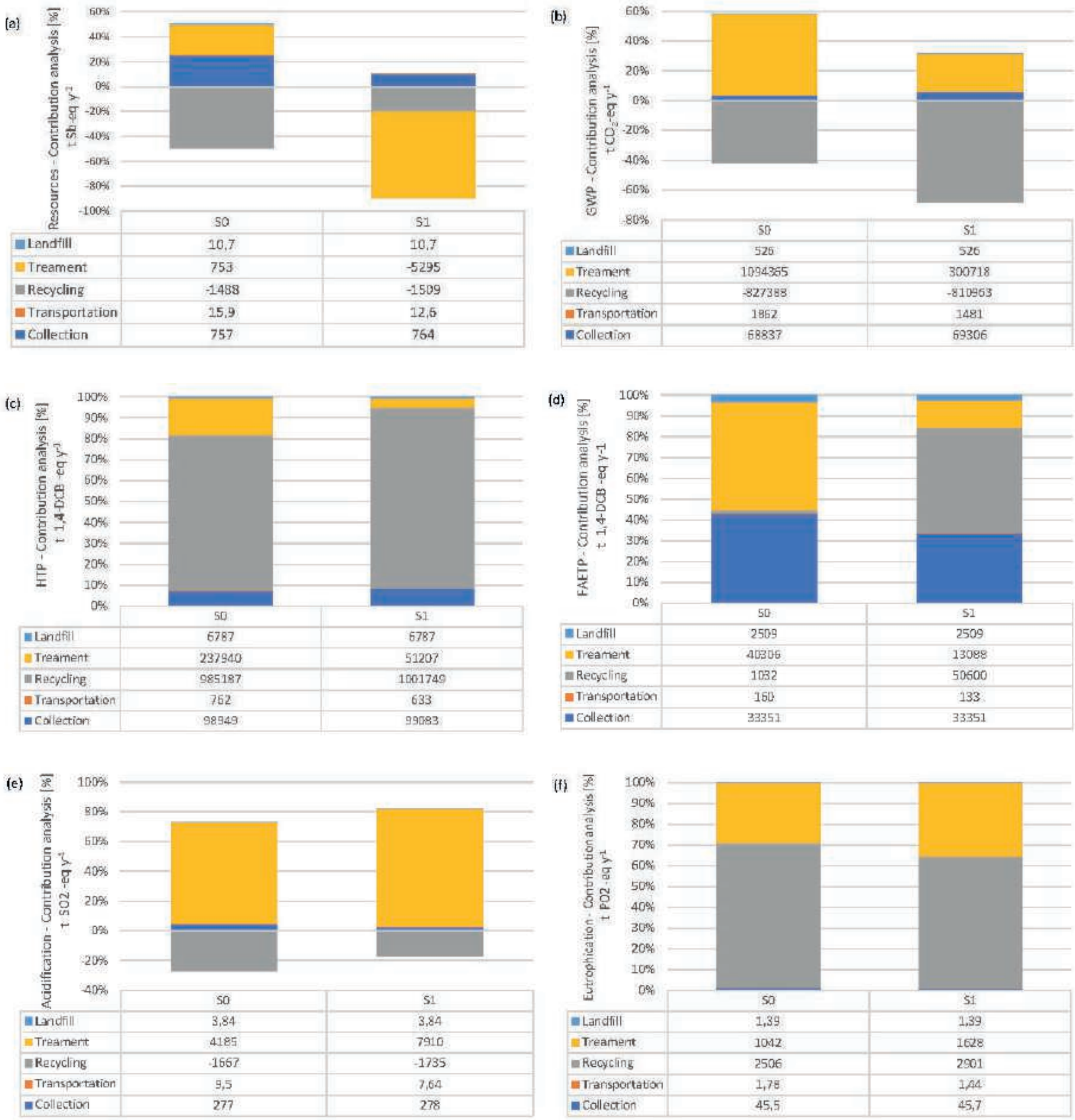

FIGURE 4: Contribution analysis of the environmental impact indicators per scenarios: (a) Resource depletion, (b) Global Warming Potential (GWP), (c) Human Toxicity Potential (HTP), (d) Freshwater Aquatic Ecotoxicity Toxicity Potential (FAETP), (e) Acidification potential and (f) Eutrophication potential. Data are reported in t-Eq per year.

gases during the process. In terms of eutrophication potential, box composting shows a relatively low value of 0.03 kg PO4-Eq, whereas AD has a higher eutrophication potential of 0.06 kg PO4-Eq, which may be attributed to nutrient losses during the process. Box composting has a significant freshwater aquatic ecotoxicity potential of 1.92 kg 14-DCB-Eq, while AD shows a negative value of -3.19 kg 14-DCB-Eq, indicating possible health-promoting effects or avoidance of toxic emissions. Resource use is moderate in box composting, with a value of 0.06 kg Antimony-Eq, while AD shows a negative value of -0.28 kg Antimony-Eq, indicating that AD may save resources through the recovery of nutrients and energy.

The impact per tonne of waste for AD is lower than the results of (Castellani et al., 2023) which used the same software for the organic fraction of municipal waste on remote islands in Italy. This difference is due to variations in the electricity mix; in the Italian case study, diesel fuel was considered.

3.2 Evaluating Biogas and Compost Plants through a SWOT Analysis

This SWOT analysis aims to evaluate the potential of establishing a biogas plant versus a compost plant for the treatment of source-separated biowaste in a German city with a population of around 200,000. The goal is to determine which option provides better economic, environmental, and social benefits. Biogas plants have the significant advantage of producing renewable energy in the form of biogas, which can be converted into electricity, heat, and

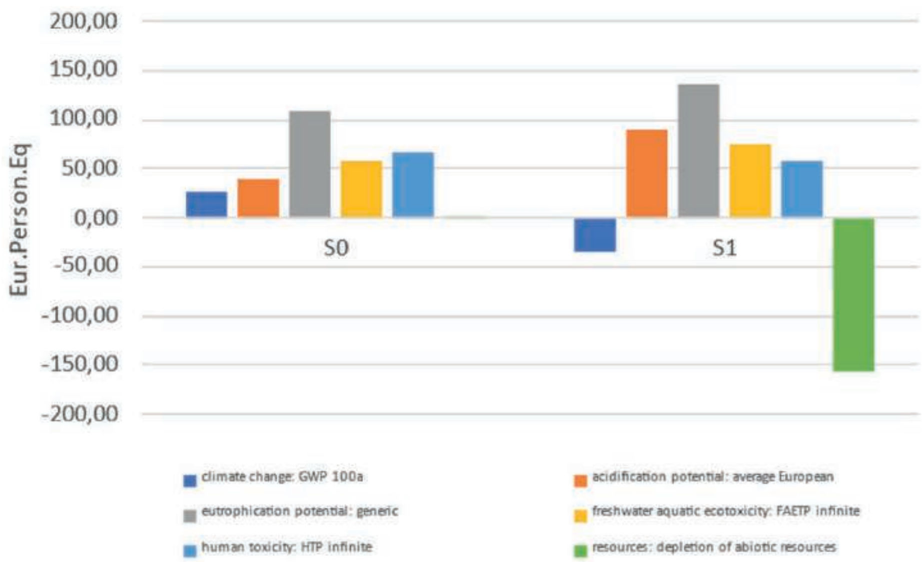

FIGURE 5: Environmental impact assessment of S0 and S1 (normalization in EP).

vehicle fuel. This contributes to the reduction of greenhouse gas emissions by capturing methane that would otherwise be released from waste decomposition in landfills (Gilbert et al., 2022). Additionally, the process generates nutrient-rich digestate, which serves as an effective fertilizer (Gilbert et al., 2022). As a result, more biogas plants were constructed for the treatment of source-separated biowaste. In 2022, for the first time, more biowaste was treated in biogas plants than in composting plants (Figure 6).

Despite their benefits, biogas plants require substantial initial investment for construction and equipment (Walk and Gambini 2024). Their operational complexity necessitates skilled labor for efficient management and maintenance. Biogas plants depend heavily on a continuous and reliable supply of biowaste, making their operation vulnerable to feedstock composition and physical contamination (Walk and Gambini, 2024). The potential for partnerships with agricultural and food industries for feedstock supply and integration with other waste management solutions presents opportunities (Figure 7).

However, biogas plants face several threats, such as potential regulatory changes that could impact their operations. Market fluctuations, particularly in energy prices and demand, can affect profitability. Competition from other renewable energy sources and waste management solutions adds to the risks.

Compost plants, on the other hand, are characterized by their lower initial investment and simpler technology, making them easier to operate and maintain (Walk and Gambini, 2024). They produce high-quality compost, providing significant environmental benefits by reducing landfill usage and associated methane emissions (Gilbert et al., 2022). However, compost plants do not recover energy and require effective odor management and significant land area for operations. Their processes can also be affected by weather conditions (Walk and Gambini, 2024).

The opportunities for compost plants include a growing market demand for organic products, local job creation, and potential partnerships with farmers and gardeners. Increasing public awareness of composting benefits also presents a positive outlook. Nonetheless, they face threats from potential regulatory changes, competition from cheaper synthetic fertilizers, challenges in market acceptance, and environmental concerns related to leachate and odor if not properly managed.

In the case of our study area, a mid-sized town, the potential benefit includes a reduced carbon footprint associated with renewable energy production. In terms of weakness and threats, impurities and the potential of biogas production from the input feedstocks are relevant. The biological treatment of organic waste, particularly biowaste, has proven challenging because the collected ma-

TABLE 3: Environmental impact assessment for the treatment options per tonne of waste.

Impacts	Unit	Box	AD	Impacts per tonnes waste	
				Box	AD
Climate change	kg CO2-Eq	339619	-458690	19,15	-25,87
Acidification potential	kg SO2-Eq	2210	5961	0,12	0,34
Eutrophication potential	kg PO4-Eq	539	1131	0,03	0,06
Freshwater aquatic ecotoxicity	kg 1,4-DCB-Eq	34092	6722	1,92	0,38
Human toxicity	kg 1,4-DCB-Eq	131042	-56518	7,39	-3,19
Depletion of abiotic resources	kg antimony-Eq	1141	-4944	0,06	-0,28

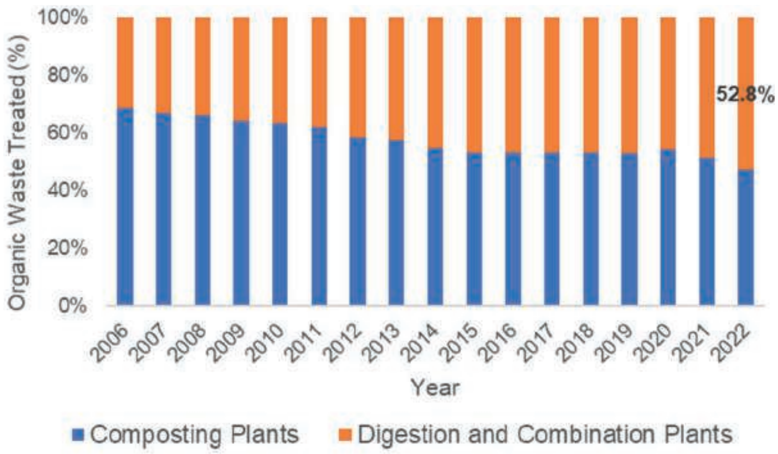

FIGURE 6: Ratio of Biowaste treated in biological facilities in Germany (German Environment Agency, 2024).

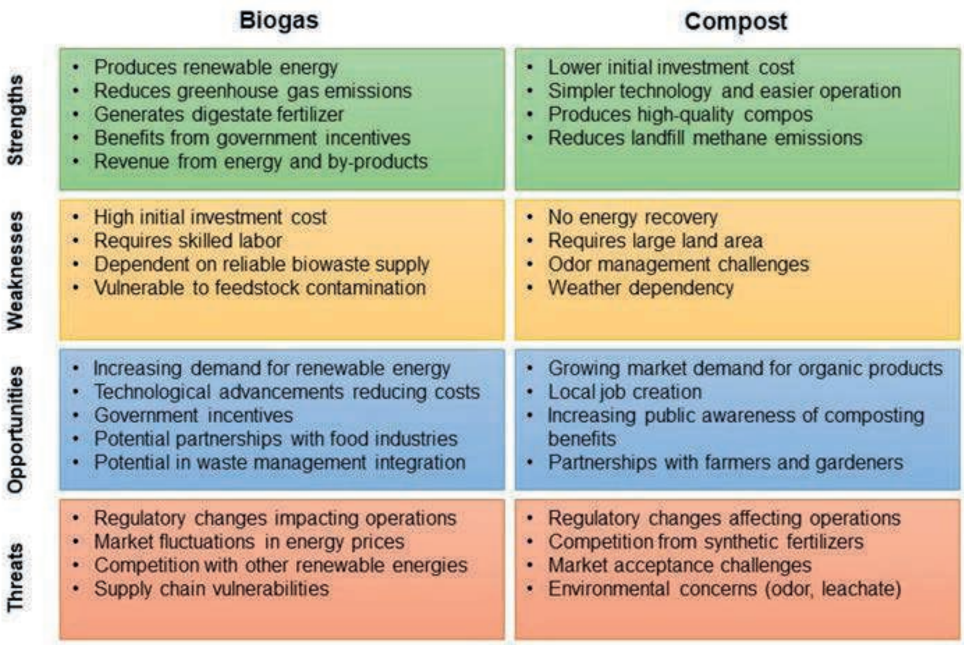

FIGURE 7: Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis for compost and biogas technology.

terial often contains various impurities and foreign matter. Depending on its quality, residual impurities in biowaste can lead to additional costs for digestate treatment. Despite processing efforts, it is not possible to completely remove these impurities, which reduces the quality of the end products and lowers the potential revenue from the commercialization of digestate and compost. This makes the biogas option even more expensive.

The quality and quantity of biowaste also vary across seasons due to changes in temperature and solar radiation. A study conducted by (Sprafke et al. 2020) estimated the specific biogas yield based on material availability in different seasons within the study area. The biogas yield ranged from 91 to 160 m³ per Mg, with seasonal fluctuations affecting waste volume, thereby making it challenging to maintain a consistent supply of biogas or biomethane. In winter, biogas production can drop to 52% of the maximum volume, leading to a CHP utilization rate of 72% without co-substrates. A common practice for optimizing plant operation is the use of co-substrates or biowaste from periods with increased biowaste volumes. However, German regulations impose limitations on the use of co-substrates up to 10% (Federal Office of Justice 2023). Additionally, storage is not a viable option, as biowaste is subject to biodegradation processes. Consequently, the volatile nature of biowaste and the uncertain availability of co-substrates present significant challenges for optimizing plant operations from a techno-economic perspective. The risks associated with biogas potential are a significant drawback. In contrast, composting is more adaptable to fluctuations in both quality and quantity. Composting is the more cost-effective option, as the town already has a compost plant that can be upgraded to accommodate the new facility.

These findings align with existing literature. Biogas plants with improved environmental and economic performance typically have a capacity exceeding 40,000 tonnes per year (Lewerenz et al., 2023; Mayer et al. 2020). The reported feedstock for these facilities contains a higher proportion of food waste than lignocellulosic material (Neri et al. 2018). However, if increasing plant capacity—whether in quantity or quality—requires extensive biowaste transportation, a smaller plant (such as this study's approximately 20,000-tonne facility for both green and organic waste) with simple technology and well emission strategies (Essonanawe Edjabou and Scheutz 2023; Bong et al. 2017) is a more environmentally friendly option than a larger, more advanced plant (Lewerenz et al., 2023).

4. CONCLUSIONS

The comparative analysis of biogas and compost plants for source-separated biowaste treatment reveals distinct differences in their environmental impacts across various categories. LCA indicates that AD has a more favorable outcome in terms of GWP, showing a net reduction of -25.87 kg CO2-equivalent per tonne of waste, which is over 200% lower than the 19.15 kg CO2-equivalent emissions from composting. This significant reduction is primarily due to the biogas produced during AD, which can replace fossil fuels and thus lower overall greenhouse gas emissions.

A SWOT analysis was used to compare the main benefits of biogas, such as renewable energy production and government incentives, with the challenges of operational complexity and national regulations. Since German regulations do not allow more than 10% co-substrate for biogas plants receiving biowaste, and the availability of biowaste in winter is low in the study area—potentially dropping to 52% of the maximum volume—it is not feasible to establish a biogas plant. Additionally, impurities in the biowaste pose a challenge, as their removal from the digestate increases the overall cost of biogas technology.

Opting for a composting plant offers advantages such as lower initial costs and simpler technology while producing a high-quality final product and reducing landfill use. The facility has over 20 years of experience in operating a composting plant, and within a new setting, improved emission control measures can be implemented to increase efficiency.

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THE POTENTIAL OF NATIVE STARCH BIOMASS TO PRODUCE MATERIALS FOR ENERGY APPLICATIONS

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ABSTRACT

Starch is widely used in the food, packaging, paper, and biomedical industries, primarily sourced from commercial crops such as potato, maize, corn, cassava, and wheat. However, native Andean potatoes, despite their high starch content and genetic diversity, remain underutilized in industrial applications. These varieties are often overlooked in favor of commercial starch sources. They are usually considered non-commercially viable due to cosmetic defects, irregular sizes, or overproduction surpluses. In this study, starch extracted from a native Andean potato variety was reinforced with Barium Titanate Oxide (BTO) to fabricate a biopolymeric film with a high dielectric constant. This composite film was employed as the triboelectric layer in a freestanding sliding Triboelectric Nanogenerator (TENG), which achieved a maximum output voltage of 25 V and a short-circuit current of 2.5 μA. This TENG was used to charge a 3.4 μF capacitor, demonstrating the potential of Andean potato starch-based films for energy harvesting applications, particularly in self-powered sensors and low-power electronic devices.

1. INTRODUCTION

Starch is a crucial food source and a renewable biomass resource widely used in industrial applications as a thickening and adhesive agent (Troncoso and Torres, 2020). Structurally, it is composed of two biopolymers, amylose and amylopectin, which have been utilized in the development of biodegradable polymers for packaging applications. The advantages of starch-based biopolymers include their biodegradability, low cost, and abundant availability (Yu et al., 2021). Moreover, it is present in a variety of plant sources, including roots, tubers, stalks, and seeds, but commercially significant starch production is primarily derived from crops such as corn, wheat, and potato (Buléon et al., 1998). The starch extracted from these crops plays a significant role in industries such as food, textiles, and paper manufacturing (Eliasson, 2004). However, the physicochemical properties of starch and its derived materials depend on their botanical origin. Previous studies have analyzed the properties of starches extracted from more than 30 varieties of Andean tubers, including various native potato species (Torres et al., 2011). It has been observed that factors such as granule size, amylose-to-amylopectin ratio, gelatinization temperature, and enthalpy vary significantly based on the starch source. Similarly, starch-derived nanoparticles exhibit distinct properties, such as variations in size and crystallinity, even when derived from potato varieties with similar amylose content and gelatinization temperatures (Torres et al., 2015).

The study of native starches is justified by several factors, including their potential for sustainable and eco-friendly production and their local availability, which can provide economic and cultural benefits (Zhu, 2020). For instance, in Peru, smallholder farmers cultivate more than 4,000 native potato varieties (Meinzen-Dick et al., 2009), each one of them with different morphological and thermal properties (Torres et al., 2011). However, these varieties are primarily used for direct human consumption rather than for starch extraction, leading to potential underutilization of a valuable resource. The International Potato Center has shown that potato processing in Andean countries, such as Peru and Bolivia, is primarily oriented toward fresh table potato consumption. The percentage of processed potatoes relative to the total production in these countries is in the range of 1.5%-3.3% (Devaux et al., 2024). This underscores the limited utilization of starch in the industry of Andean countries. Despite the limited industrial utilization of native potato starch, studies have highlighted its promising functional properties for different applications. Vilpoux (2023) studied the economic opportunities for underutilized raw materials of South American origin in the starch markets. He found that as the main cost of native starch is the cost of raw material, agricultural yields are of great importance to identify the most promising starch sources. Consider-

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ing dry matter productivity per hectare, potato remains the most productive crop in the Andean countries with great economic potential.

Choque-Quispe et al. (2024) evaluated the rheological, thermal, and techno-functional properties of starch extracted from two native Andean potato varieties. They concluded that these starches have potential applications in the food industry. While starch-based products generally have lower CO_2 emissions compared to fossil-based products when a Life Cycle Assessment (LCA) is conducted, studies indicate that their impact on eutrophication and acidification may be greater due to agricultural practices (Forfora et al., 2024). Several studies have evaluated the environmental impact of the production of starch-based biocomposites using the LCA methodology. Rojas et al. (2021) evaluated the environmental impact of bioplastics made from different type of starches. Thermoplastics made from Andean potato starches featured lower environmental impact compared to other biopolymers, such as polylactic acid (PLA). Global warning (GW), freshwater ecotoxicity (FEC), freshwater eutrophication (FEU), fossil resources (FR) and mineral resources (MR) present a lower impact for Andean potato starch compared to PLA. Their results also found that agricultural practices and starch extraction efficiency are key factors to obtain sustainable products.

In some cases, surplus or non-commercially viable potatoes could be repurposed to generate starch-based materials for other applications, contributing to waste reduction and promoting circular economy practices. One of the most interesting possible applications is its use in Triboelectric Nanogenerators (TENGs). TENGs operate based on the contact electrification phenomenon, in which charge transfer occurs between two dielectric materials during periodic contact-separation cycles (Torres et al., 2023; Torres and De la Torre, 2021). These devices can convert mechanical energy into electrical energy, potentially serving as power sources for small portable electronics such as wearable devices, sensors, LEDs, and implantable devices for wireless cardiac monitoring, among others (Kim et al., 2021).

There are many reports of the use of waste and biopolymers in TENGs. For instance, Saqib et al. (2020) developed an economical and environmentally friendly TENG using peanut shell powder (PSP) as the active material. The PSP-TENG demonstrated high performance being capable of powering LEDs and a calculator. The use of biodegradable materials, such as chitosan and cellulose nanofibrils, has also been remarked for their potential in creating self-powered devices that can degrade in physiological environments, thus minimizing environmental impact (Chaturvedi and Roy, 2024). This is particularly relevant for implantable medical devices, where the need for secondary surgeries to remove non-biodegradable components can be eliminated (Mi et al., 2022). Recent advancements have also focused on the use of recycled plastics, such as take-out boxes and plastic bags, in TENGs. For instance, a TENG constructed from waste take-out boxes achieved an output voltage of 186 V and a power density of 34 μW (Gu et al., 2023). Furthermore, the use of polyethylene waste has been explored, with findings indicating that it can effectively serve as a triboelectric material, thereby contributing to a circular economy by mitigating plastic waste (Das et al., 2024).

A notable application of Andean potato starch involves its use in the development of biopolymeric films for energy harvesting technologies. While previous studies have investigated starch-based triboelectric materials, their performance has remained limited, particularly in terms of electrical output (Ccorahua et al., 2019a; Ccorahua et al., 2019b). Herein, starch extracted from the "Yungay" variety has been used to fabricate a triboelectric layer for a TENG device, aiming to develop a more ecofriendly device with competitive electrical output for energy harvesting applications. Typically, triboelectric materials are synthetic polymers such as PTFE, and Kevlar®, which may have significant environmental impacts (Hao et al., 2024). Unlike PTFE and Kevlar®, starch-based materials degrade naturally and are extracted from bioresources. In order to improve the dielectric properties of starch, and make it a viable alternative, a starch-based composite incorporating Barium Titanate Oxide (BTO) has been developed. This composite material has demonstrated its suitability for TENG applications, offering an alternative to conventional synthetic polymers.

2. EXPERIMENTAL PROCEDURES

2.1 Materials

Potatoes (solanum tuberosum var Yungay) were bought in Lima, Peru. Barium titanate oxide (BTO, $BaTiO_3$), glycerol, hydrochloric acid (HCl), and sodium hydroxide (NaOH) were analytical grade and obtained from Sigma-Aldrich and Himedia Laboratories LLC. Kapton® films were sourced from Fuel Cell Store, while Teflon® films were acquired from Sigma-Aldrich.

2.2 Fabrication of starch-based TENGs

TENGs operate based on the principles of contact electrification and electrostatic induction. For effective charge transfer, two dielectric layers composed of materials with distinct electron affinities must be employed. Before contact, there is no charge transfer, and thus no potential difference. However, upon contact, electrons transfer from the material with lower electron affinity to the one with higher electron affinity, leading to one surface acquiring a negative charge while the other becomes positively charged. Upon separation, this charge imbalance induces an electron flow in the external circuit until electrostatic equilibrium is reached. To develop a functional starch-based TENG, it was first necessary to extract and process the starch used as the triboelectric material. For the starch extraction, fresh Yungay potatoes were washed with tap water, chopped, and homogenized using a blender. The resulting slurry was sieved and allowed to settle for 4 hours. The supernatant was discarded, and the precipitate was degreased by resuspension in a 1:1 methanol-water mixture, followed by decantation. The final starch precipitate was dried at 60°C for 24 hours.

Starch-based films were prepared using the casting method. A total of 10 g of dried starch was dissolved in 200 mL of distilled water at 95°C. Then, 0.075 g of BTO was added to the starch solution. The solution underwent partial hydrolysis in 0.1 N HCl, adjusting the pH to 2.0. Glycerol was incorporated at a 2:5 ratio (glycerol:starch, dry basis). The mixture was homogenized by stirring for 15 minutes at 95°C, after which it was neutralized with 0.1 N NaOH, adjusting the pH to 10 to halt hydrolysis. The final solution was spread onto Petri dishes and dried in an oven at 40°C for 16 hours. The resulting films were approximately 200 μm thick. Pure starch films were also prepared for comparison. The starch-based films served as one triboelectric surface, while Teflon® was used as the counterpart. The starch-based films functioned as a freestanding layer (Figure 1a), while the Teflon® layer remained stationary as the stator. A linear motor facilitated a sliding motion (Figure 1b), generating contact-separation states in the TENGs. Copper films were used as electrodes (current collectors).

2.3 Characterization techniques

Scanning Electron Microscope (SEM) was used to study the morphology of the starch-based films. The analysis was performed using an Axia ChemiSEM (Thermo Fisher) equipped with an energy-dispersive X-ray spectroscopy detector. Tests were carried out in low vacuum with a voltage of 20 kV and a working distance of ~10 mm. Fourier Transform Infrared (FTIR) spectroscopy was employed to identify functional groups in the starch-based films. Spectra were recorded using a Spectrum Two PerkinElmer spectrometer equipped with a universal ATR accessory. The spectral range was 500-4000 cm^{-1}, with a resolution of 4 cm^{-1} and 64 scans. The dielectric properties of the films were analyzed using a NOVOCONTROL Broadband Dielectric Spectrometer (BDS) with an Alpha A-High Performance Frequency Analyzer. Measurements were conducted over a frequency range of 10^{-2} to 10^{-7} Hz under an inert nitrogen (N_2) atmosphere. Temperature control was achieved using a QUATRO Cryosystem nitrogen jet. The starch-based films were cut into 30 mm diameter circular discs and placed between gold-plated electrodes. Film thickness was measured using a Mitutoyo 293-240 micrometer. The electrical output of the TENGs was assessed using a Tektronix DPO2022 oscilloscope. The generated voltage signal was recorded directly, including rectified voltage measurements. Data were collected over a 10-second interval. The short-circuit current was measured using an SR570 Stanford current preamplifier in a circuit with an equivalent resistance of 9.3 MΩ. Electrical measurement were conducted at least three times. Mechanical tests were conducted to analyze the stress-strain curves and determine the stiffness of the films. These tests were performed using a Shimadzu EZ-SX Universal Testing Machine equipped with a 500 N (±0.5%) load cell. The crosshead speed was set at 10 mm/min. The samples were cut into 5 mm x 60 mm strips. The tests were performed at room temperature (20°C). Three repetitions were conducted.

3. RESULTS AND DISCUSSION

TENGs work as a voltage source coupled with a capacitor (Niu and Wang, 2015). Like any capacitor, its energy storage capacity depends on the relative permittivity (ε_r) of the charge-storing surface. Relative permittivity quanti-

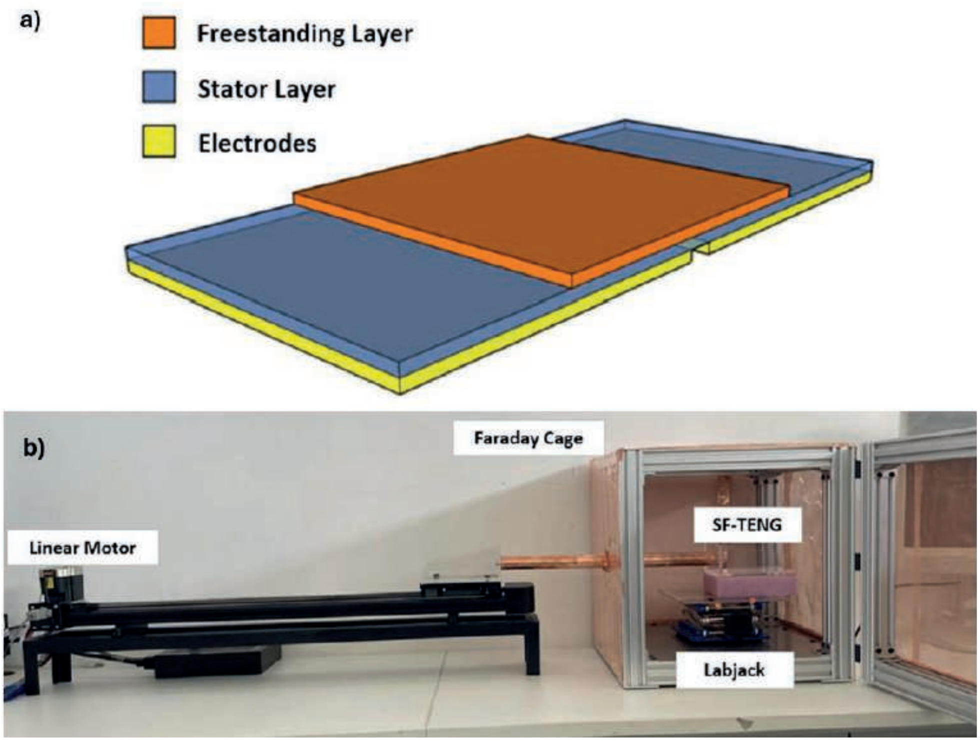

FIGURE 1: Schematic representation of the TENGs prepared for this study. Starch and starch/BTO films were used as freestanding layers. Teflon® films were used as stator layers (a). The sliding mode TENG fabricated was prepared using a linear motor that provides an oscillating movement between a starch/BTO film and a Teflon® film. The TENG was kept in a Faraday cage to avoid electric interference (b).

fies a material's ability to polarize in response to an electric field. To maximize TENG power generation, the dielectric materials used as active surfaces should have the highest possible permittivity. Several synthetic polymers, such as polytetrafluoroethylene (PTFE), Kapton®, and Kevlar®, exhibit relatively high ε_r values. However, their permittivity remains lower than that of high-permittivity ceramics (Prateek et al., 2016). To address this limitation, a high-permittivity composite was developed by incorporating BTO into a starch matrix. This starch/BTO composite was then used as one of the active surfaces in the TENGs prepared for this study.

