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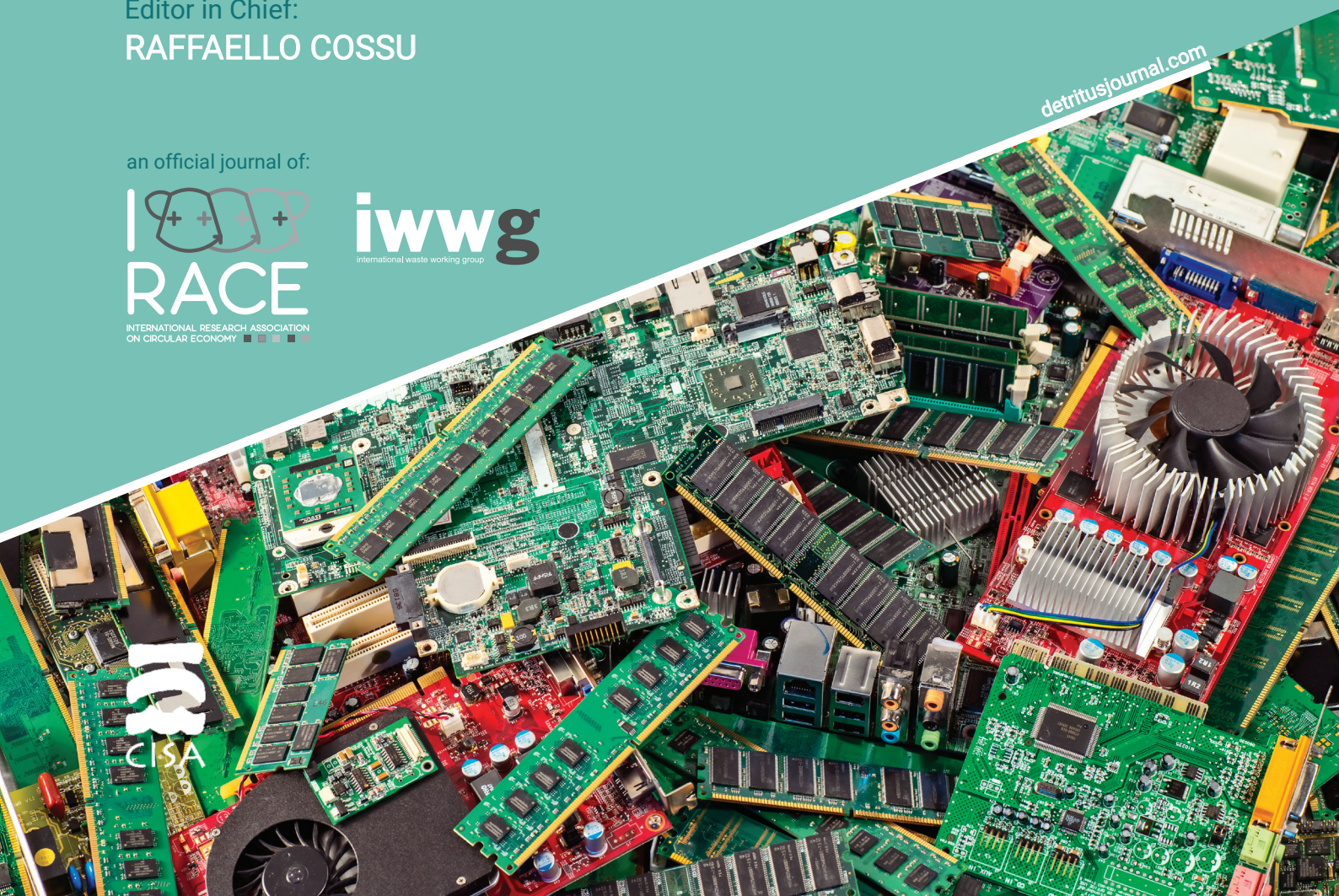
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Detritus - Multidisciplinary Journal for Waste Resources and Residues - is aimed at extending the “waste” concept by opening up the field to other waste-related disciplines (e.g. earth science, applied microbiology, environmental science, architecture, 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

ONE HEALTH AND SUSTAINABILITY: TWO SIDES OF THE SAME COIN

The recent occurrence of multiple pandemics, including COVID-19 and Mpox in people, and H5N1 influenza in farmed and wild animals, has put One Health firmly on the political agenda. However, One Health has meant different things to different people, often focussed on infectious disease and often with an anthropocentric bias. In response to this, in 2022 the recently-convened One Health High Level Expert panel, of which I was a member, developed a definition of One Health which is holistic, disease agnostic and which aims to equally protect the health and wellbeing of humans, domestic animals, wildlife, cultivated and wild plants and ecosystems (<https://www.who.int/publications/m/item/one-health-definitions-and-principles>).

A driver for a One Health approach is a realisation that the occurrence of disease threats, be they infectious or non-infectious, are almost always a result of human choices and activities. While it is easy to see links between chemical pollution and toxicity, or the hunting of wildlife for food leading to novel pathogen exposure, links between many human activities and infectious disease outcomes are not always so apparent. Many wildlife species become less abundant or disappear altogether from human-modified habitats, while others persist or increase in abundance. Pathogen prevalence in the latter can increase as these animals directly or indirectly interact with each other more frequently than when there was a higher species richness. Such survivors in human-modified habitats tend to be species that have an evolutionary history of co-existence with people and, not surprisingly, they are more likely

to harbour zoonotic pathogens than the species that are lost.

Biodiversity loss has been identified as a major driver of infectious disease emergence in people and other animals (Mahon et al., 2024), and habitat loss is the primary driver of biodiversity loss. Agriculture is the major driver of habitat loss: of all habitable land on our planet, 49% is used for agriculture, of which 78% is used to produce livestock (for housing and, predominantly, for growing animal feed) while only 22% is used to produce plant crops directly for human consumption (Figure 1, Benton et al., 2021). When one considers that humans obtain 63% of our protein needs and 82% of our calories from crops, and taking into account that plants can provide all the nutrients required by people, animal production is a very inefficient way of producing food. Yet, per capita consumption of meat has been increasing rapidly with global economic growth (Figure 2), while the human population has quadrupled in size over the past 100 years. This growing demand for meat and dairy, combined with the inefficiency of turning plants into animal products (Benton et al., 2021), has resulted in a situation where we farm 3.1 billion hectares more than we would if we didn't eat animal products - and that takes into account the land required to grow enough food crops to ensure adequate nutrition for a planet of 8 billion people (Poore & Nemecek, 2018). It is rather sobering to think that we have destroyed natural habitats covering an area the size of the USA, European Union, Australia and China combined through choice rather than through necessity.

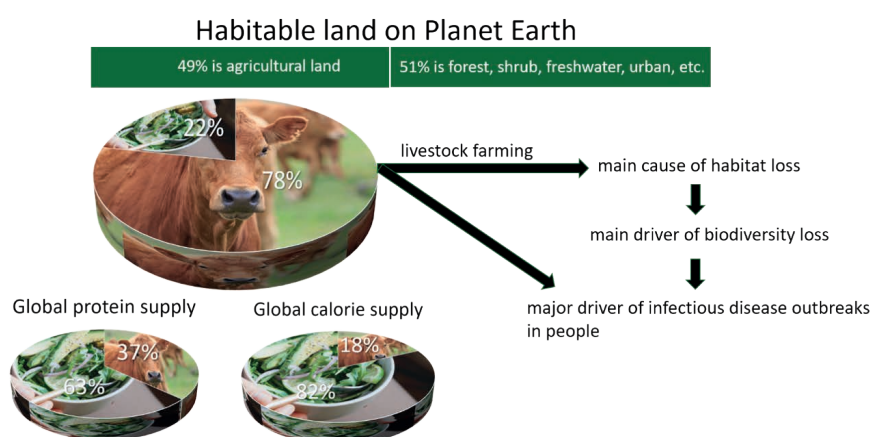


FIGURE 1: Graphic demonstrating inefficiencies in the way we use land to produce food, and some of the ways this results in increased infectious disease threats to people (percentages shown are from Benton et al., 2021).

Per capita meat consumption by type World, 1961 to 2023

Per capita meat consumption is broken down by types of meat, and is measured in kilograms per person per year.

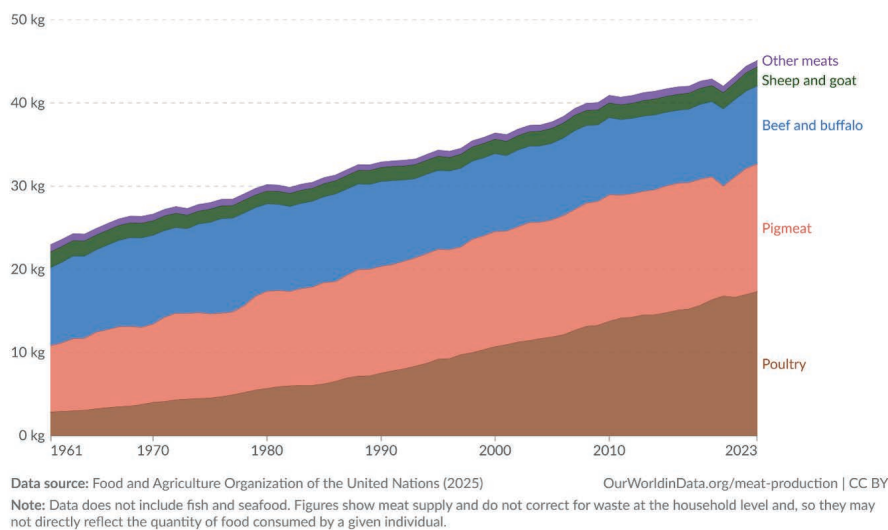


FIGURE 2: The per capita consumption of meat by humans has increased markedly over recent decades, approximately doubling over the past 60 years. Figure obtained from <https://ourworldindata.org/grapher/per-capita-meat-consumption-by-type-kilograms-per-year>.

In addition to its impact on disease emergence and occurrence through biodiversity loss, livestock production is the most frequent source of endemic zoonotic disease (Desvars-Larrive et al., 2024). For example, campylobacteriosis, which is primarily contracted from poultry products, is the most frequently reported cause of bacterial gastroenteritis in the developed world. Even when zoonotic diseases are contracted from plant products, the origin of the pathogen often is farm animal manure used to fertilise the crops. And while the intensification of livestock production may lead to increased food conversion efficiencies, it also enables the emergence and spread of new infectious disease threats, such as antimicrobial resistant strains of bacteria and highly pathogenic variants of viruses. For example, the H5N1 highly pathogenic avian influenza virus originated in intensively farmed geese in southern China.

Reducing demand for animal products can reduce habitat loss, biodiversity loss and human infectious disease emergence and occurrence. Less meat and dairy in our diets will also reduce non-infectious disease threats to people, including heart disease, type 2 diabetes and certain cancers (Papier et al., 2021). Reducing the consumption of animal products decreases other harms to people and our planet, including those mediated through scarcity-weighted freshwater abstraction, eutrophication, acidification and greenhouse gas emissions (livestock production produces more CO₂ equivalent greenhouse gas emissions than all transportation globally) (Poore & Nemecek, 2018), while increasing our food security.

For a sustainable planet, a One Health approach is required, and if we want to adopt One Health practice, we need to embrace sustainability, including in the way we produce our food. Surely if we could choose from scratch, we would eschew such an inefficient, wasteful and harmful way of feeding humanity as meat and dairy production. A frequent retort to pleas to reduce meat and dairy con-

sumption is that it disrespects long-held cultural norms. However, human cultures can change dramatically and rapidly (e.g. see <https://www.youtube.com/watch?v=2w-MOuWDwdJE>), and the per capita consumption of meat only markedly increased over recent decades (Figure 2). Our food systems are now completely unsustainable and un-One-Healthy. If we do not radically change them and reduce our consumption of animal products, we not only risk our own health but the future of our planet and of humanity.

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MEASURING WHAT WE MISJUDGE: EXPLORING THE POTENTIAL AND LIMITATIONS OF AI FOR FOOD WASTE QUANTIFICATION

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ABSTRACT

Food waste remains a critical yet insufficiently explored global challenge, and accurate quantification is essential for developing effective mitigation strategies. Traditional food waste measurement methods face multiple limitations, prompting growing interest in alternative approaches such as AI-based technologies. This exploratory study evaluates the potential of AI image analysis for food waste quantification under real-world conditions. The method involves comparing AI-estimated and human-estimated food waste weights against a benchmark of scale-measured weights to assess estimation accuracy and error patterns. Our findings indicate that while AI technologies show promise as scalable quantification tools, portion effect on estimation errors and variability in generalization across models underscores the need for thoughtful selection, and the performance could be substantially improved through further model training with larger and more diverse datasets. Overall, this study highlights both the potential and present limitations of AI-driven food waste quantification, emphasizing the need for continued research using more advanced models and expanded training data.

1. INTRODUCTION

Food loss and waste (FLW) remain among the most pressing challenges in global food systems. In Europe, more than 58 million tonnes of food are wasted annually (Eurostat, 2025) – a figure that contrasts sharply with the fact that nearly 42 million people cannot afford a quality meal every second day (Eurostat, 2023). While FLW occurs across the entire food value chain, increasing attention has been directed towards the consumption stage, where waste is generated after food has reached the consumers. In the European Union, the three largest contributors to food waste (FW) are households (53%), the manufacture of food products and beverages (19%), and restaurants and food services (11%) (Eurostat, 2025). Globally, an estimated 1.05 billion tonnes of food were wasted, accounting for 19% of food available to consumers at the household, food services, and retail levels (UNEP, 2024). These figures underscore the urgency of developing more accurate and scalable solutions for monitoring and mitigating FW, particularly in the later stages of the supply chain, namely the consumption stage (Dhir et al., 2020; Kaur et al., 2021).

FW quantification is a crucial first step with respect to the urge to develop and implement FW mitigation strate-

gies (Corrado et al., 2019; Vardopoulos et al., 2024). The traditional approaches include self-reported surveys, manual waste tracking, and compositional analyses, which have provided valuable insights but face limitations of accuracy, scalability, and cost-efficiency, which might lead to misjudgments on FW-related problems (Corrado et al., 2019; Vardopoulos et al., 2024). Recent advances in artificial intelligence (AI) and computer vision offer new opportunities to overcome these limitations. The advancement of AI unlocks a new era in food science towards more data-driven decision-making. Among various AI technologies, Large Language Models (LLMs) have witnessed successes in food safety detection and monitoring, nutritional analysis, recipe development, and diet planning (Fridolfsson et al., 2025; Ma et al., 2024). Reference to the success of using LLMs in food images (e.g. nutritional content estimation, quality inspection) (Fridolfsson et al., 2025; Ma et al., 2024), LLMs powered with a computer-vision system are capable of automatically identifying, classifying, and quantifying FW in real time, reducing reliance on subjective reporting and enabling continuous monitoring in households, food services, and retail contexts. By generating high-resolution and standardized data, AI technologies have the potential to transform FW research and practice, supporting



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more targeted activities for FW reduction with data-driven evidence (Kakani et al., 2020; Sigala et al., 2025).

However, AI in FW research remains at an early stage. Empirical research in FW quantification with AI technologies is rare in the current literature. There is also a limited understanding of how AI-enabled monitoring can improve the accuracy and efficiency of FW quantification, support real-time decision-making, and enhance the effectiveness of reduction strategies across different contexts of consumption.

Building on these gaps, this study explores the application of AI-based technologies, particularly using LLMs, for FW quantification in terms of their potential and limitations. Specifically, it addresses the following research questions:

- Is AI-based technology a reliable tool for FW quantification compared to traditional methods (e.g. subjective evaluation, manual measurement)?
- What is the level of errors when using AI for FW quantification?
- How can AI-enabled data streams be integrated into broader strategies to quantify FW at scale?

By addressing these questions, the study contributes to the literature by advancing the use of AI technologies as robust tools for FW quantification – as far as we know, the first attempt to systematically evaluate the capabilities of the open-source LLMs in FW identification and tracking. This study examines the accuracy of FW measurement by comparing subjective and objective weight data, with a particular focus on the potential of AI-based image analysis to enhance reliability. This approach contributes to advancing methodological tools for large-scale FW tracking, improving data quality, and supporting more effective strategies for FW reduction.

In the following context, Section 2 provides a background on the existing literature about FW quantification and AI for food science. Section 3 explains the research design and methodology. We extend the discussion with our analysis results in Section 4. Lastly, a conclusive summary closes this exploratory study while pointing out the limitations and directions for future work in Section 5.

2. LITERATURE REVIEW

2.1 Food waste and food waste quantification

We have been standing at a critical turning point since 2022: on the one hand, nearly one-fifth of the food available to consumers at the retail, food service, and household levels is wasted (UNEP, 2024); on the other hand, 733 million people in the world continue to suffer from hunger and 2.33 billion are in danger of food insecurity (FAO, 2024). Besides, FW contributes to a less sustainable global environment, in particular, greenhouse gas emissions, water resources, land, and biodiversity (Stancu et al., 2016). FW quantification, or FW accounting, forms the baseline of tackling any FW issues: identification of the most relevant waste streams (Corrado et al., 2019). Methodologies used for FW quantification vary from direct measurement (e.g. weighing, digital trackers) to surveys and observations. Each ap-

proach has its pros and cons, contributing differently to the advancement of FW research – direct measurement provides more details and comparable estimates while others shed lights on FW generation from behaviors of consumers and businesses (Falasconi et al., 2015; Derqui et al., 2016; Vardopoulos et al., 2024). The measured or estimated results of FW quantity share a high inconsistency rate. Lack of standardized framework and methodology, and the complexity of food systems are the major challenges (Comis et al., 2025; Filimonau & De Coteau, 2019); however, different methods to measure and achieve FW quantity contribute to the discrepancy as well (Corrado et al., 2019).