A higher permittivity leads to a greater charge density (σ), as described for the following equation for a sliding TENG (Niu et al., 2013):

$$\sigma = \frac{\varepsilon_0 (l - x) V_{oc}}{x}\left(\frac{\varepsilon_{r1}}{d_1} + \frac{\varepsilon_{r2}}{d_2}\right) \quad (1)$$

where ε_0 is the vacuum permittivity, V_{oc} is the open-circuit voltage, d_1 and d_2 are the thickness of the triboelectric layers (in this case, the starch-based and the Teflon® films), εr_1 and εr_2 are the relativities permittivities of these films, x is the separation between the triboelectric layers and l is the longitudinal size of these layers.

The output voltage of a typical TENG operating in sliding mode also depends on the charge density and can be expressed as follows (Niu et al., 2013):

$$V = -\frac{1}{w\varepsilon_0 (l - x)}\left(\frac{d_1}{\varepsilon_{r1}} + \frac{d_2}{\varepsilon_{r2}}\right) Q + \frac{\sigma\, x}{\varepsilon_0 (l - x)}\left(\frac{d_1}{\varepsilon_{r1}} + \frac{d_2}{\varepsilon_{r2}}\right) \quad (2)$$

where Q is the amount of transferred charge and w is the width of the whole structure. These equations highlight the importance of using films with high permittivity to get devices with improved performance, justifying the incorporation of BTO.

The incorporation of BTO was assessed by Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray (EDX). Figure 2a depicts the SEM image of the pristine starch film. The surface morphology reveals a relatively homogeneous structure with a smooth texture, accompanied by small pores and irregularities distributed throughout the film. The presence of these pores suggests a non-compact arrangement of the starch polymeric matrix. The Energy Dispersive X-ray (EDX) identified carbon (55.2% wt), oxygen (36.9% wt) and Na (4.4% wt) as the principal components (Figure 2c), with sodium likely originating from the extraction process. Figure 2b displays the morphology of the starch/BTO film. In contrast to the pristine film, the surface morphology exhibits a more heterogeneous structure, characterized by the presence of dispersed bright regions corresponding to BTO particles. These particles appear aggregated in certain areas, forming irregular clusters distributed throughout the polymeric matrix. EDX analysis indicate a composition of carbon (46.5%wt), oxygen (36.4% wt), titanium (9.9% wt) and sodium (4.2% wt) (Figure 2d).

FTIR also confirmed the incorporation of BTO into the starch-based films. Figure 3 presents representative spectra of pure BTO and starch/BTO films. The spectrum of pure BTO exhibits a characteristic peak at 1421 cm^{-1}, attributed to bending vibrations in the COO group, a result of acetic acid usage during BTO synthesis (Singh et al., 2017). The same peak appears in the starch/BTO spectrum, confirming the presence of BTO in the composite. Additional peaks correspond to typical starch features. The band at 930 cm^{-1} is associated with glycosidic linkages, while the 1642 cm^{-1} band corresponds to water absorption in the amorphous regions of starch. The CH deformation band at 2933 cm^{-1} is also observed (Torres et al., 2015).

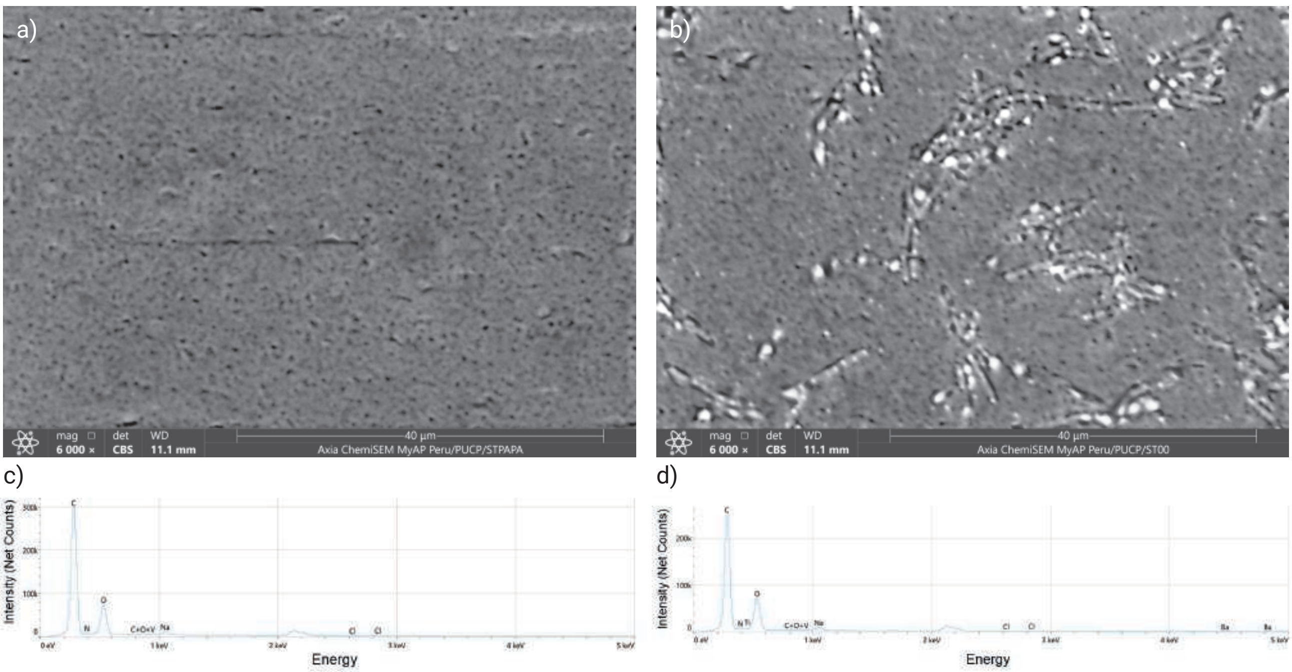

FIGURE 2: SEM images of (a) the pristine starch film and (b) the starch/BTO film, along with their corresponding EDX spectra (c) and (d), respectively.

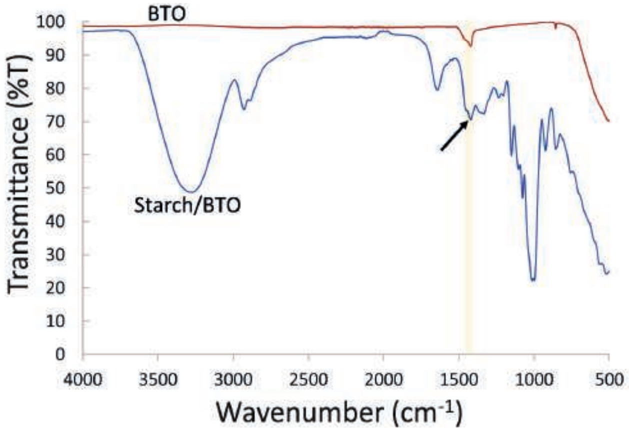

FIGURE 3: Representative FTIR spectra of pure BTO and a starch/BTO film.

BDS was performed to evaluate the dielectric properties of the prepared films. The relative permittivity of native starch films was determined to be 1.02x10^5 . In contrast, the starch/BTO composite films exhibited a significantly enhanced dielectric constant of 3.77x10^6, an increase by a factor of more than 36.

To fabricate a functional sliding-mode TENG, two different dielectric materials were required. The electrical performance of a starch/BTO-Teflon® TENG was evaluated. Figure 4 illustrates the voltage signals generated by the prepared TENGs. The voltage profile reveals a distinctive alternating pattern resulting from the cyclic mechanical motions. Each oscillation cycle spans approximately one second, with peak values ranging from 23.1 V to -21.9 V. Upon rectification via a full-bridge rectifier, the negative portion of the waveform is mirrored above the time axis, resulting in a fully positive voltage output.

Similarly, Figure 5 presents the short-circuit current signals, which range from 2.46 µA to -2.3 µA. The rectified signal exhibits a peak current of 2.42 µA. These results demonstrate that the starch/BTO composite significantly influences charge transfer efficiency and output current.

To further evaluate the practical applicability of the TENGs, their capability to charge a 3.4 µF capacitor was investigated. Figure 6 presents representative charging curves, illustrating the voltage evolution over time. The charging profile of the pure starch-based TENG reaches a plateau at approximately 1.25 V after 200 seconds. In contrast, the starch/BTO-based TENG exhibits a significantly higher plateau voltage of approximately 2 V, achieved in less than 50 seconds. This improvement is attributed to the higher dielectric constant of the starch/BTO composite, which enhances charge storage capacity and energy conversion efficiency.

These results underscore the potential of biopolymer-based dielectric materials for optimizing TENG performance. By tailoring the dielectric properties of starch-based composites, sustainable and efficient energy harvesting devices can be developed.

TENGs in the freestanding sliding mode generate electrical output through the periodic contact and relative lateral displacement of dielectric films. In this context, evaluating the mechanical properties of these films is essential, as their strength, flexibility, and durability influence their triboelectric performance and long-term stability under repeated sliding motions. Figure 7 presents the stress-strain curves for the pristine starch film and the BTO/starch composite film. These measurements were performed three times, and the elastic module was calculated using the average value. The pristine starch film exhibited an elastic modulus of 17.27 MPa, indicating a more flexible and ductile behavior with a maximum strain of approximately 18%. In contrast, the BTO/starch composite film showed a significantly higher elastic modulus of 41.988 MPa, reflecting an improvement in mechanical strength. The stress at break for the composite film was nearly three times greater than that of the pristine film. However, its elongation at break decreased to approximately 8%, suggesting increased brittleness due to the presence of BTO particles in the matrix.

Compared to other starch-based TENGs, the fabricated device exhibits significant potential for high performance. For instance, Zhu et al. (2018) developed a starch paper-based TENG that achieved an output voltage of 11.2 V, approximated as the open-circuit voltage under a 100 MΩ load resistance. The starch paper was sourced from GILRO Corp. (Israel). In contrast, Ccorahua et al. (2019a) reported

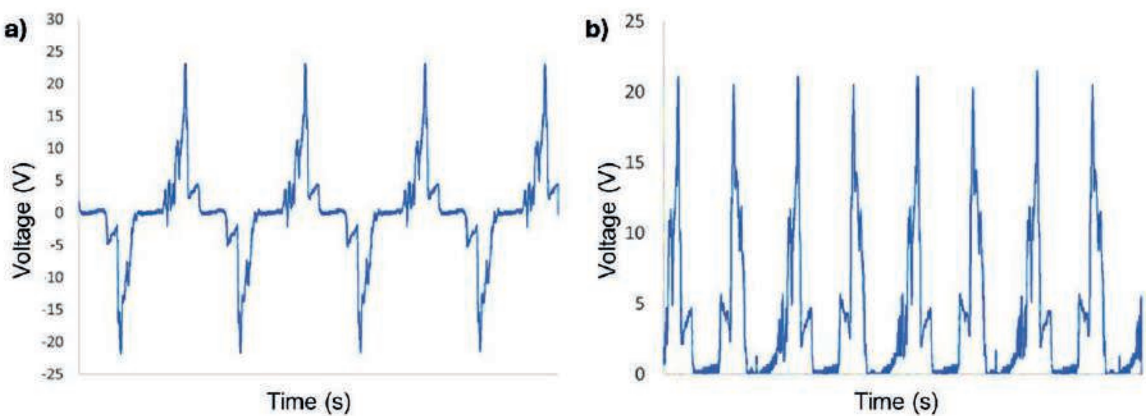

FIGURE 4: Representative open circuit voltage signals from starch/BTO-Teflon® TENGs in an open circuit mode (a) and a rectified circuit (b).

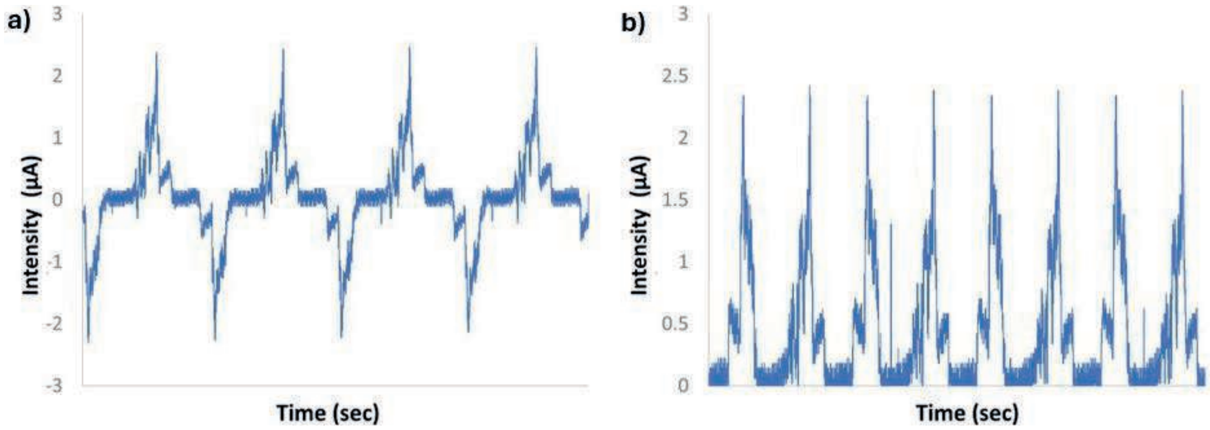

FIGURE 5: Representative short circuit current (μA) signals from starch/BTO-Teflon® TENGs in an open circuit mode (a) and a rectified circuit (b).

lower performance despite also using starch from Andean potatoes (yellow variety). Their starch-cellulose-based TENG generated a maximum output voltage of 300 mV.

It is important to note that while the fabricated TENG demonstrates remarkable performance, other devices have outperformed it. For example, a TENG incorporating a starch gel composite material with a mass ratio of 1:1.02 of corn starch gel and silicone foam produced an output voltage of approximately 280 V (Kamilya et al., 2024), enabling it to power 14 blue LEDs. The TENG using only intrinsic silicone foam achieved an output voltage of 122 V. The superior performance of this device may be attributed to the combination of silicone foam (a highly tribonegative material) and nitrile rubber (a highly tribopositive material), which are positioned far apart in the triboelectric series. Similarly, Khandelwal et al. (2021) extracted starch from the same source and developed a starch/Laver TENG (SL-TENG) that achieved a maximum voltage of 50 V, whereas the pristine starch TENG exhibited a voltage of only 10 V. The difference in performance may also be attributed to the origin of the starch used. While these studies have used wheat starch, our device utilizes starch extracted from Andean potatoes, which could introduce differences in granule size, amylose-to-amylopectin ratio, and dielectric properties. These variations may influence charge transfer mechanisms and triboelectric properties.

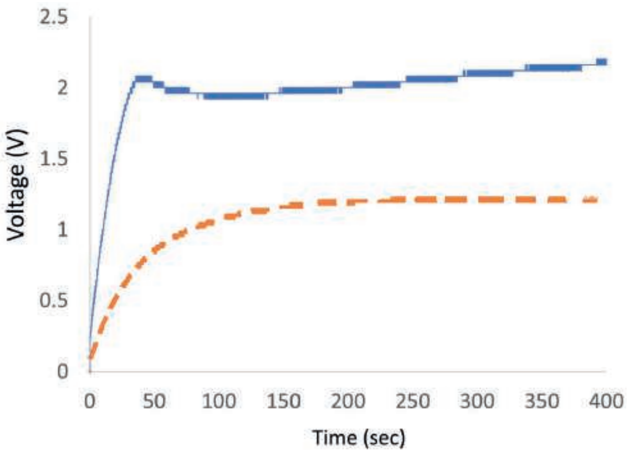

FIGURE 6: Representative time-Voltage curves for a capacitor charged using a starch/BTO-based TENG (solid line) and a pure starch-based TENG (dashed line).

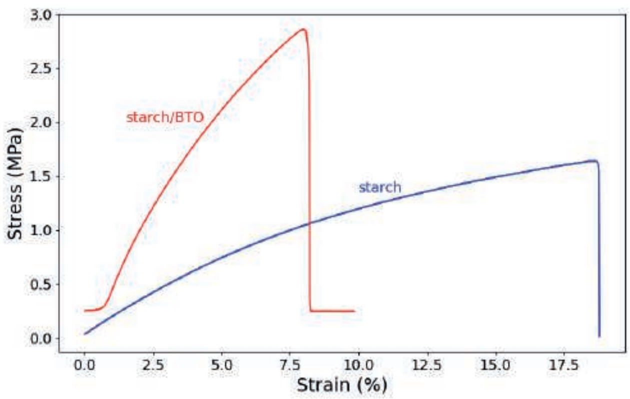

FIGURE 7: Representative stress-strain curves for the pristine starch and starch/BTO films.

Regarding sustainability, Starch Europe, the association of European Starch producers, reported in the Life Cycle Analysis (LCA) of 2022 that the starch industry has managed to reduce its CO_2 emissions by 7% overall and 19% per ton of dry substance since 2009. Its summary report state that potato starch has a carbon footprint of 474.2 kg CO_2 eq per ton of dry substance (DS). In contrast, Corn starch has a carbon footprint of 589 kg CO2 eq per tonne DS and wheat grain cultivation contributes between 480 and 740 kg CO_2 eq per tonne DS of product or coproduct. In summary, potato starch has the smallest carbon footprint which make it more appealing for applications as TENGs that looks for more environmentally friendly solutions to obtain energy. However, it is also necessary to analyze the industrial relevance of starch and its application in TENGs. In food preparation, starch is transformed into starch hydrolysate, which it is used to thicken sauces and soups. Pregelatinized potato starch is used in puddings due to its superior qualities compared to cereal starches. In the confectionery industry, it is used as a thickening agent in synthetic jellies. Potato starch processing generates a significant amount of waste, such as effluent and potato waste.

This potato waste has a high-water content (more than 80%), which makes it difficult to store and can cause serious environmental problems by polluting waterways and generating bad odors (Chauhan et al., 2023). Although it would be costly to dry this waste into dry feed, its disposal or local use as feed can contaminate soil and groundwater. In this context, repurposing potato starch for technological applications such as TENGs provides a more sustainable alternative to disposal, aligning with circular economy principles.

Ahmed et al. (2017) presented two representative TENGs, Module A (high efficiency) and Module B (lower efficiency). These modules were fabricated using synthetic polymers. Their analysis showed that most of the energy consumed in the manufacture of both modules (approximately 90%) was due to raw material requirements. Eco-indicator 99 is a method to evaluate the environmental impact of a process or a product. When comparing these TENGs with photovoltaic (PV) devices, the Eco-indicator 99 results show that both TENG modules achieve the lowest points in ecosystem quality, resources and human health. These were an order of magnitude lower than silicon-based PV modules. On the other hand, energy payback period (EPBP) is the time required for an energy system to generate the same amount of energy that was used in its production, installation, and maintenance. Module A had a 0.5-year EPBP, shorter than traditional PV technologies. Module B's EPBP was competitive but higher than organic and perovskite solar cells. The CO2 emission factor (CEF) of Module A was significantly lower than that of several PV modules. While these findings highlight the environmental advantages of TENGs, further reductions in impact could be achieved by replacing synthetic polymers with biopolymers such as starch. In this context, our TENG emerges as a promising and environmentally friendly alternative to other energy harvesting devices. However, it currently employs a synthetic polymer as one of their films. Therefore, to be considered a fully bio-based product, this component would need to be replaced. Achieving this would require identifying biopolymers that are positioned far apart in the triboelectric series, in order to maximize the output voltage. Future efforts should explore the possibility of replacing the Teflon stationary film with a suitable biological alternative, to further enhance the sustainability of the device.

4. CONCLUSIONS

This study highlights the potential of native Andean potato Yungay variety starch as a sustainable and high-performance material for energy harvesting applications. The incorporation of BTO into starch-based films resulted in a significant enhancement of dielectric properties, leading to TENG output performance. The fabricated starch/BTO-based TENG achieved a maximum output voltage of ~25 V and a short-circuit current of 2.5 μA, demonstrating its feasibility for self-powered electronic devices.

The findings emphasize the importance of utilizing underexploited biomass resources in advanced material applications. Starch from native Andean potatoes represents a valuable yet underutilized agricultural resource, offering a bio-based and biodegradable alternative to synthetic polymers. This approach aligns with circular economy principles by repurposing non-commercially viable potatoes (small or irregular size, cosmetic defects, overproduction surplus, etc.) into functional materials, contributing to waste reduction. Future research should focus on optimizing starch-based composite formulations, exploring additional functional additives, and scaling up production methods to enhance applicability in real world energy harvesting and sensor technologies.

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HYDROTHERMAL CARBONISATION OF ORGANIC WASTE FOR THERMAL ENERGY GENERATION

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ABSTRACT

There is currently no use of HTC in the energy sector, only in the waste sector to reduce the mass of sewage sludge before landfill. Different perspectives have been identified for HTC pretreatment technology in the energy sector including combustion, gasification and methanation. However, HTC can lead to a wide range of product quality considering the wide diversity in wet biowaste that can be used. In addition, as HTC is still an emerging technology on the market, there are limited references regarding the relevancy of using HTC as a thermal pretreatment from both the technical and economical point of view. To evaluate if HTC is a valuable pretreatment technology for the sake of thermal energy generation, a series of 15 different feedstock types have been tested in the HTC lab pilot of Laborelec, among which organic residues from the paper industry, food waste, green waste in summer and autumn, compost. The HTC lab pilot has a batch capacity of 100 kg wet feedstock. For each feedstock, a complete analysis of the mass and energy balances is provided together with the assessment of the final product quality. Based on the different tests realised, the methodology for mass and energy balance evaluation was also elaborated and improved to help future project managers in their project design and feasibility study. The 15 feedstock types were of very different nature and gave hydrochar of very different characteristics. However, it is possible to observe some general trends for the HTC products obtained from every feedstock type as alkalis were well reduced during the process and chlorine seems always decreased during HTC process. In most cases, based on the Van Krevelen diagram, HTC is first dominated by dehydration and then by decarboxylation. It appeared that energetic conversion of HTC products is strongly linked with the hydrochar quality. It is clear that HTC improves a lot the quality of low grade organic waste, especially wet feedstock with reasonably low ash content and makes it suitable as input to a boiler or a gasifier. It must also be noted that HTC does not bring added value for biomass that is already high grade like dry wood, as it can be directly used as a fuel. We could define three types of hydrochars for thermal conversion: high quality HTC black pellets with low ash and high calorific value that can be transported efficiently on long distances, average quality HTC black pellets with medium ash content and calorific value for which logistics should be limited to reasonable distances and low quality HTC black pellets that should not be transported and remain on their production site.

1. INTRODUCTION

Hydrothermal Carbonisation (HTC) is a thermal pretreatment process for organic waste and biomass (Hoekman et al., 2011), which is operated in saturated steam condition (between 180°C and 240°C) allowing to transform low grade organic waste into a carbon concentrated product that can be used as a renewable fuel in the energy sector.

At Laborelec, perspectives for the utilization of this process in the energy sector were drafted with the application within:

1. Combined heat and power (CHP) plants,
2. Circular green steam for district heating and industrial steam plants,
3. Thermal gasification for the generation of syngas.

In each application, HTC is first applied to a wet biowaste stream to produce a hydrochar i.e., a carbon concentrated product with high energy density, which can then be densified in black pellets. These black pellets can be transported efficiently and used as a fuel in thermal plants (Erlach et al., 2011).

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However, it should be noticed that the hydrochar quality may vary significantly depending on the biowaste type. Produced hydrochar has an ash content between 5 and 45%, a LHV between 10 and 25MJ/kg, variable chlorine and alkali concentrations, which might thus affect the efficiency of the energy conversion. Indeed, similarly to the inefficient transport of materials with a high moisture content, the transport of ash-rich materials must be avoided too as they correspond to a lower heating value and thus energy density and eventually they also generate costs for ash recycling.

Moreover, the fuel energy density has an influence on the asset performances and profitability (equipment size, OPEX, etc.). Depending on the feedstock, HTC product might then have preferred applications with optimized levelised cost of energy. When the hydrochar quality is low, some application should even be rejected to avoid unprofitability or because the potential hydrochar produced would have no interest for the market.

When a feedstock is considered for a project with an HTC pretreatment, the potential and optimal usage can be obtained by a small-scale HTC test at Laborelec: mass and energy balances between input and output streams can be quantified thanks to the analysis of both the raw material and the end-product (hydrochar).

This paper presents the analysis of 15 tests made with the HTC lab pilot at Laborelec. It gives also the interpretation of the mass and energy balances based on a specific methodology, which has been developed to provide all relevant information prior to a project development: hydrochar quality and possible usages, HTC plant sizing, required raw material quantity, etc. The results of this first part of the study are presented in section 3 and allow to have a first evaluation of HTC performances considering a wide range of feedstock types.

2. CHARACTERISATION OF FEEDSTOCK, HYDROCHAR AND DEASHED HYDROCHAR

For this assessment, the specifications of three types of products for each test were compared, all on dry basis (0% moisture content):

1. The raw feedstock,
2. The hydrochar produced and
3. The deashed hydrochar (simulated industrial quality by centrifugation, equivalent to 80% removal of Si and Al in ash, with 0% moisture content).

Some specifications were combined into relevant indexes for gasification, methanation and combustion to assess the suitability of those fuels (Erlach et al., 2012).

1. In order to assess the suitability of test samples for gasification, the gasification performance was first assessed by combining the following parameters and indexes.
   a. The volatiles (in % of dry matter): when lower than 50%, the volatile content is considered too low (and probably already too carbonised) for an efficient gasification. (50% is a rule of thumb).
   b. The H/C and the O/C (atomic) ratios in the corresponding Van Krevelen diagram: the higher the better for the gasification performance.
2. Next to the gasification performance, the risk of bed agglomeration in fluidised bed reactors was also assessed by combining the following parameters and indexes (Steurera & Ardissonea, 2015).
   a. Alkali (K+Na) in the fuel (in ppm in dry matter): the lower the better (and thus the less risky for bed agglomeration), considering a typical value of 2500 ppm and a limit value of 6000 ppm, according to biomass boiler manufacturers.
   b. Na+K/1,7: the lower the better (considering the content in ash, normalised as oxides).
   c. Ca/P: the higher the better (considering the content in ash, normalised as oxides).
   d. Ca/(Na+K): the higher the better (considering the content in ash, normalised as oxides).
   e. Si/Al: when lower than 1.5 the silicon is mainly in the form of clay (the quartz being negligible), and when above 3 the silicon is mainly in the form of quartz with risks of bed agglomeration. This ratio was computed considering the content in ash normalised as oxides and treated when normalising it as if 1.5 was the typical value and 3 the limit value (see explanations hereafter).
3. The ash removal system in combustion plants is an electrostatic precipitator (ESP) and/or bag filter in the flue gas stream. It is limited to a fly ash content (in % of dry matter) of 30% and was assessed separately. The 30% is linked to the design value of the ash removal system. This can differ from project to project. The 30% is a typical value.
4. Methanation is the reaction by which carbon oxides and hydrogen, catalysed by nickel, are converted into methane and water. In industry, there are two main uses for methanation: to purify synthesis gas (i.e. remove traces of carbon oxides) and to manufacture methane. Engie has developed catalytic methanation in its Gaya pilot plant located in Lyon France. The suitability for catalytic methanation was assessed by combining the following parameters.
   a. N content (in % dry matter): typical value of 1%, limit value of 3%. N is an issue because, during condensation, ammonia will be formed in the syngas stream. It will be converted to N_2 and H_2 into the catalyst. The N_2 in biomethane is limited by regulation. 2G biomethane plant has generally no means to take out the ammonia out of the syngas stream. Technically, this is possible but will demand an extra investment. Also ammonia is very corrosive and materials will need to be adapted.
   b. S content (in % dry matter): typical value of 0.2%, limit value of 0.5%. Sulphur poisons the catalyst in methanation process.
   c. Cl content (in ppm dry matter): typical value of 1500 ppm, limit value of 8000 ppm. Chlorine poisons the catalyst in methanation process.
5. Finally, some combustion parameters and indexes were also computed.

a. For boilers with metal temperature <550°C, the S/Cl index is a relevant corrosion index: lower than 2 indicating a high risk of corrosion, and higher than 4 a low risk. Treated similarly as the Si/Al index.
b. For boilers with metal temperature >550°C, the corrosion is assessed with the alkali in the ash (normalised as oxides, the higher the riskier), and with the Na+K+Fe+S (all in %ash normalised as oxides, the higher the riskier for molten sulphate corrosion).
c. Finally, the (Ca+K)/Si index (all in %ash normalised as oxides, the higher the riskier) is computed as an indicator of slagging and fouling risks.

Remark. There is no absolute value regarding Cl of which one can say, when Cl is lower than this absolute value there is no risk of corrosion. It depends under which form the Cl will come free in the flue gases, the presence of heavy metals like Sn, Pb, etc., the atmosphere in the boiler (reducing, oxidizing), etc. The S/Cl is the only one considered parameter for the risk of corrosion.

All indexes and parameters cited hereabove were normalised from 0 (worse value) to 1 (best value) according to some rules.

3. METHODOLOGY FOR THE HTC LAB PILOT TEST

This section describes the main steps of a standard HTC test i.e. material preparation, HTC cycle description, data logging, etc. (Lucian & Fiori, 2017).

Then the methodology to estimate the mass and energy balances will be explained together with the indicators allowing to evaluate the "HTC test" quality.

3.1 Typical HTC test description

A typical HTC test starts with the raw material preparation aiming at conditioning the tested material in the right conditions before starting.

To the contrary of the industrial process, our HTC lab pilot works in batch. The material dimensions, its weight and the average moisture in the reactor need to be controlled before starting the operation (Figure 1). Those specifications have been set by Ingelia as the designer of our pilot plant.

- max. weight on dry base is 30kg,
- max. wet volume of 100L,
- max. particle size = 40 mm,
- average moisture in process condition = 80%, lower moisture does not allow proper working of the pilot.

Note that the quantity of water required to achieve the process conditions is adjusted directly in the reactor.

After preparation, the material is weighted and charged into the reactor. At this stage, the mass and moisture content of the fresh feedstock need to be noted down meticulously, such that those two essential parameters are available for further interpretations. The fresh sample mass is used as reference for the mass yield and an error on it would change the HTC process evaluation.

The mass and the moisture of the tested sample are both linked to the reactor capacity i.e. 30kg of dry material. Exceeding this capacity would lead to issues during the HTC process (too high level in the reactor). On the opposite, if a too small quantity of feedstock is inserted into the reactor, the quantity of material recovered at the outlet could be too low to conduct all necessary analyses.

After this preparation phase, the average moisture is adjusted to 80% and the reactor is closed with a flange. Demineralised water is supplied in both the condenser and the boiler, and the test can start.

From this moment on, the boiler starts heating up until it reaches the required pressure and temperature level for the test:

1. Heating up to 4bars steam pressure (minimum pressure requirement to start heating the reactor by steam injection),
2. Pressurisation of the reactor by steam injection until it achieves equal temperature in both the boiler and the reactor,
3. Heating up to the required test temperature and pressure (220°C / 23.5 bars, Figure 2).

FIGURE 1: Raw material preparation, in this case contaminated compost of green waste.

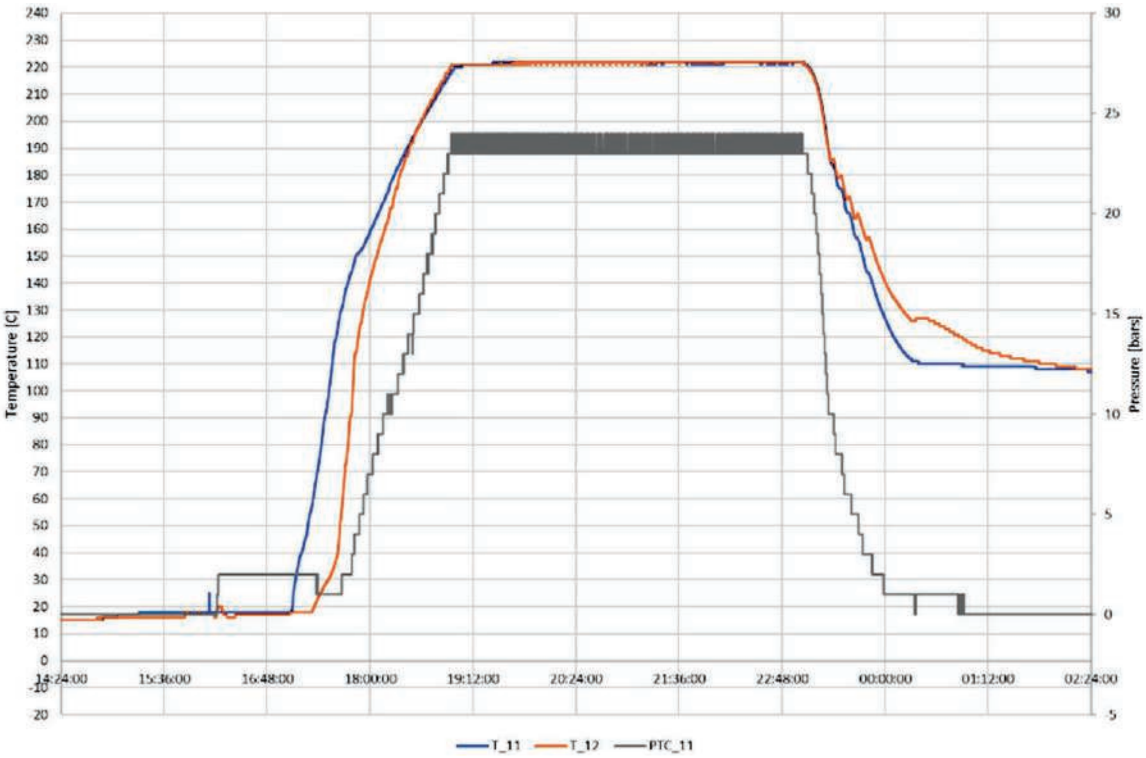

FIGURE 2: Temperature and pressure profile in a typical HTC test.

Note that to be representative of the commercial plant configuration, the test temperature and pressure were set to these values for all tests, as recommended by the designer of the HTC pilot.

After heating-up to carbonisation parameters, the reactor is maintained in steady state until the set residence time is reached i.e., typically 4 hours. In the test results presented in this paper, the residence time may vary between 3 hours or 4 hours depending on the test organisation. Sometimes technical issues resulted in a different residence time.

Then, the reactor is depressurised, and the carbonised sludge is discharged into a buffer tank by passing through the grinder. Finally, the slurry (composed of the process water and the grinded carbonised matter) is pumped into the filter press and after filtration, the carbonised material is recovered and weighted. The mass measured at this stage will be used for the mass yield computation for post-testing interpretation (Figure 3).

Finally, a hydrochar sample of 1-2kg is collected from the filtered weighted carbonised matter for lab analysis and the mass and energy (M&E) balances are obtained by comparing material properties and mass before and after the test.

3.2 Estimation of mass and energy balances

HTC is considered for its ability to pretreat wet biowaste with very low energy content into a higher value energy carrier that can be used as a fuel in thermal plant (Wang et al., 2018).

When HTC is considered as a circular fuel supply for a district heating, for industrial steam generation or for decarbonised fuel trading, the mass and energy balances are required to estimate the yield from a given feedstock and further on, to build a business model for the project including among others (Heidari et al., 2018):

- Sizing a boiler or a CHP,
- Evaluating the production cost and fuel price,
- Setting up a contract for green steam supply.

A detailed mass and energy balances assessment of the HTC process is required as its performance is highly dependent on the nature of the feedstock:

- Raw material analysis allows to have a first evaluation of the product characteristics and its adequacy regarding HTC process: moisture, carbon content, mineral load, etc.;

FIGURE 3: Carbonized material recovered after filtration.

- The analysis of the resulting hydrochar allows the assessment of the obtained energy content, carbon concentration, ash composition, chlorine and alkali reduction, etc.;
- The comparison of both analyses delivers the mass and energy yield, the elemental mass balance, any improvement in HHV/LHV and the Van Krevelen diagram.

At this stage and considering the previous chapter, it should be noted that the lab analyses are carried out respectively on the raw material as received and, on the hydrochar cakes recovered at the outlet of the filter press. However, the HTC lab pilot presents significant differences compared to an industrial HTC plant. Indeed, due to its scale, the HTC lab pilot does not include the different post-treatment steps of the reactor outflow as it exists for the industrial HTC plant, namely:

- A hydro cyclone allowing to remove small stones and small metal pieces from the mainstream containing the carbonised material (Figure 4);
- A spiral separator allowing to remove fine mineral particles from the mainstream richer in carbon;
- The final thermal drying step occurring between the filter press and the pelletisation unit;
- The pelletisation unit.

Drying and pelletisation steps have an influence on the final moisture and the density but not on the elemental composition (except for water), as opposed to both the hydro-cyclone and the spiral separator that contribute to the fuel quality improvement with an ash reduction.

Consequently, it appears that the mass and energy balances of the HTC lab pilot cannot be used straightaway in the perspective of an industrial project. Since the product obtained after a test is still in a "raw" state, compared to what we would have obtained with an industrial plant, mainly a dry and "de-ashed" pelletised hydrochar (Zhang et al., 2019). This is why, in the meanwhile Laborelec added a 3kW pelletiser to the HTC lab pilot for future tests. Figure 5 shows a direct analysis of a HTC lab pilot hydrochar product made from green waste. As can be seen, lower heating value is increased around 23,5 MJ/kg on dry basis and volaties decrease under 60% on dry basis, though ash content is slightly increased. Moisture measured at the outlet of the filter press is 64% where typical pellets moisture would be about 6%.

FIGURE 4: Representation of a hydro-cyclone.

as received *milled*

Results					
direct analysis					
	unit	*standard*	*as received*	*dry base*	*dry & ash free*
total moisture	%	*ISO 18134*	64,2	-	-
ash content @550°C	%	*ISO 18122*	3,2	9,0	-
ash content @815°C	%	*ISO 18122*	3,0	8,4	-
volatile matter	%	*ISO 18123*	21,4	59,9	65,3
fixed carbon	%	*calculated by difference*	11,4	31,8	34,7
higher heating value (HHV)	*MJ/kg*	*ISO 18125*	8,83	24,66	26,91
lower heating value (LHV)	*MJ/kg*	*ISO 18125*	6,86	23,53	25,68

FIGURE 5: Direct analysis of green waste hydrochar obtained in the HTC lab pilot.

Considering the current pilot infrastructure, it is not possible to directly measure the real mass and energy balances of the corresponding industrial plant. Interpretations or hypotheses have been used to extrapolate them.

The two main options to achieve this objective are then as follows.

1. Considering only the analyses made on the real physical products, sampled at the HTC lab pilot inlet and outlet without any interpretation. The mass balance can be done between the raw material "as received" and the hydrochar in "dry base". There will be a small error due to the moisture (which is 0 in the dry base reference), but the most important approximation is due to the ash content because it has a significant influence on the energy content and on the boiler operation later on. Neglecting the efficiency of the particles separation system will then lead to a less attractive result:
   - Higher mass balance will lead to more transportation, larger handling system, larger boiler, etc;
   - Lower energy balance and higher ash content will lower the resulting fuel price and increase marginal transformation cost, resulting in a degraded business model, etc.
2. Estimating what could be the industrial product quality based on the operational experience of an HTC plant. This would allow to improve the mass and energy relevancy compared to 1., but the risk is to over-estimate the HTC product quality conducting to a too optimistic business model. Indeed, while assuming a different final moisture is not that risky, the particles separation system will not simply reduce linearly the ash content but impact mostly the heavy and unbounded minerals concentrations (SiO_2 and Al_2O_3).

Obviously, the ideal solution would be to perform the assessment directly on an industrial HTC plant including the entire post-treatment. However, the fresh material required for such a test would be 10 tonnes (depending on the moisture), which is difficult to manage at the prefeasibility stage. Moreover, when different feedstock types or when a combination of feedstock types needs to be tested, the time and cost of such qualification tests become prohibitive. Nevertheless, this has in the meanwhile been considered at a later stage, when project perspectives are confirmed, to validate the project business model on a larger industrial testing facility, like the one available in Náquera, Spain with Ingelia company (HTC process owner).

Considering the purpose of these tests in our field activity, the second approach (simulating an industrial HTC plant on the basis of the hydrochar obtained at the outlet of the HTC lab pilot) is the preferred option. Estimate the efficiency of the particles separation will be continuously improved thanks to the return of experience.

So, from the abovementioned discussion, a methodology has been built to assess the HTC process on different input materials.

1. In any case, the material quality cannot be higher than the "dry ash free" reference. This seems obvious but it gives an easy and direct asymptote when post-treatment is discussed. This remains also valid when further chemical treatment to improve quality is envisaged.
2. The reference material at the HTC process inlet is always the raw material as received because this is the one that must be handled and processed.
3. The moisture of the final product is always considered at 6% corresponding to the average moisture in resulting black pellets. This low moisture is very important for logistics but higher moisture could be considered when the fuel is fired locally.
4. Only the default post-treatment path is considered, including hydro-cyclone and spiral separator only. Its efficiency has been established by Ingelia to 80% in the removal of unbounded minerals measured in the ash analysis of the hydrochar i.e. alumino-silicates SiO_2 and Al_2O_3. This efficiency was set on the basis of the experience of the equipment providers and Ingelia.
5. Clean water recirculation in the process is considered to avoid recirculation of chlorine and alkali that would lead to a higher concentration in the final product.

In the following, this extrapolation of the industrial product quality from the pilot quality will be identified as "industrial properties".

The elemental ash are re-estimated considering the new normalised values and their weighted average.

All formulas used to compute the parameters of the different sample types (dry, dry ash free, as received, industrial quality, industrial dry quality) are described as follows.

$$A_{moist} = A_{dry} * (1 - MC_{new})$$

$$A_{moist,changed\ ash} = A_{dry} * \ (1 - MC_{new}) * \left(\frac{1 - AC_{new}}{1 - AC_{old}}\right)$$

$$AC_{new} = AC_{old} * (1 - MC_{new}) * \alpha$$

$$\alpha = \frac{\sum ash\ elements\ in\ \%\ ash\ @815\ as\ oxides\ in\ new\ sample}{\sum ash\ elements\ in\ \%\ ash\ @815\ as\ oxides\ in\ old\ sample}$$

$$H/C_{atomic} = \frac{H\ content}{C\ content} * \frac{atomic\ weight\ C}{atomic\ weight\ H}$$

$$O/C_{atomic} = \frac{O\ content}{C\ content} * \frac{atomic\ weight\ C}{atomic\ weight\ O}$$

$$B_{fuel} = B_{ash@815\ as\ oxides} * \ AC$$

with

- A_{dry} being any parameter coming from the direct or the elemental analysis (but not from the analysis of the major elements in the ash), in a "dry" sample (moisture content equal to zero);
- A_{moist} being any parameter coming from the direct or the elemental analysis (but not from the analysis of the major elements in the ash), in a "moist" sample (any sample with a moisture content different from zero);
- $A_{moist,changed\ ash}$ being any parameter coming from the direct or the elemental analysis (but not from the analysis of the major elements in the ash), in a "moist" sample (any sample with a moisture content with a moisture content different from zero) where the ash composition was changed;

- MC being the moisture content, measured on the basis of ISO18134 standard;
- AC being the ash content measured at 815°C like fossil coal;
- B_{fuel} being the percentage of any of the major elements in the ash, measured at 815°C like fossil coal, and reponderated as oxides;
- $B_{ash@815\ as\ oxides}$ being the percentage of any of the major elements in the ash, measured at 815°C, and reponderated as oxides;
- Atomic weight C = 12.01, of H=1.08, of O=16.00.

Note that hypotheses 3 and 4, can always be challenged and optimised based on further experience. Indeed, when the prefeasibility study with the HTC lab pilot confirms the interest of a specific fuel supply chain, it is recommended to confirm it by a test on an industrial plant (in continuous operation mode as available with Ingelia) including the complete post-treatment. This real scale test also allows to measure the OPEX of the plant and to confirm the preliminary business model. In parallel, the efficiency of the particles separator can also be measured and the hypothesis on its efficiency will be improved for each project.

3.2.1 Presentation of the test results and interpretation

Giving the wide diversity of material that can be treated by HTC and the potential process effect on the specific elemental composition that may also vary for a same feedstock coming from different locations, both the presentation and the interpretation of an HTC test results are not easy.

Moreover, a certain level of discussion will remain depending on the material tested. Indeed, it will always be easier to make results interpretations on well-known and simple feedstock (fresh wood for instance) when similar tests results are available and can be compared. Inversely, interpretations of tests are less straightforward when the feedstock is tested for the first time, and with no repetition of the test on this feedstock.

It was then required to build a systemic methodology to be used for every HTC test and based on our own perspective for the energy sector. In the next chapter, test results will be then always presented as follows. When required, highlight of potential error propagation in the measurement chain will be also given.

- In Table 2 mass and energy results can be found: the direct analysis, the elemental analysis (including chlorine and alkali) and the main ash composition are given for the fresh material as received and the industrial product (see Appendix). As a reminder, the industrial product is estimated considering a moisture of 6% for pellets and minerals separation system with efficiency of 80% on SiO_2 and Al_2O_3 concentration in the "dry hydrochar" that comes out of the HTC lab pilot.
- The detailed mass balance description: the global mass yield is presented: mass of the fresh material sample (measured), mass of the industrial product recovered (estimated from the mass measured at the filter press outlet).

The evolution of the elemental composition is presented on both the concentration and the absolute mass. Both views are required to understand the effect of HTC on the material. Indeed, the decrease in absolute mass causes an increase in concentration. The opposite is never possible of course as the absolute mass balance is always either zero or negative (no creation of material).

Note that for both concentration and mass balance, the elements were all compared based on their relative proportion in the fuel (and not on their proportion in the ash at 815°C), necessitating that the content of some elements (major elements in the ash) were multiplied by the corresponding ash content at 815°C in the sample.

However, in some case, a mass gain can be observed on some specific element like, for instance, iron (Fe) or others. This can be explained by different reasons depending on the element considered.

- The error propagation in the measurement chain. Indeed, when HTC has no effect on a given element, the concentration increases because of the global mass reduction but the mass of the element is constant. In the balance estimation, this brings division by very small number giving the impression of a mass gain, but this is false. In any case, a mass gain will have to be interpreted as no absolute mass variation for this specific element.
- Value obtained by difference. This is typically the case for the fixed carbon in the direct analysis or the oxygen in the elemental analysis. The reason for this is similar than previously. Difference in close number can lead to big error propagation.
- The sampling technique.

Of course, these phenomena are even more impacted by the quantity of material recovered at the filter press outlet. Therefore, the mass of the fresh material sample is key to ensure the test result quality. Indeed, using less material is better to avoid problems during the test but, on the other hand, a too low quantity will give more uncertainty on the mass balance. The biggest challenge being with very wet materials (>85% moisture) as the maximal volume in the reactor is reached with a very small amount of dry material. In this case, the test should be repeated, and the M&E balance made on the average measurement.

Van Krevelen diagram is usually used by the coal industry or solid fuel traders to evaluate their product maturity based on the atomic carbon concentration related to volatile compounds (Figure 6). It is also very appropriate to compare the hydrochar with the degree of fossilation of reference coal types anthracite, subbituminous coal and lignite.

As HTC is close from the fossile coal formation process, this diagram is well adapted to evaluate HTC process performance on a given feedstock.

Moreover, it also allows to compare different feedstock types before and after HTC or with references found in the literature.

Effects of process parameters can also be evaluated thanks to this diagram as different residence times or tem-

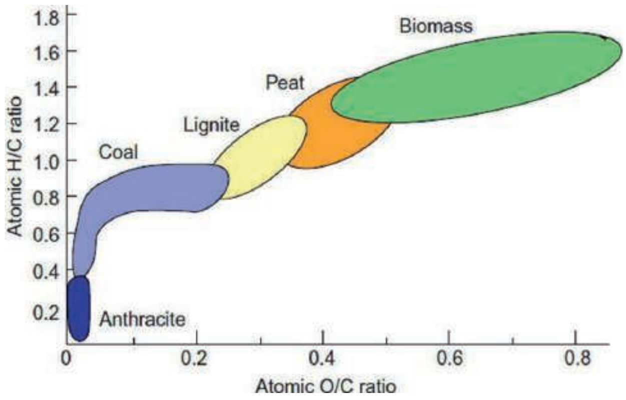

FIGURE 6: Representation of a hydro-cyclone.

perature levels will lead to a different product transformation.

The “demethanation” corresponds to a decrease in CH_4 molecules in the hydrocarbonate chain, the “dehydration” corresponds to a decrease of H_2O molecules and the “decarboxylation” corresponds to a decrease of CO_2 molecules. HTC is mainly dominated by dehydration.

LHV evolution can also be deducted from the Van Krevelen diagram. Indeed, LHV will increase when the ratio H/C increases and when ratio O/C decreases.

The change in high heating value (HHV) and low heating value (LHV) is described together in the detailed energy balance with the evolution of the ash fusion temperature or AFT (HT, hemispherical). Then, the “higher energy balance” and the “lower energy balance” are presented considering the weight of both the input raw material and the output HTC product (estimated). Both values are presented because the “high energy balance” represents the real material transformation. In contrast, the “low energy balance” represents the gain of the feedstock in market value.

It results that every material tested has its own and complete HTC identity card offering a complete overview of both technical aspects entering in the thermal asset conception and business data to evaluate the business model performances.

3.2.2 Calculation of HHV and LHV

According to ISO-18125, the gross calorific value or high heating value HHV is measured. A weighed portion of the analysis sample of the solid biofuel is burned in high-pressure oxygen in a bomb calorimeter under specified conditions. The effective heat capacity of the calorimeter is determined in calibration experiments by combustion of certified benzoic acid under similar conditions, accounted for in the certificate.

HHV is calculated from the corrected temperature rise and the effective heat capacity of the calorimeter, with allowances made for contributions from ignition energy, combustion of the fuse(s) and for thermal effects from side reactions such as the formation of nitric acid (Dashti et al., 2019). Furthermore, a correction is applied to account for the difference in energy between the aqueous sulphuric acid formed in the bomb reaction and gaseous sulphur dioxide, i.e. the required reaction product of sulphur in the biofuel. The corresponding energy effect between aqueous and gaseous hydrochloric acid can be neglected due to the usually low value for the correction regarding solid biofuels.

The net calorific value at constant pressure $q_{p,net,m}$ or low heating value LHV is calculated from the measured HHV or $q_{v,gr,d}$ with the following formula.

$$q_{p,net,m}=\{q_{v,gr,d}-212*w(H)_d-0.8*[w(O)_d+w(N)_d]\}*(1-0.01*M))*24,43*M$$

$$q_{p,net,d}*(1-0.01*M)-24.43*M$$

where

- $q_{p,net,m}$ is the net calorific value at constant pressure in joules per gram (or kJ/kg) of the biofuel with moisture content M (usually as received M_{ar});
- $q_{v,gr,d}$ is the gross calorific value at constant volume in joules per gram (or kJ/kg) of the moisture-free fuel.
- When fuel composition is affected by pretreatment, HHV can also be recalculated on the basis of the elemental composition together with the specific elemental heating values:

  $$HHV=0.3491*[C]+1.1783*[H]+0.1005*[S]-0.0151*[N]-0.1034*[O]-0.0211*Ash_{dry}$$

- But ash composition of biomass fuels must be estimated at 550°C according to ISO-18122 for biomass, in order to keep the volatiles in the ash for further detailed ash analysis e.g. by ICP. Indeed some of those volatiles like KCl play an important role in slagging and fouling generated by the combustion in a boiler. But when carbonates in ash @550°C remain significant, then the formula is no longer correct. This occurs e.g. when Ca in ash is high. In that case the following formula’s will give the best estmate:

  $$HHV=0.01*[carbonates]+0.3491*([C])-[carbonates]+1.1783*[H]+0.0151*[N]-0.1034*[O]-0.0211*A_{dry}$$

  where

  $$carbonates=(Ash_{dry@550°C}-Ash_{dry@815°C})*12.011/28$$

This shows that the contribution to the heating value is not the same when C is bounded in carbonates or elemental.

4. MASS AND ENERGY BALANCE FOR THE 15 HTC TESTS IN LAB

The mass and energy balances of the feedstock types that have been tested in the HTC lab pilot can be found in Table 1 and in Figure 7. The mass yield is the ratio between the mass hydrochar as industrial (kg) and the mass feedstock as received (kg).

It appears that:

- The main driver of the mass yield is the initial moisture content as feedstock of very different nature having similar initial moisture are in the same range.
- The energy yield is more variable depending on the feedstock characteristics.
  - Energy yield of degraded feedstock is below the average (food waste, raw compost, etc.). However, exceptions can be found when the feedstock is pollut-

TABLE 1: Mass and energy balance of the feedstock types that have been tested in the HTC lab pilot pilot.

Feedstock	Mass feedstock as received (kg)	Mass hydrochar as industrial (kg)	Mass yield	Lower Energy yield	Higher Energy yield
Bark	25	7.3	29.2%	70.8%	62.8%
Primary paper sludge	42.5	12.2	28.7%	188.2%	86.3%
Biological paper sludge	30.0	8.3	27.8%	125.3%	68.4%
Mixed paper sludge	42.5	9.3	21.9%	85.3%	60.1%
Green waste in summer	14.5	3.4	23.5%	147.5%	98.3%
Dead leaves	14.5	2.0	13.7%	104.2%	62.0%
Jelly residues	94.78	2.39	2.5%	30.5%	29.0%
Food waste	86.9	3.8	4.3%	123.9%	35.2%
Shredded root residues	13.6	5.8	42.8%	57.4%	55.4%
Raw compost	15.5	3.5	22.5%	44.2%	40.2%
Compost refusal	7.2	4.1	52.2%	82.4%	78.9%
Compost grade 20-80	10.1	5.4	53.3%	80.3%	76.1%
Aerobic sludge from potatoes industry	43.7	4.7	10.8%	346.5%	73.0%
Grey starch from potatoes industry	46.3	10.9	23.4%	319.3%	140.2%
Grey starch from potatoes industry	59.3	5.6	9.4%	345.8%	73.7%

ed with plastics (like compost 20-80 and compost refusal). Plastics being not degradable, this may explain the lower impact of the material degradation on the energy yield.

- When fresh biowaste is treated, energy yield is higher than average. This shows why it is important to treat feedstock as fresh as possible to keep as much as possible carbon and energy before degradation starts (see green waste).
- When moisture is very high (>85%) like for food waste (in this case) and jelly residue, the energy yield is very low. However, these tests should be repeated because of respectively, the material degradation initiated before the test and the very low mass yield. Small measurement errors can have big consequences.

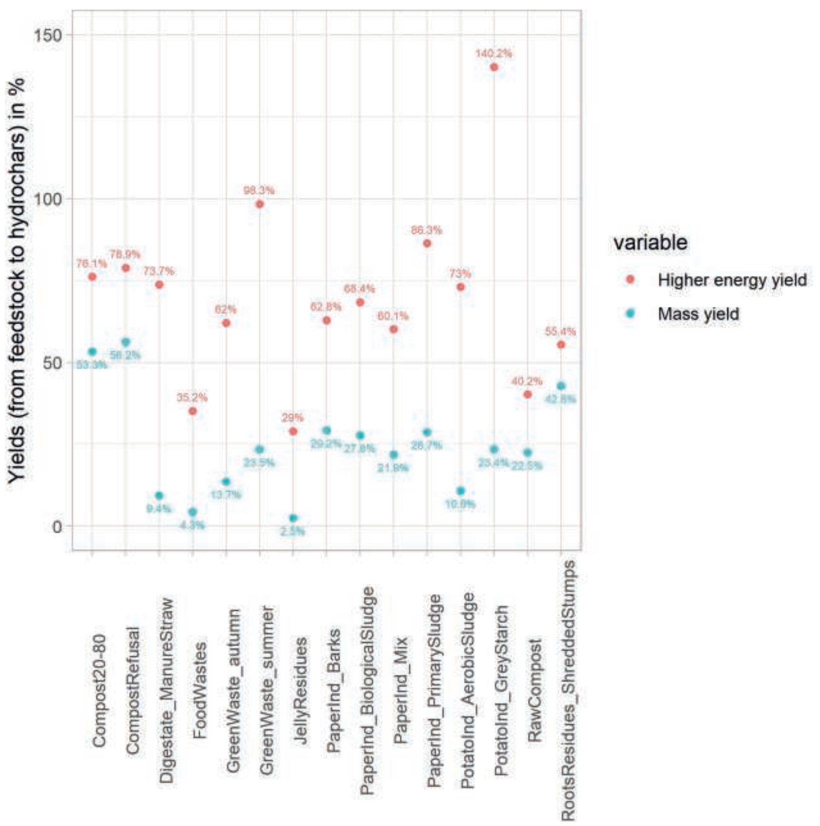

FIGURE 7: Overview of mass and energy balances for the performed HTC tests.

- In most cases, when feedstock is not already degraded or not too wet, energy yield varies from 60% to 85%, which is coherent with references found in the literature.

Energy yield on LHV is more variable and should be interpreted as product quality/value evolution through HTC with respect to the LHV and ash content achieved after transformation: As in any case HTC leads to an increase of LHV, the lower energy yield is above 100% when the initial moisture is about 70% or above. The lower energy yield of degraded material is very low (<60%). Exceptions are however, visible on degraded feedstock containing plastics. Probably because it is not degradable. The C losses are then lower.

Roots residues, jelly residues and food waste should not be considered because of either the problem met during the test or the very small mass measurement that may lead to potential errors.

Figure 8 presents every feedstock transformation on a single Van Krevelen diagram (round shape are the raw materials and square are the hydrochars).

Except very specific cases, it appears that most of hydrochars are in the lignite area i.e. O/C in the range of 0.2-0.4 and H/C in the range of 0.8-1.3.This is further illustrated in the figure showing the typical coal family area on the Van Krevelen diagram (Figure 6).

It appears that the O/C ratios of the tests are well concentrated around the average value of 0.3246 which is typical of lignite. Regarding H/C ratios, the values are more spread around the average of 1.2174. This may be explained by the main effect of HTC observed on the Van Krevelen diagram i.e., the dehydration corresponding to H_2O removal. Then, it seems that HTC has its main effect on the O/C ratio. The effect on the H/C ratio is then mainly due to the H_2O removal (2 atoms of H for 1 atom of O).

Note that this should be confirmed with more tests to increase the size of the database used for the Gauss curves (Khan et al., 2019).

Of course, dehydration is not the only transformation as it has been also observed that a small quantity of carbon is also released in the process water or as CO_2 with the COV released during the process.

HTC seems then dominated by dehydration with decarboxylation at the second order. For one specific feedstock (aerobic sludge from potatoes industry) decarboxylation was probably dominating but the reason might be the feedstock origin i.e., from lake water.

Regarding Ash Fusion Temperature (AFT), it seems that no general trend can be observed for every feedstock. However, it appears that the AFT is either constant or higher after transformation (no diminution).

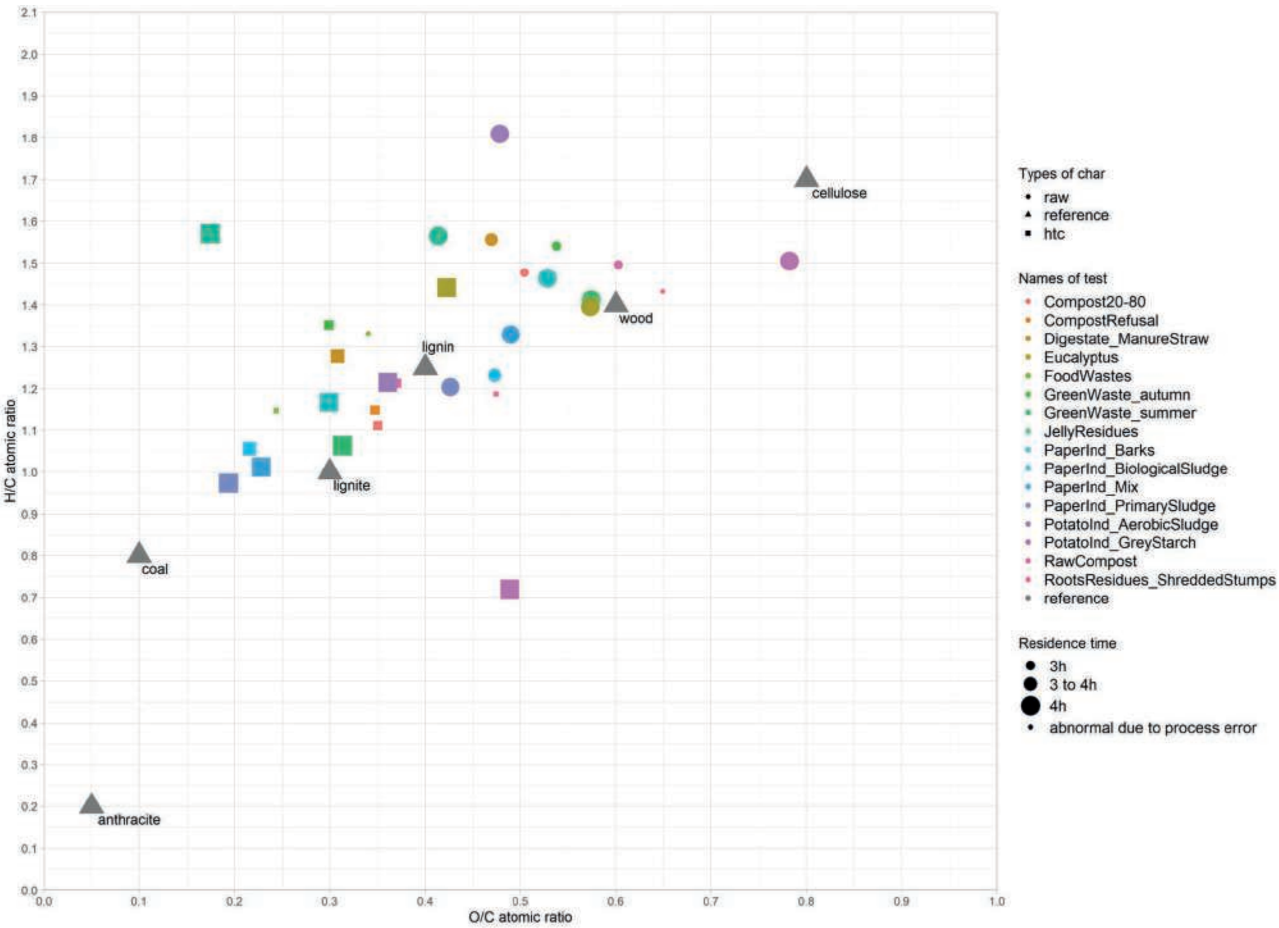

FIGURE 8: Van Krevelen diagram with all performed HTC tests.