2.2 Methodological approaches for food waste quantification

Methodological approaches for FW quantification discussed in this paper give exclusive attention to the methods for collecting primary data, for the reason that we aim to evaluate an alternative method or tool for primary FW data collection. Direct and non-direct measurement methods are both widely used in the existing literature; furthermore, a combination of methods is employed to enhance the robustness of the research (Filimonau et al., 2022; Vardopoulos et al., 2024).

Direct measurement includes physical weighing and volumetric evaluation. According to the different methodologies applied, the measured weights or volumes are in different unit formats, such as per meal/tray, of each type of food component, or per person/entire sample size (Vardopoulos et al., 2024). However, these methods are highly resource-demanding, including cost, time, expertise and direct access to the research targets, consequently limiting the scalability of the research results (Corrado et al., 2019).

Waste registration and questionnaires are used to measure FW quantity at both business and individual (or household) levels indirectly. The commonly used techniques to register FW quantity or conduct a FW diary are visual observation and self-reporting. Compared to direct measurement methods, they are more approachable operationally and financially, repeatable, and practical for a large-scale implementation, despite the drawbacks of data quality due to inaccurate data entry, subjective enlistment, sample bias, and other concerns (Corrado et al., 2019; Vardopoulos et al., 2024).

2.3 AI for food science

Digital innovations have been largely integrated into the research and applications in food science and food systems, offering impressive positive outcomes which cannot be achieved by non-digital approaches. Taking a few examples, real-time tracking and visualized reports to the key stakeholders, and nudging effects at an immediate and long-term level on individuals. AI, in particular, LLMs among various AI technologies, have been catching eyes in recent years for their high reputation in data analysis and interpretation (Kakani et al., 2020; Ma et al., 2024; Yu et al., 2025). LLMs are a group of advanced models which are developed and trained to generate text by predicting the next word based on an input text. Powered by deep learn-

ing algorithms, these models are powerful in processing natural languages, predicting, making decisions, and performing other complex text-based tasks (Ma et al., 2024). The big names of LLMs with different developers include but not limited to ChatGPT by OpenAI, Gemini by Google, Llama by Meta, Claude by Anthropic, DeepSeek by DeepSeek, and Qwen by Alibaba. Taking OpenAI as an example, ChatGPT is only one model developed for natural language processing tasks such as text and code generation, data analysis and visualization, image analysis and creation, deep searching, and so on (OpenAI, n.d.). However, developed by the same company, ChatGPT is outperformed by another model, GPT-4o, in the context of visual and audio processing tasks (OpenAI, n.d.). Despite the tailored LLMs for specific tasks, the general performance and capabilities of an LLM depend on model complexity, data volume, and computational power, although all models share a similar fundamental backbone. From this perspective, LLMs stand for large-scale pre-trained language models (Ma et al., 2024). One of the straightforward indicators is the parameter size, which, to some extent, differentiates LLMs from other small language models. In the context of AI, parameters refer to the internal variables learned during training that determine how the model processes inputs and generates outputs. The number of parameters represents a model's capacity, as larger models typically possess greater representational power and can capture more nuanced patterns. The LLMs exemplified before have model versions ranging from billions to trillions parameters (Ma et al., 2024).

LLMs have been experimented with and quickly adapted in many fields of food science, such as predictive analysis for food safety, regulatory compliance automation, food quality control and inspection, quality improvement according to consumer feedback analysis, efficiency improvement of the whole food supply chain, food fraud detection, recipe generation, and nutritional analysis for diet planning (Kakani et al., 2020; Ma et al., 2024). Which, the last two applications highlight the capabilities of LLMs in food image processing, and therefore, the potential application to FW research. In the context of recipe generation, it can capture the information by reading food images and generate recipes to meet specific dietary requirements or preferences. On the other hand, LLMs can understand complex dietary data by extracting key information about food components and quantities, so that personalized nutrition advice and diet plans can be generated (Lo et al., 2024; Ma et al., 2024; Fridolfsson et al., 2025). Lo et al. (2024) achieves mean absolute errors lower than 5% even in challenging conditions when comparing the estimated results by GPT-4V to those of dietitians. Not only are common food items correctly identified, but also regional ones with cultural and geographic features. The estimation results of the portion size are close to those evaluated by humans, although the model is not designed to process depth or spatial information in the food images and bears a certain level of estimation errors. Leading LLMs like ChatGPT and Claude demonstrate an accuracy level of food weight estimation from the images, close to the self-reporting method

in another recent work in dietary assessment (Fridolfsson et al., 2025).

LLMs have shown notable capabilities in food and food component recognition in the research field of nutrition and diet. In the meantime, the application of weight estimation has achieved performance no worse than traditional self-reported methods; however, unlike the traditional methods, LLMs process the information without subjective bias, and they are free from social desirability effects or participant burden. LLMs can support tasks like automation at a large scale and continuous passive monitoring, hence offering efficiency and scalability. This turns LLMs into a potential and valuable tool for other scientific research tasks, including research in FW. Meanwhile, limitations of LLMs persist, at least for the current stage. The accuracy of the volume estimation from 2D food images needs real-world validation.

2.4 AI for food waste

The academic discussion around digital innovations in FW has been expanding, but to our best knowledge, the implementation of AI technologies in FW is very limited. Kitro, the Swiss startup, integrates a self-developed AI model with the IoT solution for FW management. Through grounded data analysis, operational optimization for food businesses is achieved, and benefits the users with up to 55% of FW reduction and 5% cost saving (Martin-Rios et al., 2020). However, the AI technology used by Kitro is only a small friction. Kitro's AI-empowered solution is designed specifically for food service providers with commercial purposes; it is limited in generalization. In an earlier attempt with a small sample size (n=54), a leading LLM, GPT-4o by OpenAI, is used to process the food images taken in the real-world environment. It shows remarkable capability in food recognition and component identification, and a significant linear discrepancy between the AI-estimated and self-reported FW weights (Yu et al., 2025). To our best knowledge, this paper takes the first experiment and comparison study on different open-source LLMs in FW identification and quantification with the purpose of accuracy evaluation.

3. DATA COLLECTION AND METHODOLOGY

3.1 Research design and data collection

This exploratory study was designed to evaluate and compare the accuracy of food weight estimation and food identification generated by LLMs and human judgment using food images captured in real-world environments. The study was conducted within the framework of the PERFETTO project, financed by the European Union, which aims to reduce consumer FW in the restaurants through behavioral nudges – such as doggy bags and half-portion – and employs AI-assisted monitoring technologies within a large-scale field experiment in 40 restaurants in the Umbria region of Italy. The primary objective was to assess the reliability and practical applicability of AI-based estimation by benchmarking its outputs against scale measurements and comparing them to human estimates. To this end, a dual data collection framework was implemented, consist-

ing of food images, scale-based measurements, AI-generated estimates, and human-based assessments.

For the human estimation component, purposive sampling was employed, targeting academic researchers and specialists in waste management, sustainability, and economics. As a non-probability sampling strategy, purposive sampling offers operational feasibility and analytical relevance for exploratory research (Vehovar et al., 2016). The rationale for targeting this participant group was that their professional activities are often associated with waste quantification, waste source accounting, and numerical assessment, making them a relevant stakeholder group for studies related to FW estimation. However, participants were not recruited on the basis of expertise in food portion-size or food weight estimation. To further expand the participant pool and improve coverage across relevant disciplines, a snowball recruitment approach was adopted, whereby initial participants were invited to refer other qualified experts (Ting et al., 2025). We should note the potential selection bias and limitation of the sample representativeness. Information about participants' familiarity with food types, cultural background, demographic characteristics, and prior training in volumetric estimation was not collected. Consequently, the influence of these factors on human estimation performance could not be assessed and should be considered when interpreting the results.

Data collection was conducted across three distinct periods between 2025 and 2026. The dataset comprises two main sources: image batch i with food images, scale-measured weights, and image description collected directly by the research team in both household and out-of-home dining settings, and image batch ii supplementary data contributed by a group of academic experts, who followed detailed guidelines provided by the researchers. In addition to collecting the same data as image batch i, this batch also included weight estimation of 9 images by these experts. The scale-measured food weights ranged from 17 g to 621 g in image batch i and from 5 g to 550 g in image batch ii.

All food images were captured in free environments to reflect real-world consumption contexts. For all observations in image batch i, a digital kitchen scale (Brand: SUNLUX MDC005; CE certificated) with weighing precision of 1 g and maximum weighing capacity of 5 kg, was used to record the precise weight of food in the images, while a smartphone camera was used to capture corresponding images. Before each weighing action, simple check and zero calibration was conducted according to the manufacturer's instructions. To reflect real-world settings, images

were collected under unconstrained conditions rather than following a strictly controlled protocol. Photographers were not instructed to use specific camera angles, distances, or lighting conditions, but only instructed to utilize household kitchen scales and smart phones following the simple guidelines. It was suggested but not mandatory to take photos from multiple angles and depths, or photograph a wide diversity of food types, portion sizes, containers, and culinary culture. No reference objects of known dimensions were included in the images. This design was intended to evaluate the baseline capability of LLMs to perform weight estimation and food recognition from ordinary user-generated photos without task-specific training or additional guiding information. However, details on the scales used to measure weights of image batch ii was not collected. Some measurement heterogeneity may exist within the benchmark dataset. Given the exploratory nature of this study, the scale-measured weights were nevertheless considered the most objective reference available for evaluating human and AI estimations under real-world conditions.

This systematic data collection procedure generated paired datasets comprising food images, ground-truth weight measurements, AI estimations, and human estimates, thereby enabling direct and objective comparison across different weight measurement methods. Table 1 summarizes the overall data collection design and dataset structure, while Figure 1 presents representative image examples, which primarily depict food items, with containers and dining surfaces forming the dominant background elements.

3.2 AI model implementation

7 open-source LLMs were employed to evaluate and compare the accuracy of AI-based food weight estimation and food identification. As summarized in Table 2, these models were developed by different organizations and vary substantially in their parameter sizes, reflecting differences in model scale, architectural complexity, and representational capacity. Each model was used to process the same set of images and pre-designed prompts to ensure the comparative study. The standard prompts ensure a fair evaluation of the LLM models. Sophisticated prompts with additional details might improve the performance of results, but they might fail to reflect the real-world scenarios (Fridolfsson et al., 2025). Therefore, the prompts were deliberately kept simple to establish a baseline evaluation. Minimal contextual guidance was provided solely to reduce unrealistic estimations, for example the two weight ranges which were derived from the scale-recorded weight ranges of image batch i and image batch ii.

TABLE 1: Summary of data collection design and dataset structure.

Data collection period	Apr-Jul 2025	Sep-Oct 2025	Jan-Feb 2026
Data contributors	Researchers	Academic experts	Academic experts and specialists
Key data collected and collection methods	Food images, Scale-measured food weight	Food images, Scale-measured food weight, Human estimates	Human estimates
Food types	First main dish, Second main dish, Pizza, Sandwich, Side dish, Dessert, Beverage, Soup, Pastry		
Cuisine Culture	Italian, Western (International), Asian, Indian, Middle Eastern		

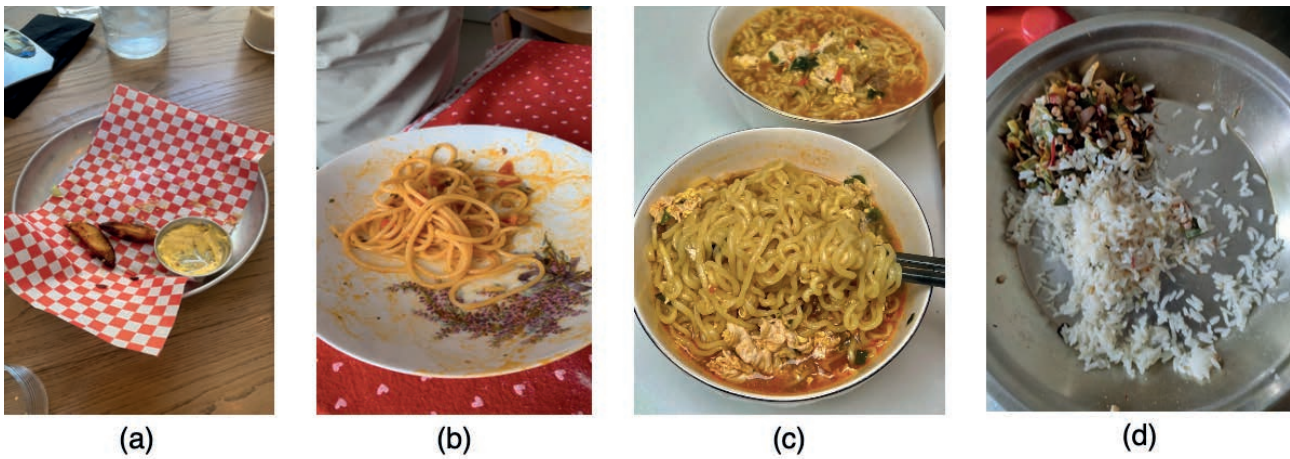


FIGURE 1: Examples of food images collected.

"You are a food waste analyst. You received an image of food leftovers for your research. Given the image, provide the following information: the type of the main food in the image; the estimated weight of the food in the image in grams. In general, food leftover weights are between 10 grams and 750 grams. Aim to be as accurate as possible in your weight estimation." – Prompt applied to the analysis of image batch i.

"You are a food waste analyst. You received an image of food leftovers for your research. Given the image, provide the following information: the type of the main food in the image; the estimated weight of the food in the image in grams. In general, food leftover weights are between 4 grams and 750 grams. Aim to be as accurate as possible in your weight estimation." – Prompt applied to the analysis of image batch ii.

By systematically testing models spanning diverse origins and parameter ranges, this study provides a comparative assessment of their effectiveness in performing multimodal tasks involving natural language understanding and image-based food weight quantification.

Open-source LLMs were intentionally selected to enable a transparent and reproducible evaluation of baseline model performance for FW quantification. In contrast to proprietary models (e.g. GPT-4 and Claude), open-source frameworks provide full access to model code and architecture, enable local deployment, and allow flexible system configuration, thereby ensuring experimental control, enhanced data privacy, and avoiding vendor lock-in. These characteristics make open-source models particularly suitable for systematic benchmarking studies in which models are assessed in their out-of-the-box configurations using a standardized prompt. Moreover, these models facilitate future development, including fine-tuning, domain-specific adaptation, and customization. While these capabilities are not exploited in the present study, they provide a strong basis for extending this work toward more practical systems. In this regard, open-source models are valuable for subsequent projects in FW quantification, continuous monitoring, and targeted intervention development, enabling the construction of more accurate, context-sensitive, and application-oriented AI systems.

TABLE 2: List of open-source LLMs for food image analysis.

Model	Developer	Release Date	Approx. Parameters	Deployment
Granite Vision 3.2 2B	IBM	2025 February	2 billion	LM Studio
Internvl3 2B Instruct	OpenGVLab	2025 April	2 billion	LM Studio
Llama 4 Scout 17B 16E Instruct	Meta	2025 April	16 billion	Groq
Moondream 2B 2025-04-14	Moondream	2025 April	2 billion	LM Studio
Qwen 2.5 VL 3B Instruct	Alibaba Qwen	2025 March	3 billion	LM Studio
Qwen3 VL 32B Instruct	Alibaba Qwen	2025 October	32 billion	Together.ai
Smolvlm2 2.2B Instruct	Huggingface	2025 February	2.2 billion	LM Studio

Abbreviations: Granite Vision 3.2 2B – Granite; Internvl3 2B Instruct – Internvl3; Llama 4 Scout 17B 16E Instruct – Meta-LLaMA; Moondream 2B 2025-04-14 – Moondream; Qwen 2.5 VL 3B Instruct – Qwen2.5; Qwen3 VL 32B Instruct – Qwen3; Smolvlm2 2.2B Instruct – SmolVLM2

Note:

Granite: <https://huggingface.co/ibm-granite/granite-vision-3.2-2b>

Internvl3: <https://huggingface.co/OpenGVLab/InternVL3-2B>

Meta-LLaMA: <https://huggingface.co/meta-llama/Llama-4-Scout-17B-16E-Instruct>

Moondream: <https://huggingface.co/moondream/moondream-2b-2025-04-14-4bit>

Qwen2.5: <https://huggingface.co/Qwen/Qwen2.5-3B-Instruct>

Qwen3: <https://huggingface.co/Qwen/Qwen3-VL-32B-Instruct>

SmolVLM2: <https://huggingface.co/HuggingFaceTB/SmolVLM2-2.2B-Instruct>

3.3 Dataset structure

Following data cleaning, processing, and elaboration, two structured datasets were constructed with estimated weights, weight estimators, scale-measured weights, and image descriptions for analysis.

The first dataset – sub dataset – comprises human-based food weight estimations of 9 selected food images. A total of 52 participants completed this estimation task through an online survey administered via Google Form, in which the same 9 images were presented in a fixed order. As noted in Section 3.1, participants, those were invited to the survey, also contributed to construct the second image batch. To avoid familiarity effects, the image selection for the estimation task was therefore restricted to the first image batch. The selected images were chosen to provide a representative subset of image batch i in terms of food type (e.g. pastry, savory, snack, starter or soup, main meal), photo-taking conditions and visual complexity. Specifically, the images capture a range of scenarios in free environments, including meals photographed both at home and outside the home, foods presented in different types of containers, and foods that were either partially consumed or untouched. This design was intended to balance respondent burden and data quality while ensuring sufficient variability. Nevertheless, limitations and potential sources of bias arising from this subset selection should be acknowledged. For instance, the selected images do not adequately represent the diversity of food cultures, which could compromise the verification outcome. Furthermore, the images selected for human estimation task only weights from 19 g to 127 g. Consequently, larger portion sizes are underrepresented in the evaluation. This is partially attributable to the theme of the online survey, “Food (Plate) Waste Weight Estimation”, which favored the selection of images with partially consumed food and, therefore, generally smaller remaining portions.