5. CONCLUSIONS

The 15 tested feedstock types were of very different nature (Surup et al., 2020) and gave hydrochar with very different characteristics (Table 2 in Appendix). However, it is possible to observe some general trends for the HTC products obtained from every feedstock type.

- Alkalis are greatly reduced during the process, which is a positive effect considering Ash Fusion Temperature. When alkali were not decreased (see grey starch), additional test should be performed on the feedstock with the 'process water to dry matter' ratio as parameter to verify if improvement is possible.
- Cl seems always decreased during HTC process. When the decrease is smaller, the process water over dry matter ratio should also be tested to verify if improvement is feasible.
- In most cases, based on the Van Krevelen diagram, HTC is first dominated by dehydration and then by decarboxylation. Different trends have also been observed on very specific feedstock (aerobic sludge), but this may be due to the origin of the raw material i.e., earth, soft water, or marine water. Indeed, depending on the origin, the C, H, O elements have different initial ratios and might be bounded differently with, as a consequence, a different behaviour in the HTC process.

Note that all these interpretations have been confirmed in the meanwhile with additional tests to extend the database representativity and the trends reported in this report have been confirmed.

Regarding the methodology described in this paper, some adaptations are required to improve the readability of the mass balance. Indeed, in this methodology, the initial statement was to provide to future project developers a clear view of the mass and energy balances related to a specific project i.e., the ratios between the raw material and the product obtained after transformation in an industrial plant.

However, by doing so, the elemental mass balance is affected by the initial water concentration. Indeed, water remains the main compound in mass in every case as most of the feedstock tested are meant to be wet and have above 50% moisture. Then, when considered in the elemental mass balance, all other species seem very slightly affected by the HTC process and it is hard to make conclusions about the migration of certain species towards the hydrochar or the effluent. Indeed, it would have been interesting to see if some trends could be identified in this perspective to evaluate if and in which proportion every element are either bounded to the solid phase or can be leached out in the liquid phase.

For further HTC test, it is then recommended to make the elemental mass balance analysis on dry basis. This will allow to have the picture of what remains in the solid phase after HTC treatment. By definition, what is not in the solid phase will be retrieved mainly in the liquid effluent (whith typically 65-70% of the HTC output) or in the volatiles released during the process (generally 2-4% of the raw material dry mass). In this paper, this can be done by consulting tables given in every material overview. For further reporting, the elemental mass balance will be presented on a dry basis only.

Considering the mass and energy balances evaluated for every tested feedstock, the chemical composition of the feedstock plays an important role in the HTC performance as well as in the energetic conversion of its products. Therefore, it is important to examine the complete pretreatment process of the fuel including its optional posttreatment with chemicals. This can help us understanding what could be the final product quality or if some molecules are present as organics or inorganics, the latter will be easily "washed out".

RECOMMENDATIONS

Depending on the origin of the raw material, some of the parameters of the HTC process, such as:

- the residence time in the reactor,
- the process temperature,
- or the ratio of the process water and the dry matter in the reactor,

can be adapted.

It is then recommended to repeat some of the tests presented in this paper with different process conditions to optimise the HTC pretreatment.

The results obtained with the HTC lab pilot have been validated against the industrial HTC demo plant of Ingelia with success. But It is still recommended to test some of the feedstock types in such a facility. This will allow to assess the:

- the reactor size,
- the batch vs continuous process,
- the efficiency of the particles separation system for ash reduction,
- the final HTC product quality.

It would also be interesting to figure out how the quality of some hydrochar (e.g., from the paper industry) could be further improved by the implementation of chemical treatment after the process. Indeed, those kinds of post-treatment are often referenced in the literature to extract components of interest such as the phosphorus (Milotti et al., 2020). HTC is well adapted to such a process because of the liquid form of the product after treatment and before filtration, which eases chemical treatment. In particular, acid leaching aiming at reducing ash content could be further studied. Some preliminary test realised in the frame of a master thesis at LBE showed promising results in this perspective at lab scale. Further investigations could determine how to implement such a process at industrial scale and if this additional operation can be profitable i.e. the cost of operation vs the additional market value of the product (Papa et al., 2021).

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WASTEWATER TREATMENT USING BLACK SOLDIER FLY LARVAE: THEORETICAL FRAMEWORK AND PRELIMINARY TESTING FOR CONTINUOUS REACTOR DESIGN

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ABSTRACT

The use of Black Soldier Fly (BSF) larvae has recently been introduced, through the so-called LarWaR process (LARvae for WAstewater treatment and Resource recovery), as a promising alternative biological treatment for high-organic-content wastewater. LarWaR has proven effective in managing high concentrations of organic substances while recovering high-value resources in the form of larval biomass. This study summarises the state of the art of key process aspects within a theoretical design framework, highlighting the persisting research gaps. Additionally, it investigates an appropriate treatability test for designing and reliably predicting the performance of a continuous reactor treating artificial wastewater. A series of preliminary batch tests were conducted to determine the expected substrate consumption rates (v_s) — fitted using a Michaelis-Menten-like relationship — and removal efficiencies at different loads (F/L, mgC/larva/day). A continuous test was then perfomed to validate the results from the treatability batch tests. The fitted Michaelis-Menten-like model for v_s values proved to be a reliable tool for reactor design, as the steady-state performance (v_s = 0.72 mgC/larva/day; η = 36%) closely matched predictions from the treatability test (v_s = 0.86 mgC/larva/day, η = 43%). Finally, the study explored the maximum effective reactor depth (h) for the LarWaR system through video monitoring of larval behavior in deep liquid substrates. Observations revealed physical limitations restricting larval movement to the first few centimeters (3-4 cm) of the liquid surface, providing crucial insights for optimizing reactor depth. These findings contribute to improving the design methodology and scalability of the LarWaR process.

1. INTRODUCTION

1.1 State of art

Black soldier fly (BSF) larvae are conventionally used as an alternative technology for the treatment of solid biowaste, with the benefit of effectively stabilizing and metabolizing putrescible waste, converting it into valuable larval biomass.

During the larval stage – the only feeding stage — which lasts between 2 to 4 weeks under optimal conditions, the larvae can efficiently consume and metabolize a wide variety of organic wastes such as food scraps, spoiled feed, animal manure, etc. (i.a. Isibika et al., 2021).

This process results in significant volume and mass reduction of the waste — up to 70% — while converting it into nutrient-rich larval biomass. The biomass, composed of up to 48% protein and 35% fat in the prepupal stage (Gold et al., 2018), is suitable for use in animal feed or as a feedstock for industrial applications (chitin, biolubricants, proteins, etc. Surendra et al., 2020). Overall, the use of BSF larvae presents an efficient, low-cost, and eco-friendly approach to managing putrescible waste, aligning with circular economy principles by recovering high valuable resources from waste streams (Cossu et al., 2020).

Recently, the LarWaR process (Larvae for Wastewater treatment and Resource recovery) has been introduced for treating high-organic-content wastewaters as well. This process offers a highly promising alternative to conventional biological processes, with removal kinetics up to three times higher than those of the conventional aerobic processes (Grossule et al., 2021; Grossule, 2024; Grossule and Lavagnolo, 2020), while recovering high-value resources (i.e. larval biomass).

While BSF larvae have been successfully used to treat solid biowaste (Grossule et al., 2024), their application to liquid substrates is impaired by the high larval mortality. As terrestrial organisms, BSF larvae are prone to drowning in pure liquid environments. LarWaR process overcomes

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this critical issue by means of a patented solution (Italian Patent n. 102021000016700; PCT/IB2022/055888; priority 25/06/2021), consisting in the use of a porous supporting material, to be installed in the reactor and to be saturated by the treatment targeted liquid. The aim is to provide a physical support for larvae mobility allowing them to dive for eating and reemerge for breathing (Grossule and Cossu, 2021).

Several key aspects of the LarWaR process have recently been investigated with a view to optimizing the process and advancing toward the definition of reactor design and sizing. Main findings can be summarised in the following theoretical design framework.

1.2 Theoretical design framework

LarWaR reactor design and sizing involves the definition of the following key aspects (Figure 1): A) Suitability of wastewater for the LarWaR process; B) Larvae kinetics (i.e. specific substrate consumption rate; v_S, mgC/larva/day) and removal efficiencies (η, adimensional or %); C) Larval density (larvae/cm^2) and supporting material; D) Reactor volume and dimensions (surface-A; depth-h).

A) Suitability of wastewater for the LarWaR process

A wastewater can be considered suitable for LarWaR treatment process when it allows high larval development, low mortality and effective removal of organic matter, which occur under the following two conditions:

- Presence of high organic content, with concentrations exceeding the Treatment Threshold Limit (TTL), which may vary based on the quality of the liquid substrate. For example, Grossule et al. (2023) found that, in the case of their tested leachate, a TOC concentration above 2000 mgC/L was necessary to ensure optimal process performance.
- Appropriate nutritional quality of the organic substrate. Nutritional quality is related to the presence of dominant macronutrients such as proteins (P), non-fibre carbohydrates (NFC), and lipids (L), and their relative abundance (X_i, i = P, NCF or L, calculated as ratio between the single macronutrient concentration and sum of P, NCL and L). Substrates with good nutritional quality have been identified by Grossule et al. (2025), when X_L < 0.6, X_P > 0.05, and when X_P > 0.5 if X_{NFC} > 0.2. Additionally, when X_P ranges between 0.05-0.15 a good quality substrate occurs if X_{NFC} > X_L.

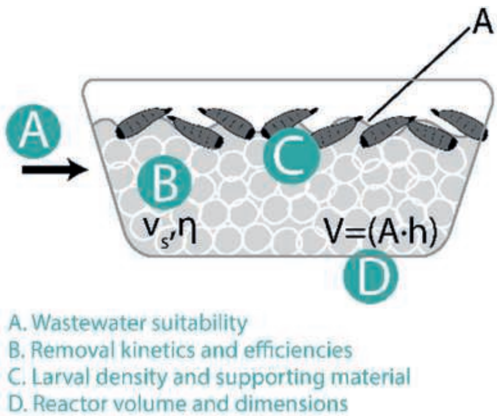

FIGURE 1: Scheme of key aspects to be defined in view of reactor design and sizing. v_s = specific substrate consumption rate (mgC/larva/day); η = removal efficiency (adim or %); V = volume (L); A = surface (cm^2); h = depth (cm).

If the wastewater meets these two conditions, it can be deemed suitable for the LarWaR process, and the design and sizing of the LarWaR reactor can proceed.

B) Process kinetics and removal efficiencies

Substrate removal kinetics, expressed by the specific substrate consumption rate (v_S, mgC/larva/day), and removal efficiency (η, adimensional or %) can be defined for a continuous reactor, using the following Equations (Equations 1 and 2):

$$v_s = \frac{Q(S_0 - S_e)}{X_0} \quad (1)$$

$$\eta = \frac{(S_0 - S_e)}{S_0} \quad (2)$$

where:
v_s = specific substrate consumption rate (mgC/larva/day)
η = removal efficiency (-)
Q = flowrate (L/d)
S_o, S_e = Influent and effluent substrate concentrations (mgC/L)
X_0 = initial number of larvae

According to Grossule et al. (2023), v_s is primary influenced by the organic load, i.e. by the Food/Larvae (F/L) ratio expressed as Total Organic Carbon (TOC) fed per larvae per day (mgC/larva/day). F/L can be expressed by combining the Equation 1 and Equation 2 as follow (Equation 3):

$$F/L = \frac{QS_o}{X_0} = \frac{QS_o}{X_0}\ \frac{(S_0 - S_e)}{(S_0 - S_e)} = \frac{v_s}{\eta} \quad (3)$$

According to the Equation 3, v_s is directly proportional to F/L, whereas η is inversely proportional.

v_s increases nonlinearly with F/L following a Michaelis-Menten like relationship (Grossule et al., 2023), which can be expressed according to Equation 4:

$$v_s = \frac{v_{s\,max} \cdot F/L}{K_s + F/L} \quad (4)$$

where:
$v_{s,max}$ = max specific substrate consumption rate (mgC/larva/day)
K_s = half saturation constant (mgC/larva)

The relationships between F/L, v_s (fitting a Michaelis-Menten like relationship) and η, is graphically illustrated in Figure 2.

The Michaelis-Menten like relationship can be defined, for a specific wastewater, by means of a treatability test, which involves performing a series of batch tests to determine v_s and η values at different F/L ratios. This relationship can be then used to design the reactor volume (as described at the point D).

C) Larval density and supporting material

Definition of optimal larval density and supporting material is crucial for the design of the LarWaR process.

According to Grossule (2024), the optimal larval density should maximize removal efficiencies without compromising survival rate (i.e. avoiding larval starvation and competition for breathing), while the optimal supporting material should maximise porosity (n=liquid volume/total reactor volume filled with supporting material=V_l/V_{tot}) without compromising the ability of larvae to move and survive.

Larval density is typically defined as surface area density (Cl_V, larvae/cm^2), rather than volumetric density (Cl_V, larvae/cm^3), for both liquid and solid substrates. This is because larval metabolism depends strongly on atmospheric oxygen, which is primarily available at the substrate-air interface on the substrate surface. Previous studies have investigated the optimum larval density for solid substrates, suggesting values between 1 and 5 larvae/cm^2 to avoid overcrowded conditions, which can slow larval development, reduce survival rates, and hinder process optimization due to feed competition (Abduh et al., 2018; Cattaneo et al., 2025; Parra Paz et al., 2015).

In contrast, under liquid substrate feeding, higher larval densities can be used without negatively affecting the process. Grossule (2024) investigated LarWaR performance under different supporting materials (plastic granules, Pall rings and geomat) featuring different porosities (35%, 75%, 92% respectively), and different superficial larval densities (4, 8, 16 and 32 larvae/cm^2). The study concluded that materials with higher porosity support greater larval densities and, consequently, higher organic loads with reduced reactor volumes. However, porosity exceeding 90% might not provide sufficient solid support to larvae. Optimum conditions were observed at a larval density of 16 larvae/cm^2 with pall rings (featuring a porosity n=75%) as supporting material.

D) Reactor volume and dimensions

In order to define the reactor volume, the hydraulic retention time (HRT, days) can be primarily calculated as follow:

$$HRT = \frac{V_l}{Q} = \frac{S_0 \cdot \eta}{Cl_A \cdot v_s} \cdot h \qquad (5)$$

where:
$V_l = n \cdot V_{tot}$ = liquid volume
$Cl_A = X_0/A$ = larval surface area density (larvae/cm^2)
A = surface area (cm^2)
h = reactor depth (cm)

From equation of HRT, liquid and total reactor volumes can be calculated as follows:

$$V_l = HRT \cdot Q = \frac{Q \cdot S_0 \cdot \eta}{Cl_A \cdot v_s} \cdot h = \frac{Q \cdot S_0}{Cl_A \cdot F\ \ L} \cdot h \qquad (6)$$

$$V_{tot} = \frac{V_l}{n}$$

In Equation 6, once the Michalis-Menten-like relationship has been determined, the design F/L can be chosen as a trade-off between maximizing loads (and minimizing volumes, as shown in Equation 5, Figure 2) and achieving acceptable removal efficiencies. Once the F/L is fixed, the only remaining parameter in Equation 6 needed to calculate the reactor volume is the reactor depth (h).

1.3 Research gaps and aims of the study

Considering the above-mentioned key aspects investigated in previous studies (Figure 1), several research gaps still persist:

A) *Suitability of wastewater for the LarWaR process*. Grossule et al. (2023) suggested a TTL of 2000 mgC/L, based on the treatment of an artificial leachate. However, this concentration limit may vary depending on the quality of the liquid substrate. Further studies are required to generalise the TTL under optimal nutritional quality of the liquid substrate.

B) *Process kinetics and removal efficiencies*. v_s values were determined for different artificial wastewaters and organic loads through batch tests, yielding variable values between 0.25 and 2.25 mgC/larva/day under substrate loads ranging from 0.1 to 2.6 mgC/larva/day (Grossule et al., 2023). However, v_s values obtained under batch conditions may be overestimated, particularly under long HRT conditions, which can facilitate parallel substrate attenuation mechanisms beyond larval metabolism, such as bacterial oxidation, adsorption, precipitation, (Grossule et al, 2023).
Appropriate treatability batch tests with suitable HRT should be established to determine the Michaelis-Menten-like relationship and validated through continuous experiments.

C) *Larval density and supporting material*. Grossule (2024) identified optimum conditions at Cl_A = 16 larvae/cm^2 with pall rings. However, Cl_A can be further optimized by investigating densities between 16 and 32 larvae/cm^2, while alternative supporting materials with porosities ranging between 75% and 90% should also be tested. Moreover, a crucial aspect regarding the supporting material remains unaddressed: it should not only provide adequate support for the larval mobility while maximizing porosity but also facilitate the effective separation of larval biomass at the end of the larval stage.

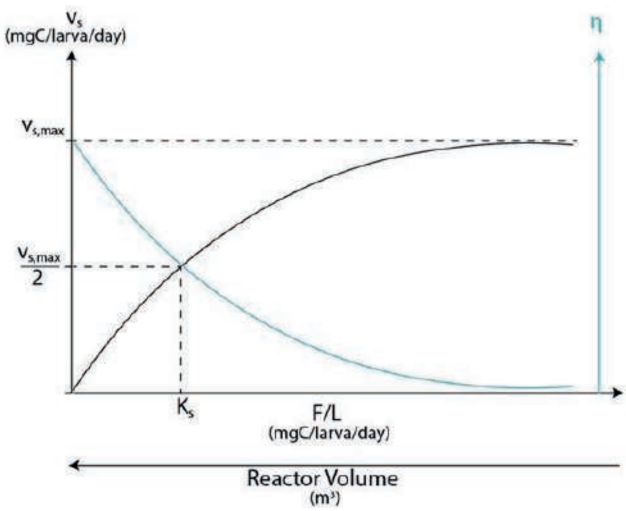

FIGURE 2: raphical illustration of the relationships between F/L, v_s (fitting a Michaelis-Menten like relationship) and η. Reactor Volume is then inversely proportional to F/L according to Equation 5.

D) *Reactor volume and dimensions*. In Equation 6, the only parameter that has been completely overlooked by research so far is the reactor depth (h), which corresponds to maximum substrate depth within which larvae can operate effectively. Some studies have investigated the effect of solid substrate depth on BSF larvae performance, concluding that larval survival and waste reduction efficiency are significantly impaired when depths exceed 5 cm (Abduh et al., 2018; Brits 2017; Dortmans et al., 2017). Greater depths may limit natural air circulation within substrate, leading to anaerobic conditions once interstitial air is depleted, which hinders larval respiration. When dealing with liquid substrates, larval respiration can only occur at the liquid-air interface, posing an even greater challenge since interstitial air within the waste mass is unavailable. However, no data are currently available regarding the maximum depth accessible to larvae under complete absence of free oxygen within liquid substrate.

Considering the abovementioned research gaps, present study conducted three tests to investigate the following issues:

- Treatability test: to determine the Michaelis-Menten-like relationship through a series of batch tests conducted under appropriately short HRT to minimize parallel substrate attenuation mechanisms.
- Continuous test: To validate the v_s and η values obtained through the preliminary treatability batch test.
- "Big Brother" test: To determine the maximum liquid substrate depth, representing the effective liquid height of the LarWaR reactor (h).

2. MATERIALS AND METHODS

2.1 Treatability test

A preliminary treatability test was performed on artificial wastewater through a series of batch tests to determine the v_s and η values at different F/L ratios, with the goal of identifying the Michaelis-Menten-like relationship (Equation 4, Figure 2).

Batch reactors consisted of plastic boxes (13.5 cm x 13.5 cm x 5.5 cm) containing young BSF larvae (6-days-old, 13 mg as average wet weight per larva) and granular plastic material (VALOX®, 2-3 mm diameter), completely saturated with artificial wastewater, which was replaced daily (HRT = 1 day) up to 10 days. The HRT was selected as a first attempt (to be validated through continuous testing), to be shorter than that of Grossule et al. (2023; ~7 days) in order to limit the possible effect of parallel substrate attenuation mechanisms and the overestimation of v_s values.

Each reactor was covered with a permeable non-woven fabric and sealed with a perforated plastic lid. The test was conducted in thermally insulated room maintained at 25-30°C with a photoperiod of 18/6 h Light/Dark.

Five F/L ratios were tested in triplicate (0.11, 0.53, 1.06, 2.65, 5.29 mgC/larva/day), adjusting the daily volume of feeding artificial wastewater (30-250mL) and larvae density (1-6 larvae/cm^2) accordingly.

Artificial wastewater was prepared according to the recipe described by Grossule et al. (2023) with the following concentrations: TOC = 3980 mgC/L, COD = 13100 mgO_2/L, BOD_5 =4489 mgO2/L, TKN =3598 mgN/L, NH_4 = 3197 mgN/L, Organic nitrogen = 401 mgN/L.

Artificial wastewater from Grossule et al. (2023) was selected, being previously tested and proven suitable for the LarWaR treatment process, characterized by a high organic content and an appropriate nutritional quality of the organic substances.

At the time of wastewater replacement, the extracted volume was measured, sampled and analysed for TOC concentration. Larvae were sampled every two days, individually weighted and returned to the box. Larval development was monitored by measuring the average larval wet weight. Wastewater treatment performance was assessed by measuring average v_s and η values. v_s values were fitted using a Michaelis-Menten like relationship (Equation 4) and compared with those obtained from longer HRT batch tests (~7 days) by Grossule et al. (2023).

2.2 Continuous test

A continuous test was performed in order to validate the v_s and η values obtained through the preliminary treatability test. The experimental setup consisted of five reactors connected in series, each composed of a plastic box (13.5 cm x 13.5 cm x 5.5 cm) containing granular plastic material (VALOX®, 2-3 mm diameter), completely saturated with 150 mL artificial wastewater. Each reactor was covered with a permeable non-woven fabric and sealed with a perforated plastic lid. A peristaltic pump continuously fed the reactors with wastewater from a starting storage tank, while effluent was collected in a final storage tank (Figure 3). 160 BSF larvae (6-days-old, 15 mg as average wet weight per larva) were placed in each reactor. The en-

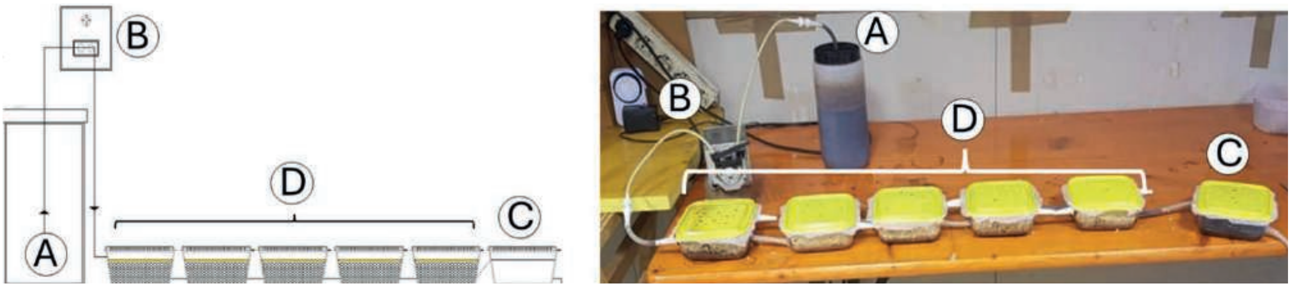

FIGURE 3: Scheme (left) and picture (right) of the test set up. A) Input wastewater storage tank; B) peristaltic pump; C) effluent wastewater collection tank; D) LarWaR reactors connected in series.

vironmental conditions and the recipe for preparing the artificial wastewater were the same as those used in the treatability test. The reactors were operated at a flow rate of Q = 0.426 L/d (HRT = 1.76 days), under a F/L = 2 mgC/larva/day, calculated using Equation 3 (S_0 = 3760 mgC/L, X_0 = 800 larvae).

Daily, fresh influent wastewater was provided and output storage tank was emptied. Approx. every 2 days, effluent wastewater was sampled and analysed for TOC concentrations and larvae were sampled and weighted to monitor the variation of the average larval wet weight.

The reactor was operated for 12 days until reaching the steady state, when TOC effluent concentrations were virtually constant.

At steady state conditions, v_s and η values were calculated using to Equations 1 and 2, respectively, and compared to expected results both from treatability test (HRT = 1 day) and Grossule et al., (2023), which were obtained from longer HRT batch tests (~7 days).

2.3 "Big brother" test

The experiment was conducted by placing 15-days old BSF larvae into glass batch reactors (10 cm in diameter and 14 cm in height) containing supporting material fully saturated with artificial wastewater at a water depth of 8 cm. Each reactor was covered by a permeable non-woven fabric to avoid oviposition by other flies but allowing air circulation.

Four larval densities were tested (2, 4, 8, and 16 larvae/cm²), using pall rings as supporting material (Grossule 2024). Larval densities were selected to investigate the potential impact of larval density on larval behaviour, remaining below the threshold density reported by Grossule (2024). Larvae behaviour was monitored for 48 hours by means of a video camera recording continuously at a frame rate of 29 fps.

The artificial wastewater was prepared by diluting low-fat milk with tap water (1:10) and served as high-quality diet to prevent any influence of poor quality diet on the results (Grossule et al., 2024).

All tests were conducted under room temperature (approx. 20°C) under continuous lighting.

Scheme of the tests and reactors set up is illustrated in Figure 4.

2.4 Analytical methods

TOC was determined using a TOC–VCSN Shimadzu Analyzer, COD and BOD5 were determined according to the standard Italian method IRSA-CNR (29/2003 vol. 2 n. 5130; 29/2003 vol. 2 n. 5120 B2). Ammonia nitrogen was measured with a distillation-titration procedure and TKN was measured through a distillation-titration procedure after an acid digestion phase. Organic nitrogen was then calculated by subtracting $N\text{-}NH_4$ from TKN.

3. RESULTS AND DISCUSSION

3.1 Treatability test

Figure 5 illustrates the variation of specific substrate consumption rates (v_s, mgC/larva/day) with F/L (mgC/larva/day) and the fitted Michaelis Menten-like relationship (Equation 4), derived from both the treatability test (under an HRT = 1 day) and Grossule et al., (2023) (under longer HRT batch tests ~7 days). The v_s values obtained by Grossule et al. (2023) were significantly higher than those from the treatability test, particularly at high F/L, demonstrating the possible impact of long HRT on the overestimation of substrate consumption rates. v_s values from both treatability test and Grossule et al. (2023) followed a Michae-

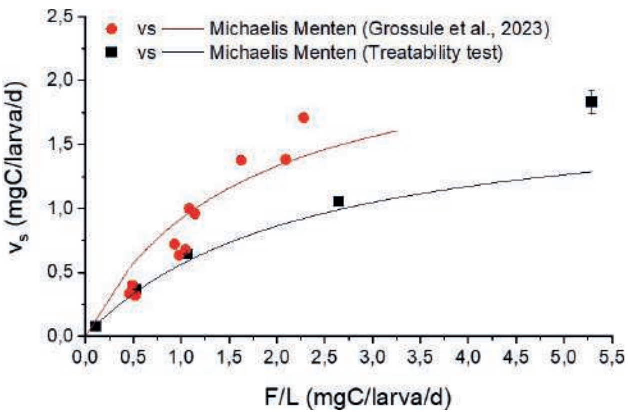

FIGURE 5: Variation of specific substrate consumption rates (v_s, mgC/larva/day) with F/L (mgC/larva/d) and the fitted Michaelis Menten-like relationship (Equation 4) obtained from both the treatability tests (under an HRT = 1 day; R^2=0.83) and from Grossule et al., (2023) (under longer HRT batch tests ~7 days, R^2=0.74).

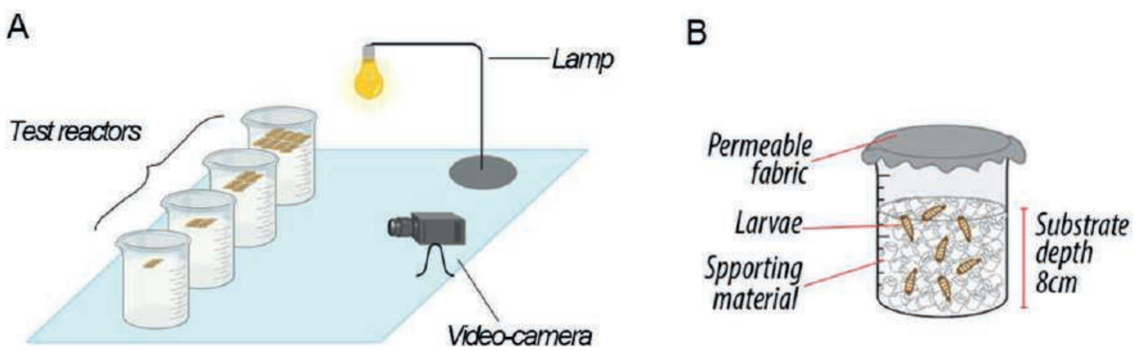

FIGURE 4: A) Scheme of tests set up for the testing of four larval densities (2, 4, 8, 16 n. larvae/cm²); B) Reactors set up (Pall rings as supporting materials; Grossule, 2024).

lis-Menten-like relationship (Equation 4), with the following parameters:

- Treatability test: $v_{s,max}$ = 1.8336, K_s = 2.2552
- Grossule et al. (2023): $v_{s,max}$ = 2.395 mgC/larva/day, K_s = 1.6mgC/larva/day

Based on these parameters, the expected v_s and η values for the continuous test (calculated with Equations 4 and 3, respectively) were:

- Treatability test: v_s = 0.86 mgC/larva/day, η = 43%
- Grossule et al. (2023): v_s = 1.33 mgC/larva/day, η = 67%

3.2 Continuous test

Figure 6 illustrates the variation over time in effluent TOC concentrations and removal efficiencies in the continuous reactor (Figure 6A), as well as the variation over time in the average larval wet weight in the five-box series of the continuous reactor (Figure 6B).

The TOC concentration dropped from 3,760 mgC/L to 2,690 mgC/L by day 6, achieving a removal efficiency of 30%. It further decreased to 2,400 mgC/L by day 12, reaching a removal efficiency of 37% at which point virtually steady-state conditions were achieved. Larval development was greater in the last box compared to the first in the series, with the maximum average larval wet weight at the end of the test reaching 96.6 mg/larva (SE 10.1) in box D1 and 51.3 mg/larva (SE 5.7) in box D5.

Figure 7 illustrate the variation of v_s (mgC/larva/day) with F/L (mgC/larva/day), including the fitted Michaelis-Menten-like relationship and the η (%) obtained from the treatability test. In the same figure, the results from the continuous test are highlighted in red. At steady-state conditions, v_s and η in continuous test were 0.72 mgC/larva/day and 36%, respectively, closely matching the values predicted by the treatability test (v_s =0.86 mgC/larva/day, η = 43%). This agreement validates the expected results and confirms the appropriateness and reliability of the treatability test, performed at shorter HRT compared to Grossule et al. (2023). In contrast, batch tests at high HRT performed by Grossule et al. (2023), being possibly affected by parallel substrate attenuation mechanisms, overestimated both v_s and η values.

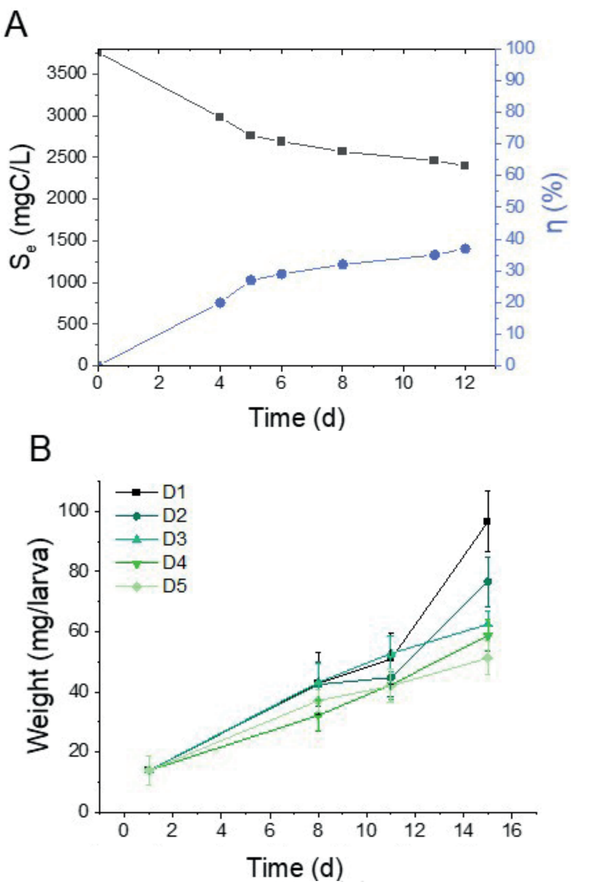

FIGURE 6: (A) Variation over time in effluent TOC concentrations and removal efficiencies in the continuous reactor. (B) Variation over time in the average larval wet weight in the five-box series of the continuous reactor.

3.3 "Big brother" test

From the video monitoring, an initial acclimation period of the larvae was observed, during which they were primarily distributed along the dry walls of the reactors, attempting to escape. The acclimation phase ended after a few hours, when larvae began to move within the liquid-solid matrix, searching for food and a dark environment, being larvae photophobic (Salam et al., 2022). From this point forward, regardless of larval density, larvae mostly remained within the top 3-4 cm of the reactor (Figure 8), although occasionally some larvae moved toward the bottom.

4. CONCLUSIONS

The definition of an appropriate treatability test for designing and reliably predicting the performance of a continuous reactor was investigated through a series of preliminary batch tests using artificial wastewater. These tests aimed to determine the expected v_s values (fitted by a Michaelis-Menten curve) and η values at different F/L ratios, which were then validated using a continuous test operated at a fixed F/L.

Treatability tests, performed through short HRT batch tests (HRT =1 day), minimized the influence of parallel sub-

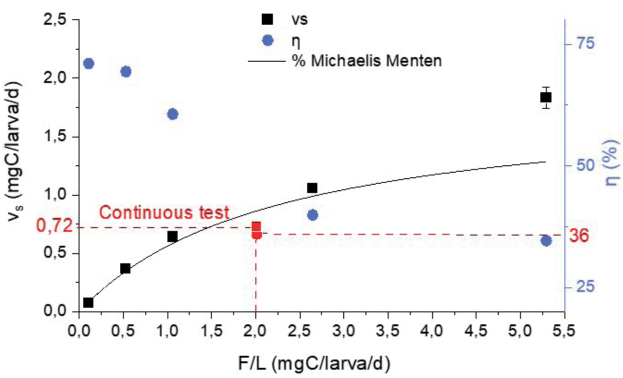

FIGURE 7: Variation of v_s (mgC/larva/day) with F/L (mgC/larva/d) (with the fitted Michaelis Menten-like relationship, R^2=0.83) and the η (%) obtained from the treatability test. In red the results from continuous test: v_s=0.72 mgC/larva/d, η= 36%.

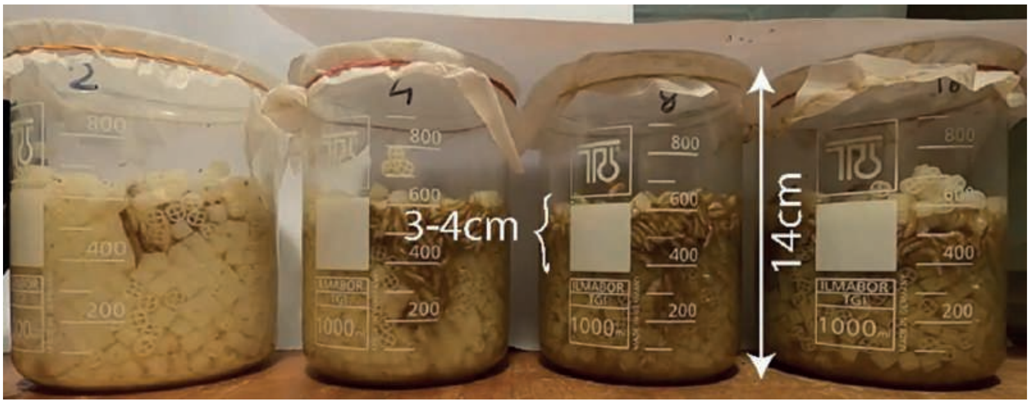

FIGURE 8: Video frame from the video monitoring of the 'Big Brother' test.

strate attenuation mechanisms and prevented the overestimation of v_s values, providing a more reliable tool to predict the performance of a continuous reactor. Consequently, the fitted Michaelis-Menten-like relationship was proven to be a reliable tool for designing and predicting the performance of the continuous reactor. At steady state conditions the reactor achieved v_s and η values closely matching those predicted by the treatability test. Additionally, the continuous reactor exhibited a startup period of just 12 days — significantly shorter than the typical startup periods required by conventional biological processes (ranging from weeks to months) (Ferraris et al., 2009; Khalili et al., 2013). The startup period may also be further reduced by using older larvae as incolum.

Video monitoring of larval behavior in deep liquid environments was conducted to investigate the maximum effective depth (h) of the LarWaR reactor. The analysis identified physical limitations to larval movement, restricting their effective activity to the first few centimeters of the liquid substrate.

By defining and validating reliable treatability tests and identifying the effective depth (h) of the LarWaR reactor, this study has contributed to improving the scalability of the LarWaR process. However, technical and operational challenges persist in scaling up the process. These challenges include:

i. Identifying the optimal support material and the most effective method for separating larval biomass at the end of the larval stage;
ii. Developing an efficient full-chain management system for larval biomass, from the provision of young larvae for inoculation to the marketability of larval biomass at the end of the process, including legal considerations;
iii. Determining the best trade-off between maximizing treatment efficiency (low loads, larger reactor volumes, and lower biomass generation) and maximizing larval biomass production (high loads, smaller reactor volumes, and lower treatment efficiency).

Future research will focus on designing and implementing a pilot-scale test on real wastewater streams, guided by the proposed design framework.

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CISA

INNOVATION IN CONSTRUCTION AND DEMOLITION WASTE SELECTION FOR THE PRODUCTION OF HIGH-QUALITY RECYCLED AGGREGATES

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ABSTRACT
Italian production of construction and demolition waste (CDW) reached about 62 million tons in 2022. Despite the high recovery rate (79.8 percent), most of the treated CDW is stored waiting to be used. In most cases, the recycled aggregates (RAs) resulting from CDW processing turn out to be of low quality and mostly destined for "low-grade" applications (road and railway pavements, civil engineering works, backfills or environmental recoveries). The use of RAs in so-called "high-grade" applications, such as concrete production, is unfortunately limited today by several factors, including the type and origin of RAs, their mechanical properties (often lower than those of natural aggregates) and the potential release of contaminants. In fact, concrete production requires an RA that has similar performance to natural aggregate. This is the main objective of the Life CDW Circle project, co-funded by the European Union and presented in this paper, which aims to achieve total recycling and use of treated CDW, thanks to an innovative sorting technology that allows the separation of different aggregate fractions (aggregates, bricks, tiles, etc.) and the production of RAs with high added value. During the experimental activities, the resulting RAs will be characterized and used for concrete production. After the experimental phase, the project partners will develop appropriate business models, creating an ecosystem with sector stakeholders. The aim of the paper is to provide an overview of CDW and RAs production and use in Italy. In addition, the new Life CDW Circle project structure and objectives will be presented.

1. INTRODUCTION

Construction and demolition waste (CDW) is the most significant special waste flow at the European level, estimated to be more than 800 million tons per year (EUROSTAT). In Italy, hazardous and non-hazardous special waste production reached about 161.5 million tons in 2022. Among these, just over 80 million tons (50 percent) are CDW and excavated soil and rocks. Excluding the latter (about 23 percent), the remaining 62 million tons consist of CDW (ISPRA, 2024).

Through the Directive 2008/98/EC, the European Union imposed, by 2020, a minimum threshold of 70 percent by weight of non-hazardous CDW to be prepared for reuse, recycling or other material recovery, including backfilling operations, to which each Member State had to comply. Depending on construction methodologies, materials used, and demolition techniques, each EU country has CDW that are more or less heterogeneous and composed of different inert fractions, which may facilitate or hinder recovery operations. Before 2020, countries with recovery rates close to 100 percent were the Netherlands (100 percent of CDW destined for recycling operations) and Malta (20 percent of CDW destined for recycling, the remainder for backfilling operations). In contrast, the countries with lower recovery rates were Bulgaria (25 percent) and Slovakia (50 percent), with the portion of non-recovered CDW destined for disposal (Damgaard, 2022). Among these, Italy appears to be one of the most virtuous countries on the European scene, with a recovery rate of about 80 percent, higher than the 70 percent value imposed by Directive 2008/98/EC (ISPRA 2024).

Although the recovery rate in Italy is quite high, most of the CDW that undergo treatment operations are stored waiting to be used. High recovery rates are therefore not indicative of high circularity in materials management. This mainly comes from the origin and nature of CDW, which are closely related to past construction practices and current demolition techniques. In particular, demolition in Italy is mostly non-selective and dependent on various factors

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such as location and organization of the site, age of the structure, construction materials used, construction type, etc. Thus, demolition occurs in a single stage, in which there is little or no distinction of the different types of materials. CDW entering the treatment plants are therefore heterogeneous, both in terms of form and composition. As a result, the recycled aggregates (RAs) leaving the treatment plants will be low-quality aggregates and not entirely suitable for use in the construction sector. In fact, nowadays, RAs are mostly used in "low-grade" applications (road construction, backfills, and environmental recovery), which still require the respect of certain properties by RAs themselves. Due to the mechanical properties of RAs, which are lower than those of natural aggregates, their use in "high-grade" applications, such as concrete production, is still very limited (Coelho & de Brito, 2011; Silva et al., 2017; Diotti et al., 2020).

In fact, companies operating in concrete production have to face several critical issues related to the use of this type of material in partial or total replacement of natural aggregates, i.e., limited availability of RAs with suitable characteristics for the given application, reduced knowledge of the real potential of the material, and lack of regulatory clarity.

Among the many limitations that affect the use of RAs for the production of concrete, one of the most important is certainly related to their low mechanical properties when compared to those of natural virgin raw materials. With a view to an economy based on circularity and a more efficient use of RAs, the Life CDW Circle project, started in November 2023, co-funded by the European Union and involving 8 partners, aims to produce RAs with high added value from CDW, through the implementation of a new and innovative treatment plant equipped with optical selection technology. Indeed, thanks to the latter, it will be possible to separate the different CDW aggregate fractions (aggregates, bricks, tiles, etc.) and produce high quality RAs suitable for concrete production.

The aim of the paper is therefore to provide an overview of the state of the art of CDW and RAs production and use in Italy. In addition, the new European Life CDW Circle project will be presented, describing its structure, objectives and expected environmental, social and economic benefits.

2. FROM CONSTRUCTION AND DEMOLITION WASTE (CDW) TO RECYCLED AGGREGATES (RAS)

2.1 Origin and merceological composition of CDW

Construction and demolition waste (CDW) come mainly from the following sectors (Reis et al., 2021; Ronchi & Nepi, 2021):

- Demolition: CDW from the demolition of the building heritage, consisting of materials heterogeneous in nature, shape and size (aggregates, bricks, ceramics, concrete, plastics, metals, etc.);
- Construction: CDW from the construction of the building heritage, consisting mostly of "clean" materials (remnants of construction materials, packaging, etc.);
- Maintenance: CDW from renovation and/or maintenance activities of the building heritage, consisting of materials similar to those obtained from demolition but with greater presence of finishing materials;
- CDW from calamitous events (earthquakes, floods, etc.).

According to data from association surveys conducted by ANPAR (National association of producers of recycled aggregates; "Associazione Nazionale Produttori Aggregati Riciclati"), 58 percent of CDW in Italy come from small demolition, renovation and/or maintenance operations of existing buildings. The remaining fraction of CDW comes from construction sites (major demolitions, 22 percent), industrial activities (16 percent) and calamitous events (4 percent) (Ronchi & Nepi, 2021).

The characteristics of CDW in terms of merceological composition and physical, chemical and environmental properties vary depending on the area considered and the construction and demolition techniques. At the local level, and in particular in Lombardy (a region located in Northern Italy) and in accordance with the elaborations of the MUD 2018 ("Modello Unico di Dichiarazione Ambientale") data, 95 percent of CDW is composed of materials classified with the following EWC ("European Waste Catalogue") codes:

- EWC 17.09.04 - "Mixed waste from construction and demolition activities, different from those listed under the codes 17.09.01, 17.09.02, 17.09.03" (about 45%);
- EWC 17.05.04 - "Soils and rocks, different from those listed under the code 17.05.03" (about 26%);
- EWC 17.03.02 - "Bituminous mixtures, different from those listed under the code 17.03.01" (about 8%);
- EWC 17.04.05 - "Iron and steel" (about 6.5 percent);
- EWC 17.01.01 - "Cement" (about 5.5%);
- EWC 17.01.07 - "Mixtures or waste of cement, bricks, tiles and ceramics, different from those listed under the code 17.01.06" (about 3.5%)
- EWC 17.05.08 - "Crushed stone for railway ballast, different from those listed under the code 17.05.07" (about 1.5%).

2.2 Demolition techniques and treatment plants

The demolition procedure must be evaluated case by case and is dependent on several factors such as location and organization of the construction site, age of the structure, materials used during construction, type of construction, size of the intervention, etc. (Silva et al., 2017). As these factors vary, the company can then choose the most congenial demolition technique, specifically:

- Non-selective demolition: it is generally developed in a single phase and there is no distinction between the different fractions that will constitute the CDW. As a result, the CDW entering the treatment and recovery plants will be characterized by strong heterogeneity, both in terms of nature and composition, and the output RAs will be of low quality;
- Selective demolition: it is developed in multiple operational phases and requires more planning and design

(site space, schedules, equipment, labor, etc.). Selective demolition thus allows for an initial sorting of the different components (concrete, paper and cardboard, wood, metals, glass, plastics, ceramics, etc.), even before the CDW enter the treatment plants. Each material is stored in special piles and then allocated to its recovery sector.

In the Italian context, non-selective demolition is unfortunately still widespread, through which very heterogeneous CDW are obtained and, consequently, less performing RAs than natural ones. It is evident how the implementation of selective demolition practices allows to separate homogeneous fractions of materials to be destined to appropriate treatment and recovery operations, increasing their level of recyclability and improving their quality (Silva et al., 2017).

At the regulatory level, the incentive for the implementation of selective demolition practices can be found in section 6-quinquies of Article 205 of Italian Legislative Decree 152/2006 (section added through Legislative Decree 116/2020, which transposes European Directive 2018/851), which states the following (in Italian): "*The Ministry of the Environment and Protection of Land and Sea promotes, after consulting with trade associations, selective demolition, in order to allow the safe removal and treatment of hazardous substances and facilitate the high-quality reuse and recycling of residues from construction and demolition activities through the selective removal of materials, as well as ensuring the establishment of construction and demolition waste selection systems at least for wood, mineral fractions (cement, bricks, tiles and ceramics, stones), metals, glass, plastic and plaster*".

Once demolition has taken place, CDWs are transferred to appropriate treatment plants, which can be divided into two macro-types: stationary plants and mobile plants.

Stationary plants are very complex plants both in terms of technology employed and management; they occupy a rather large area and are generally equipped with several crushing, sorting and screening stations, through which RAs of different grain sizes can be produced. They are powered by electricity, provide high productivity in terms of tons per year, better dust control, and the possibility of creating a local catchment area for demolition companies. On the other hand, the disadvantages include the high initial investment required to install and start up the plant and the high environmental impact values, mainly related to the transport of CDWs from the demolition site to the plant itself.

Mobile plants are generally less complex than stationary plants and have fewer processing stations (usually single crushing and screening); this leads to lower quality RAs output. These types of plants are generally diesel-powered and, compared to stationary, allow somewhat limited productivity in terms of tons per year of CDW processed. However, they can be transported and installed at demolition sites in order to carry out targeted treatment campaigns and are characterized by a lower initial investment. In addition, since the treatment plant is mobile, there is no longer a need for the transport of CDWs from the demolition site to the plant itself; this helps to reduce impacts in terms of emissions (Zhao et al., 2010, Pacheco & de Brito, 2021).

In the Lombardy region (Italy), about 86 percent of CDWs are processed in mobile plants, while the remainder (14 percent) are sent to stationary plants (Borghi et al., 2018). As a result, the RAs leaving these plants are strongly heterogeneous and have highly variable physical, chemical and performance properties.

2.3 Treatment technologies

The treatment processes for CDW to obtain recycled aggregates (RAs) are multiple and vary depending on a number of factors: nature of input materials (CDW), expected and desired quality of output materials (RAs), location of the plant, available technologies, possible presence of contamination elements in the input materials. In general, in a conventional treatment plant for CDW of average quality, the main operational steps can be summarized as follows (Silva et al., 2017, Bressi & Facchin, 2018):

Pre-treatment operations

- CDW input to the plant;
- Preliminary visual inspection of incoming CDW, with the aim of identifying any materials unsuitable for treatment;
- Weighing, acceptance and storage pending subsequent treatment steps;
- Possible manual sorting and preliminary removal of undesired or oversized materials (steel, wood, plastic, paper, glass, etc.);
- Possible preliminary crushing of larger blocks in order to obtain materials with dimensions suitable for treatment. Hydraulic breakers mounted on crawler or wheeled excavators are usually used at this stage.

Treatment operations

- Feeding CDW to the plant;
- Mechanical crushing of CDWs, generally performed by crushers (the most common are jaw, impact and gyratory crushers). The purpose of this stage is to reduce the size of the CDW in order to obtain a predetermined grain size suitable for subsequent treatment stages. Depending on the quality of the RAs to be obtained and the future applications of the same, several crushing stages can be envisaged;
- Deferrization, usually performed by means of self-cleaning magnets, the efficiency of which depends on several factors: distance between magnet and material flow, volume of material in transit, speed of the conveyor belt and angle of positioning of the magnet with respect to the belt itself. They are placed at various strategic points on conveyor belts and are used to separate metals from the rest of the material;
- Separation of the lightweight fractions (bricks, wood, plastic, paper, etc.) from the heavier aggregates by dry, wet or innovative processes;
- Screening, with the aim of performing a size selection of the different fractions, which will be stored in separate piles;
- Verification of the eco-compatibility of the different particle size fractions (usually by performing leaching

tests) and CE marking, in accordance with the relevant technical standards;
- Storage pending placing on the market.

The separation phase of undesired fractions (bricks, wood, plastics, paper, etc.) during treatment operations is crucial for obtaining good quality RAs. Separation technologies that are commercially available and already operational in treatment plants are many and differ from each other depending on the characteristics of the material to be treated (CDW), the organization and potential of the plant, and the desired quality of the output RAs. Separation processes can be divided mainly into (Schnellert & Mueller, 2010):

- Dry separation processes;
- Wet separation processes;
- Innovative separation processes.

2.3.1 Dry separation processes

In turn, dry separation processes can be divided into two different types:

- Density separation processes, which occur in air separators. Here, the separation of light fractions from heavier fractions takes place by means of an air flow that "directs" the lighter fractions into a different output canal than that used for the heavy fractions;
- Separation processes by magnetic or electronic properties, which occur through the use of magnets or electrical conductors capable of producing an electromotive force (separation by electromagnetic induction). An example is the technology using rotor equipped with magnets, which makes it possible to separate non-ferromagnetic metals (rejected by electromagnetic induction) from ferromagnetic metals (attracted by magnets) and non-conducting materials.

2.3.2 Wet separation processes

Wet separation processes take place by exploiting the density gap among the different fractions and the density of the medium used (usually water). The technology adopted varies depending on the organization of the individual treatment plant. Unlike air treatment technologies and to ensure the proper implementation of wet separation, the plant must be equipped with a water and wastewater treatment circuit in order to guarantee recirculation of process water and to limit water consumption. Compared with air separation processes, wet separation processes allow better removal of fine fractions and better control of the particle sizes of the output products, ensuring higher quality of the RAs obtained at the end of the process.

2.3.3 Innovative separation processes

The separation stage of unwanted fractions (bricks, wood, plastics, etc.) during treatment operations is crucial for obtaining good quality RAs. In fact, the aforementioned fractions have lower mechanical performance than the inert fractions and, if not properly separated, would result in reductions in the quality of the RAs exiting the treatment operations. Depending on plant organization, available technologies, and the characteristics of the incoming CDW, air or wet technologies may not be sufficient to ensure proper separation of light fractions from heavier aggregates.

In recent years, studies have focused on the possibility of introducing innovative separation technologies based on optical sorting and/or artificial intelligence (Cirelli Angulo et al., 2013, Dodampegama et al., 2023). Optical separation treatments are already widely used to treat other types of waste (e.g., plastics, glass, etc.) and recent studies have demonstrated their applicability for CDW treatment as well.

The advantages of adopting optical separation technologies are many: improved quality of the RAs exiting the treatment plant, reduction of processes after the separation stage (possible further crushing and screening), and savings in terms of water and energy use (there is no longer a need to introduce wastewater treatment and recycling circuit as for wet separation technologies). On the other hand, disadvantages include high initial investment and maintenance costs (in terms of trained personnel, sensors, databases, possible upgrades, etc.). Depending on whether the technology is more or less advanced, multiple optical sorting stations may then need to be installed to enable the separation of the different fractions, resulting in higher initial and operating costs.

2.4 Recycled Aggregates (RAs)

The treatment plants in Italy are generally equipped with "conventional" technologies, which mainly consist of mechanical crushing, deferrization, simple selection of light and undesirable fractions, and screening; as a result, the output recycled aggregates (RAs) will have rather low quality. Due to the low mechanical properties of RAs and the treatment operations that do not allow their full valorization, they are mostly used as unbound or hydraulically bound material in the road and railway sector, for bituminous mixes and surface treatments of roads and trafficked areas (82 percent) or for backfilling and environmental restoration (11.5 percent). On the other hand, only about 7.2 percent is used for concrete production, with a rather clear division between non-structural (6.8 percent) and structural (0.4 percent) concrete (Ronchi & Nepi, 2021).

As previously mentioned, RAs have lower mechanical properties than natural aggregates commonly used for concrete production. Therefore, the correct evaluation of their characteristics in terms of technical-mechanical performance is a key factor in the proper mixing of concrete with recycled materials. In fact, unlike natural aggregates, RAs consist of the original aggregate to which old cement paste remains "adhered" (in more or less quantity depending on the quality and nature of the treatment processes); due to its poor characteristics, it turns out to be the main responsible for the reduction of the RAs properties, giving the latter greater porosity and water absorption and lower density and resistance to fragmentation (Rémond et al., 2019).

In fact, the above-mentioned aggregate properties are those that most influence the characteristics of both fresh and hardened concrete. Figure 1 shows a schematization of a recycled aggregate, consisting of original aggregate, old adhered mortar and old interfacial transition zone (ITZ) between the two components. Once added to the concrete,

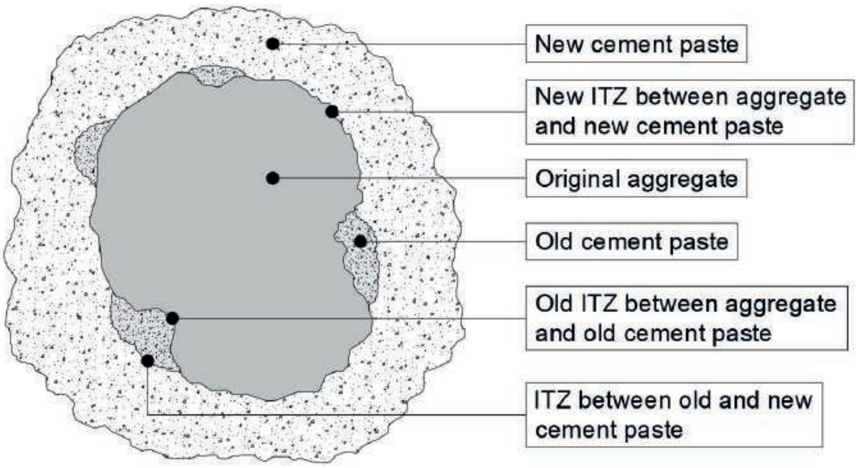

FIGURE 1: Schematization of a RA (original aggregate, old cement paste, old ITZ) once added to concrete (RA, new cement paste, new ITZs between RA and new cement paste and between old and new cement paste).

the new cement paste covers the recycled aggregate, creating a new ITZ.

However, the presence of adhered cement paste does not turn out to be the only factor responsible for the reduction of the properties of RAs; in fact, the treatment processes adopted (particularly the number of crushing steps), the aggregate grain size, the type of original material, and the strength of the parent concrete also contribute to the reduction of the mechanical properties of RAs, as compared to those of natural aggregates.

Table 1 shows the typical intervals of density, water absorption and fragmentation resistance values of RAs compared to natural aggregates (NAs) and, for each of the mentioned properties, highlights the main causes leading to its penalization (Verian et al., 2018, Piccinali et al., 2022).

It can be seen from the table that the specific gravity of RAs is lower than that of natural aggregates. Consequently, concrete produced with RAs will have a lower density than concrete produced with natural aggregates; this difference grows as the substitution percentage between NAs and RAs increases (Caggiano et al., 2012, Verian et al., 2018).

Because of the higher water absorption, great care must be taken both during mix design and during casting, carefully assessing the moisture content of the RAs used; in fact, high values of water absorption cause a faster loss of workability in concrete (Verian et al, 2018).

Finally, reduced resistance to fragmentation of RAs causes a reduction in the compressive strength of concrete (Omary et al, 2016).

3. CONCRETE MADE WITH RECYCLED AGGREGATES (RAS)

3.1 Current Italian regulations

The use of RAs as a replacement for natural aggregates in the production of concrete is provided and regulated by Italian legislation, which, in relation to type and nature of RAs and strength and exposure class of concrete, imposes limit values of substitution percentage. In addition to this, the maximum replacement percentage should also consider the availability of RAs in the area where the construction site will be located, in order to limit transportation costs and thereby reduce related environmental impacts. Table 2 summarizes the main concepts expressed by the different current regulations in Italy regarding the characterization and use of RAs for concrete production.

The Italian Structural Code (NTC 2018) provides Table 11.2.III, which shows the percentages of use of RAs al-

TABLE 1: Comparison among typical intervals of specific gravity, water absorption and resistance to fragmentation (Los Angeles) values of recycled aggregates (RAs) versus natural aggregates (NAs) and main causes leading to their penalization (Verian et al., 2018, Piccinali et al., 2022).

Property	U.M.	NAs	RAs	Causes of penalization
Specific gravity	kg/m^3	2400-2910	1910-2700	• Cement paste adhered on RAs surface • Treatment process (n. of crushing steps) • Type of original material • Strength of parent concrete
Water absorption	%	0.05-5.2	2.70-14.70	• Cement paste adhered on RAs surface • Micro-cracks on RAs surface • RAs size • Type of original material • Strength of parent concrete
Resistance to fragmentation (Los Angeles)	%	11.5-38.9	20.0-51.5	• Cement paste adhered on RAs surface • Cracked particles during treatment processes • RAs water absorption • RAs porosity

TABLE 2: Main provisions contained in current Italian regulations on the characterization and use of recycled aggregates (RAs) for concrete production.

Standard (name)	Brief description	Main provisions
Ministerial Decree January 17, 2018 (Aggiornamento delle "Norme Tecniche per le Costruzioni")	• Definition of principles for the design, execution and testing of constructions	• Suitability of aggregates from recycling processes (according to UNI EN 12620) for structural concrete production • Reference table for the use of RAs for concrete production is Tab. 11.2.III: it shows the allowed percentages in relation to concrete class and RAs origin • Corrections to the empirical formulas of some properties of concrete produced with RAs (tensile strength, elastic modulus)
UNI EN 12620 (Aggregati per calcestruzzo)	• Specification of the properties of aggregates and fillers obtained from the processing of natural, artificial or recycled materials mixed for the production of concrete complying with the requirements of EN 206-1	• Geometrical, physical and chemical requirements of aggregates • Section 5.8, Table 20: shows the constituents of coarse RAs, their description and the different classification categories in relation to the constituent and its percentage content by mass
UNI 8520-2 (Aggregati per calcestruzzo - Istruzioni complementari per l'applicazione della EN 12620 - Parte 2: Requisiti)	• Supplementary instructions for the application in Italy of UNI EN 12620 • Specification of the characteristics of aggregates and fillers, defined and classified in accordance with UNI EN 12620, destined for the manufacture of concretes	• Section 4.2: only certain types of coarse RAs (according to Table 20 of UNI EN 12620) are suitable for concrete production (according to UNI EN 206) • Possibility of using fine RAs and recycled mixes for concrete production, adopting proper precautions • Section 4.5.1, Table 2: allowable limits for fines content in aggregates of different types • Section 4.6, Table 3 (recalling section 5.5 of UNI EN 12620): allowable limits and test methods for the evaluation of density and water absorption of RAs • Table 4: allowable limits and test methodologies for the evaluation of chemical constituents of RAs • Table A.1, Code A: additional requirements and critical issues of different types of RAs
UNI EN 206 (Calcestruzzo - Specificazione, prestazione, produzione e conformità)	• Requirements for: materials, properties of concrete, limitations on concrete composition, delivery of concrete, procedures for production control, criteria and evaluation of compliance • Its application in Italy for structural concrete requires the UNI 11104, which is an integral part of the document	• Recommendations regarding coarse RAs, with diameter ≥ 4 mm • Table E.2: limits for replacement of coarse natural aggregates with coarse RAs, depending on the type of RAs (Type A or Type B) and exposure classes of concrete • Table E.3: recommendations for coarse RAs according to EN 12620 (properties, reference Paragraphs of EN 12620, type of RAs and category)
UNI 11104 (Calcestruzzo: Specificazione, prestazione, produzione e conformità – Specificazioni complementari per l'applicazione della EN 206)	• Supplementary provisions for the application in Italy of UNI EN 206 • It applies to concrete for cast-in-place structures, precast structures and precast structural components for buildings and civil engineering structures	• Use of RAs according to UNI 8520-2 and UNI EN 12620 • Table 4: maximum replacement percentages of coarse natural aggregates with coarse RAs according to the type of RAs (Type A or Type B), strength class and exposure class of concrete

lowed in relation to the concrete strength class and the origin of the RAs themselves. In the mentioned table, the maximum substitution percentage between natural aggregate and mixed coarse RAs (rubble) is 100%, for non-structural concrete of strength class C8/10. As the strength class increases, the allowable substitution percentage decreases and coarse RAs from demolition of concrete only is accepted. NTC 2018 also includes some corrections to the empirical formulas provided for the evaluation of tensile strength and elastic modulus of concrete.