The second dataset – full dataset – consists of the complete set of 91 food images collected in real-world environments. These images were subsequently processed by the 7 selected LLMs, each independently generating food weight estimates, thereby producing 7 distinct sets of AI-generated outputs – a total of 637 observations.

The resulting integrated dataset enables multi-dimensional comparative analysis across three estimation modalities: (i) precise scale-based measurements as objective benchmarks, (ii) human visual estimation, and (iii) AI estimation by multiple LLMs. This comprehensive data structure supports robust evaluation of both estimation accuracy and inter-model variability, while allowing systematic assessment of the reliability and generalizability of AI-LLM-based food waste measurement under unconstrained, real-world conditions.

3.4 Data analysis and statistical methods

For both the human-based and AI-generated weight estimation datasets, estimation errors were first computed as the difference between estimated food weights and the corresponding scale-based measurements, which served as the ground-truth reference in this study. Multiple sta-

tistical indicators were calculated to evaluate estimation errors and dispersion, including standard deviation (SD), mean absolute error (MAE), mean absolute percentage error (MAPE), mean error (ME), and mean percentage error (MPE). MAE quantifies the average magnitude of the estimation error in absolute terms, providing a direct indication of how large the errors are, while ME reflects the direction of the errors and thus indicates the tendency towards overestimation or underestimation. In contrast, MAPE and MPE express errors as percentage-based metrics. They are more sensitive to small reference values and may amplify the apparent magnitude of errors associated with small portions. SD characterizes the variability of the errors and therefore provides insight into the consistency of the estimation pattern. These metrics were used to conduct systematic comparisons between human and AI estimation performance. In addition, a scatter plot was conducted using ME provided by survey participants and by all LLMs, respectively, to examine potential systematic patterns and biases.

Following the evaluation of AI-human performance on food weight estimation, inter-model evaluation across the 7 LLMs was subsequently performed. Scatter plots were employed to investigate and visualize potential error patterns, model-specific biases, and inter-model variability. Together, these quantitative and visual approaches provide a comprehensive framework for evaluating estimation performance and uncovering underlying trends.

In addition to food weight estimation, the accuracy of food recognition derived from image analysis was systematically evaluated. For each image, all LLMs generated not only quantitative weight estimates but also descriptive textual outputs identifying the food items present. These descriptions were subjected to a structured, line-by-line verification process conducted independently by the research team, using the image descriptions recorded at the data collection phase as reference and following a predefined evaluation protocol to ensure consistency and minimize subjective bias.

The verification protocol comprised multiple criteria: (1) exact keyword matching between model-generated labels and ground-truth food items; (2) category-level matching when exact identification was not achieved (e.g., classifying pain au chocolat as pastry rather than requiring exact naming); (3) partial item matching was considered failed recognition (e.g., identifying only “mushroom” when mushroom and chicken were present); (4) mismatches arising from cultural interpretation were assessed contextually, such that cross-cultural approximations (e.g., Chinese “jianbing” identified as a burrito) were accepted, whereas semantically inconsistent matches (e.g., pizza) were rejected; (5) generic meal-type descriptions (e.g., “breakfast” or “brunch”) were treated as failed recognition when not accompanied by correct food item identification; and (6) variations in cooking method were disregarded in recognition assessment, while misidentification of sauces, condiments, or liquids was excluded from error evaluation. This multi-criteria framework enables systematic assessment of semantic recognition accuracy while accounting for linguistic variability, cultural interpretation, and practical

tolerance thresholds in real-world food image analysis.

Inferential and agreement analyses were conducted alongside descriptive statistics. Preliminary examinations of absolute error distributions using histogram and Shapiro-Wilk test indicated that the absolute errors of all models distributed significantly from normality. Accordingly, non-parametric statistical methods were adopted for subsequent analyses. A Friedman test was first applied to assess overall differences in absolute estimation errors across models, followed by post-hoc Wilcoxon signed-rank tests with Holm correction to identify pairwise differences (Granato et al., 2013). To further examine performance structure, Wilcoxon rank-sum test and Spearman correlation (Granato et al., 2013) analysis were used to assess the relationship between portion size and estimation error. In contrast, formal inferential testing for human–AI comparisons were not performed due to the limited size of the subset sample, which restricts statistical power. Finally, inter-rater agreement for the food recognition evaluation protocol was assessed using Cohen's kappa statistic (Cooper et al., 2006; Wani et al., 2024), applied to a randomly selected subset of 100 observations drawn from the full dataset. The subset included 12 or 13 images from each LLM outputs, thereby providing balanced coverage across all models. The two volunteering raters, those are not involved in this work, carried out assessment independently according to the predefined six-criterion protocol and image descriptions. This allows for comprehensive model comparison, targeted diagnostic assessment, and validation of the subjective evaluation protocol.

4. RESULTS AND DISCUSSION

Since MAPE and MPE impose greater penalties on estimation errors associated with smaller portion sizes, thereby amplifying relative inaccuracies for images with low-weight food items. The sub dataset used for the human–AI comparative analysis contains food weights representing a relatively small portion size range – larger portion sizes were underrepresented in this comparison. Therefore, for results reporting, MAE was adopted as the primary performance indicator, supported with ME and SD for the insights of potential error patterns. Other metrics were provided only in the supplementary document.

4.1 Human-AI performance on food weight quantification

The following analyses are based on the subset of 9 selected images, for which both human and AI weight estimates were available. Based on MAE, more than half human participants outperformed AI models for small-portion food weight estimation tasks, with the top-performing LLM (Qwen3) ranking 31st. This result indicates that, under unconstrained real-world conditions, human visual judgment currently demonstrates superior accuracy on smaller portions compared to state-of-the-art open-source LLMs. This finding highlights a substantial performance gap between human cognition and AI-based inference in complex visual estimation tasks, particularly when precise quantitative judgment is required. This is aligned with the study of

Liu et al. (2025), who discovered that the accuracy of using the AI method to estimate the food weight – liquid food in a hospital environment – was lower than the visual estimation method. However, we must acknowledge that this comparison was conducted using on a subset of food images with small portion weights. Therefore, larger portion sizes were insufficiently evaluated. Additionally, all LLM outputs were generated without any task-specific fine-tuning or additional data training and relied solely on a standardized, minimal prompt, thereby reflecting the models' baseline performance for fairness evaluation in this study.

The SD metric reveals a markedly different consistency of estimation errors, with lower values indicating a more stable error pattern. At the individual level, 6 participants exhibited lower SD values than the top-performing LLM (Qwen3), however, when considering the overall performance across all participants, the mean SD of human estimations (SD=35.9) was higher than that of Qwen3 (SD=19.9), suggesting that, on average, Qwen3 tended to follow more systematic and structured error patterns than the human participants as a group. This behavior reflects a model-specific tendency toward consistent over- or under-estimation of the food weights across our sample dataset, such as systematic overestimation by Qwen3 (ME=36) and underestimation by Moondream (ME=-69.6). Compared to humans, whose estimations exhibit greater variability across individuals and images, AI models demonstrate stronger internal consistency, albeit with persistent directional bias.

Interestingly, all LLMs except Moondream overestimated the food weights, while humans tended to underestimate the weight in our study (Table 2) – the average ME value of all human estimations is negative (-11.6). The general overestimation of LLMs and underestimation of humans contrasts with the findings of the authors' earlier study, which used ChatGPT-4o of OpenAI for the same food-weight-estimation task (Yu et al., 2025) and a comparative study by Liu et al. (2025) – AI methods give underestimations while humans overestimate.

Furthermore, within this evaluated range, the superior human performance suggests that humans may possess a comparative advantage in visually estimating small food portions and dish sizes, a pattern also reflected in Figure 2. In contrast, current LLMs appear less robust in handling small quantities. However, given the restricted weight range evaluated, this finding should be interpreted as specific to the evaluated portion-size range rather than as evidence across the full dataset.

4.2 Inter-model evaluation on food weight quantification

Table 3 reports the comparative performance of the 7 LLMs using MAE, ME, and SD, based on the analyses of the full dataset unless otherwise specified. Qwen3 demonstrates the lowest estimation error (MAE=68.6), followed by Meta-LLaMA (MAE=110). These models outperform the remaining LLMs in absolute error terms, indicating comparatively stronger capacity in food weight estimation from images. Fridolfsson et al. (2025) report that proprietary

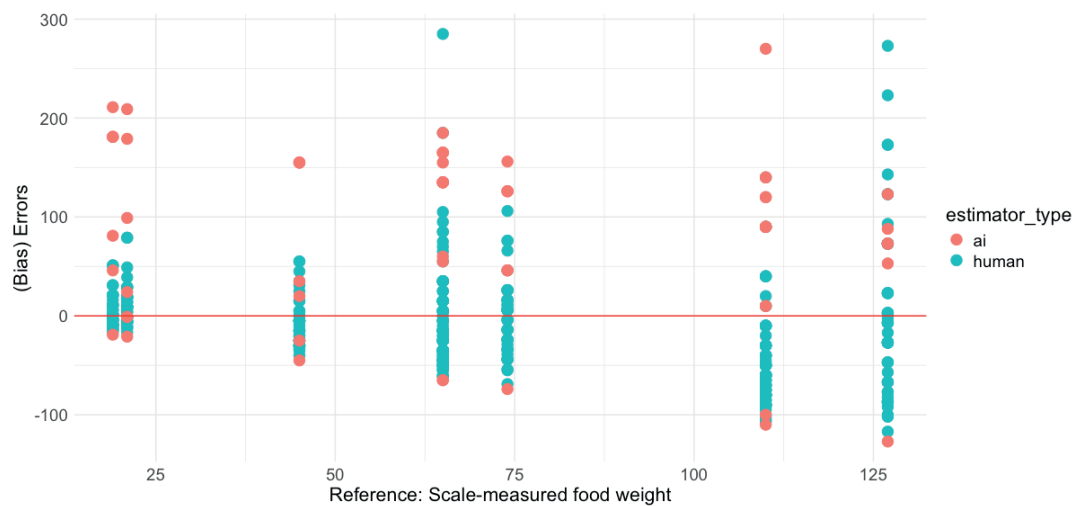


FIGURE 2: Scatter plot of human-ai estimation (bias) errors. Note: Bias Errors (BE) of each survey participant (blue points) and LLMs (red points) were plotted with the benchmarking reference weights measured by the scale.

models (e.g. ChatGPT-4o, Claude 3.5 Sonnet, and Gemini 1.5 Pro) achieve a MAPE of approximately 36-37% in FW estimation tasks. In comparison, the best-performing model (Qwen3) yields a MAPE of 66.5%, highlighting considerable higher estimation error under the present experimental conditions.

TABLE 3: Performance summary of food weight estimation by LLMs and human.

Model	MAE	ME	SD
(Based on the full dataset of 91 images)			
Granite	131.2	87.2	78.8
Internvl3	122.5	-12.3	106.7
Meta-LLaMA	110.0	64.4	80.0
Moondream	269.5	3.3	640.8
Qwen2.5	120.9	54.3	80.3
Qwen3	68.6	15.0	68.2
SmolVLM2	144.4	77.8	77.9
All LLMs	138.2	41.4	259.4
(Based on the sub dataset of 9 images)			
Granite	134.9	134.9	36.1
Internvl3	101.8	96.0	60.5
Meta-LLaMA	96.6	96.6	47.4
Moondream	69.6	-69.6	37.8
Qwen2.5	115.1	114.9	53.5
Qwen3	36.0	36.0	19.9
SmolVLM2	176.1	176.1	50.8
All LLMs	103.1	82.1	59.7
All humans	37.1	-11.6	35.9

Notes: The values of MAE, ME, and SD, which were calculated for all LLMs and all human participants, were calculated based on the pooled 7 x 91 estimates (637 observations of the full dataset for LLMs), 7 x 9 estimates (63 observations of the sub dataset for LLMs), and 52 x 9 estimates (468 observations of the sub dataset for humans). Abbreviations: MAE – Mean Absolute Error; ME – Mean Error; SD – Standard Deviation.

In terms of bias patterns, most LLMs continue to exhibit systematic overestimation of food weights, consistent with findings from the smaller subsample analysis. Internvl3 constitutes an exception with underestimations. The persistence of overestimation across models indicates structural challenges in estimating weight from two-dimensional images, particularly under heterogeneous real-world conditions.

Notably, SD values do not align perfectly with overall accuracy performance. While Qwen3, the top-performing model in this exploratory work, achieved the lowest SD, indicating the most consistent weight estimation pattern, other relatively accurate models did not necessarily exhibit lower SD values. This finding suggests that lower estimation errors does not always imply greater consistency in the distribution of errors.

Inferential analyses supported the descriptive comparisons of model performance. The Friedman test revealed significant differences in absolute estimation errors among the LLMs ($p < 0.0005$), indicating substantial heterogeneity in estimation performance. Post-hoc pairwise Wilcoxon signed-rank tests with Holm correction further showed that Qwen3 consistently achieved significantly lower errors than all other models (all $p < 0.0005$) (more details reported in the supplementary document). These findings correspond the descriptive results and confirm the superior estimation performance of Qwen3 in this inter-model evaluation.

To further examine the distributional patterns of estimation errors, a scatter plot (Figure 3) was used to visualize the relationship between the scale-measured food weights and AI-estimated weights across all LLMs. Except for Moondream with some outliers, all other models demonstrate a consistent downward tendency in the error distribution. This pattern indicates a systematic shift in estimation bias, where smaller portion sizes tend to be overestimated, while larger portion sizes are more likely to be underestimated. Such results suggest the presence of scale-dependent estimation bias in LLM-based weight inference from images.

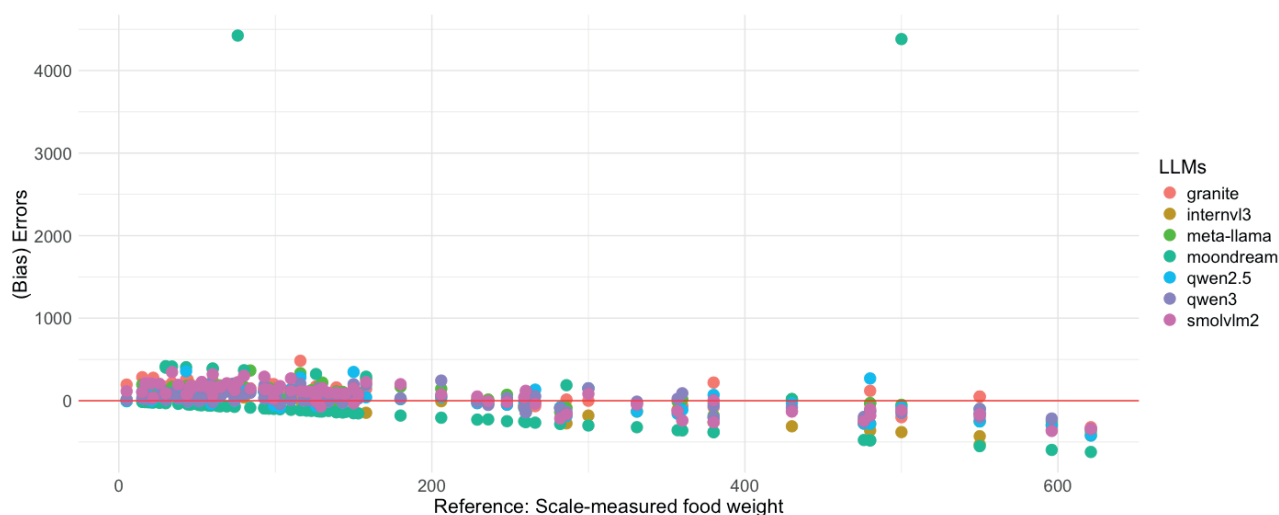


FIGURE 3: Scatter plot of AI estimation (bias) errors. Note: Bias Errors (BE) of each LLM were plotted with the benchmarking reference weights measured by the scale.

Given the observed relationship between estimation errors and portion sizes, model performance was further compared across small and large portions which were divided according to the average of scale-measured weight (160 g). Based on MAE, small portions exhibited lower absolute errors, with mean errors approximately 65 g smaller than those observed for large portions. In contrast, MAPE values were 173.3% higher for small portions, indicating substantially poorer accuracy. Wilcoxon tests confirmed that differences in both MAE and MAPE between the two portion-size groups were statistically significant (both $p < 0.005$). Moreover, the significant positive Spearman correlation observed for Qwen3 ($\rho = 0.41$, $p < 0.0005$) indicates that absolute errors tended to increase with portion size. These findings provide evidence that estimation performance is scale dependent. It also suggests that although LLMs achieved lower errors, but relative errors increased considerably for smaller portions, probably due to small denominators in the sample. This pattern partially agrees with Fridolfsson et al. (2025), who observed decreasing accuracy with increasing portions, but through the calculation of MAPE (20% to 30% approximately lower for small portions) rather than MAE.

Beyond portion size effects, dataset composition and image heterogeneity may also influence estimation performance. With the exception of Granite and Qwen2.5, which showed only minor MAE differences of 3.7 g and -5.7 g, respectively, when moving from the smaller subset to the full dataset, the remaining LLMs exhibited larger changes in MAE. In addition, all models exhibited increased SD values, indicating less consistent error patterns. Moondream showed the largest increases in both MAE (199.9) and SD (603). These results suggest that increasing image variability may negatively affect both accuracy and error consistency, raising concerns regarding the robustness and generalization of certain models.

Overall, the inter-model evaluation highlights substantial variation in predictive accuracy, bias structure, and robustness across LLMs. These findings underscore the importance of careful model selection and further mod-

el-specific calibration when deploying AI-LLM-assisted systems for FW quantification in real-world environments.

4.3 Inter-model evaluation on food recognition

Beyond quantitative differences in estimation accuracy, substantial qualitative variation was observed in the food recognition outputs generated by different LLMs. Models differed markedly in the depth and granularity of their image-based descriptions. Some LLMs produced highly detailed outputs, identifying specific food items, individual ingredients, cooking methods, and even distinguishing culinary styles or cultural origins – a similar pattern demonstrated in our earlier study (Yu et al. 2025). In contrast, others generated relatively basic descriptions, often limited to single-word labels or broad food category classifications (Table 4). The accuracy rates of the 7 LLMs range from 62.6% to 83.5%, with an average accuracy of 69.1%, which is notably lower than the performance observed (+98% accuracy rate) in our previous study using ChatGPT-4o for food recognition tasks (Yu et al. 2025). This difference suggests that model performance may vary depending on task complexity, dataset characteristics, model architecture and capacity.

Importantly, descriptive sophistication does not uniformly translate into higher weight estimation accuracy. While Qwen3 demonstrates strong performance in both detailed food recognition and relatively accurate weight estimation, other models achieve comparatively better numerical estimation despite simpler descriptive outputs or lower accuracy in food identification, such as Internvl3 and Qwen2.5. This pattern suggests that accurate semantic recognition and accurate food-weight estimation rely on partially distinct model capacities rather than a single underlying competence. Table 4 presents representative examples illustrating differences in descriptive depth and their relationship with estimation performance.

In addition, model accuracy was compared across the full dataset and its sub dataset in Table 5. At the aggregate level, difference in overall average accuracy was observed, with accuracy increasing slightly from 69.1% for the full dataset to 74.2% for the smaller subset sample. Internvl3, Me-

TABLE 4: Summary of LLMs in food recognition with their output examples and accuracy rates.

Detailed level of output	Model	Examples of description outputs	Accuracy
High	Qwen3, Meta-Llama	Pasta with dark sauce (likely mushroom or truffle-based); leftover cooked meat with mushrooms; Stir-fried cabbage with carrots and diced meat (likely pork or ham); Tom Yum soup (or similar Thai-style spicy soup)	~78% - 92%
Medium	Internvl3, Qwen2.5,	ground meat with nuts and raisins; stir-fried vegetables with meat; Instant Noodles	~63% - 69%
Low	Granite, Moondream, SmoIVLM2	pasta; Pastry; breakfast;	~62% - 71%

ta-LlaMA, and Qwen3 showed minor changes in accuracy rate, indicating relatively stable and consistent performance across both datasets, therefore a degree of robustness to sample size variation. However, Granite, Moondream, and SmoIVLM2 increased their accuracy rates by approximately 11.8%, 14%, and 12.4%, respectively, when applied to the smaller dataset. In contrast, Qwen2.5 experienced a decline in performance, with its accuracy rate decreasing by 9.3%. Moreover, model accuracy in food recognition was investigated between small and large portion-size groups – an evaluation with Wilcoxon test which was conducted to disclose the potential relationship between portion size and weight estimation errors. The results showed no significant difference in the accuracy rates ($p=0.43$) between the two groups.

Inter-rater agreement, calculated with Cohen's k statistic ($k = 0.817$, $p<0.0005$), indicates almost perfect agreement between the two independent raters, supporting the consistency of the six-criterion food recognition evaluation protocol and the evaluated results in this work.

In short, LLMs handle the tasks of food weight estimation and item identification with different capacities. While aggregate performance appears relatively stable, model-specific variability remains, underscoring the importance of inter-model evaluation and cautious model selection in AI-based food recognition and identification.

5. CONCLUSIONS

This study provides early empirical evidence on the application and comparative evaluation of open-source LLMs for FW quantification and recognition, addressing a critical gap in AI-enabled FW measurement and tracking research. Despite rapid advancements in AI applications across food science, empirical validation of AI-based FW measurement remains limited. By comparing AI-estimates, human judgments, and scale measurements under real-world conditions, this study contributes to methodological understanding of AI-based FW quantification and its practical limitations.

The findings suggest that AI-based FW measurement system, while promising some operational advantages, have not yet achieved reliability, in particular, small-portion FW quantification tasks in comparison to human visual judgement. However, AI-LLMs show stronger internal consistency and more structured error patterns, indicating a trade-off between accuracy and consistency. This implies

that AI systems may currently function better as decision-support tools rather than standalone measurement instruments in FW monitoring.

Error analysis reveals systematic bias and model-specific patterns. Most models exhibited a tendency toward over-estimation of food weights, while human estimators slightly underestimated. Furthermore, weight estimation accuracy is portion-dependent, with better performance observed for smaller portion sizes. Model performance in weight estimation and food recognition also varies across architectures and dataset configurations. Some models demonstrate stable generalization capabilities, while others are highly sensitive to image heterogeneity and dataset expansion.

Despite these limitations, AI-enabled FW quantification provides important opportunities for scalable sustainability monitoring. Open-source LLMs offer advantages in transparency, reproducibility, and customizable deployment for longitudinal FW tracking. AI systems can potentially support real-time behavioral feedback, policy evaluation, and automated waste monitoring across food consumption environments.

TABLE 5: Performance summary of LLMs in food recognition.

Model	Accuracy
(Based on the full dataset of 91 images)	
Granite	65.9%
Internvl3	65.9%
Meta-LlaMA	76.9%
Moondream	63.7%
Qwen2.5	64.8%
Qwen3	83.5%
SmoIVLM2	62.6%
All LLMs	69.1%
(Based on the sub dataset of 9 images)	
Granite	77.8%
Internvl3	66.7%
Meta-LlaMA	77.8%
Moondream	77.8%
Qwen2.5	55.6%
Qwen3	88.9%
SmoIVLM2	75.0%
All LLMs	74.2%

From a managerial perspective, AI-based FW monitoring can further support operational optimization in the food service sector, including portion design, consumer behavior interventions, and digital feedback systems. However, practitioners should avoid over-reliance on AI estimates. In this context, hybrid human–AI monitoring frameworks may provide more reliable FW management solutions.

This study has several limitations. First, the sample characteristics, although reflective of real-world conditions, remains limited in terms of item and photo-taking environment diversity, culinary representativeness, and weight or portion differences. While evaluating human-AI estimation in food weights, the dominance of small-portion samples within the subset may have contributed to the observed performance gap, representing a potential limitation of this sub-sample and warranting cautious interpretation of comparative results. Additional limitation concerns participant characterization when evaluating the human estimations. Factors concerning participants' familiarity with the food items and volumetric estimation tasks were not collected. These factors may influence human's visual food weight estimation performance and therefore represent potential sources of unexplained variability in the results. Second, 2D image-based estimation inherently restricts volume and depth inference. Future research should explore multi-modal AI architectures integrating depth sensing, IoT-based monitoring, and domain-specific fine-tuning. Comparative studies between human and AI evaluation should pay special attention to the potential portion-size effects and use sample with good representativeness when it is feasible. Furthermore, researchers could investigate the extent to which individual characteristics influence estimation accuracy, explore other open-source and proprietary models, as well as cross-cultural dietary datasets, are also necessary to improve generalizability. Third, the nature of this exploratory study should be acknowledged. As an initial investigation into the capabilities of LLMs for FW quantification, the current study intentionally did not impose highly standardized protocols, predefined or specific optimization procedures. This design choice reflects realistic conditions and provides a preliminary understanding, therefore serves as a foundation for further methodological development. Future research could incorporate standardized image acquisition procedures, the use of reference objects or predefined photographic area (e.g. fixed dimension and depth) for food weight estimation, and model fine-tuning strategies (e.g. specific-task training, refined prompt) to enhance the overall performance of AI-empowered food image analysis.

In short, this study provides foundational evidence on AI-enabled FW quantification while highlighting the methodological, technical, and practical challenges that must be addressed before large-scale deployment.

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UPCYCLING OF PAPER TOWEL WASTE – ENZYMATIC SACCHARIFICATION FOR A CIRCULAR ECONOMY

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ABSTRACT

The increasing demand for renewable carbon sources and the depletion of fossil resources highlight the need for sustainable solutions in the chemical industry. This study evaluates the potential of used paper towels as a feedstock for glucose production and subsequent biotechnological applications. A paper towel sorting and processing concept was developed for a model municipality. Pilot scale sample sorting was conducted to assess practical feasibility and impurity content. Targeted interventions in public facilities led to impurity levels below 1% (w/w) in some samples. Enzymatic saccharification with commercial enzyme blends achieved yields of up to 98.4% with unused paper towels under optimized laboratory conditions. At pilot scale, saccharification reached yields of up to 57%, mainly limited by mixing dynamics and microbial contamination. Sanitization reduced contaminants but did not completely prevent environmental microbial growth, leading to a reduction in saccharification time from 48 h to 24 h to improve energy efficiency. The resulting glucose syrups were tested as the main carbon source for the growth of five model microorganisms (*Saccharomyces cerevisiae*, *Escherichia coli*, *Lactobacillus rhamnosus*, *Cupriavidus necator* and *Penicillium verruculosum*). The results demonstrate that glucose from upcycled paper towels is broadly suitable and, in some cases, superior to laboratory-grade glucose for microbial fermentation, as the obtained syrups contain additional fermentable sugars, highlighting a promising pathway for sustainable carbon sourcing in the bioeconomy.

1. INTRODUCTION

Considering the global challenges posed by diminishing fossil resources and advancing climate change, bioeconomy has become increasingly vital for fulfilling the carbon demands of the chemical industry through the combination of a circular economy and upcycling processes (Verma & Jones, 2025). Key elements include carbon capture and utilization, recycling streams and biomass, focusing especially on the multi-use and long-term carbon sequestration of biogenic residues and waste materials (European Commission, 2020, 2025).

Among biomass streams, municipal solid waste is a material stream that largely avoids conflicts of use (fuel versus food) (Langsdorf et al., 2021; Volkmar et al., 2023). Due to its high proportion of over 94% of plant-based biomass, lignocellulosic biomass is a very powerful and primary resource (Pietzsch, 2017, p. 80). This natural composite of lignin, hemicellulose and cellulose

enables numerous value chains and products from non-food feedstocks such as biofuels, biosurfactants, organic acids and other chemical products (Du et al., 2026; Sulis et al., 2025; Volkmar et al., 2023). Their efficient production requires the separation of the three components, for which a series of pretreatment steps have been established (Nair & Verma, 2025; Segers et al., 2024). Due to this structural complexity, the focus for material utilization is on cellulose, as cellulose not only constitutes the largest proportion of plant biomass but, unlike the other two components, is a polymer with a regular structure that is enzymatically broken down by cellulases into its glucose monomers (Usmani et al., 2021). For the saccharification and biotechnological conversion of sugars from lignocellulosic feedstocks, main processes are distinguished as separate hydrolysis and fermentation (SHF), simultaneous saccharification and fermentation (SSF) or consolidated bioprocessing (CBP) according to the sequence of process steps (Verardi

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et al., 2023). The enzymes required for the lignocellulosic degradation can be added from an external source or simultaneously produced by suitable microorganisms on the same feedstock base (Jahangeer et al., 2025).

The feedstock selected in this study, paper towels, combines the characteristics of a widely available, largely unused fraction of the residual waste stream with a favorable material composition. Due to a comparatively homogeneous composition and a low-lignin content, as most of the lignin has already been removed during the pulping process, complex treatment steps are not necessarily required for material utilization (Naujock & Blechschmidt, 2021).

The continued use of paper towels as single-use items in public institutions, catering and trade has contributed to residual waste in public institutions, with approximately 70,000 tons generated annually in Germany (Euromonitor International, 2017). Despite separate collection in washrooms, these towels are typically incinerated with other residual waste, dismantling their cellulose backbone and releasing carbon dioxide. In contrast to this practice, used paper towels represent a promising, homogeneous and relatively clean waste fraction for repurposing.

Conventional recycling processes, as applied to paper and cardboard, are only practicable to a limited extent for paper towels. In contrast to e. g. standard writing paper, paper towels contain wet strength agents, which significantly hinder the disintegration of the paper towels and consequently complicate the recycling process (Federal Environmental Agency, 2023). In addition, existing take-back and recycling schemes for used paper towels, as selectively offered by companies such as Tork and Kimberly-Clark, are currently implemented only on a limited scale (Kimberly-Clark; Tork). In contrast, upcycling offers a promising alternative. The cellulose fibers can be enzymatically hydrolyzed into glucose, a versatile substrate for biotechnological processes, thus enabling the production of valuable compounds, such as bioplastic precursors, biosurfactants and organic acids. This contributes to meeting the demand for renewable raw materials without imposing any additional restrictions on the public, thereby enhancing the acceptance of sustainable waste management practices.

No specific methods for the enzymatic saccharification of paper towel waste as a standalone substrate have been described to date. In contrast, numerous established approaches exist for the processing and saccharification of lignocellulosic raw materials such as wood or straw, which generally require a combination of mechanical, thermal, and chemical pretreatment steps to remove lignin and increase enzyme accessibility (Kaltschmitt et al., 2016).

A recent study investigated the enzymatic saccharifiability of mixtures of beech wood cellulose and municipal biowaste. Beech wood sawdust was fractionated into cellulose and non-cellulosic components using an Organosolv process, while the biowaste was sterilized at 100°C for several hours prior to saccharification. The resulting hydrolysates were evaluated for their suitability as a substrate for the cultivation of the mould *Mucor*

indicus and the yeast *Saccharomyces cerevisiae*, as well as for their conversion to ethanol. This work, which follows a conceptually similar approach, underscores the potential of utilizing (ligno-)cellulosic residues and waste streams, particularly when considering regional feedstock availability (Rudnyckij et al., 2024).

Another recent study examined the valorization of paper towel waste fibers through their conversion into rigid board materials for potential building applications. Various manufacturing approaches and adhesive systems, including starch- and casein-based formulations, were evaluated, and the resulting panels were characterized in terms of their mechanical, thermal insulation, and moisture-related properties. While the developed materials exhibited promising insulation performance and mould behavior comparable to conventional wood-based products, their mechanical strength was insufficient for load-bearing applications. These findings highlight both the potential and the limitations of paper towel waste as a resource, emphasizing the need for alternative utilization pathways (Payne, 2023).

A further study investigated the chemical depolymerization of paper towel waste, focusing on the effect of organic carbonates during microwave-assisted digestion. The study utilized paper towel waste sourced from Hong Kong International Airport. (Dutta et al., 2020)

Another previous study investigated the enzymatic saccharification of various waste paper materials using cellulases derived from *Trichoderma viride*. The authors evaluated sugar release across multiple incubation periods and observed that most substrates exhibited their highest sugar yields during the initial stages of hydrolysis. Among the tested materials, brown envelope paper, foolscap paper and office paper showed comparatively high sugar yields, whereas other materials displayed lower conversion efficiencies. (Mokatse & van Wyk, 2021) These results demonstrate the general feasibility of enzymatic cellulose hydrolysis from paper-based waste and underline the strong influence of substrate composition and structure on saccharification performance. However, paper towels as a distinct waste fraction were not considered in that study, and systematic investigations into their enzymatic saccharification behavior remain lacking.

Against this background, the present study aims to explore the enzymatic conversion potential of used paper towels into glucose and assesses its suitability for selected biotechnological applications by evaluating the growth of relevant prokaryotic and eukaryotic production microorganisms. Furthermore, this study includes the development of a sorting strategy for paper towels using a model municipality. Since the development of a collection concept is highly dependent on specific regional conditions, it is not considered in detail within the scope of this study and should be adapted accordingly to the local circumstances. In contrast, the sorting concept for washroom waste is analyzed in greater detail, as the composition of washroom waste is assumed to be relatively consistent across different regions.

2. MATERIALS AND METHODS

2.1 Collecting and sorting concept

To develop a concept for the collection, sorting and transport of washroom waste in an example city of medium size (approximately 41,500 inhabitants), a cadaster of public facilities was initially established and a survey was distributed to the majority of public facilities within the model municipality. The survey addressed the categorization of the public facilities, methods of hand-drying employed in washrooms, the number of individuals using the facilities, annual paper towel consumption and the types or brands of paper towels utilized. The data collected was used to estimate the amount of washroom waste generated and served as a database for the planning of the logistics for paper towel collection in collaboration with the local waste management organization.

By collecting and manually sorting samples of washroom waste from several public facilities, the percentage by weight as well as the types of impurities were determined. To extend the storability of the paper towels for further experiments, the paper towels were air dried. In order to minimize impurities prior to collection, a notice was displayed in the washrooms encouraging the separate disposal of paper towels.

For the optimization of waste sorting from all public facilities within the municipality, a trial sorting was performed at a pilot-scale sorting facility. This procedure included sieving into four fractions (< 10 mm, 10-30 mm, 30-80 mm, > 80 mm) and the use of a near-infrared sensor.

2.2 Saccharification of paper towels

2.2.1 Enzyme analysis

Commercial cellulases derived from the fungal species *Trichoderma reesei*, as well as commercially available cellulase blends, were investigated for the saccharification of unused reference paper towels at a shaking flask scale. For characterization and comparison of the enzymes, total cellulase activity (including endo-, exo- and β -glucosidases) was assessed using the dinitrosalicylic acid (DNS) assay, which quantifies the release of reducing sugars. The test principle is based on a color change reaction from yellow to brown, as reducing ends generated by enzymatic hydrolysis of the carboxymethylcellulose (CMC) substrate react with dinitrosalicylic acid (Miller, 1959, p. 427).

After sampling, the supernatant was obtained by centrifugation at 21,130 x g for 15 minutes, followed by immediate transfer of the supernatant. For each sample, 250 μ L supernatant was mixed with 750 μ L of a CMC solution (1.5% in 0.3 M $\text{Na}_3\text{C}_6\text{H}_5\text{O}_7$ buffer, pH 4.5) and incubated at 50°C for 20 minutes. Subsequently, 500 μ L of DNS reagent (146.88 g/L $\text{C}_4\text{H}_4\text{KNaO}_6 \times \text{H}_2\text{O}$, 4 g/L Na_2SO_4 , 4 g/L phenol, 5.07 g/L 3,5-dinitrosalicylic acid, 10.19 g/L NaOH, brought up to 1 L with deionized water) was added. Each sample was boiled at 100°C for 5 minutes and immediately placed in an ice bath for 5 minutes. Photometric analysis was performed using a 96-well plate at a wavelength of 546 nm in a plate reader (Multiskan Go, ThermoFisher Scientific Inc.). For background absorption correction, a negative control was prepared for each sample by omitting the

incubation step at 50°C according to test instructions. A positive control was established using a standardized dilution of commercial cellulases from *T. reesei* (C2730 Sigma-Aldrich).