The European Standard for aggregates (UNI EN 12620) specifies, in addition to the properties of natural aggregates, the geometric, physical and chemical requirements that RAs must meet. In Section 5.8, it provides a table in which the constituents of coarse RAs and their description are listed; this table is accompanied by Table 20, in which the different classification categories of coarse RAs are highlighted in relation to the constituents and their mass percentage content (for example, a RA classified as Rc_{90} indicates a RA in which the mass percentage content of Rc (concrete-based constituent) is greater than or equal to 90%).

The Italian Standard for aggregates (UNI 8520-2) includes supplementary instructions for the application in Italy of UNI EN 12620 and only provides for the use of certain types of coarse RAs (classified according to Table 20 of UNI EN 12620) for concrete production. RAs are classified into two types: Type A (higher performance, consisting mostly of concrete and with lower contents of other materials) and Type B (lower performance, consisting of concrete and other lighter masonry- and bituminous-based materials, glass, etc.). The standard also prescribes the possibility of using fine RAs and recycled mixes for concrete production, but only by taking appropriate precautions.

The European Standard for concrete (UNI EN 206) provides recommendations for coarse RAs with diameters larger than 4 mm. Table E.2 shows the limits for the replacement of natural coarse aggregates with coarse RAs in relation to their type (Type A or Type B) and the exposure class of concrete; for more "severe" exposure classes, the allowable replacement percentages decrease, up to a maximum of 30% for Type A RAs and 20% for Type B RAs, reaching a maximum of 50% for exposure class X0 (for both types of RAs. On the other hand, Table E.3 gives some recommendations regarding the properties of coarse RAs, according to EN 12620 (fines content, resistance to fragmentation, bulk density, water absorption, constituents, content of water-soluble sulfates and acid-soluble chloride ions, etc.) and shows the reference paragraphs of EN 12620, the type of RAs (A or B) and the category.

The Italian Standard for concrete (UNI 11104) considers the established practice of concrete use in Italy and is the national application document of UNI EN 206, previously described. Table 4 of UNI 11104 provides maximum replacement percentages of coarse natural aggregates with coarse Ras, depending on the type of RAs (Type A or Type B), strength class and exposure class of concrete. Type B RAs, which are less performing, can only be used in non-structural concrete with strength class C8/10 and in maximum replacement percentage up to 100%. For higher strength classes, the only coarse RAs allowed are Type A, with maximum replacement percentages up to 60% for exposure class X0 and strength class between C12/15 and C20/25. As the strength class increases and for more "severe" exposure classes, the maximum allowable replacement percentages decrease, reaching values of 20% and 30%.

Finally, it is worth mentioning the recent publication of the new Ministerial Decree June 28, 2024, n. 127 (so-called "End of Waste inert waste from CDW" Decree). The latter does not specifically deal with the use of RAs for concrete production, but establishes specific criteria according to which inert waste from construction and demolition activities and others of mineral origin, subjected to recovery operations, cease to be qualified as waste, according to Article 184-ter of Legislative Decree 152/2006. Specifically, in its 9 Articles and 3 Annexes, in addition to recalling the criteria for the End of Waste status, the present Ministerial Decree establishes:

- The categories of waste eligible for the production of RAs, recalling them by EWC codes of the European Waste Catalogue (Annex 1, paragraph (a), Table 1);
- The inspections to be carried out by the treatment and recovery plant operator on incoming waste (Annex 1, paragraph (b));
- The "minimum" treatment process and storage and handling arrangements (Annex 1, paragraph (c));
- The quality requirements of the RAs produced (Annex 1, paragraph (d)). In particular, the Decree specifies the following (paragraph (d.1), in italian): "*Per ogni lotto di aggregato recuperato prodotto è garantito il rispetto di parametri di cui alla Tabella 2 a seconda degli utilizzi cui sono destinati i lotti di aggregato recuperato prodotto previsti dall'Allegato 2 (articolo 4)*". In fact, the Decree provides a list of applications for which the produced RAs may be destined (Annex 2) and the limit concentrations of certain chemical control parameters, depending on the expected use of the batch of RAs under consideration (Annex 1, Table 2);
- The leaching test on the RAs produced (Annex 1, paragraph (d)). In particular, the Decree specifies the following (paragraph (d.2), in italian): "*Ogni lotto di aggregato recuperato prodotto deve essere sottoposto all'esecuzione del test di cessione per valutare il rispetto delle concentrazioni limite dei parametri individuati in Tabella 3. Sono esclusi dal test di cessione i lotti di aggregato recuperato prodotto destinati al confezionamento di calcestruzzi di cui alle NTC 2018 con classe di resistenza maggiore o uguale di C12/15. [...] Per la determinazione del test di cessione si applica l'appendice A alla norma Uni 10802 e la metodica prevista dalla norma UNI EN 12457-2*";
- The reference technical standards for the CE marking of RAs (Annex 1, paragraph (e) and Annex 2, Table 5), among which there is also UNI EN 12620 concerning concrete.

Thus, the "End of Waste Decree" just described is a valuable legislative tool for the regulation of the CDW recovery sector and, consequently, for the production of good-quality RAs, so as to promote their marketing and use in accordance with the principles of sustainability and circular economy.

3.2 Properties of concrete with recycled aggregates (RAs)

The properties of concrete produced with partial or total replacement of natural aggregates with RAs turn out to be greatly influenced by the characteristics of the latter. In particular, Table 3 shows the concrete properties that are most affected by the use of RAs (compared with those of concrete produced with NAs) and, in case of penalization, reports the main causes.

It can be seen from Table 3 that the characteristics and nature of RAs significantly influence the properties of the concrete produced with them.

Regarding fresh concrete, a rapid loss of workability occurs, mainly caused by the higher water absorption of RAs and the replacement rate between NAs and RAs themselves (Piccinali et al., 2022). In order to achieve the same or close to the expected workability value, the use of special admixtures (appropriately dosed and provided at the mix design stage) or the pre-saturation of RAs before casting can be adopted (Rashid et al., 2020).

Overall, concrete produced with RAs shows lower mechanical performance than that produced with NAs. As for compressive strength, the value is lower, with a greater reduction in concrete mixtures produced with RAs from concrete alone than in those produced with mixed RAs (Piccinali et al., 2022). An important parameter is certainly the water/cement ratio (w/c); in fact (Thomas et al., 2013, Thomas et al., 2018):

- For low w/c values (< 0.5 approx.), the weaker part of the concrete is represented by the interface between original aggregate and old cement paste, still possibly adhered to the surface of the RA; thus, the final strength of the concrete depends on the type of RAs used (in particular, on the nature and strength of the parent concrete);
- For high w/c values (> 0.6 approx.), the weaker part of the concrete is represented by the interface between

TABLE 3: Properties of concrete with recycled aggregates “RAs” (compared with concrete produced with natural aggregates “NAs”), causes of their possible penalization (“main causes”) and main references (“ref.”).

Property	Description	Main causes	Ref.
Workability	• Rapid loss of workability • Lower workability as the NA–RA substitution percentage increases	• Water absorption of RAs • Shape and surface area of RAs • NA-RA substitution percentage	• Rashid et al., 2020 • Piccinali et al., 2022
Density	• Lower density • Lower density as the NA–RA substitution percentage increases	• Density of RAs • NA-RA substitution percentage	• Thomas et al., 2013 • Piccinali et al., 2022
Compressive strength	• Lower compressive strength • Lower compressive strength for concretes produced with mixed(*) RAs compared to those produced with RAs from concrete only(**)	• Water absorption of RAs • Strength of original concrete • Presence of cement paste adhered to RAs surface • Water/cement ratio • RAs resistance to fragmentation • Type and quality of RAs • NA-RA substitution percentage	• Thomas et al., 2013 • Thomas et al., 2018 • Piccinali et al., 2022
Tensile strength	• Lower tensile strength • Lower tensile strength for concretes produced with mixed RAs compared to those produced with RAs from concrete only	• Presence of cement paste adhered to RAs surface • Porosity of RAs • Water/cement ratio • Type and quality of RAs • NA-RA substitution percentage	• Thomas et al., 2013 • Eckert & Oliveira, 2017 • Piccinali et al., 2022
Elastic modulus	• Lower elastic modulus • Lower elastic modulus for concretes produced with mixed RAs compared to those produced with RAs from concrete only	• NA-RA substitution percentage • Presence of cement paste adhered to RAs surface • Type and quality of RAs • Water/cement ratio	• Coppola, 1998 • Qasrawi & Marie, 2013 • Geng et al., 2019
Shrinkage	• Higher shrinkage as the NA–RA substitution percentage increases	• Presence of cement paste adhered to RAs surface • Porosity of RAs • Water/cement ratio • Type and quality of RAs • NA-RA substitution percentage	• Eckert & Oliveira, 2017 • Geng et al., 2019 • Rashid et al., 2020
Durability	• Lower resistance to chloride penetration	• NA-RA substitution percentage • Porosity of RAs • Water/cement ratio	• Qasrawi & Marie, 2013 • Yildrim et al., 2015
	• Lower resistance after freeze/thaw cycles	• Water absorption of RAs • Presence of cement paste adhered to RAs surface • Water/cement ratio	• Yildrim et al., 2015 • Guo et al., 2017
	• Higher carbonation depth • Higher carbonation rate	• Water/cement ratio • Concrete compressive strength • NA-RA substitution percentage	• Thomas et al., 2013
Environmental compatibility	• Conflicting results • RAs from concrete only lead to a significant release of total Cr (predominant presence of cement) • RAs from mixed CDW lead to a high release of sulphates (due to ceramic materials and gypsum) • No significant results in terms of contaminants release from test on monolithic concrete with RAs, thanks to the containment function of the cement matrix on RAs itself	• Type and composition of RAs • Presence of cement paste adhered to RAs surface • Size of RAs	• Diotti et al., 2020 • Diotti et al., 2021

(*) Mixed RAs: RAs composed of aggregates and other materials (ceramics, bricks, cement, etc.)
(**) RAs from concrete only: RAs composed mainly of crushed concrete

new and old cement paste, still possibly adhered to the surface of the RA; thus, the final strength of the concrete is similar regardless of the RAs nature.

Regarding tensile strength, RAs with less cement paste adhered and less porous structure provide better performance. In addition, regardless of the RAs nature, the tensile strength decreases as the w/c ratio and the replacement percentage between NAs and RAs themselves increase (Thomas et al., 2013).

Generally, higher replacement rates also lead to a decrease in the elastic modulus of concrete; this is mainly due to the presence of adhered cement paste and micro-cracks on the surface of RAs, which lead to an increase in their porosity and a decrease in mechanical properties (Geng et al., 2019, Qasrawi & Marie, 2013).

The replacement rate between NAs and RAs also influences the concrete shrinkage; in fact, the higher the replacement rate, the higher will be the shrinkage (Eckert & Oliveira, 2017, Geng et al., 2019). However, the shrinkage phenomenon can be contained by using special admixtures, properly dosed and provided during the mix design phase (Rashid et al., 2020).

Regarding the durability of concrete produced with RAs, few studies are available in the literature and provide sometimes conflicting results. A higher replacement rate between NAs and RAs leads to a lower resistance to chloride penetration, mainly due to the higher porosity of the RAs themselves. In addition, a decrease in w/c ratio may lead to a decrease in chloride penetration (Qasrawi & Marie, 2013, Yildrim et al., 2015).

After freeze-thaw cycles, the strength of concrete produced with RAs is lower than that of conventional concrete, mainly due to the higher water absorption and the presence of adhered cement paste on the surface of RAs (Guo et al., 2017).

For the same w/c ratio, the carbonation rate (expressed in mm/day$^{0.5}$) increases as the replacement rate between Nas and RAs increases. In addition, as the compressive strength increases, the carbonation rate decreases. The main factors governing carbonation rate are alkalinity (which reduces carbonation rate) and concrete permeability (Thomas et al., 2013).

Finally, with regard to environmental compatibility, the factors that most influence the release of contaminants from granular RAs are composition, size, and presence of adhered cement paste. In particular, RAs from concrete-only demolition generally exhibit rather high chromium release, due to the presence of cement, while RAs from mixed and non-selective demolition exhibit rather high sulfate release, mainly due to the presence of ceramic materials and gypsum. Once incorporated into concrete, RAs are covered by the cement paste, which operates a containment function and limits their release (Diotti et al., 2020, Diotti et al., 2021).

4. PRESENTATION AND OBJECTIVES OF THE LIFE CDW CIRCLE PROJECT

It is clear from the previous paragraphs that the possibility of using recycled aggregates (RAs) from the treatment of construction and demolition waste (CDW) for the production of concrete is subject to quite a few critical issues, mostly related to past construction and modern demolition techniques, low quality of the material coming out of treatment plants, lack of regulatory clarity, limited knowledge of the real potential of the materials considered, and absence of a competitive market that can compete with commonly used natural aggregates.

Indeed, proper and conscious use of RAs offers significant economic, environmental and social benefits: reduction in raw material consumption, improvement in waste and resource management, reduction in landfill disposal, reduction in CO_2 emissions, and protection of the landscape.

FIGURE 2: Logos of the Life CDW Circle project and the European Life program.

As already highlighted in Sections 2.3 and 2.4 of this paper, the treatment plants in Italy are equipped with "conventional" technologies, based on mechanical crushing, deferrization, screening and simple separation of light and/or unwanted fractions. The main "problem" is therefore represented by the limited possibility of separation and sorting of aggregates from other weaker fractions (bricks, ceramics, cement, etc.). In fact, the latter are mainly responsible for obtaining very heterogeneous RAs, having low physical, chemical and mechanical properties and low added value; this affects their full possibility of use for concrete production.

In light of this, it is of fundamental importance to implement and develop solutions that are able to provide RAs exiting treatment plants with added value, which is necessary to increase their competitiveness in the market and to make them suitable for use in concrete production. A better and more careful separation of inert fractions from light and undesirable fractions in the sorting step would ensure obtaining RAs with more homogeneous characteristics within the same pile and with definitely higher performance and added value; this turns out to be one of the objectives of the new Life CDW Circle project (whose logo can be seen in Figure 2), started at the beginning of November 2023 with a duration of 42 months (ending April 2027), co-funded by the European Union and consisting of 8 partners.

In fact, the project aims to design and install, at one of the coordinating partner's sites in the province of Brescia (Italy), a new-generation treatment plant that will not only be able to remove metals, plastics, wood, and contaminants from aggregates, but will also be able to sort mineral materials according to texture and color; this will be achieved through the introduction into the treatment flow of an optical sorting stage (the technology for which is provided by one of the project partners), which, through the use of sensors, will allow the sorting of different types of material, ensuring greater stability and uniformity of the individual output fractions.

In addition to the type and performance of the sorting technology, another crucial aspect that must be considered is the economic sustainability of the process, which sees a contrast between the low commercial value of today's RAs and the high installation and maintenance costs of the aforementioned technology; the added value of the output product must therefore guarantee a return on the initial investment and maintenance costs.

The high added-value RAs obtained from the new treatment plant will then undergo technical and environmental characterization in order to assess their suitability for the production of structural and nonstructural concrete.

The technical characterization will be done by evaluating the geometric, physical and chemical properties required by UNI EN 12620 (water absorption, particle and bulk density and particle size distribution). In addition to those of the aggregates, technical, physical and chemical requirements of the brick fraction obtained from the treatment process will also be evaluated, in accordance with UNI EN 13139 (aggregates for mortar).

On the other hand, the environmental suitability of the granular RAs will be assessed by performing leaching tests in accordance with UNI EN 16637-3. In addition to tests on granular aggregates, an assessment of the leaching behavior of monolithic concrete will also be carried out, in accordance with UNI EN 16637-2. Finally, ecotoxicity tests will be carried out on RAs and bricks (granular materials) and concrete (monolithic material) in order to assess possible toxic effects on the environment and human health.

Once the characteristics of high-added value RAs obtained from the innovative process have been analyzed and compared with those of natural aggregates and RAs obtained from a conventional process, C25/30 and C30/37 class concrete mixtures will be designed with the addition of the RAs. Tests will be carried out on these concrete mixtures to assess their properties in the fresh state (workability), in the hardened state (compressive strength, tensile strength, modulus of elasticity, shrinkage) and to investigate their durability (carbon dioxide penetration, chloride penetration, resistance after freeze/thaw cycles and corrosion tests on concrete reinforced with steel bars).

The concrete mixtures with RAs analyzed in this way will first be compared with mixtures produced with natural aggregates and with RAs obtained from conventional treatment processes, and then used for the production and characterization of full-scale structural elements (beams, plates, walls, etc.). The aim of this experimental phase is to evaluate the actual behavior of the produced structural elements and compare them with the same elements made from conventional concrete or concrete with low-quality RAs.

With the results obtained, it will then be possible to optimize the production process, facilitating its replicability to other plants once the project is completed.

Finally, for the entire duration of the project, local (province of Brescia) and regional (Lombardy) surveys will be carried out on the quantitative flows of CDW, their management and treatment methods, and their destination, in order to monitor the state of the art and any further developments in the sector. In addition, part of the activity will be devoted to monitoring and assessing the direct and indirect impacts of the project from the environmental and socio-economic perspectives. In fact, LCA (Life Cycle Assessment) and LCC (Life Cycle Costing) analyses will be carried out, CO_2 emissions will be assessed and monitored, and the KPI (Key Performance Indicator) database will be periodically compiled and updated, a step that is essential to monitor the real impacts of the project both during its lifetime and in subsequent years.

The environmental, social and economic benefits, highlighted above, can thus be related to the Life CDW Circle project by means of the following four macro-categories of benefits, which briefly describe the transition from the current situation (baseline) to the expected results at the end of the project:

- Reduction in raw material consumption: the Life CDW Circle project aims to produce RAs with high added value, suitable for concrete production, helping to reduce the extraction of natural aggregates from quarries;
- Improved waste management: the Life CDW Circle project aims to implement extensive recovery of construction and demolition waste (CDW), helping to reduce the amount of waste to landfill;
- Reduction of CO_2 emissions: the Life CDW Circle project aims to install an innovative treatment plant that operates with low CO_2 emissions;
- Efficient resource management: the Life CDW Circle project aims at the potential market introduction of RAs with high added value, which can be a real competitive factor and be used to replace natural raw materials.

5. CONCLUDING REMARKS

This paper provides a detailed overview of the current situation of recycled aggregates (RAs) management and use in Italy, highlighting benefits and critical issues. An analysis of the literature shows that the use of RAs as a partial replacement of natural aggregate for concrete production is possible and is also provided by current regulations, which give limit percentages depending on the type of RAs and concrete characteristics (strength and exposure). The origin, processing technologies, physical, chemical and performance properties, and possible release of contaminants by RAs are among the main factors to be analyzed and considered for their proper and conscious use for concrete production.

The Life CDW Circle project aims to address the aforementioned critical issues, which limit the use of RAs for concrete production, through the implementation of an innovative treatment plant for obtaining RAs with high added-value and an in-depth characterization of RAs themselves and of concrete produced with them. The project thus represents a novelty on the Italian scenario and aims, once concluded, to be replicable even at other plants both in Italy and abroad, so as to fully embrace the principles of circular economy and of a more conscious and responsible use of resources.

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REVISITING THE CIRCULAR MANAGEMENT OF HEALTHCARE WASTE: THE 10R CIRCULAR ECONOMY HIERARCHY

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ABSTRACT

This is a position paper to support the application of the Circular Economy (CE) hierarchy to management of healthcare waste (HCW). This hierarchy is based on the 10R typology and includes the strategies Refuse, Reduce, Resell/Reuse, Repair, Reprocess, Refurbish, Remanufacture, Repurpose, Recycle and Recover (energy). Disposal was added as a sink of residues from the CE strategies. The need for circular management of HCW using the 10R hierarchy, its comparison with other hierarchies and its relationship with a typical HCW management system are discussed. In the author's view, the 10R hierarchy proposed in this paper is best suited for circular management of HCW, but indicative risks, knowledge gaps and policy recommendations must be addressed. Implementation of the 10R CE hierarchy can accomplish (1) waste prevention, (2) medical product life extension, (3) reduction of environmental footprint, (4) significant cost savings and (5) alignment with major regulations. End-of-pipe treatment and disposal would be required for the downgraded infectious fraction of HCW.

1. INTRODUCTION

In March 2020, the European Commission published its communication "A new Circular Economy Action Plan (CEAP) for a cleaner and more competitive Europe" (EC, 2020). The CEAP is a key component of the European Green Deal, which is the EU (European Union) roadmap towards climate neutrality by 2050. The EU Green Deal is integral to the Commission's strategy to implement the United Nations (UN) 2030 Agenda and its Sustainable Development Goals (SDGs).

The policy framework of the CEAP focuses on the following thematic areas: (1) production of sustainable products, (2) transformation of industrial processes within 7 key product value chains (e.g., vehicles, packaging, buildings, etc.) to unlock economic value and create important synergies, (3) ensure less wastes and more value from using them as toxic-free secondary material, (4) making circularity work for people, cities and regions, (5) implement crosscutting actions, such as tying the Circular Economy (CE) to climate neutrality, and (6) lead efforts at global level, e.g., reach a global agreement on plastics.

Healthcare waste (HCW) exerts significant environmental footprint and its management belongs to the third thematic area listed above. However, established technologies (e.g., recycling, incineration, sanitary landfilling) are typically used and circular management is lacking (Fletcher et al., 2021). In a Waste Management Editorial, Voudrias (2018) outlined the procedure for applying the CE model for management of HCW, based on the EU waste hierarchy. The latter, however, focuses on implementation of the less damaging strategies for waste management rather than on maximizing the value of products, materials and resources in the economy (Fletcher et al., 2021). The production of sustainable products is implicitly included in the prevention strategy of the EU waste hierarchy, but more detailed strategies are needed to accomplish it. This can be done by replacing the EU waste hierarchy with the CE hierarchy, as implemented by Voudrias (2023) for management of COVID-19 HCW. Several studies dealt with circular management of HCW, e.g., Debnath et al. (2022), Fan et al. (2021), Felix et al. (2022), Ibn-Mohammed et al. (2021), Kane et al. (2018), Teymourian et al. (2021) and Wuyts et al. (2020). These and many others were cited in the review by Voudrias (2023).

This is a position paper to support the application of the CE hierarchy to management of HCW. The approach is based on the 10R typology and includes the strategies Refuse, Reduce, Resell/Reuse, Repair, Reprocess, Refurbish, Remanufacture, Repurpose, Recycle and Recover (energy), with Disposal as a sink of residues from all previous strategies (Figure 1). Unlike other R-hierarchies (e.g., 3R), the 10R strategies have the following targets: (1) The first four strategies (Refuse, Reduce, Resell/Reuse, Repair) target

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waste prevention. (2) The next four strategies (Reprocess, Refurbish, Remanufacture, Repurpose) target life extension of medical products being at the end of their lifecycle. (3) The last two R strategies (Recycle, Recover (energy)) and the Dispose strategy target reduction of environmental footprint (Figure 1). The definitions of the R-strategies are according to Reike et al. (2018). A short discussion of each R-strategy follows.

2. THE 10R STRATEGIES

2.1 Refuse (R0)

Refuse is defined as buy less, consume less, prevent waste production and refers to products and substances before they become waste. For example, buying and consuming less is accomplished when hospitals optimize and screen disposable custom packs, which are used to reduce clinical errors and cross contamination. Once opened, their contents become HCW, even if they have never been used.

To prevent waste production, hospitals can implement Life Cycle Assessment (LCA) and "environmentally preferable purchasing" of products and services, which produce less hazardous waste (article 3 of Waste Framework Directive – WFD, 2008) and improve the hospital environment for staff and patients. For example, hospitals can: (1) Offer excess supplies to other healthcare institutions before expiration date, or apply the Chemical Waste Exchange approach (Barbosa et al., 2020). (2) Substitute plastic materials, such as the swabs in test kits, with non-plastic equivalents (Abhilash and Inamdar, 2022). (3) Utilize medical products with lower contents of hazardous components, such as plasticizers, stabilizers and dyes in plastic healthcare products, which could be toxic, endocrine disruptors or carcinogens. EU requires that healthcare products containing hazardous additives at >0.1% w/w to be labelled, thus providing information to stakeholders to make a buying decision.

2.2 Reduce (R1)

Reduce is achieved by using smaller amounts of materials in product manufacturing, extending the useful life of the product before it becomes waste and decreasing unnecessary product use. Examples of materials appropriate for reduce without compromising safety are gloves and other personal protection equipment (PPE) and packaging for PPE, vaccines and test kits. Glove overuse has a negative environmental footprint and results in unnecessary cost increase, which could be avoided by implementing the reduce strategy.

2.3 Resell/Reuse (R2)

This is not a waste management operation, but refers to using again a product or component for the same purpose it was originally conceived. Many healthcare products can be designed for reuse after disinfection. These include: scalpels, surgical and isolation gowns, table covers, plastic sharps containers, vaccine vials, N95 respirators, face masks, other PPE and drapes. There are, also, disposable and single-use materials, such as single-use plastic (SUP) products, which were introduced in the healthcare industry for infection control and convenience, but their abuse resulted in excessive cost and HCW generation. To address the problem of plastic pollution in EU, starting in 2021, all SUP products for which there are reasonable alternatives were banned. However, the COVID-19 pandemic delayed and, in some circumstances, reversed the SUP ban, resulting in an overwhelming generation of masks and other PPE waste.

Although several studies on successful reuse of SUPs have been published, the viable alternative would be the development of reusable healthcare products, such as face masks and isolation gowns for healthcare personnel, because of lower overall cost and lower waste generation (review by Voudrias, 2023).

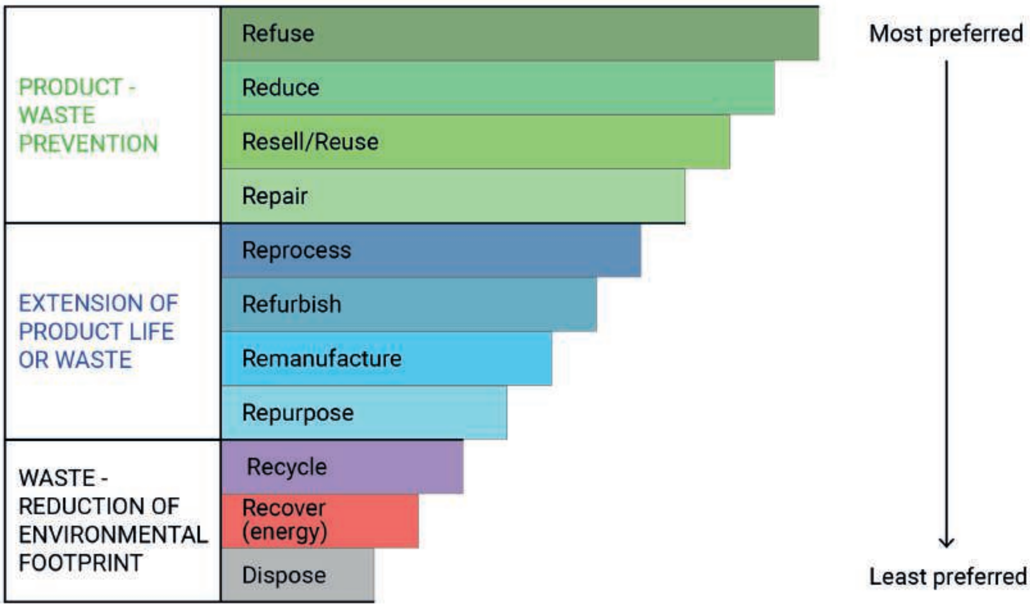

FIGURE 1: Circular economy hierarchy. Further developed based on Reike et al. (2018), Stanislaus (2019) and Voudrias (2023).

2.4 Repair (R3)

Repair is usually applied but not limited to longer-lived medical devices, such as X-ray machines, magnetic resonance imaging and computer tomography scanners, in order to extend their life, make them operate again after a malfunction or to avoid a device failure by applying a maintenance program. If not repaired, these devices would be removed from the economic system and would become HCW. In Europe and North America, repair and maintenance of medical devices is conducted by their manufacturers or specialized third-parties and represent an industry >1 billion USD.

2.5 Reprocess (R4)

Single-use devices (SUDs), such as arthroscopic shaver blades, surgical shavers, surgical staplers, hearing aids, endoscopes, catheters and manual ventilation valves, are suitable disposable devices used by healthcare organizations, instead of cleaning and sterilizing their reusable analogues. All medical devices must be adequately cleaned and sterilized following a single use, in order to prevent potential spreading of pathogens. Thus, reprocessing of SUDs refers to their recovery after repairing, cleaning, sterilizing and repackaging (review by Voudrias, 2023). Reprocessing is performed by device manufacturers or specialized third-parties, with economic savings for hospitals ranging between 40 – 60% of the price of the new device and improved environmental footprint because of diverting SUDs from sanitary landfills and incinerators.

There are two important safety issues caused by: (1) Insufficient sterilization and (2) mechanical or chemical impairment because of repeated SUD reprocessing (Kane et al., 2018). For example, deaths were caused by inadequately sterilized reprocessed endoscopes and catheters. Such problems resulted in loss of trust for reprocessed SUDs, regardless the US Government Accountability Office report stating that “available information does not indicate that use of reprocessed SUDs presents an elevated health risk” (USGAO, 2008). To solve these problems, one strategy could be to design a device for a fixed and predetermined number of reprocessing cycles, before the device becomes obsolete and is disposed of as HCW. Another strategy could be to develop “hybrid” devices with the parts entering the human body to be removable and replaceable. Addressing the safety issues may, also, restore trust for reprocessed devices among healthcare personnel and patients and maintain the economic and environmental benefits (Kane et al., 2018).