2.2.2 Saccharification parameters and by-product analysis

The saccharification experiments of the paper towels were conducted at three different scales: 100 mL shaking flasks (50 mL working volume), a 15 L reactor (7 – 10 L working volume), and a 1000 L pilot scale reactor (800 L working volume). For both commercially available cellulase blends and cellulases from filamentous fungi, optimal parameters, including temperature and pH, were determined using shaking flask experiments conducted with an orbital shaker at 100 rpm. Additionally, the optimal enzyme-to-substrate ratio and saccharification duration were assessed. Optimization of substrate load (mass of substrate per liter) was subsequently transferred to larger scales.

The optimal cellulase blend for paper towel saccharification was identified by comparing saccharification yields achieved with each blend under optimized conditions. pH stability in shaking flask experiments was maintained using a citric acid-phosphate buffer (0.452 g/L $\text{C}_6\text{H}_8\text{O}_7$, 0.752 g/L Na_2HPO_4 , pH 5.0) with paper towels cut into 1 x 1 cm pieces. In larger scale experiments, deionized water was used as the saccharification medium, with pH adjustments made using phosphoric acid and sodium hydroxide. For the 15 L scale, paper towels were cut into 2 x 2 cm pieces, while in the 1000 L scale, they were mechanically shredded and suspended in deionized water. For comparability, all experiments in the shaking flask and 15 L scales were performed with unused reference paper towels to determine optimal parameters. The saccharification of used paper towels was investigated at pilot scale. For the scale-up from 15 L scale to 1000 L scale, the focus was on optimizing process parameters to maximize the saccharification yield. The corresponding pilot trials were primarily conducted for process optimization rather than statistical validation. Therefore, each experimental condition was investigated only once ($n = 1$) also due to the limited number of pilot trials. An overview of the pilot process parameters is provided in Table 1. The first 1000 L pilot trial primarily served as a technical commissioning run for start-up and integration of the plant equipment (including interconnection of components, shredding technology for paper towels) and was not conducted under fully optimized process conditions. Consequently, the data obtained from this trial were not considered in the subsequent evaluation.

The solution of glucose hydrolyzed from paper towels was concentrated into a storage-stable glucose syrup (50-60% total sugars) using a falling film evaporator (70-90°C) as part of three pilot campaigns. The resulting syrup was utilized to investigate the suitability of hydrolyzed glucose as a component in fermentation media. In the third campaign, the hydrolyzed glucose solution was sterile filtered prior to concentration to remove any introduced contaminants. Pure cultures of selected contaminants

TABLE 1: Varied process parameters in 1000 L pilot scale.

Process parameters	First pilot scale	Second pilot scale	Third pilot scale
Substrate	Unused reference paper towels	Used reference paper towels	Mixture of different used paper towels
Temperature in °C	50	55	55
Enzyme-to-substrate ratio in % (w/w)	5.0	5.0	4.5
Substrate load in g/L	20	40	44

were identified for one hydrolysis by 16S rRNA gene sequencing using standard primers. This was performed by an external laboratory.

The saccharification yields of various unused and used paper towels were calculated based on the glucan content, as determined by acid total hydrolysis, but were adjusted to reflect that the theoretical maximum mass of releasable glucose exceeds the pure glucan mass due to the incorporation of water molecules when glycosidic bonds are cleaved during hydrolysis. Glucose quantification was carried out via high-performance liquid chromatography (HPLC). Potential by-products (e. g. acetic acid) that may form during saccharification were also analyzed via HPLC. The presence of metabolites resulting from possible contamination (ethanol, acetic acid and lactic acid) was also examined via HPLC. The HPLC system was equipped with an organic acid resin column (polystyrene-divinylbenzene copolymer, CS-Chromatographic Service GmbH, 300 x 8 mm) operated at 40°C. The mobile phase consisted of 0.004 M sulfuric acid and was delivered at flow rate of 0.8 mL/min under isocratic conditions. The injection volume was 10 µL, and the total run time was 30 min. Detection was performed using a refractive index detector. Sugars (glucose, cellobiose/sucrose, xylose/fructose) were quantified by HPLC using external standards for calibration. Sample concentrations were calculated from the corresponding calibration curves. Samples for HPLC analysis were centrifuged at 21,130 x g for 20 minutes and filtered through a 0.2 µm pore size membrane prior to measurement. The saccharification yield was calculated as described in Formula 1.

$$\frac{(\text{Released glucose [g]} \cdot 0.9) / \text{paper towel glucan content [g]} \cdot 100\%}{100\%} = \text{saccharification yield [\%]} \quad (1)$$

2.2.3 Sanitization

Since paper towels from washroom waste may be contaminated, particularly with fecal bacteria, spiking experiments using *Escherichia coli* (DSM 498) as an indicator organism were conducted to investigate under which sanitization conditions the fecal bacteria can be fully inactivated, thereby ensuring the hygienic safety of the waste.

For the spike experiments, an initial streak plate of *E. coli* was prepared on CCA agar (Sigma-Aldrich, CAS 1473387-52-8) for isolation of single colonies. Subsequently, a single colony was transferred into a 250 mL shaking flask containing 100 mL of medium composed of 5 g/L meat peptone and 3 g/L meat extract, and was cultivated at 36°C for 24 h. Afterwards, the saccharification setups (see Section 2.2.2) were spiked with 1 mL resulting *E. coli* culture. The incubation of the spike experiments was

conducted in a water bath at 50°C and at 70°C. Samples were withdrawn after 0.5 h, 1 h, 2 h and 24 h. To evaluate the inactivation of *E. coli* in the spiked saccharification experiments, serial dilutions of 1 mL samples from each setup were prepared using 0.154 M NaCl. Subsequently, 0.1 mL aliquots were plated on agar consisting of 5 g/L meat peptone, 3 g/L meat extract and 12 g/L agar-agar. The efficacy of inactivation was assessed by enumerating *E. coli* colonies following incubation of the plates at 36°C for seven days.

2.3 Suitability of hydrolysis glucose in fermentation media

To investigate the suitability of glucose syrup derived from paper towel saccharification as a universal energy and growth substrate, various biotechnologically relevant microorganisms were cultivated. The following microorganisms were tested: *Saccharomyces cerevisiae* (baker's yeast) as an ethanol producer, *E. coli* (DSM 498) for a diverse product spectrum, *Lactobacillus rhamnosus* as a producer of a precursor of bioplastic (polylactic acid), *Cupriavidus necator* (DSM 545) for PHA-production and *Penicillium verruculosum* (neotype strain, DSM 2263) as a representative for filamentous fungi like *Aspergillus niger* for citric acid production. The growth of bacteria and *S. cerevisiae* was determined by measuring the optical density at a wavelength of 600 nm (OD600). For the filamentous fungus, growth was assessed by biomass production via dry matter (DM) measurement after drying to constant weight at 105°C. Outliers were identified using Grubbs' test (two-tailed, significance level $\alpha = 0.05$) and removed in a single iteration. Statistical significance of differences between syrup-based media and the control was evaluated using Student's t-test (two-tailed, unpaired, significance level $\alpha = 0.05$, assuming equal variances).

S. cerevisiae was cultivated in 100 mL shaking flasks (working volume 50 mL) containing 15 g/L glucose and 5 g/L peptone from casein at pH 7.4, at 36°C for 24 h. *E. coli* was grown in a medium consisting of 0.001 M MgSO_4 , 0.0001 M CaCl_2 , 0.001 M filter-sterilized Thiamine-HCl x 2 H_2O , 2 g/L glucose, 6 g/L Na_2HPO_4 , 3 g/L KH_2PO_4 , 1 g/L NH_4Cl , and 0.5 g/L NaCl, at a pH of 7.4, at 36°C for 24 h (German Collection of Microorganisms and Cell Cultures GmbH, 2022). The cultivation of *L. rhamnosus* was performed in a medium containing 10 g/L peptone from casein, 10 g/L meat extract, 5 g/L yeast extract, 20 g/L glucose, 1 g/L Tween-80, 2 g/L K_2HPO_4 , 5 g/L sodium acetate, 2 g/L $(\text{NH}_4)_3$ citrate, 0.2 g/L MgSO_4 x 7 H_2O and 0.05 g/L MnSO_4 x H_2O , at a pH of 6.5, at 37°C for 48 h (German Collection of Microorganisms and Cell Cultures GmbH, 2007). *C. necator* was grown in a medium composed

of 10 g/L glucose, 4.3 g/L Na_2HPO_4 , 1.5 g/L KH_2PO_4 , 1 g/L $(\text{NH}_4)_2\text{SO}_4$, 0.2 g/L $\text{MgSO}_4 \times 7 \text{H}_2\text{O}$, 0.01 g/L $\text{CaCl}_2 \times 2 \text{H}_2\text{O}$, 0.06 g/L $\text{Fe}(\text{NH}_4)_2(\text{SO}_4)_2$ and 1 mL of a trace element solution consisting of 0.67 g/L $\text{CoCl}_2 \times 6 \text{H}_2\text{O}$, 0.03 g/L $\text{MnCl}_2 \times 4 \text{H}_2\text{O}$, 0.3 g/L H_3BO_3 , 0.01 g/L $\text{CuSO}_4 \times 5 \text{H}_2\text{O}$, 0.1 g/L $\text{ZnSO}_4 \times 7 \text{H}_2\text{O}$ and 0.0085 g/L NiSO_4 at a pH of 7.0 at 30°C for 72 h (Berezina, 2013, p. 193). *P. verruculosum* was cultivated in a medium containing 15 g/L glucose and 5 g/L peptone from casein with pH adjusted to 5.5, at 31°C for 144 h. All cultivations were performed using an orbital shaker. Agitation was maintained at 150 rpm for *C. necator* and at 100 rpm for all other cultures.

To assess the suitability of the glucose syrups derived from the pilot experiments for cultivation of the model organisms, the syrups were used as the main, but not necessarily the only, carbon source in place of laboratory-grade glucose. For comparability, the same cultivations were also conducted using identical media but with laboratory-grade glucose instead (control medium). Both the control medium and the media with the respective syrups were adjusted to the same initial glucose concentration. However, as a result of the varying viscosities of the syrups, it was difficult to accurately set the target glucose concentration. Due to the resulting deviations in glucose concentration between syrup-based media and controls, the increase in optical density or dry matter was normalized to the initial glucose concentration of each medium. For cultures grown in syrup-based media, the respective growth parameter was multiplied by glucose concentration of the control medium divided by glucose concentration of the syrup-based medium (factors ranging from 0.8595 to 1.3297). Glucose consumption during cultivation was verified by HPLC analysis, ensuring its utilization by the microorganisms for growth. Total sugar concentrations varied between media due to the presence of additional fermentable sugars in the syrup-based media and were not taken into account as the syrups were intended to substitute glucose rather than the entire carbon source. Non-glucose sugars were considered co-components, with glucose defined as the target substrate. Therefore, no negative control without glucose or syrups was included.

3. RESULTS AND DISCUSSION

3.1 Collection and sorting process

According to the conducted survey, paper towels were

identified as the predominant drying method in washrooms across most public facilities (90%) within the model municipality. A diverse range of paper towel brands and types was reported, reflecting variability in supplier selection among facilities. Within the model region, an estimated 71.2 tons of dry paper towels were used annually by approximately 41,500 inhabitants. This corresponds to a total washroom waste generation of 87.4 tons, of which 83.8 tons consist of moist used paper towels. Following sorting, 80.2 tons of moist used paper towels can be made available for saccharification across the entire model municipality. The paper towel waste used in this study consisted of samples totaling more than 150 kg.

Manual sorting of the collected washroom waste samples from volunteering public facilities indicated impurity levels ranging from 0.12% to 29.38% by weight. Notably, in almost one-third of these facilities, impurity levels below 1% (w/w) were observed, while approximately 58% exhibited impurity levels up to 12% (w/w) and approximately 8% showed impurity levels exceeding 12% (w/w). The implementation of washroom notices encouraging proper disposal practices appeared to have a positive effect on impurity content, resulting in a decrease from 2.17% (w/w) to 0.86% (w/w) in one participating facility. Common impurities included tissues, plastic packaging, cardboard rolls, and paper products (Figure 1).

In the pilot-scale sorting trials, sieving eliminated 0.33% (w/w) of the whole washroom waste. This fraction mainly consists of small impurities and small paper towel pieces. With the employed two-step near-infrared sorting, a paper towel loss of 4.3% (w/w) was observed, while the sorted fraction reached a purity of 99.6% paper towels by weight. A total of 91.0% (w/w) of existing impurities was eliminated from the sorted washroom waste. Despite the use of screening and near-infrared technology during trial sorting, additional measures such as wind sifting were identified as necessary to further minimize impurities. This was particularly important for eliminating rolling impurities, such as bottles, which tend to roll on the conveyor belt and thereby impede the sorting process. The required mechanical sorting can be effectively managed with existing technologies.

3.2 Saccharification of paper towels

The investigation of various enzyme blends revealed that the highest saccharification yield (98.4%) was

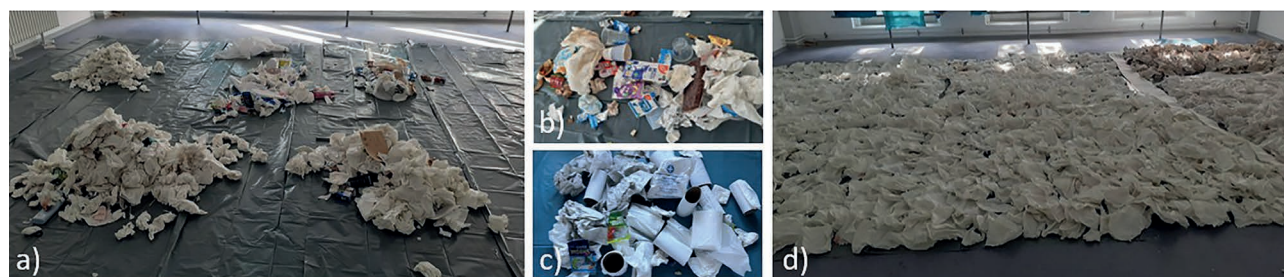


FIGURE 1: Manual sorting of a washroom waste sample from a participating facility into the target fraction of paper towels and the impurity fraction: a) unsorted washroom waste, b) and c) impurity fraction, d) target fraction of paper towels (laid out for drying).

achieved with one commercially available enzyme blend Novonesis Cellic® CTec3 HS under optimal process conditions with unused reference paper towels as substrate in shaking flask scale. Yields of up to 88.3% were attained by other commercially available enzyme blends. Although total cellulase activity was maintained constant across all assays, commercially available preparations derived from individual filamentous fungi generally exhibited lower efficiencies; for instance, saccharification yields of 46.4% and 70.8% were achieved with cellulase preparations from *Trichoderma reesei* from various suppliers/manufacturers. Furthermore, greater batch stability and broader pH tolerance were displayed by Cellic® CTec3 HS, representing significant advantages for industrial applications. All assays were analyzed after 48 h of saccharification.

In shake flask experiments, the optimal parameters for saccharification with Cellic® CTec3 HS were determined to be 55°C, pH 5.0, 100 rpm, 20 g/L substrate load, 5% (w/w) enzyme-to-substrate ratio and 48 h incubation time. Under these conditions, a maximum saccharification yield of $98.4 \pm 1.5\%$ ($n = 3$) was achieved with unused reference paper towels. Additionally, saccharification across 12 different paper towel brands was tested. Even the paper towels with the lowest saccharification yields reached 55.4% ($n = 2$) conversion rates under the aforementioned conditions.

As shown in Figure 2, on a 15 L scale, a saccharification yield of $63.3 \pm 2.8\%$ ($n = 3$) after 48 h and $56.9 \pm 1.5\%$ ($n = 3$) after 24 h was achieved under almost identical conditions except for stirring at 200 rpm and an increase of the substrate load to 40 g/L.

This reduction in saccharification yield from 98.4% in shaking flasks to 63.3% at the 15 L scale after 48 h is primarily attributed to altered mixing dynamics and contamination by environmental microorganisms, rather

than to the increase in substrate load. This assumption is supported by the observation that the substrate load could be increased to 40 g/L at the 15 L scale with only a slight reduction in saccharification yield of 3-5 percentage points.

For unused reference paper towels, the application of an additional sanitization step at 90°C prior to saccharification (for one or two hours) to combat microbial contamination resulted in only a slight increase in saccharification yield to $62.6 \pm 2.4\%$ ($n = 4$) after 24 h (in case of sanitization for two hours), which does not justify the substantial increase in energy expenditure. Especially considering that spike experiments demonstrated that prolonged treatment at 50 and 55°C during saccharification as well as short-term pretreatment at 70°C for 30 minutes were sufficient for complete inactivation of *E. coli*. Thus, an additional sanitization step was considered unnecessary from a purely hygienic perspective. However, since the growth of environmental microorganisms (particularly spore-forming species) was observed even with unused paper towels, and because a high microbial load can result in sugar depletion due to metabolization, this issue is expected to be even more pronounced with used paper towels, which exhibit a higher level of contamination. For this reason, sanitization was implemented at the pilot-scale for used paper towels despite the substantial energy requirements. Nonetheless, sanitization alone did not prove sufficient to completely prevent microbial growth during saccharification. Consequently, it was deemed necessary to reduce the saccharification duration from the optimal 48 to 24 h. The increase in sugar yield that could be obtained by extending saccharification for an additional 24 h was not sufficient to justify the additional energy required to maintain a temperature of 55°C during this period.

According to the data shown in Figure 3, after 24 h a saccharification yield of 58.6% was achieved in a 1000 L pilot-scale experiment with used reference paper towels

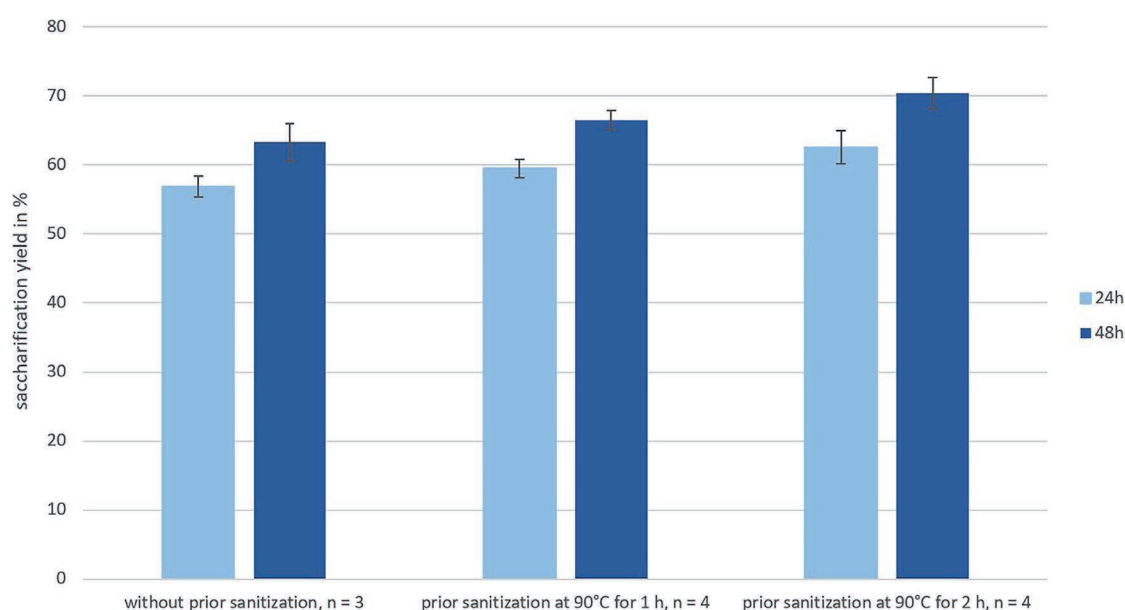


FIGURE 2: Effect of sanitization time at 90°C on the saccharification yield of unused reference paper towels after 24 h and 48 h (15 L scale). Conditions: 55°C, pH 5.0, enzyme-to-substrate ratio 5% (w/w), substrate load 40 g/L; yield expressed relative to glucan content.

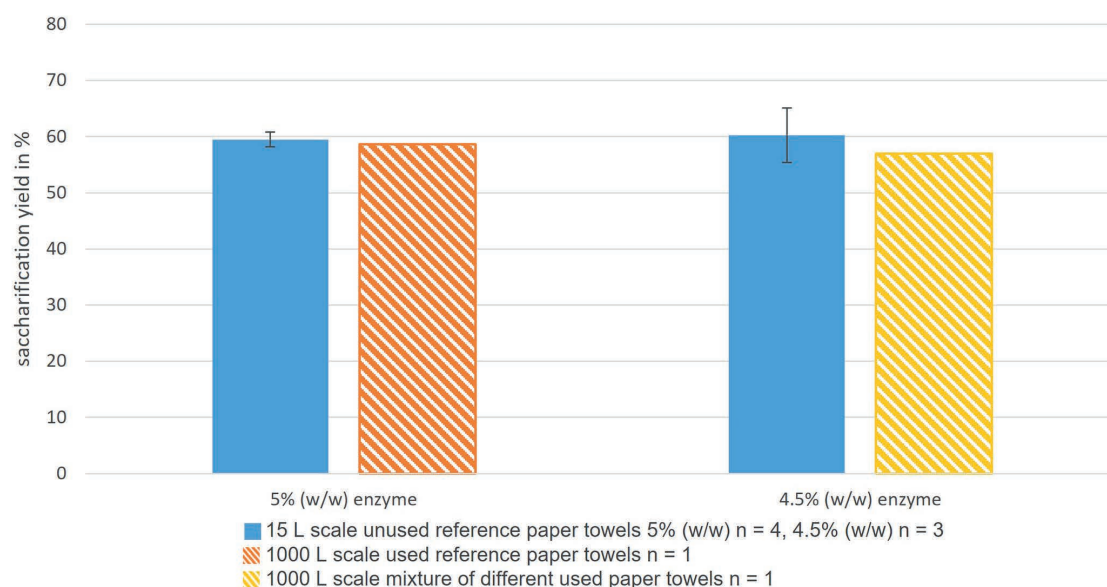


FIGURE 3: Saccharification yields of used and unused reference paper towels after 24 h of enzymatic hydrolysis at the 15 L and 1000 L scales (55°C, pH 5.0; 4.5% and 5% enzyme-to-substrate ratio; 40 and 44 g/L substrate load; prior sanitization at 90°C for 1 h).

as substrate (at 55°C, pH 5.0, 60 rpm, 40 g/L substrate load and an enzyme-to-substrate ratio of 5% (w/w)). Compared to the saccharification yield obtained at the 15 L scale ($59.5 \pm 1.3\%$, $n = 4$), no notable scale-up effect was observed. With a slightly elevated substrate load of 44 g/L and mixed-type used paper towels, a comparable saccharification yield could be achieved (57%), even when the enzyme-to-substrate ratio was simultaneously reduced to 4.5% (w/w). As shown in Figure 3, it was also confirmed at the 15 L scale that this 10% reduction in enzyme-to-substrate ratio did not affect the saccharification yield ($60.3 \pm 4.8\%$, $n = 3$).

Even after concentration of the glucose solution to a total sugar content of 50-60%, spore-forming environmental microorganisms could still be detected in the glucose syrup, indicating their survival under these conditions. However, no proliferation of these microorganisms was detected during storage of the syrups obtained from pilot-scale experiments 1 and 2. Proliferation was only observed after dilution to lower sugar concentrations. In order to further ensure the purity and stability of the product, the hydrolysate from the third pilot-scale experiment was subjected to sterile filtration before concentration. In total, three glucose syrups were produced during the pilot-scale experiments.

3.3 Suitability of hydrolysis glucose in fermentation media

To evaluate the suitability of the syrups, each microbial test organism was cultivated in media in which hydrolysis-derived sugars, primarily, but not exclusively, glucose (syrups 1-3), served as the main carbon source, and the results were compared to growth in control media containing laboratory-grade glucose. Figure 4 presents the final optical density or, for *P. verruculosum*, the dry biomass achieved under these conditions. The data was normalized

to the corresponding value obtained with media containing laboratory-grade glucose, which was set at 100%. For each organism, six biological replicates were performed.

Saccharomyces cerevisiae showed equal or slightly enhanced growth in all syrup-based media compared to the control. The strongest effect was achieved with syrup 1, resulting in $126 \pm 5\%$ of the control, which was statistically significant. Growth supported by syrup 2 and syrup 3 was close to that obtained with the control medium ($111 \pm 12\%$ and $100 \pm 9\%$, respectively), as the differences were not statistically significant. Variability across biological replicates remained relatively low, indicating robust utilization of the glucose syrup by the yeast. It should be noted, however, that the tested syrups contained additional sugars such as xylose/fructose and cellobiose/sucrose (Table 2), which were absent from the control medium. Since hemicellulose that is also present in paper towels is a polysaccharide composed of various hexoses and pentoses (Shinde et al., 2022, p. 2), and *S. cerevisiae* is capable of metabolizing sugars other than glucose (e. g. fructose and sucrose (Kaltschmitt et al., 2016, p. 1503)), the slight increase in growth in syrup-based media is likely due to the overall higher concentration of fermentable sugars. Nevertheless, the results clearly demonstrate that the hydrolysis-derived glucose syrups are well suited as main carbon sources for *S. cerevisiae*, as none of the three syrups exhibited any evidence of inhibitory components relevant for this yeast.

Escherichia coli exhibited a slightly different trend. Growth in syrup 1 and 3 ($115 \pm 4\%$ and $113 \pm 11\%$, respectively) significantly exceeded that in the control, while syrup 2 showed significantly reduced growth ($79 \pm 6\%$). Variability was low for syrups 1 and 2 but increased with syrup 3. These results suggest that *E. coli* can metabolize the hydrolysate sugars efficiently, although inhibitory impurities may be present in syrup 2, limiting performance.

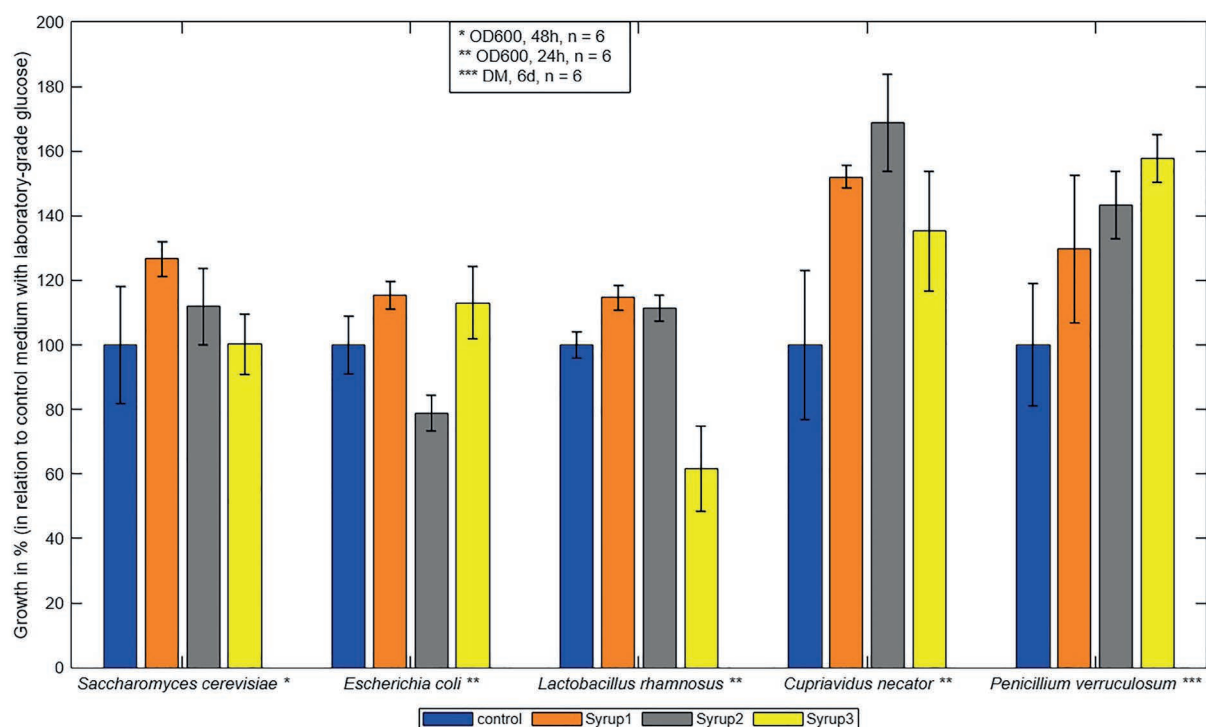


FIGURE 4: Relative growth of five microbial species cultivated with three syrup-based media compared to laboratory-grade glucose-based control media. Growth of *Saccharomyces cerevisiae* (48 h, OD600), *Escherichia coli* (24 h, OD600), *Lactobacillus rhamnosus* (24 h, OD600), *Cupriavidus necator* (24 h, OD600) and *Penicillium verruculosum* (6 days, dry matter). Values are expressed as percentage of the control medium (100%). Bars represent mean $\pm$ standard deviation (n = 6).

One inhibiting compound might be lactic acid that was found in the hydrolysis syrups and might stem from microbial contamination of the paper towels. Sequence analysis of contaminants revealed the presence of, among others, *Bacillus licheniformis*, *Paenibacillus thailandensis*, and *Bacillus smithii*, which are able to survive under the conditions prevailing during pretreatment and hydrolysis and are, in principle, capable of lactic acid formation (Chawla & Goyal, 2024, pp. 2-3; Khianggam et al., 2009, pp. 565–566; Zhao et al., 2024, 1-4). Lactic acid is known to have antimicrobial properties (Alakomi et al., 2000, p. 2001). However, these are mainly attributed to its undissociated form at low pH-values (Gonçalves et al., 1997, p. 350), whereas in the media used with *E. coli* the pH was adjusted to 7.4. Inhibitors could also originate from additives or wet-strength agents used during paper towel manufacturing. However, the chemical characterization and quantification of these additives was not included in this study and is not feasible given the variable composition of paper towel waste in terms of both the types and proportions of different components. Furthermore, the composition and

number as well as the amount of additives in mixtures of collected paper towels from real-world implementation are expected to vary considerably, since the proportions of paper towels from different manufacturers or brands can differ between collection batches. Since syrup 1 and 2 were derived from the same brand and type of paper towels, it is unlikely that manufacturing residues were the cause of the inhibited performance from syrup 2 compared to syrup 1. Moreover, the paper towels utilized for the hydrolysis leading to syrup 2 and 3 were used and therefore a similar level of contaminants was present for both.

Growth of *Lactobacillus rhamnosus* was significantly enhanced in media containing syrup 1 and syrup 2 ($115 \pm 4\%$ and $111 \pm 4\%$, respectively), whereas growth was significantly reduced with syrup 3 ($62 \pm 13\%$), accompanied by increased variance among biological replicates. These findings suggest that the composition of syrup 3 may negatively affect this lactic acid bacterium for one of the three potential reasons: due to inhibitory substances present in the various types of paper towels or contamination of the individual substrate sample tested or

TABLE 2: Sugar concentrations and density of the three hydrolysis syrups.

	First pilot scale	Second pilot scale	Third pilot scale
Glucose concentration in g/L	378.1	466.8	532.7
Cellobiose/sucrose concentration in g/L	23.8	18.2	26.7
Xylose/fructose concentration in g/L	100.9	111.2	158.8
Density in g/cm ³	1.21	1.26	1.34

the presence of the aforementioned lactic acid. However, at higher pH values, inhibition of *L. rhamnosus* is mainly caused by intracellularly accumulated lactate, rather than by extracellular lactic acid (Gonçalves et al., 1997, p. 350) as it is the undissociated form of lactic acid at low pH values that can penetrate cytoplasmic membranes (Alakomi et al., 2000, p. 2001). In this instance, an initial pH-related effect of lactic acid on *L. rhamnosus* can be ruled out, since all media were adjusted to a neutral pH. Compared to the other microorganisms tested a higher glucose concentration is necessary for *L. rhamnosus*. For this the syrups were diluted less than in the other media. It is therefore possible that *L. rhamnosus* is not necessarily more susceptible to the accompanying substances than the other microorganisms tested, but rather that the higher concentration of such compounds was the decisive factor. It should be noted that *L. rhamnosus* is only one representative for lactic acid bacteria. Therefore, no general conclusions regarding the growth of lactic acid bacteria on the syrup can be drawn from these results alone. As different representatives of this group of production microorganisms may vary in their sensitivity, it is generally essential to carry out suitability tests using the relevant strains.

In contrast, *Cupriavidus necator* exhibited statistically significantly improved growth with all syrups. Syrup 2 supported the highest increase ($167 \pm 15\%$), followed by syrup 1 ($152 \pm 4\%$) and syrup 3 ($135 \pm 19\%$). Since *C. necator* is known for its highly versatile metabolism (Le Zhang et al., 2022, p. 2), the aforementioned additional sugars present in the syrups (e.g. cellobiose/sucrose and xylose/fructose, and possibly other mono- and oligosaccharides) may contribute to the enhanced growth. Moreover, this pronounced stimulation suggests that the hydrolysis-derived syrups may also contain other growth-promoting compounds, possibly organic acids, as indicated by the detected lactic acid.

Penicillium verruculosum also showed enhanced growth and reached $129 \pm 23\%$ in syrup 1, $143 \pm 10\%$ in syrup 2 and $157 \pm 7\%$ in syrup 3, with growth in syrups 2 and 3 statistically significantly higher than in the control. The partially wide error margins observed may be a result of limitations in the robustness of biomass quantification at the small culture scale employed in this study. Based on the results, it can be assumed that no inhibitory compounds relevant to *P. verruculosum* are present in the syrups. On the contrary, the data suggest that the syrups may contain favorable accompanying compounds, e.g. additional sugars from hemicellulose or inactivated enzymes from the saccharification process, as *P. verruculosum* is able to metabolize not only glucose but a wide range of carbohydrates, organic acids, fatty acids, amino acids (Rabha & Jha, 2017).

4. CONCLUSIONS

This study demonstrates the suitability of repurposing used paper towels as a sustainable and efficient source of glucose for biotechnological applications. The development of a suitable sorting concept, consisting of sieving, wind sifting and two-step near-infrared

sorting, enabled a nearly pure paper towel feedstock for efficient enzymatic saccharification. Using Novonesis Cellic® CTec3 HS resulted in over 98% saccharification yields under laboratory conditions and satisfactory and reproducible conversion rates at both 15 L and 1000 L scales in stirring reactors (63.6% and 58.6% after 24 h with used reference towels), despite challenges such as mixing dynamics and environmental microbial contamination. While a decrease in saccharification yield was observed when scaling up from laboratory to 15 L scale, no further scale-up effects were detected between the 15 L and 1000 L scales, suggesting that the process can be scaled up further in stirring reactors. The slight difference in saccharification yield at the 15 L scale compared to the 1000 L scale can most likely be attributed to the change from unused reference paper towels in the 15 L scale to a mixture of different used paper towels (with a different composition compared to the reference towels) in the 1000 L scale. Additionally, it was demonstrated that the increase in substrate load to 44 g/L and reduction in enzyme-to-substrate ratio by 10% to 4.5% (w/w) can be achieved without significant losses in saccharification yield.