2.6 Refurbish (R5) and remanufacture (R6)

Refurbish is defined as replace modules or components in large products at the end or close to the end of their lifetimes, resulting in lower quality (shorter warranty) than the original product (review by Kane et al., 2018). Remanufacture is defined as disassemble, replace modules or components in large products at the end or close to the end of their lifetimes and reassemble, resulting in the same or greater quality than the original product (review by Kane et al., 2018). The most appropriate medical devices for these strategies are those of high value and low criticality, such as imaging equipment, anaesthesia machines, patient monitors, furniture and large surgical equipment, which do not need vigorous sterilization and should be easily accessible for cleaning and part replacement.

2.7 Repurpose (R7)

In repurposing, the original product is used for another function. Repurposing of a medical device means to make it suitable for new healthcare applications, different user cohorts and new geographical areas (Loomba, 2014). It is performed on low criticality and high value devices, such as ultrasound machines, and low criticality and low value medical products, such as face masks, gloves, other PPE. For example, an ultrasound device used in a hospital prenatal care is adapted for clinical applications, such as massage, nerve regeneration or reduction of cancer cells. Waste masks were studied for concrete manufacturing and other civil engineering applications (review by Voudrias, 2023).

2.8 Recycling (R8)

Recycling is defined as using the raw materials of waste components after separation and collection. The recycled materials do not maintain the structure characteristics of the original products and can find many other applications (Reike et al., 2018). There are two types of waste components, which can be recycled: (1) High criticality, low value components, such as syringes, catheters, endoscopes and bandages, which usually become infectious waste and must be disinfected before recycling. (2) Low criticality, low value components, such as blue wrap, IV bottles, other sterile liquid containers, glass vials, Al caps, vaccine plastic packaging, face masks and single-use compression sleeves, after separation from high criticality waste and actually becoming domestic-type waste (review by Voudrias, 2023).

There are, also, recycling barriers, which include: (1) Low cost of virgin raw materials, (2) cost increase because of disinfection for safety reasons, (3) complicated structure of recyclables, (4) legal measures forbidding recycling of hazardous components and (5) “safety-first” culture by erroneously perceiving the recyclable materials as hazardous (review by Voudrias, 2023). In terms of circular economy, the objective is to “upcycle”, i.e., convert the recovered materials into value-added engineering materials from environmental and economic point of view. For example, upcycling of face mask waste can be accomplished by: (1) carbonization to adsorbents, gas sensors, electrodes, carbon nanotubes or (2) catalytic conversion to biofuels (review by Voudrias, 2023).

2.9 Recovery of energy (R9)

HCW contains material with high calorific value, such as plastics, wood, paper and paperboard. The energy embodied in residual HCW can be captured by well-established technologies, such as: (1) incineration of HCW, (2) coprocessing of disinfected HCW components with municipal waste to produce sanitized refuse-derived fuel and (3) pyrolysis to produce syngas, oil and char (review by Voudrias, 2023).

2.10 Disposal

As explained above, the CE approach is possible to specific HCW components, with the remainder to be diverted to incineration or sanitary landfilling after disinfection. The 10R strategies described above, except "refuse" and "reduce", generate residues and waste, which require safe disposal. Similarly, the hazardous compounds of the original material tend to accumulate with recycling and potentially become a threat to human health and the environment, unless safely disposed of (review by Voudrias, 2023).

3. DISCUSSION

3.1 Why circular management of HCW?

Unlike the linear economy model, the objective of the circular HCW management is to extract the maximum value from raw materials and medical products and convert waste to resources. This will result in reduced environmental footprint, e.g., reduced waste production and greenhouse gas emissions, reduced energy consumption and cost savings, as well as in safety improvement for both patients and employees. As an example, it was estimated that a 1000-bed hospital in the USA could reduce waste by 15.5 tonnes/y if it switched to reusable sharp containers from disposable ones, with parallel cost savings of $175,000/y (Kwakye et al., 2011). According to David Lawrence, MD, former Chairman & CEO of Kaiser Permanente, "we think of environmental protection as preventive medicine on a grand scale". Nevertheless, the highest priority of a healthcare institution is to provide high quality care.

Procedures for circular management of HCW using the EU waste hierarchy and COVID-19 HCW using the 10R CE hierarchy were presented by Voudrias (2018) and Voudrias (2023), respectively.

3.2 Relationship between HCW management system and 10R hierarchy

The purpose of the HCW management system is to avoid and/or minimize waste generation and reduce its hazard properties and environmental impact, at the most cost-effective way. An indicative HCW management system consists of the following five component systems: (1) The system of HCW production, (2) the system of handling, segregation, on-site transport and temporary storage at the source, (3) the system of collection and transport out of the healthcare unit, (4) the system of treatment and (5) the system of disposal (WHO, 2014; Voudrias and Graikos, 2014).

The effectiveness of HCW management system can be assessed by waste audits, which can be used to monitor the amounts and types of HCW generation, segregation, storage, transportation, treatment and disposal. This waste composition information can be used to identify and correct wrong management practices (Voudrias, 2018). In the process of waste audit, various monitoring indicators can be used, such as: (1) Total HCW generated in kg or kg/d, (2) HCW unit production rates in kg/patient/d and kg/bed/d, (3) percentages of segregated components, e.g., % infectious or % pharmaceutical waste and (4) percentage of actually collected vs. generated waste (Kermenidou et al., 2019).

There is a two-way relationship between the HCW management system and the 10R strategies. For example, the first four strategies (Refuse, Reduce, Resell/Reuse, Repair) affect mainly the system of HCW production and implicitly all other systems of HCW management, because these are sized and costed based on the amount produced and being treated. The Recover energy strategy will affect the size and cost of treatment and disposal systems.

The system of handling, segregation, on-site transport and temporary storage at the source will involve segregation of HCW in subcategories, according to local or national regulations, for example, infectious, pharmaceutical, sharp, etc. This is a very important separation, because each of the produced subcategories will be subject to management using the appropriate R strategies. In this case, the remaining six strategies (Reprocess, Refurbish, Remanufacture, Repurpose, Recycle, Recover energy) can be used. Implementation of these strategies will obviously affect the design of collection and transport system. If source-segregation is not practiced, the total amount of HCW is considered hazardous and has to be incinerated and landfilled, thus, failing to apply circular management and implementing end-of-pipe treatment.

3.3 The need for the 10R CE hierarchy

For all practical purposes and, in this case, the management of HCW, it is important to develop a common understanding of what CE is. Although the 3R concept of "reduce, reuse, recycle" establishes a generally accepted perception of CE in theory and practice, there are circular systems with varying numbers of R strategies, such as 4R, 5R, 6R and 10R. However, there are different definitions for these strategies in the literature, indicating conflicting views among authors. Not only scientists, but also governments and international organizations use conflicting or divergent definitions. For example, EU uses 3R for "reuse, recycle, recover", whereas the UN and OECD (Organization for Economic Cooperation and Development) use 3R for "reduce, reuse, recycle" (Reike et al., 2018).

In order to provide clarity in the field, Reike et al. (2018) summarized the divergent concepts and synthesized the most common prospects on R-strategies into a single 10R systemic typology. The 10R CE hierarchy of Figure 1 is not identical with the latter, but it is based on a similar typology and defines distinct strategies significantly contributing to CE. Such strategies may need to be combined in practice, depending on the complexity of products or wastes (e.g., HCW) to be managed.

The proposed in this paper 10R categorization system may be used by public authorities, businesses, investors and financing organizations to improve their understanding of activities advancing CE and support them in selecting, financing and developing such activities, with respect to circular management of HCW. By applying the 10R hierarchy, we can achieve increasing resource efficiency and decreasing environmental footprint from HCW management.

3.4 Comparison of different CE hierarchies

The 10R CE hierarchy presented in this paper is based on the 10R typology published by Reike et al. (2018), but it is not identical. The former includes the strategies Reprocess and Dispose and lacks the strategy Remine of the latter. The Reprocess strategy is applied to SUDs, an important category of HCW, and, in the author's view, should be a distinct strategy in the 10R hierarchy for management of HCW. The Dispose strategy is necessary for management of residues generated by higher priority R-strategies. Cossu and Williams (2024) emphasized the crucial need of acceptable "Back to Earth" sinks during the global transition to a circular economy. The Remine strategy proposed by Reike et al. (2018) refers to recovering resources from old landfills, but in the case of HCW disposal, such recovery is probably not significant. Therefore, Remine is implicitly included in the Dispose strategy.

The comparison of different CE hierarchies with respect to their R-strategies is presented in Table 1. The Fan et al. (2021) hierarchy is identical to that of Reike et al. (2018), whereas the Stanislaus (2019) hierarchy is a 9R hierarchy, almost identical to that of Reike et al. (2018), but lacking the Remine strategy. In the author's opinion, the 10R hierarchy proposed in this paper is better suited than other R-hierarchies (e.g., 3R) for circular management of HCW for the following reasons:

1. It emphasizes on waste prevention, before materials become HCW (e.g., Refuse, Reduce, Reuse).
2. It emphasizes on product life extension, going beyond Reuse (e.g., Repair, Reprocess, Refurbish, Remanufacture, Repurpose). For comparison, the 3R hierarchy after Reuse would go directly to Recycle.
3. It reduces environmental impact, using the energy-intensive strategy of Recycling as the last resort. By minimizing the amount of HCW going to Recover (energy) and Dispose (sanitary landfilling), it lowers the environmental footprint of hospitals and other healthcare institutions. By comparison, in the 3R hierarchy Recycling is a major strategy, accepting significantly larger amounts of materials.
4. It provides significant cost savings through Repair, Reprocess, Refurbish, Remanufacture and Repurpose of medical devices, instead of purchasing new ones. It, also, creates new employment positions for these industries. For comparison, the 3R approach would be to Recycle after a single use or reuse.
5. It aligns with policy frameworks, such as the CEAP of the EU and WHO guidelines on HCW management.

4. FINAL REMARKS

The CEAP of EU does not specifically address HCW, but its emphasis on CE and sustainable waste management provides the legal basis that can be adopted by HC institutions to enhance circular practices and sustainability. However, adopting the CE strategy to HCW management may be subject to risks, such as: (1) Low market penetration of reprocessed SUDs, because of negative public perception, (2) presence of hazardous substances in CE products and (3) lack of economic incentives, such as tax reductions for CE products. There are knowledge gaps, which need to be addressed, for example: (1) Manufacture healthcare plastic products using one type of plastics with minimum pigment content, (2) develop technologies for separation and recycling of complex plastic healthcare products and (3) manufacture "hybrid" devices with the parts entering the human body to be replaceable. New policy initiatives are, also, necessary, for example: (1) Regulate and tax medical products with no recycling potential, (2) implement "environmentally preferable purchasing" and (3) educate and train the public in CE-related issues. In the author's view, the 10R hierarchy proposed in this paper is best suited for circular management of HCW, but the above indicative risks, knowledge gaps and policy recommendations must be addressed.

As indicated above, there are many HCW individual components, which could be managed by selecting R-strategies from the CE hierarchy and avoiding incineration and sanitary landfilling. For example, plastic materials are some of the most abundant components of HCW and persistent environmental contaminants at the global scale. Personal protective equipment (gloves, masks,

TABLE 1: Comparison of different CE hierarchies for management of HCW, with respect to their R-strategies.

This paper	Reike et al. (2018)	Fan et al. (2021)	Stanislaus (2019)
Refuse	Refuse	Refrain (Refuse)	Refuse
Reduce	Reduce	Redesign and Reduce	Reduce
Resell/Reuse	Resell/Reuse	Reuse	Reuse
Repair	Repair	Repair	Repair
Reprocess	-	-	-
Refurbish	Refurbish	Refurbish	Refurbish
Remanufacture	Remanufacture	Remanufacture	Remanufacture
Repurpose	Repurpose	Repurpose	Repurpose
Recycle	Recycle	Recycle	Recycle
Recover (energy)	Recover (energy)	Recover	Recover
Dispose	Remine	Remine	-

gowns) are plastic materials, which were accumulated in residential districts, floating in coastal waters and washed up on shores around the world during the COVID-19 pandemic. By applying circular management activities, the global persistence problem of plastics can be minimized or solved.

The purpose of the HCW management system is to avoid and/or reduce waste generation and reduce its hazard properties and environmental impact, at the most cost-effective way. Implementation of the 10R hierarchy can accomplish (1) waste prevention, (2) medical product life extension, (3) reduction of environmental footprint, (4) significant cost savings and (5) alignment with major regulations. Focusing directly on recycling does not necessarily promote CE, because recycling dismantles products to recover and use them as raw materials, instead of maintaining them in the economy. Therefore, priority should be given to other R-strategies, according to Figure 1. Furthermore, creating value from the dominant infectious fraction (containing usually unsorted contaminated with bodily fluids and downgraded materials) requires excessive amounts of energy and increased cost. To close material cycles of such materials, treatment and disposal at their end-of-life cycles would be necessary.

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DEVELOPMENT OF GOLD NANOSTARS DOPED FLEXIBLE SUBSTRATE FOR POLYSTYRENE MICROPLASTIC DETECTION USING SURFACE-ENHANCED RAMAN SCATTERING (SERS)

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ABSTRACT

Microplastics are plastic fragments smaller than 5 millimeters, originating from primary sources such as manufactured beads and fibers and secondary degradation of larger plastic materials. As a significant environmental pollutant, microplastics require sensitive and efficient detection techniques. This study presents a simple and cost-effective surface-enhanced Raman scattering method using a flexible substrate composed of gold nanostars deposited on filter paper. Polystyrene particles with an average size of approximately 0.5 μm were used as a model microplastic pollutant to evaluate the performance of the flexible substrate. The surface-enhanced Raman scattering signal enhancement was analyzed using a benchtop Raman system with a 532 nm excitation wavelength, achieving a detection limit as low as 5 μg/mL and an enhancement factor of approximately 1300. The feasibility of detecting other microplastics, including polyethylene, polypropylene and polyethylene terephthalate, was assessed. The results demonstrate that the gold nanostar-based flexible surface-enhanced Raman scattering substrate offers a highly sensitive, portable, and cost-effective alternative for real-world microplastic monitoring in aquatic environments, outperforming conventional spectroscopic techniques.

1. INTRODUCTION

Plastics have become an indispensable material in modern society due to their durability, cost-effectiveness, and versatile applications. However, their widespread use has led to the accumulation of microplastics (MPs), which are categorized into primary MPs intentionally manufactured as microbeads in cosmetics, synthetic fibers, and industrial abrasives, and secondary MPs which result from the fragmentation of larger plastic waste due to environmental factors such as UV exposure, and mechanical wear (Truong Tran Nguyen et al., 2023). MPs vary in size, shape, and chemical composition, including polystyrene (PS), polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), and polyvinyl chloride (PVC), etc.

MPs infiltrate the environment through degradation from various sources of plastic fragmentation, such as plastic products, paint, road markings, tire dust, cosmetics, and toothpastes (Ghosh et al., 2023). Once released into the aquatic environments, MPs contaminate oceans, rivers, and even drinking water, contributing to severe pollution (Ashrafy et al., 2023). Exposure to MPs has been linked to inflammation, toxicity, and bioaccumulation, raising concerns about their long-term impacts. Studies indicate that developing countries in Southeast Asia are among the largest contributors to MPs pollution (Ng et al., 2023; Pan et al., 2024; Zhao & You, 2024).

To detect MPs in aquatic ecosystems, various analytical techniques have been developed, including optical microscopy, scanning electron microscopy (SEM), transmission electron microscopy (TEM), gas chromatography/mass spectrometry (GC-MS), and Fourier-transform infrared spectroscopy (FTIR) (Dong et al., 2023; Huang et al., 2023; Randhawa, 2023). However, these methods often suffer from limitations such as low sensitivity, high sample preparation requirements, and inability to detect small-sized MPs (Y. Zhang et al., 2023). Raman spectroscopy, particularly Surface-Enhanced Raman Scattering (SERS), has emerged as a powerful alternative due to its high sensitivity, chemical specificity, and minimal sample preparation (Chakraborty et al., 2023; Mikac et al., 2023). SERS enhances Raman signals by several orders of mag-

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nitude via localized surface plasmon resonance (LSPR) in metallic nanostructures, making it suitable for detecting low concentrations of MPs (D.-Y. Lin et al., 2023; Xie et al., 2022).

Silver nanoparticles and gold nanoparticles, which have various morphologies, including nanospheres, nanorods, and nanoplates, are investigated to achieve stronger enhancement factors (EF) in SERS methods. Among these materials, gold nanostars (GNS) indicate significant improvements in Raman signal enhancement (S. Lin et al., 2019; López-Lorente, 2021). Traditionally, SERS substrates are fabricated from rigid materials such as glass and silicon; however, these substrates can be difficult to prepare due to their hydrophobic surface (Y. Zhang et al., 2023). Flexible substrates based on polydimethylsiloxane, polymethyl methacrylate, and particularly paper have received significant attention due to their low-cost, simple fabrication, ease of noble nanoparticles attachment, and compatibility with portable Raman equipment (Z. Li et al., 2020; D. Zhang et al., 2021).

In this study, we developed a flexible SERS substrate based on GNS deposited on filter paper for detecting MPs in water, focusing on polystyrene (PS) as a model MPs. Unlike conventional rigid SERS substrates (glass or silicon), our approach uses filter paper as a low-cost, flexible platform for nanoparticle deposition. By demonstrating the feasibility of GNS-based SERS detection, this study provides a method for improved real-world monitoring of MPs in environmental samples.

2. MATERIALS AND METHODS

2.1 Materials

Tetrachloroauric (III) acid ($HAuCl_4xH_2O$, ~52% Au basis), ascorbic acid ($C_6H_8O_6$, 99%), triton X-100, sodium dodecyl sulfate (SDS, 97%), trisodium citrate ($C_6H_5Na_3O_7$, 99%) and n-hexane ($CH_3(CH_2)_4CH_3$, 97%) were purchased from Sigma-Aldrich. Polystyrene powder (PS, standard sample, Mw~6.500) was from Waters. Deionized (DI) water 17.8 MΩ was used throughout the experiments. All chemical materials were GR grade.

2.2 Methods

2.2.1 Preparation of nanoparticles

Preparation of PS particles: this procedure is a modification based on a previous report (Dastbaz et al., 2021). Firstly, 0.25 g of PS powder was dissolved in 5 mL n-hexane at 50°C for 30 minutes. Subsequently, 5 mL of 0.05 M SDS was added to the mixture, which was stirred at 50°C for 60 minutes to achieve a homogeneous emulsion. Finally, the emulsion sample was placed in rotary vacuum evaporator at 50°C for 5 hours to remove n-hexane.

Preparation of gold nanostars: A mixture containing 250 µL of $HAuCl_4$ (0.01 M), 1.0 ml of aqueous 0.2 M Triton X-100 solution, 30.0 µl of $AgNO_3$ (0.01 M), and 3.75 ml DI water was stirred. Then, 250 µl of ascorbic acid (0.1 M) was added to the mixture. This mixture immediately changed from slightly yellow to colorless and cobalt, respectively, indicating formation of GNS.

2.2.2 Fabrication of flexible SERS substrates

The protocol for preparation of the flexible SERS substrate is shown in Figure 1. A 1x4 cm piece of Whatman filter paper was immersed into GNS colloidal solution in the presence of 20 mg/mL trisodium citrate (TSC) for 5 minutes. Next, the filter paper was completely dried in an oven at 37°C. The protocol has been repeated at least 10 times, resulting in the preparation of the flexible SERS substrate.

2.2.3 Characterization and SERS measurement

The spectrum of GNS was recorded using UV-Vis spectrophotometer (Jasco V-670). The micrographs of GNS and PS particles were examined by Transmission electron microscopy (Jeol-1010) and Scanning electron microscopy (Hitachi S-4800), coupled with energy-dispersive X-ray spectroscopy (EDX) for elemental analysis.

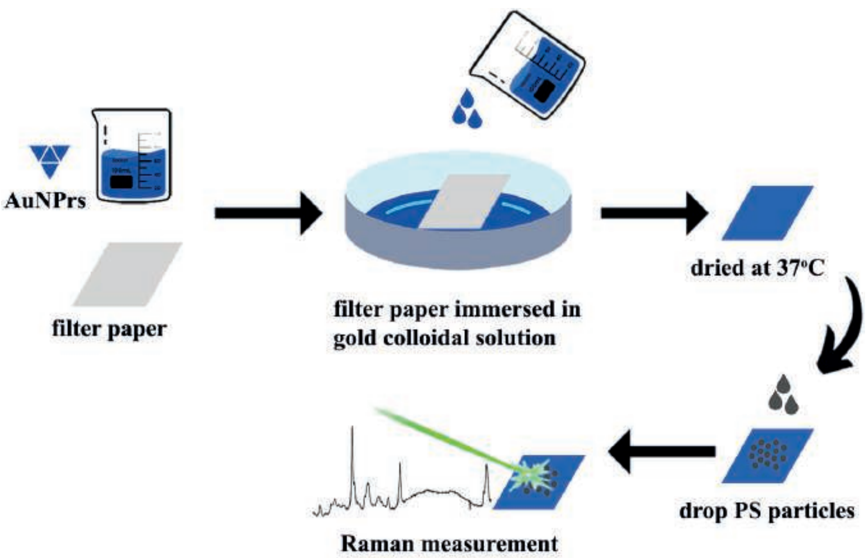

FIGURE 1: The protocol for preparation of the flexible SERS substrate.

3. RESULTS & DISCUSSION

3.1 Characterization

Figure 2 shows the characterization results of nanoparticles. Figure 2a presents the scanning electron microscopy (SEM) image of the PS particles. The image clearly shows that the PS particles are spherical in shape and have a relatively uniform size distribution, with an average particle size of approximately 0.5 µm. This is further supported by the particle size distribution histogram (Figure 2b), which indicates that most synthesized PS particles range from 350–500 nm, peaking around 400–450 nm, thus suggesting a narrow size distribution. The uniform spherical morphology of the PS particles is beneficial for several reasons. First, it ensures a consistent interaction between the PS particles and the SERS substrate, leading to more reproducible SERS measurements. Second, the size of the PS particles is environmentally relevant. Microplastics are classified into primary and secondary. Primary microplastics are those directly manufactured in that size, such as microbeads in cosmetics, while secondary microplastics result from the breakdown of larger plastic items. The 0.5 um size of the PS particles used in this study falls within the range of secondary microplastics, which are the most prevalent type found in aquatic environments, making their detection critical for assessing environmental impact (Rochman et al., 2015). Therefore, the ability of the SERS substrate to effectively detect PS particles of this size is of particular importance for environmental monitoring applications.

The optical properties of the GNS were characterized using UV-Vis spectroscopy. As shown in Figure 2c, the UV-Vis spectrum of the GNS exhibits a broad surface plasmon resonance (SPR) band centered at 635 nm, indicating that the GNS were successfully synthesized with the star-like morphology with sharp tips leading to a strong localization of the electromagnetic field at these tips, resulting in efficient SERS enhancement. The morphology of the GNS was further investigated using TEM analysis. Figure 2d shows the TEM image of the GNS, revealing that the GNS had a spherical core with a diameter of approximately 37 nm, surrounded by multiple protruding branches with an average length of 80 nm. The sharp tips of the nanostars act as "hot spots," where the electromagnetic field is greatly amplified. When the PS particles are located in close proximity to these hot spots, their Raman signals are significantly enhanced, enabling their detection at very low concentrations.

Figure 3 illustrates the analysis of the SERS substrate. The photograph of GNS (Figure 3a) attached to filter paper, where the loading of GNS is a homogeneous dark blue color, demonstrating the successful deposition of the GNS onto the substrate. The filter paper, which is a low-cost

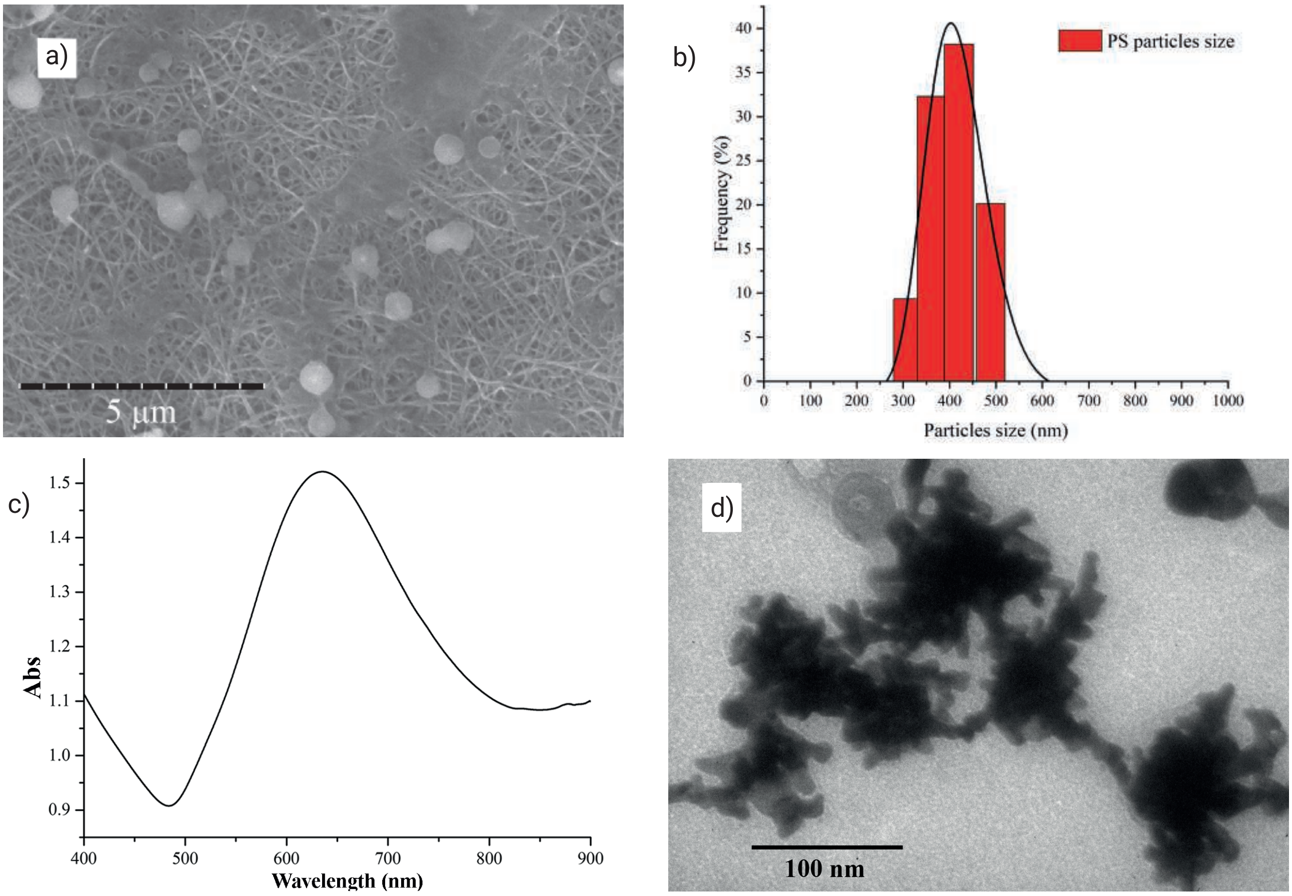

FIGURE 2: SEM image of PS particles (a); Particle size distribution of PS based on DLS (b); UV-Vis spectrum of GNS (c); TEM image of GNS (d).

and readily available material, provides a flexible and porous support for the GNS. The porosity of the filter paper allows for efficient penetration of the analyte solution, ensuring that the PS particles come into close contact with the GNS.

The distribution of the GNS on the filter paper was examined using SEM. Figures 3b and 3c show the SEM micrographs of GNS deposited on the filter paper. Figure 3b shows a low-magnification SEM image of the GNS-coated filter paper. The image reveals that the GNS are uniformly distributed on filter paper, across the entire flexible surface of the SERS substrate. This uniform distribution of the GNS is essential for achieving a consistent SERS enhancement over the entire substrate. Furthermore, the high-resolution SEM image (see Figure 3c) reveals the high density dispersion of GNS with the presence of numerous sharp tips. These sharp tips enhanced the generation of electromagnetic hot spots, leading to a significant increase in the SERS signal intensity.

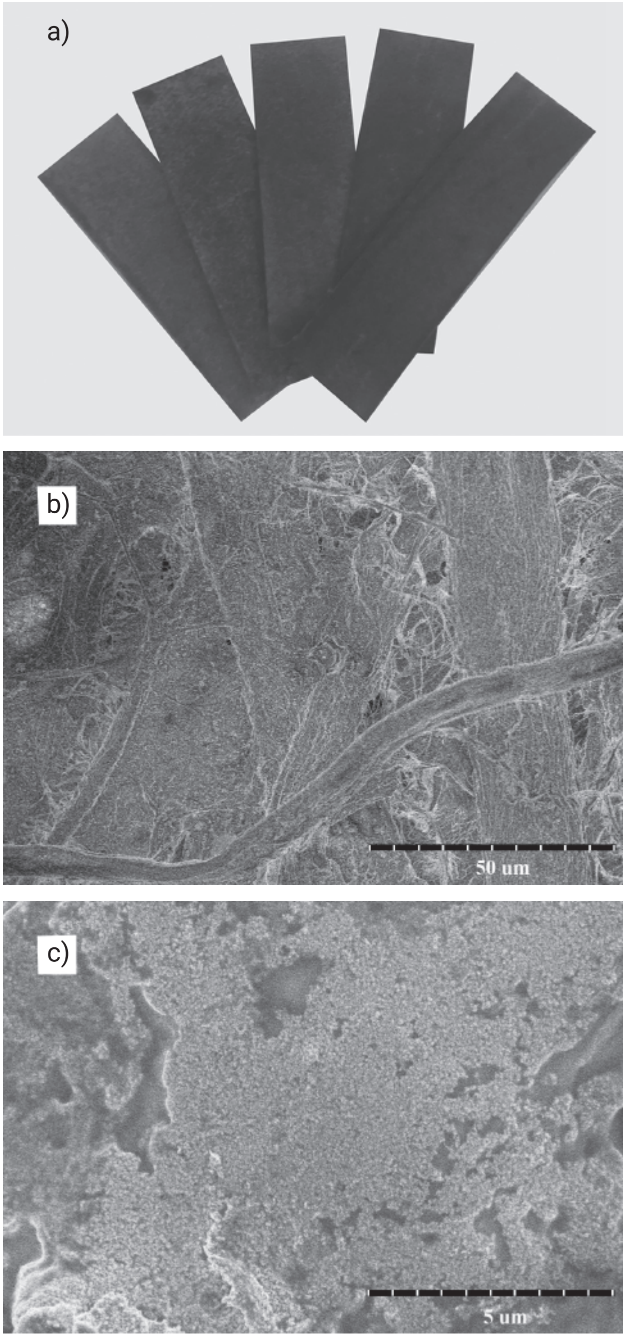

FIGURE 3: SEM image of flexible SERS substrate (a); SEM image of GNS deposited on filter paper (b); and enlarged SEM of GNS deposited on filter paper (c).