While *E. coli* as a fecal indicator can be completely inactivated during saccharification, the presence of spore-forming environmental microorganisms necessitates either a pretreatment of the paper towel waste or a posttreatment of the hydrolysate. However, a one-hour sanitization step at 90°C prior to saccharification alone was insufficient to control the contaminants. Given the need for additional contamination control measures, and considering the only marginal increase in saccharification yield observed with extended saccharification times, a process duration of 24 h was selected as optimal over 48 h, balancing energy consumption, process efficiency and microbial stability. In the third pilot-scale experiment, sterile filtration of the hydrolysate was implemented to completely eliminate any remaining contaminants in the product. Results from the 15 L scale with unused reference paper towels encourage the assumption that, when sterile filtration is employed, the initial sanitization step prior to processing can be omitted. However, this assumption has not been tested with used paper towels. Thus, further investigation is required.

The optimal parameters for saccharification of used paper towels at scales ≥ 1000 L were determined to be as follows: 1 h sanitization at 90°C, substrate load of ≥ 44 g/L, pH 5.0, 60 rpm, enzyme-to-substrate ratio of 4.5% (w/w), temperature of 55°C and a saccharification duration of 24 h.

In the growth experiments, the hydrolysis-derived glucose syrups (50-60% total sugar content) generally supported equal or improved growth compared to laboratory-grade glucose for most of the tested microorganisms, indicating good overall suitability as main carbon sources. In case of the metabolically versatile organisms, like *S. cerevisiae*, *C. necator* and *P. verruculosum*, that can utilize sugars other than glucose, enhanced growth might be due to additional fermentable sugars and other potentially growth-promoting co-components present in the syrups. Negative effects were limited to individual syrup-organism combinations and are most likely related to the presence

of inhibitory impurities and potentially to concentration effects arising from different dilution requirements, rather than to a fundamental incompatibility of the syrups. Overall, the syrups performed well in this growth analysis, but their variable compositions and organism-specific sensitivities underline the need for strain- and batch-specific suitability testing.

In summary, the findings highlight the potential of paper towel waste in local bioeconomy value chains, contributing to circular material flows and the generation of value-added biotechnological products. This approach offers a practical pathway for carbon upcycling, combining environmental benefits with high biotechnological potential that can be implemented with existing technologies.

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RECYCLING-ORIENTED IDENTIFICATION OF FOSSIL-BASED PLASTICS AND BIOPLASTICS IN PACKAGING WASTE USING HYPERSPECTRAL IMAGING AND HIERARCHICAL CLASSIFICATION

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ABSTRACT

The increasing use of bioplastics in packaging leads to their presence within conventional plastic waste streams, where even minor cross-contamination can compromise recycled material quality. Therefore, rapid and efficient material identification strategies are required to support high-purity sorting processes. This study evaluates the applicability of short-wave infrared hyperspectral imaging (SWIR-HSI: 1000-2500 nm) combined with chemometric and machine-learning approaches for the automatic classification of fossil-based plastic and bioplastic flakes from household packaging waste. Five fossil-based polymers commonly used for plastic packaging, i.e., polyethylene terephthalate (PET), high-density polyethylene (HDPE), polypropylene (PP), polystyrene (PS), expanded polystyrene (EPS), and three polylactic acid (PLA)-based bioplastics derived from disposable food packaging items were investigated. Hyperspectral images of the studied samples were acquired in the SWIR range and divided into calibration and validation datasets to develop and evaluate the proposed classification model. After spectral preprocessing, Principal Component Analysis (PCA) was used to explore class separability and guide the development of a hierarchical Partial Least Squares-Discriminant Analysis (Hi-PLS-DA) model. The proposed methodology achieved high predictive performance on the independent validation dataset, with sensitivity and specificity ranging from 0.96 to 1.00. Although conceived as a proof of concept, the proposed approach demonstrates the feasibility of combining SWIR-HSI with hierarchical chemometric classification for recycling-oriented identification of fossil-based plastics and PLA-based bioplastics, supporting the development of more effective sensor-based sorting strategies.

1. INTRODUCTION

The global increase in plastic production is associated with a substantial growth in plastic waste generation, with mismanaged plastic waste projected to nearly double by 2050 if current management practices remain unchanged (Pottinger et al., 2024). Alongside conventional fossil-based polymers, the packaging sector is progressively introducing bioplastics, often perceived as environmentally friendly alternatives, particularly for packaging materials and disposable items, in line with the European Packaging and Packaging Waste Regulation (PPWR) (European Commission, 2024). However, despite their growing adoption and potential as sustainable alternatives to traditional plastics, their actual environmental benefits and end-of-life management remain widely debated in the scientific literature (Lavagnolo et al., 2020; Cucina et al., 2021; Das et al., 2025). Furthermore, although recent European regulations

promote the use of compostable packaging for selected applications (European Bioplastics, 2025), the increasing diffusion of bioplastics raises additional challenges for waste management systems, particularly when these materials enter conventional plastic recycling streams, as even small contamination levels can compromise the quality of recycled materials (Alaerts et al., 2018). Materials Recovery Facilities (MRFs) therefore face increasing operational challenges. Traditional sorting strategies rely on the recognition of established polymer families, whereas the integration of bioplastics requires the introduction of additional material classes and updated decision logics to ensure reliable material recovery (Gadaleta et al., 2023). The introduction of bioplastics into existing municipal solid waste management systems may affect treatment efficiency, requiring appropriate sorting strategies (De Gisi et al., 2022). In practice, bioplastics that are intended to



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be collected with organic waste are frequently mis-sorted and may enter conventional plastic recycling streams (De Gisi et al., 2022). For this reason, their identification during sorting becomes important to prevent contamination and support appropriate waste management (Ulrici et al., 2013; McLauchlin et al., 2014; Cosate de Andrade et al., 2016; Alaerts et al., 2018). In this context, sensor-based sorting represents a key strategy to improve the quality of recovered plastic fractions, as it enables rapid, non-destructive and automated material identification directly along sorting lines. However, the increasing heterogeneity of post-consumer packaging waste makes material recognition more challenging. Spectral variability may arise from polymer formulation, color, thickness, surface roughness, additives, fillers, ageing, contamination and object geometry (Araujo-Andrade et al., 2021).

Among sensor-based sorting technologies, near infrared (NIR) and short-wave infrared (SWIR) optical detection is widely used for polymer recognition in recycling applications, while hyperspectral imaging (HSI) represents an advanced approach because it enables pixel-wise chemical characterization by simultaneously acquiring spatial and spectral information (Serranti et al., 2020; Araujo-Andrade et al., 2021; Bonifazi et al., 2025a). These sensor-based approaches enable rapid and non-destructive material characterization, supporting automated sorting operations in modern recycling facilities. Nevertheless, the high dimensionality of hyperspectral data and the spectral similarity among plastic materials require robust chemometric and machine-learning approaches to transform spectral signatures into reliable classification rules, as demonstrated in similar case studies (Tamin et al., 2021; Henriksen et al., 2022; Bonifazi et al., 2022, 2025b; Cheng et al., 2025; Li et al., 2025; Serranti et al., 2026). On this basis, the present work evaluates the applicability of SWIR-HSI (1000-2500 nm) combined with PCA-guided hierarchical classification strategy for the recycling-oriented identification of fossil-based plastics and PLA-based bioplastics in packaging waste flakes.

2. MATERIALS AND METHODS

2.1 Fossil-based plastic and PLA-based bioplastic samples

The investigated dataset consisted of plastic packaging waste flakes (approximately 1–5 cm in size) obtained by mechanical comminution of post-consumer household plastic packaging items commonly found in municipal waste streams. The samples exhibit a wide range of colors, including both transparent and opaque plastic materials (Figure 1). The total number of studied samples was 240 flakes, divided into:

- 150 flakes of fossil-based plastics from packaging, comprising 30 flakes of expanded polystyrene (EPS) sourced from food packaging, 30 flakes of polystyrene (PS) derived from yogurt cups, 30 flakes of polyethylene terephthalate (PET) sourced from water bottles, 30 flakes of high-density polyethylene (HDPE) from detergent bottles and food containers, and 30 flakes of poly-

propylene (PP) collected from rigid food containers.

- 90 flakes derived from three types of polylactic acid (PLA)-based bioplastic packaging items. These consisted of 30 flakes obtained from the comminution of PLA-based drinking cups (labeled as CUP), 30 flakes from PLA-based coffee capsules (labeled as CAP-SULE), and 30 flakes from PLA-based disposable plates (labeled as PLATE).

Figure 1a shows the samples used as calibration dataset, whereas Figure 1b shows the samples used as validation dataset.

2.2 Hyperspectral imaging acquisition

Hyperspectral images were acquired at the Raw Materials Laboratory (RawMaLab) of the Department of Chemical Engineering, Materials & Environment, Sapienza University of Rome, using the pushbroom Sisuchema XL™ Workstation equipped with the ImSpector™ N25E spectrograph (Specim, Spectral Imaging Ltd., Oulu, Finland). The imaging configuration consisted of a 15 mm lens providing a field of view of approximately 20 cm and a pixel resolution of 625 µm/pixel. The lighting was reproduced by applying a diffuse line illumination unit. The acquired hyperspectral images were automatically calibrated in reflectance using an internal reference standard before line-by-line scanning.

2.3 Data processing and performance evaluation

PLS_Toolbox (version 9.3, Eigenvector Research Inc.) operating in the MATLAB® environment (version R2024b, The MathWorks Inc.) was used for spectral preprocessing, exploratory analysis and classification modelling. Different pre-processing techniques and combinations of algorithms were tested to enhance relevant spectral information and reduce unwanted spectral variability, following the examples usually adopted in literature (Rinnan et al., 2009; Vidal and Amigo, 2012). Standard normal variate (SNV) was applied to reduce multiplicative scattering effects related to differences in particle geometry, surface roughness and illumination conditions (Eigenvector Research, 2021). Subsequently, a first derivative using the Savitzky–Golay method was applied to enhance spectral band resolution and reduce baseline-related effects, thereby reducing noise amplification (Eigenvector Research, 2019). In addition, the Gap Segment first derivative was evaluated as an alternative derivative algorithm. This method estimates the first derivative using spectral segments separated by a defined gap, reducing the influence of high-frequency noise while enhancing relevant spectral features (Eigenvector Research, 2013). Finally, mean centering was performed to center the variables, facilitating multivariate modeling by placing all variables on a common scale around zero (Eigenvector Research, 2011).

Principal component analysis (PCA) was chosen to perform exploratory analysis of class variability, to identify and remove outliers (Bro and Smilde, 2014).

Based on PCA insights, a hierarchical classification model strategy was developed to identify the eight target spectral classes: EPS, PS, PET, HDPE, PP, CUP, CAPSULE, and PLATE. A hierarchical classification approach is suit-

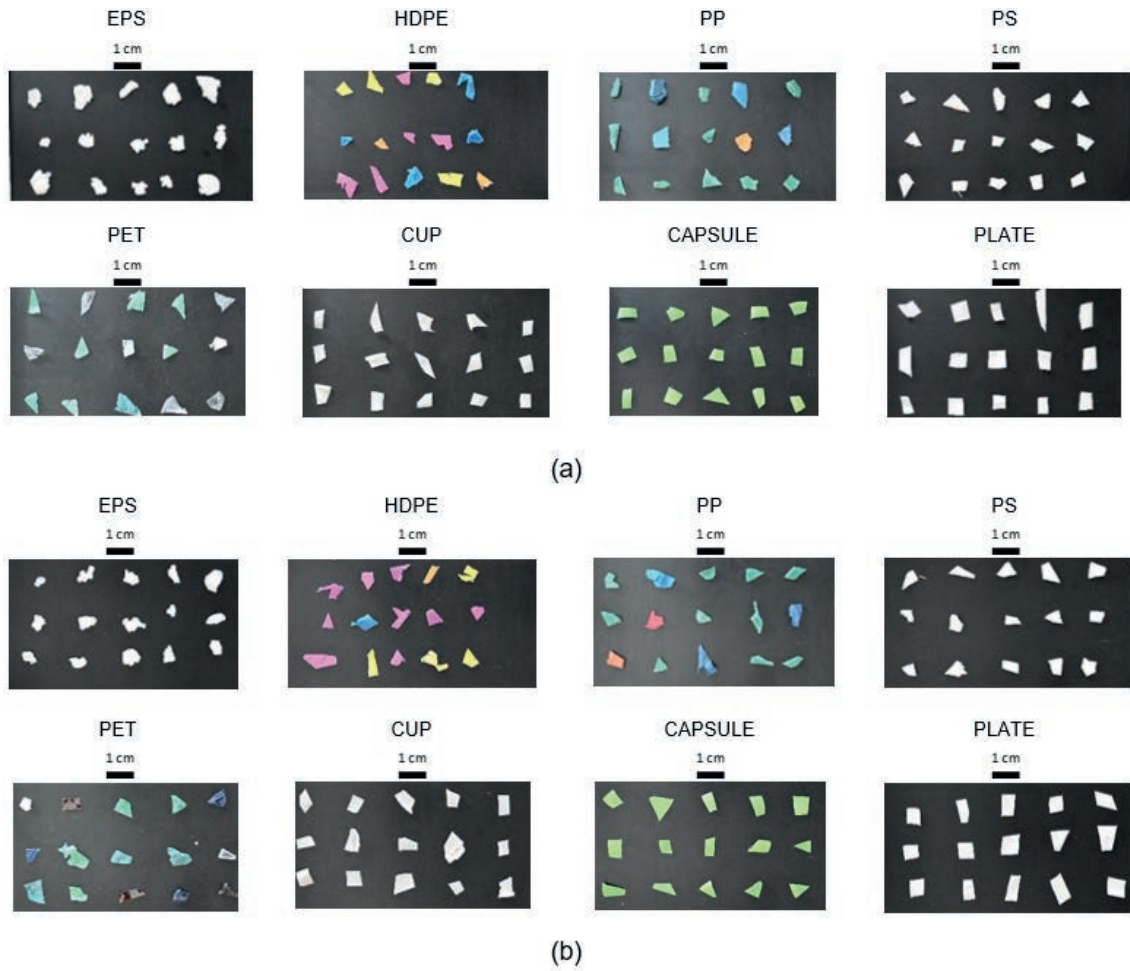


FIGURE 1: Source images of the samples used in this study and their corresponding labels (EPS, PS, PET, HDPE, PP, CUP, CAPSULE, and PLATE): (a) calibration dataset and (b) validation dataset.

able for datasets with many classes and similar spectral signatures, as it organizes the classification into successive levels, progressively separating samples from broad groups to individual classes (Bonifazi et al., 2025). Partial Least Squares - Discriminant Analysis (PLS-DA) was employed as the classification method at each hierarchical level. PLS-DA is a supervised technique that needs prior knowledge of the data (Barker and Rayens, 2003), which is based on the reduction of dimensionality through Partial Least Squares regression (PLS-R) with discriminating characteristics (Ballabio and Todeschini, 2009; Ballabio and Consonni, 2013). An additional class, labelled NC (Not Classified), was included to assign samples that did not meet the acceptance criteria for any predefined class, typically due to exceeding threshold values for Q-residuals or Hotelling's T-squared (T^2) statistic (Eigenvector Research, 2025).

The Venetian Blinds (with a number of data splits equal to 10) cross-validation method was chosen, in order to evaluate the complexity of models and to select the appropriate number of latent variables (LVs) (Eigenvector Research, 2024). Cross-validation was used mainly for model optimization, whereas the predictive capability of the final hierarchical model was assessed using the independent

validation dataset.

The classification performances of the model were reported in terms of class predicted member map and statistical parameters in calibration (Cal) and cross-validation (CV) phases: Sensitivity and Specificity (equations 1 and 2).

$$\text{Sensitivity} = \frac{TP}{TP+FN} \quad (1)$$

$$\text{Specificity} = \frac{TN}{TN+FP} \quad (2)$$

where TN (True Negatives) are correctly identified non-members and FP (False Positives) are samples incorrectly classified as members of the target class. Values approaching 1.0 for both metrics indicate a robust model (Eigenvector Research, 2018).