3.2 SERS performance

Figure 4 illustrates the Raman performance of polystyrene (PS) solid powder (a), normal Raman of PS particles dispersed in water at concentrations of 10 mg/mL on filter paper (b); and 200 µg/mL on a surface-enhanced Raman scattering substrate (c). In PS powder, characteristic Raman signals were identified at the following peaks: 1001 cm^{1}, corresponding to the aromatic ring C-C stretching mode; 1031 cm^{1}, attributed to C-H in-plane deformation; 1150 cm^{1}, associated with C-C stretching; 1602 cm^{1}, indicative of ring skeleton stretching; 2901 cm^{1}, related to asymmetric CH stretching; and 3051 cm^{1}, linked to aromatic CH stretching. These peaks are consistent with previously reported values for PS and serve as a spectral fingerprint for its identification (Kihara et al., 2022; Schiavi et al., 2023). The normal Raman spectra of PS particles dispersed in water at a concentration of 10 mg/mL was measured using a normal filter paper substrate. The spectrum exhibits the aromatic ring C-C stretching mode at 1001 cm^{1}, and lacked most of characteristic peaks associated with PS. In contrast, the SERS spectrum of PS particles dispersed in water at a much lower concentration of 200 µg/mL, measured using the GNS-coated flexible substrate, shows a significantly stronger signal. The peak at 1001 cm^{1} is clearly visible, and some of the other characteristic peaks of PS, such as those at 1150 cm^{1} and 1602 cm^{1}, also become apparent. This dramatic increase in signal intensity demonstrates the effectiveness of the GNS-coated flexible substrate in enhancing the Raman signal of PS particles. Consequently, the Raman peak located at 1001 cm^{-1} was selected as reference peak for the EF calculation (Xu et al., 2020).

The Raman peak at 1001 cm^{1}, corresponding to the aromatic ring C-C stretching mode, was used for the EF calculation. This peak is strong, well-defined, and consistently observed in all the spectra, making it a reliable reference for comparing the signal intensities. The EF was calculated according to the formula below, where I_{SERS} and I_{Raman} were the intensities of the normal Raman and SERS signals of the characteristic peaks as well as C_{SERS} and C_{Raman} were the concentration of PS particles dispersed in water the normal for normal Raman and SERS analytic, respectively:

$$EF = \frac{I_{SERS}}{I_{Raman}} x \frac{C_{Raman}}{C_{SERS}}$$

Figure 5 shows the "fingerprint" peaks of PS particles on SERS substrate. Various concentrations of PS particles exhibited a characteristic peak at 1001 cm^{1}, as shown in Figure 5a. The intensities corresponding to various concentrations of PS particles in water were presented in Figure 5b. The results clearly demonstrated that the intensity of the characteristic peak increased with rising concentra-

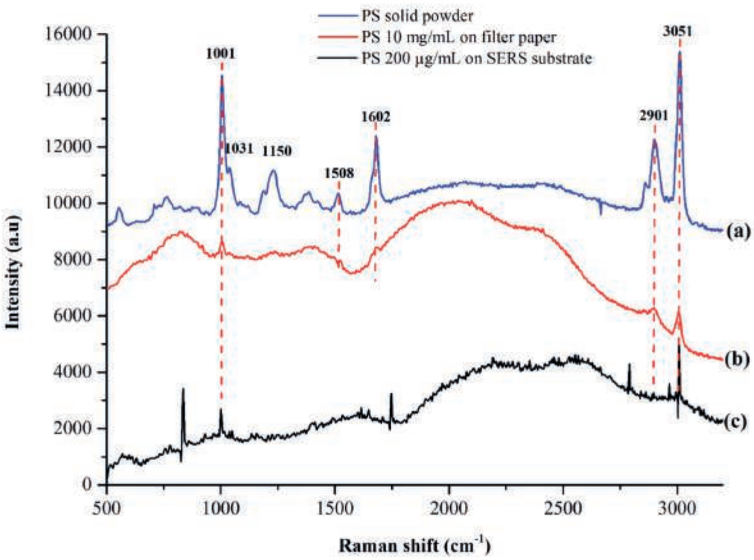

FIGURE 4: The Raman spectrum of PS solid powder (a); normal Raman of PS particles dispersed in water at concentrations of 10 mg/mL on filter paper (b); and 200 µg/mL on a surface-enhanced Raman scattering (c).

tions of PS particles. The results show that the flexible SERS substrate can detect PS particles at concentrations as low as 5 µg/mL. This detection limit is significantly lower than that of conventional Raman spectroscopy, which typically requires concentrations above 50 mg/mL for the detection of PS microplastics. The average calculated EF was approximately 1350, indicating that the SERS substrate, composed of GNS attached to filter paper, effectively enhanced the Raman signal.

The size of MPs can indeed affect their detection using GNS SERS. The SERS enhancement is most effective when the MPs are in close proximity to the GNS surface. Smaller MPs have a higher surface area-to-volume ratio, which means a larger proportion of the MP is in close contact with the GNS, leading to a stronger SERS signal. Larger MPs, on the other hand, may not interact as effectively with the GNS surface, resulting in a weaker SERS signal. However, the 0.5 um PS particles used in this study are within the optimal size range for effective SERS detection using GNS. This size is small enough to ensure close interaction with the GNS, yet large enough to provide a sufficient Raman signal. The flexible SERS substrate developed in this study has the potential to detect MPs of various sizes, but the SERS enhancement may vary depending on the size and shape of the MPs. Further research is needed to optimize the substrate for different MP sizes and shapes.

Moreover, the flexible SERS substrate developed in this study demonstrated a comparable performance to recent advancements in SERS-based microplastic detection (Liu et al., 2024; Mikac et al., 2023). These studies reported an ultrasensitive detection limit of 6.5 µg/mL for polystyrene nanoplastics using a SERS-based method, as well as a detection limit of 25 µg/mL using Ag@AuFilm SERS substrate, further confirming the effectiveness of SERS for mi-

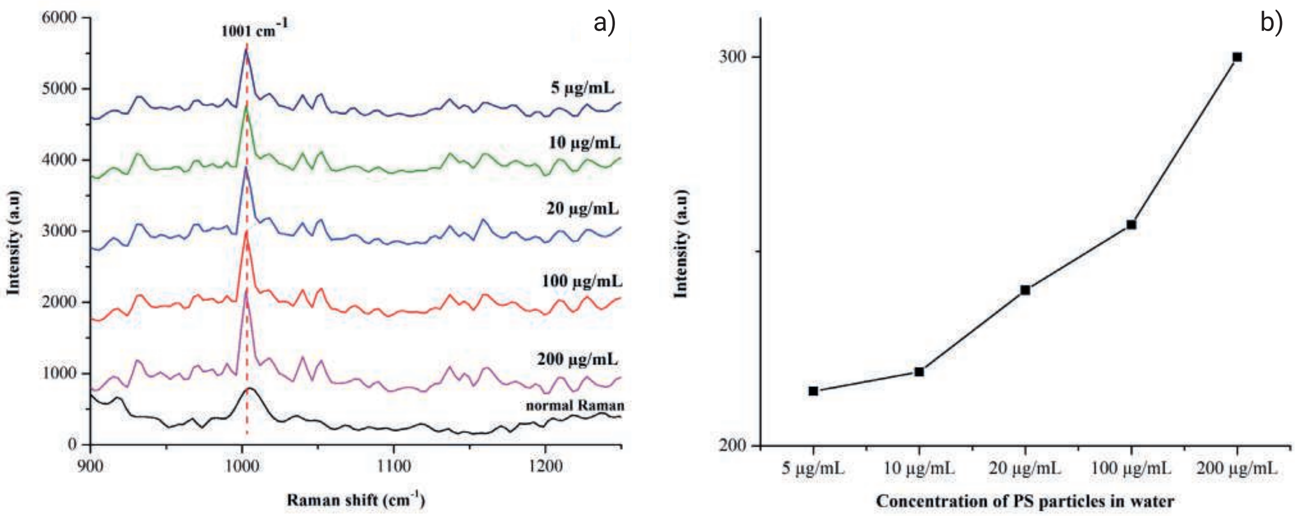

FIGURE 5: Raman spectra of various concentrations of PS particles in water on SERS substrate (a); and intensities of characteristic peak 1001 cm^{-1} (b)

croplastic analysis. These comparisons highlight the high sensitivity and practical applicability of the flexible SERS substrate developed in this work, making it a promising alternative for real-world microplastic monitoring in aquatic environments.

In addition to PS, the flexible SERS substrate was also tested for its ability to detect other common types of MPs, including PE, PP, and PET (Mallik et al., 2023; Yin et al., 2021). Preliminary results indicate that the substrate can effectively detect these microplastics as well, although the SERS enhancement efficiency may vary depending on the polymer type. The Raman spectra of PE, PP, and PET on the SERS substrate showed distinct peaks that are characteristic of each polymer, confirming their identification. However, the intensities of these peaks were generally lower than those observed for PS under the same experimental conditions. This suggests that the SERS enhancement factor may be different for different types of microplastics, possibly due to variations in their Raman scattering cross-sections, particle size, shape, and interaction with the GNS on the substrate. The stronger Raman signals observed for PS can be attributed to its aromatic rings, which resonate effectively with the excitation laser (A. Willitsford et al., 2013; A. H. Willitsford et al., 2016). Furthermore, molecules that achieve better surface adsorption through mechanisms like π-π stacking, thiol bonding, or electrostatic interaction experience greater SERS enhancement. The aromatic rings in PS facilitate a stronger interaction with noble metal surfaces via π-metal interactions (C. Li et al., 2022; Zhou et al., 2024). In contrast, PE, PP, and PET may not adsorb as as effectively. PE and PP, being made of aliphatic hydrocarbons, which have weaker Raman scattering. While PET contains aromatic components, its more complex structure may lead to less favorable orientation and interaction with the SERS substrate.

4. CONCLUSIONS

In summary, this study demonstrates the successful development of a flexible SERS substrate for the detection of PS microplastics in water. Herein, we developed a method utilizing a flexible SERS substrate in combination with a benchtop Raman spectrometer for the detection of PS particles in water, a prevalent MPs in the environment. The flexible SERS substrate, fabricated by depositing GNS onto filter paper, offers a simple, cost-effective, and sensitive method for microplastic detection. This approach enabled the detection of PS particles at a low concentrations limit of 5 μg/mL, and a high enhancement factor with an average EF over 1300 for PS particles. Thus, this method presents a cost-effective and promising procedure for the detection of MPs in aquatic environments.

ACKNOWLEDGEMENTS

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CHALLENGES TO HANDLING POLLUTION AS CRIME

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1. INTRODUCTION

In many jurisdictions around the world, violation of environmental statutes is treated as a criminal offense. However, very often, these offenses are regarded as "technical" crimes rather than morally reprehensible acts. Similar to minor infractions like driving slightly over the speed limit or downloading music or movies illegally, breaches of environmental laws, especially those that do not cause immediate or visible harm, often lack the strong moral stigma typically associated with conventional crimes. This perception is rooted in the invisible and delayed nature of environmental damage, where the harmful effects may not be immediately apparent and can take years, even decades, to fully become manifest. As a result, violations like minor illegal dumping, unauthorized emissions, or small-scale deforestation are frequently considered light, or sometimes even rationalized, both by offenders and by society at large. Yet, these seemingly insignificant breaches can accumulate over time, leading to severe and sometimes irreversible environmental degradation. Effective enforcement of environmental protection laws faces significant challenges due to the gap between the legal classification of environmental offenses and the public's moral judgment. This is in addition to other challenges, including technical and procedural.

2. POLLUTION AS A CRIME

Crime is traditionally defined as a wrongful act against society, rather than just an individual. Crimes disrupt public order, harm collective well-being, and violate laws designed to protect the common good. Under this framework, pollution incidents are strong candidates to be classified as crimes because they do not merely affect a single person or a small group but inflict harm on entire communities, ecosystems, and future generations. The impact of pollution extends beyond immediate victims, affecting air quality, water sources, soil fertility, and even global climate stability, making it a societal concern that demands criminal accountability.

Unlike private disputes, where an individual seeks personal compensation, pollution-related harm is widespread, affecting people indiscriminately, often without their direct knowledge or consent. When industries discharge toxic waste into rivers, release harmful emissions into the air, or improperly dispose of hazardous materials, the effects are felt by a large group of people. Respiratory diseases, cancer risks, biodiversity loss, and economic damages to agriculture and fisheries are just some of the consequences. Given that pollution diminishes public health, economic productivity, and environmental sustainability, treating it as a crime aligns with the principle that society as a whole suffers from the wrongdoing.

Moreover, classifying pollution as a crime ensures that those responsible—whether corporations, government entities, or individuals—are held accountable under stricter legal frameworks. Civil penalties, such as fines or compensatory damages, often fail to deter polluters, especially wealthy corporations that can absorb such costs as routine expenses. Criminal prosecution, on the other hand, carries stronger consequences, such as imprisonment for executives, business shutdowns, or heavy legal sanctions, which act as a more effective deterrent. Recognizing pollution as a crime reinforces the idea that harming the environment is not just a regulatory violation but a moral and legal offense against society, requiring serious legal action to prevent future harm.

3. CHALLENGES TO REDRESSING POLLUTION AS A CRIME

3.1 Social Challenges

One of the major challenges in redressing pollution as a crime stems from how society perceives pollution incidents. Unlike crimes such as assault or murder, which evoke strong moral condemnation due to their immediate and visible harm, pollution is often viewed differently. The effects of pollution typically unfold gradually and indirectly, making the harm less apparent to the public. As a result, society often fails to attach the same moral weight to acts of pollution as it does to violent crimes. Furthermore, because pollution is frequently a byproduct of essential economic activities like manufacturing, transportation, and energy production, it is seen less as a deliberate wrongdoing and more as an unfortunate necessity. Approaches that frame environmental damage from market activities as a market failure—characterized by negative externalities or

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societal costs not borne by the polluter (Germani, 2004; Turner et al., 2010)—tend to emphasize the economic dimension of pollution, often at the expense of its moral and ethical implications. Within this framework, environmental regulation is primarily seen as a tool to internalize these costs and correct market failures. Freeman's view, which urges society to "compare what it receives from pollution control and environmental protection activities with what it gives up by using resources taken from other users" (Freeman, 1998), reflects this utilitarian logic. While economically pragmatic, such a perspective raises ethical concerns. It treats environmental protection as a resource trade-off, neglecting the intrinsic value of nature, the unequal burden on vulnerable communities, and our moral responsibilities to future generations. Reducing pollution control to an economic calculation risks commodifying ethical obligations and disregarding principles of justice and ecological stewardship.

Adding to this complexity is the fact that polluting industries often play vital roles within communities by providing employment, goods, and services. Historical incidents, such as the counter-demonstrations by employees of Chisso Corporation during the Minamata mercury poisoning crisis, illustrate how deeply economic dependence on polluting industries can shape public opinion (Allchin, 2002). For much of history, pollution was not recognized as a crime largely because environmental harm was poorly understood. Traditional industries operated with little to no environmental regulation, and pollution was even viewed as a marker of industrial progress and national prosperity (Fenger, 2009). In such a context, framing pollution as a criminal act clashes with long-standing societal narratives about economic growth and modernity.

Moreover, pollution presents a unique problem of shared responsibility, further complicating efforts to assign moral or legal blame. Unlike individual acts of crime, pollution is often the cumulative result of actions by multiple parties—factories, governments, consumers, and businesses—making it difficult to pinpoint a single culprit. This diffusion of responsibility allows both individuals and corporations to downplay their contributions and moral accountability. Additionally, many polluting industries wield considerable political and economic influence, often shaping public perception through lobbying, advertising, and public relations campaigns that minimize the perceived severity of environmental damage. As a result, pollution is frequently framed as a regulatory or technical issue rather than as a severe moral or criminal failure, hindering the efforts to treat it with the seriousness it deserves.

This societal tendency to treat pollution crimes lightly has influenced statutory frameworks as well. For instance, while violations of environmental statutes in India are technically criminal offenses, they are classified as non-cognizable even when the prescribed punishment includes imprisonment for three years or more (normally, criminal offenses for which punishment exceeds three years are considered cognizable offences in India where the police can arrest an accused without a warrant and can initiate an investigation without prior permission from the court). This designation is due to explicit provisions in the statutes (Priya et al., 2024). This phenomenon reflects an underlying hesitancy to equate environmental harm with more traditional forms of criminality.

3.2 Technical challenges

Redressing pollution as a crime presents significant technical challenges, primarily due to the complexities involved in proving causality. Establishing that a particular emission or discharge directly caused specific damage, including loss of life or property, is an arduous task—particularly under the criminal standard of proof, which demands that guilt be established beyond reasonable doubt. Pollution-related harm often manifests gradually over time, rather than as an immediate and obvious consequence, making it difficult to trace the harm back to a single event or polluter. The problem of delayed effects compounds the difficulty of building a compelling, scientifically rigorous case. It is because of these evidentiary hurdles, strong ex-ante regulation and its effective implementation are widely regarded as preferable approaches to managing pollution. Ex-ante measures are especially valuable when harm is diffuse (Shavell, 2018), when identifying the polluter is difficult, or when the actual harm of an activity is uncertain or unfolds over time. Although lower administrative costs are often cited in support of ex post regulation—where action is taken only after harm has occurred—the potential severity and uncertainty of pollution-related harm argue strongly for preventive regulation. Ex-ante regulatory frameworks allow authorities to intervene before damage occurs, thereby reducing reliance on complex and costly litigation while enhancing environmental and public health protection. However, when harm does occur, despite preventive efforts, it must still be addressed and remedied. Notwithstanding the difficulties, there have been important advances in attribution. A notable example is the case of Ella Kissi-Debrah in the United Kingdom, where a coroner concluded that air pollution was a significant contributing factor to her death (Dyer, 2020), offering hope that more precise attribution of pollution-related harm is possible.

Another major technical hurdle arises from the complexity of the scientific and technical issues involved in pollution cases. Trials often require deliberations on intricate environmental, chemical, and health data that extend well beyond the general expertise of the judiciary. Judges and juries are tasked with making legal decisions based on highly specialized information, raising concerns about the adequacy of fact-finding and the risk of misunderstanding or oversimplification. To address this, certain jurisdictions have adopted mechanisms such as the Daubert guidelines, which set standards for the admissibility of expert scientific testimony in courts (Gatowsky et al., 2001). While not a complete solution, such frameworks help ensure that technical evidence presented during trials meets standards of relevance and reliability, partially mitigating the challenges of scientific complexity in pollution litigation.

To effectively communicate the complex scientific details involved in environmental crimes to the court, techniques similar to those used in traditional criminal investigations—such as crime scene reconstruction—can be adapted. Environmental crime scene reconstruction involves piecing together scientific, geographic, and temporal data to create a clear narrative of how the pollution occurred, its sources, the pathways it followed, and the resulting harm (Achathuparambil Gopalakrishnan et al., 2025). By visualizing the sequence of events—using maps, models, expert testimony, and simulations—such reconstructions can help judges better understand causality and the extent of damage, making technical evidence easier to handle by courts.

3.3 Procedural challenges

One of the primary procedural challenges in redressing pollution as a crime arises from the high standard of proof required in criminal cases. Proving guilt beyond reasonable doubt makes the chances of failure much greater compared to when pollution is treated as a civil wrong, where the balance of probabilities suffices. Moreover, the law of limitation can obstruct the institution of criminal proceedings, especially since many pollution-related harms, such as diseases like asbestosis, have long latency periods—often taking many decades to manifest (Bianchi et al., 1997). This delay complicates timely legal action. Another significant difficulty lies in fulfilling the two essential elements for a criminal conviction: the guilty act (*actus reus*) and the guilty mind (*mens rea*). While it is relatively straightforward to demonstrate the occurrence of the harmful act, establishing the polluter's intent or knowledge of wrongdoing is far more challenging. To address this, many jurisdictions have introduced principles of strict liability for environmental crimes, eliminating the requirement to prove *mens rea* and thereby facilitating the prosecution of pollution offenses (Kidd, 2002).

In addition to the above hurdles, the structure of criminal proceedings presents some specific difficulties in the prosecution of environmental crimes. Generally in criminal cases, the prosecution is undertaken by the state on behalf of the victims, which can lead to problems such as poor follow-up, lack of specialized environmental prosecutors, or even corruption and collusion between prosecution and defense. The involvement of powerful corporate defendants exacerbates these challenges, as their access to superior legal resources and influence often overwhelms the prosecution's capabilities. The complexity and technicality of environmental crimes demand skilled and committed prosecution teams, without which the legal redressal process risks becoming ineffective. Thus, procedural and legal barriers hinder the effective criminalization and prosecution of pollution offenses.

4. CHANGE IN SOCIETAL PERCEPTION: THE KEY TO TACKLING THE CHALLENGES

The various challenges in redressing pollution as a crime discussed above highlight the critical need for a shift in public perception regarding environmental offenses. In democratic societies, where public opinion significantly influences policymaking and governance, changing how people view environmental harm can have far-reaching effects. When the public begins to treat environmental crimes with the same seriousness as other criminal acts, it creates pressure for governments to enact more effective legislation, including stricter laws, proper enforcement, and strengthened legal redress mechanisms. Moreover, heightened public awareness and concern can lead to increased investments in scientific research and technological innovation, which are essential for accurately identifying polluters and proving their responsibility in court. Ultimately, public perception serves as a powerful driver in transforming environmental protection from a procedural formality into a robust system of criminal accountability.

And there are compelling reasons why the public should view pollution as a serious and moral offense. Foremost among them is the undeniable harm pollution causes to human health—ranging from respiratory illnesses to cancer and even premature death. It infringes upon the fundamental human right to clean air, safe water, and a healthy living environment, all of which are essential for dignity and well-being. Beyond health consequences, pollution is deeply unjust: it disproportionately affects marginalized and low-income communities who often lack the political voice or resources to resist environmental degradation in their neighborhoods.

Another important reason is the long-term consequences of pollution that extend far beyond the current generation. The damage caused today can persist for decades or be irreversible, compromising the quality of life for future generations and threatening the planet's sustainability. At its core, pollution reflects societal greed and irresponsibility, prioritizing short-term economic gains over long-term environmental and human welfare. Pollution is largely avoidable. With responsible behavior, sound policies, and sustainable practices, much of the environmental harm can be prevented. Recognizing pollution as a serious offense is not only a moral imperative but also a practical necessity for ensuring justice, equity, and sustainability.

Starting from a young age, inculcating the idea that pollution is not just a minor, albeit regulated, crime, but a serious moral wrong can be a powerful remedy against future environmental crimes. Early education in environmental ethics should go beyond facts and figures to instill a deep sense of responsibility and care for the natural world. When children are taught to see pollution as a harmful act—one that endangers human health, degrades ecosystems, and undermines the rights of others—they are more likely to grow into adults who view environmental harm as unacceptable. Practical engagement from an early age, such as participation in waste-picking, clean-up drives, recycling programs, or school-based sustainability projects, reinforces this understanding by turning values into action (Gutberlet at al., 2020; Sholanke& Gutberlet, 2020). Equally important is helping young people recognize the social dimensions of pollution: teaching them that environmental damage often disproportionately affects vulnerable and marginalized communities builds empathy and a strong sense of social justice. This approach fosters not only environmental awareness but also civic responsibility, equipping future generations to advocate for stronger environmental protections, uphold laws, and challenge practices that harm the planet and its people.

5. CONCLUDING REMARKS

Although there are numerous challenges to addressing pollution as a crime—ranging from technical and procedural barriers to legal loopholes and institutional weaknesses—the most fundamental and prominent obstacle is the lack of seriousness with which society views pollution crimes. This widespread indifference undermines enforcement, weakens legal accountability, and allows polluting behaviors to persist without moral or social condemnation. Therefore, the most powerful remedy lies in transforming public perception. A genuine change in mindset—where pollution is seen not as an unfortunate byproduct of progress but as a morally and legally unacceptable act—is essential for meaningful change. This shift must begin early, through education that instills environmental ethics, social responsibility, and a deep respect for the rights of others and the planet.

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Grassroots Innovations from Youth

MAKING OUR WASTE VISIBLE

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1. INTRODUCTION

Graduate and undergraduate students of the Community-Based Research Lab (CBRL) at the University of Victoria in Canada have created a public exhibit on the theme Making our Waste Visible. During the exhibit, they also conducted interactive workshops on participatory research methods and shared a Virtual Reality simulation via VR headsets to communicate waste related issues (Figure 1).

These events were organized in partnership between CBRL and the McPherson library at the University of Victoria. The exhibit was held at the main library of the University of Victoria and during the Science Rendezvous event at Camosun College in Victoria (Canada) between April and May 2024 (Figure 2).

The overall purpose of the exhibit and the workshops were to engage the university community and the public with waste related questions, by confronting the participants with the everyday generation of waste, showing alternatives to wasting and stimulating inquiries reflecting on what happens to our waste once it is out of our reach and out of sight? What are the wider social and environmental implications of waste? Why are we generating so much garbage? Could we avoid producing waste? Are there differences in the kind of waste? The exhibit has touched on these questions by using provocative photos, infographics and texts.

2. WASTE TAKING CENTER STAGE

In 2020, humanity crossed a striking and unsettling threshold: for the first time ever, the combined mass of all human-made objects, now reaching 1.3 trillion metric tons, exceeded the total biomass of every living organism on Earth (Elhacham et al., 2020). Most of these human-made objects become waste at some point. The exponential increase in global waste generation has turned into a planetary environmental and climate crisis of unprecedented scale and complexity.

Plastic is a key villain in these developments, and in every stage of the plastic life cycle environmental health implications are generated. Another reason lies in the fact that plastics account for 3.4% of global greenhouse gas emissions (OECD, 2022). Virgin plastic production alone is responsible for around 80% of these emissions associated with the plastic life cycle (The Pew Charitable Trusts and Systemiq, 2020). Notably, approximately 75% of these emissions arise prior to the polymerization stage, underscoring the carbon-intensive characteristics inherent in chemical manufacturing processes (Karali, Khanna & Shah, 2024). In preparing key facts in the form of infographics some of the complexities related to plastic waste were brought to the visitors of the exhibit (Figure 3).

Plastic waste becomes visible as discard after consumption, when it is littered, ends up in garbage or recycling bins or when it becomes fugitive, widely distributed by wind and water, finally ending up entangled in nature and ingest-

FIGURE 1: VR section of the photo exhibit using VR storytelling.

FIGURE 2: Poster display at the exhibit in the library entrance hall.

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FIGURE 3: Problems and solutions to plastic waste based on data available in 2022.

FIGURE 4: E-waste and ideas to address the impacts.

ed as microplastics. Despite these known impacts the production and consumption of plastics are still on the rise.

The negative effects of uncollected, mismanaged, dumped, or incinerated waste, affects the environment, oceans, the climate, and food chains, compromising the quality of life for humans and all other planetary life, with expected negative cumulative effects for the near future.

Another example of waste showcased in detail during the exhibit is electric and electronic waste. The following Figure 4 summarizes some of the facts to become aware of.

Food waste was another significant proportion of waste generation that was introduced during the exhibit with some facts and ideas (Figure 5). Linear food systems characterized by the production, distribution, consumption, and disposal of food, have direct and detrimental implications for ecological and social sustainability across multiple scales. Global efforts to address these challenges are compromised by the fact that an estimated 30% of all food produced worldwide remains uncollected, unsorted, and undonated, with its inherent value ultimately lost to landfills. This context underscores the urgent need to close food resource loops in order to mitigate environmental, economic, and social losses.

At each stage of the food supply chain, the primary drivers of food loss and waste are closely linked to trade requirements, external quality standards, industry specifications, inappropriate packaging decisions, and a combination of wasteful consumer and retailer behaviors. Collectively, these factors reveal the systemic nature of the forces shaping food loss and food waste patterns (Zhao et al., 2019).

3. GRASSROOTS ACTORS - WASTE PROTAGONISTS

Given the mostly informal nature, it is difficult to produce reliable statistics on the exact number of individuals working as waste pickers worldwide (Figure 6). A conservative estimate by the International Labour Organization (ILOSTAT, 2024) suggests 6.9. million people employed in the waste and recycling industry. ILOSTAT recognizes that this is an underestimation due to data limitations, since the more marginal workers in the industry such as waste pickers that are homeless or live in collective households are exuded from this number (ILOSTAT, 2024). The international Non-Governmental Organization called Women in Informal Employment Globalizing & Organizing - WIEGO on the other hand suggests 15 to 20 million informal workers in waste management and recycling (WIEGO, n.d.). Most waste pickers work under precarious, unhealthy, and poorly paid conditions and mostly fall through the cracks of census data collection. More research is needed to refine these numbers and thus shed light on this, in many countries, still mostly unrecognized sector whose contributions to local communities and the environment are undervalued.

4. FINAL REMARKS

Current measures to reduce waste are insufficient to avoid increased pollution from waste, to address the pressures on natural systems and to achieve a circular economy. Consumers need to be better informed about the impacts of waste as well as about alternatives and solutions to reduce waste generation.

A better understanding of the impacts, complexities and dimensions involved in the daily act of generating waste is urgently needed. While waste is part of our everyday life experience, we distance ourselves from whatever happens to waste after discard, and we believe that the waste management system takes care of it. Waste management is more than just a man behind a truck, as Marsha Serville-Tertullien, a Professor at Trent University, had put it in one of my classes. Education and awareness building is important to address the global crises, stressing the need to rethink and change practices, behaviors, principles, worldviews, institutions, social structures, and systems in general. Studying waste allows us to draw these connections to key societal issues ranging from environmental degradation and climate change to poverty and justice, public policy to community development and Sustainable Development Goals. This was one of the objectives pursued with the exhibit the workshops and the Virtual Reality immersion.

The exhibit can be visited at: https://www.cbrl.uvic.ca/creative-resources-for-community-knowledge-cocreation.

FIGURE 5: Problems and solutions associated with food loss and food waste.

FIGURE 6: Facts on waste pickers.

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CISA

DETRITUS & ART / A personal point of view on Environment and Art

by Rainer Stegmann

The cycle of nature is always fascinating. After a sleeping period in winter nature of plants shows all its beauty in spring and summer: an endless variety of beautiful blossoms. It has all its meaning; the goal is reproduction, the preservation of life. But why are these blossoms so beautiful and smell so good? Probably to attract bees and other insects for pollination with subsequent fertilizing. But why are they so beautiful in a great variety, is there a competition for attracting insects? The most beautiful or best smelling is served first? I have no idea but I am happy that such a variety of beauty exists which in my view is probably not important for nature to exist, or?

What about the beauty of plants in autumn; all the colorful leaves often turning to yellow and red, the golden autumn or Indian Summer. What about the beauty of flowers have before they die as the hydrangea? Makes that any sense for maintaining the circles of life, to preserve biodiversity? For me, that is even more difficult to understand. In Autumn fruits are produced serving as food for all kinds of creatures. Fruits and leaves fall to the ground where they are degraded by microorganism and other soil organism to serve the soil with nutrients and produce humus where new life is born. It is a perfect cycle that we try to implement in Circular Economy of materials and especially in separate biowaste collection and composting. Compost is brought back to the soil to act as the “naturally” fermented plant residues do. But a minority of the composts are not suitable for land application due to their content of pollutant concentrations that exceed the limit values. Such pollutants are in most cases heavy metals as Copper, Lead, Zink but also organic compounds as PAHs, PCBs and others. In such cases, more efforts are necessary to control the quality of the separate collected biowaste.

With some imagination, I dare say that the separate collection and fermentation of biowaste also serve in most cases to allow beauty in nature.

In the next issue I will present a photo where you may guess its origine.

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