3. RESULTS AND DISCUSSION

3.1 Average raw and preprocessed reflectance spectra

Figure 2 shows the average raw reflectance spectra and the preprocessed spectra of the analyzed spectral classes. As observed in Figure 2a, the raw spectra exhibit distinct reflectance profiles within the SWIR range (1000-2500 nm),

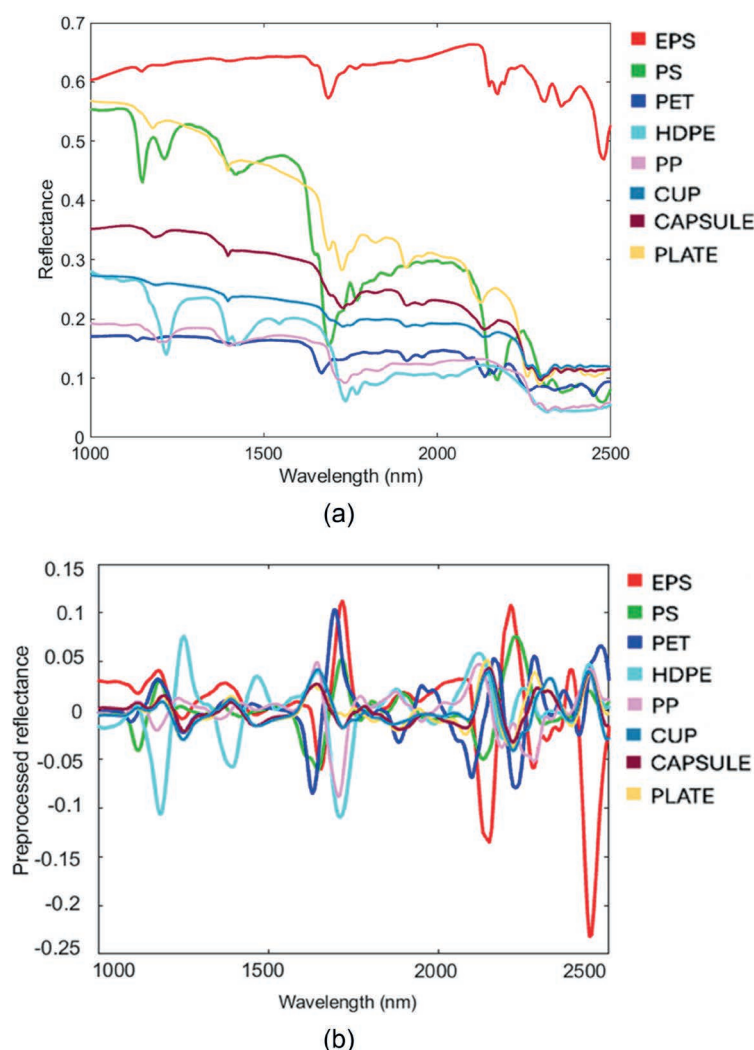


FIGURE 2: (a) Average raw and (b) preprocessed reflectance spectra of the investigated classes in the SWIR range (1000-2500 nm).

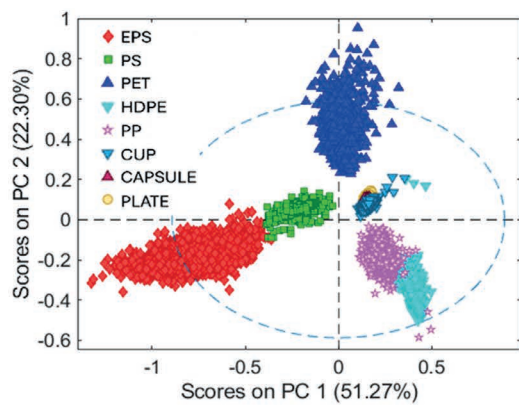
which are characteristic of each examined material. In this spectral region, the observed features are mainly related to overtones and combination bands of molecular vibrations involving C–H, O–H and C=O functional groups, which are commonly present in polymeric materials and/or associated additives and residues. In particular, variations in band position, intensity and shape across the investigated classes suggest differences in chemical composition, polymer structure and formulation, supporting the suitability of SWIR spectroscopy for material discrimination. Moreover, as illustrated in Figure 2b, the application of the combined preprocessing strategy (SNV, first derivative with a 5-point window and mean centering), enhanced these spectral differences by reducing scattering effects and emphasizing diagnostic spectral features, thereby improving the characteristic spectral fingerprints of the investigated polymers.

3.2 Hi-PLS-DA model building

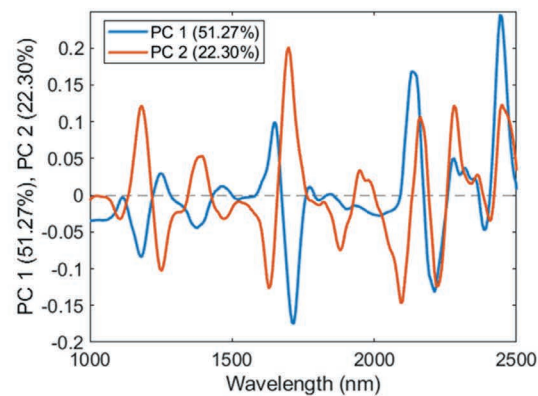
The architecture of the hierarchical PLS-DA model (Hi-PLS-DA) was directly supported by the exploratory PCA results obtained after evaluating different preprocessing combinations for each decision rule. As illustrated by the

PCA score and loading plots (Figure 3), specific preprocessing strategies enhanced the relevant spectral features and maximized the class separability required at each hierarchical level.

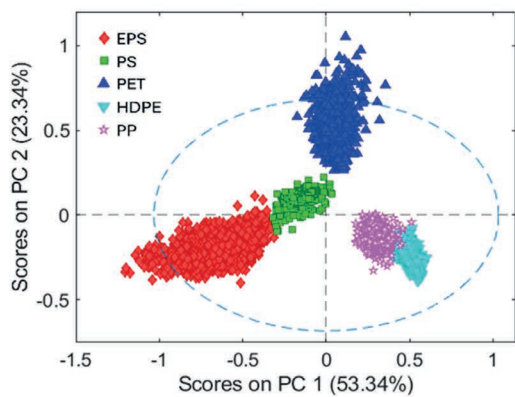
For Rule 1, the combination of SNV, first derivative (11-point window), and mean centering provided a clear separation between fossil-based plastics (EPS, PS, PET, HDPE and PP) and PLA-based bioplastics (CUP, CAPSULE and PLATE), as shown in the PCA score plot (Figure 3a), where PC1 and PC2 explained 51.27% and 22.30% of the total variance, respectively. The corresponding loading plot (Figure 3b) highlighted the spectral variables contributing to the observed class separation. For Rule 2, the same preprocessing strategy of Rule 1 revealed two well-defined spectral macro-groups corresponding to EPS/PS/PET and HDPE/PP, as shown in the PCA score plot (Figure 3c), where PC1 and PC2 explained 53.34% and 23.34% of the total variance, respectively. The corresponding loading plot (Figure 3d) highlighted the spectral variables contributing to the separation between these two macro-groups (EPS/PS/PET and HDPE/PP). For Rule 3, the combination of SNV, first derivative (15-point window), and mean center-



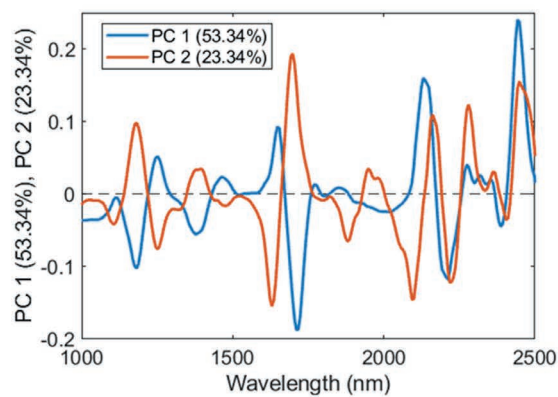
(a)



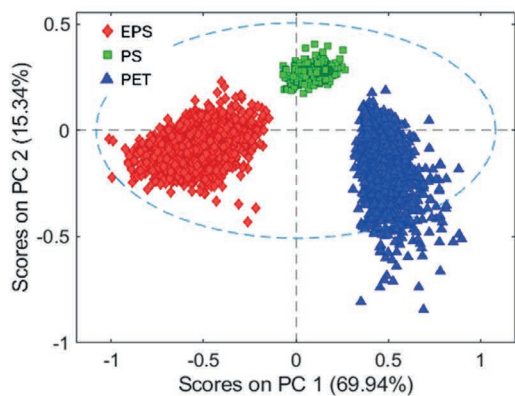
(b)



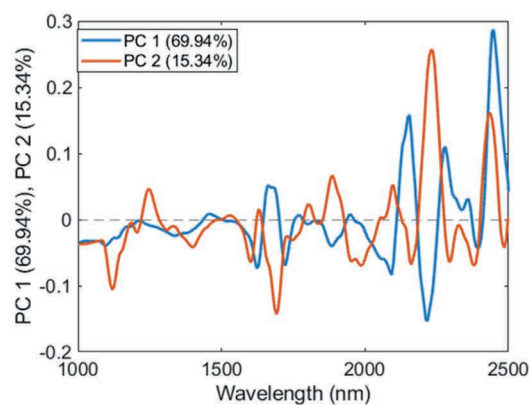
(c)



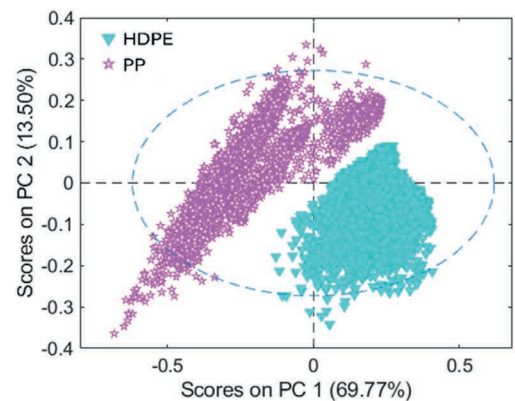
(d)



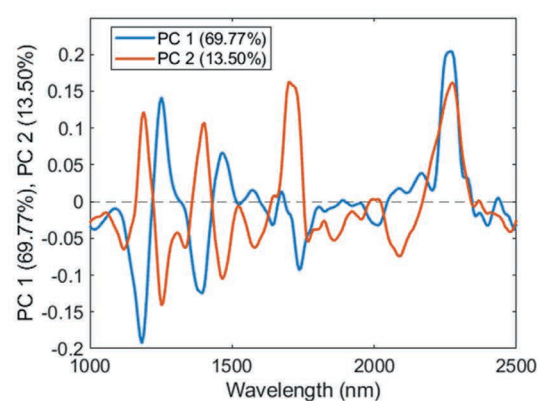
(e)



(f)



(g)



(h)

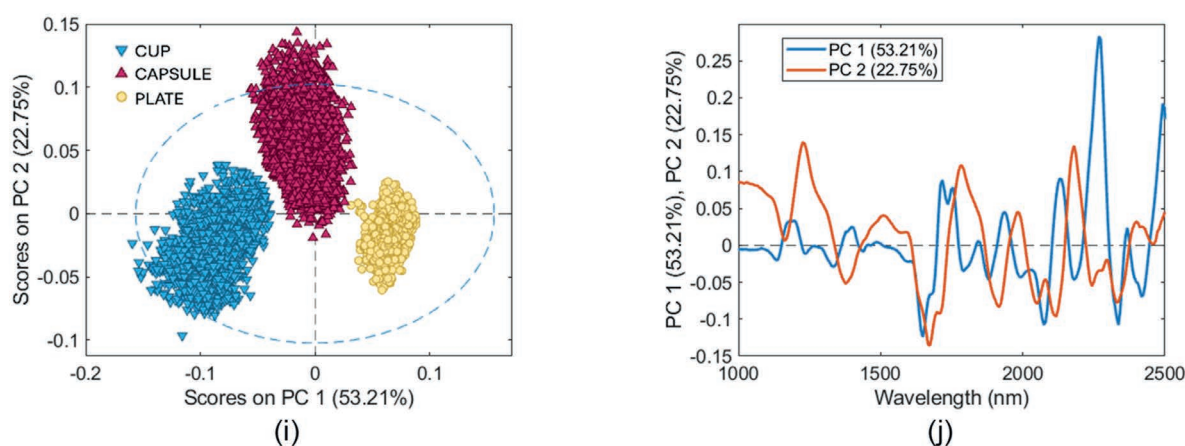


FIGURE 3: Exploratory PCA results obtained after applying the different preprocessing strategies selected for each hierarchical decision rule. (a) PCA score and (b) loading plots of Rule 1; (c) PCA score and (d) loading plots of Rule 2; (e) PCA score and (f) loading plots of Rule 3; (g) PCA score and (h) loading plots of Rule 4; (i) PCA score and (j) loading plots of Rule 5.

ing improved the discrimination among EPS, PS, and PET, as shown in the PCA score plot (Figure 3e), where PC1 and PC2 explained 69.94% and 15.34% of the total variance, respectively. The corresponding loading plot (Figure 3f) highlighted the spectral variables contributing to the discrimination among EPS, PS and PET classes. For Rule 4, the combination of SNV, first derivative (11-point window), and mean centering provided satisfactory separation between polyolefin classes, i.e., HDPE and PP, as shown in the PCA score plot (Figure 3g), where PC1 and PC2 explained 69.77% and 13.50% of the total variance, respectively. The corresponding loading plot (Figure 3h) highlighted the spectral variables contributing to the discrimination between HDPE and PP classes. Finally, for Rule 5, the combination of SNV, Gap Segment first derivative (gap = 5, segment = 5) and mean centering allowed effective discrimination among the three PLA-based bioplastic classes (CUP, CAPSULE and PLATE), as shown in the PCA score plot (Figure 3i), where PC1 and PC2 explained 53.21% and 22.75% of the total variance, respectively. The corresponding loading plot (Figure 3j) highlighted the spectral variables contributing to the discrimination among CUP, CAPSULE and PLATE classes, indicating that, although all samples were PLA-based, differences in formulation, additives, colour and/or product-specific characteristics contributed to their spectral separation.

Overall, the PCA results showed that tailoring the preprocessing to the specific discrimination task at each node improved class separability and provided the rationale for the hierarchical classification model implemented in this study.

Figure 4 shows the resulting hierarchical structure, in which a dedicated PLS-DA model is implemented at each decision node. An optimal number of two LVs was selected for all PLS-DA models. The model architecture was designed to reflect the progressive spectral separability identified during the exploratory analysis using PCA, and it was implemented as a sequence of successive decision rules, i.e., PLS-DA models, from Rule 1 to Rule 5. Samples not fulfilling the classification criteria at any decision level were

assigned to the NC (Not Classified) category. The resulting hierarchical structure is detailed as follows:

- Rule 1 was defined in order to provide 3 outputs: (i) fossil-based plastics (EPS, PS, PET, HDPE, PP), which are further classified through Rules 2, 3 and 4; (ii) bioplastics (CUP, CAPSULE and PLATE), which are further classified through Rule 5; (iii) NC.
- Rule 2 was defined in order to provide 3 outputs: (i) EPS, PS and PET, which are further classified through Rule 3; (ii) HDPE and PP, which are further classified through Rule 4; (iii) NC.
- Rule 3 was defined in order to provide 4 outputs: (i) EPS; (ii) PS; (iii) PET; (iv) NC.
- Rule 4 was defined in order to obtain 3 outputs: (i) HDPE; (ii) PP; (iii) NC.
- Rule 5 was defined in order to obtain 4 outputs: (i) CUP; (ii) CAPSULE; (iii) PLATE; (iv) NC.

3.3 Classification results

The class-predicted hyperspectral maps obtained using the Hi-PLS-DA model showed strong agreement with the expected polymer classes in the validation dataset (Figure 5). The model correctly discriminated fossil-based plastics and bioplastic samples, preserving their spatial distribution within the hyperspectral image. Comparison with the ground truth (Figure 5a), thus, confirmed the reliability of the classification, with misclassifications limited to a small number of pixels located mainly along sample edges (Figure 5b). In some cases, these discrepancies can be attributed to light-scattering effects and border effects at sample edges, which can lead to spectral mixing and alter the recorded reflectance signal at the pixel level. This behavior is commonly observed in pixel-wise hyperspectral classification, where boundary pixels may include mixed spectral information from the target material and the surrounding background or adjacent regions.

The statistical results reported in Table 1 confirm the high performance and stability of the hierarchical Hi-PLS-DA model across all decision rules, with very consistent values between calibration (Cal) and cross-validation (CV)

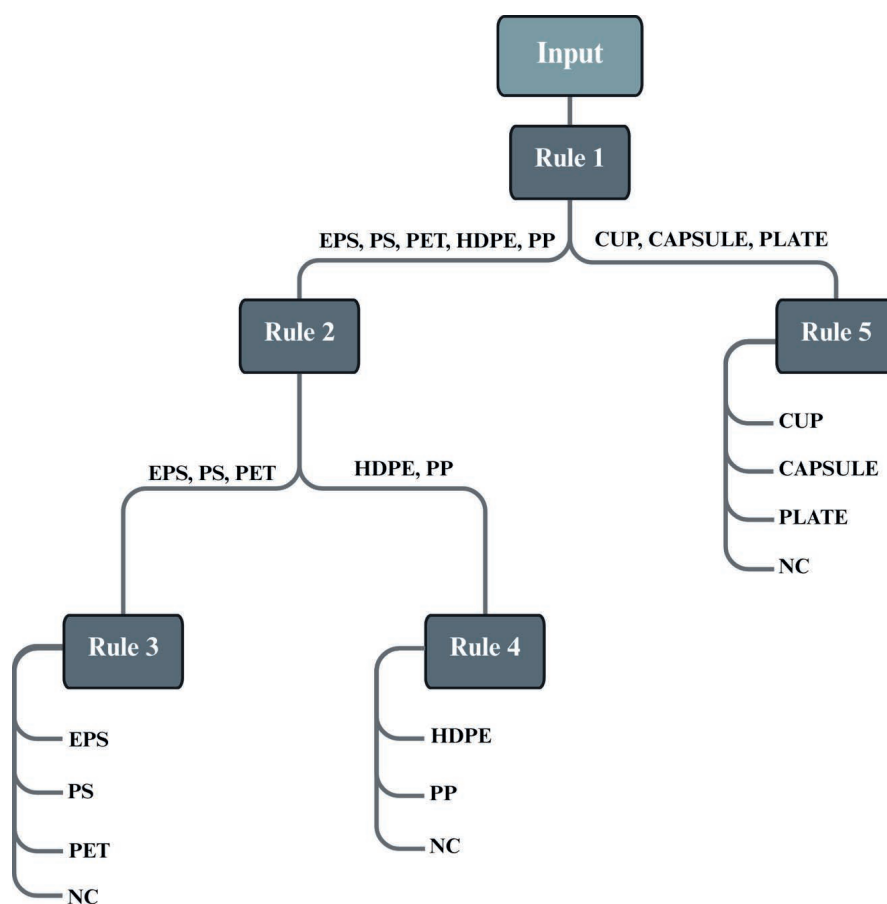


FIGURE 4: Hierarchical structure of the Hi-PLS-DA classification model, showing the five sequential decision rules. NC = Not Classified.

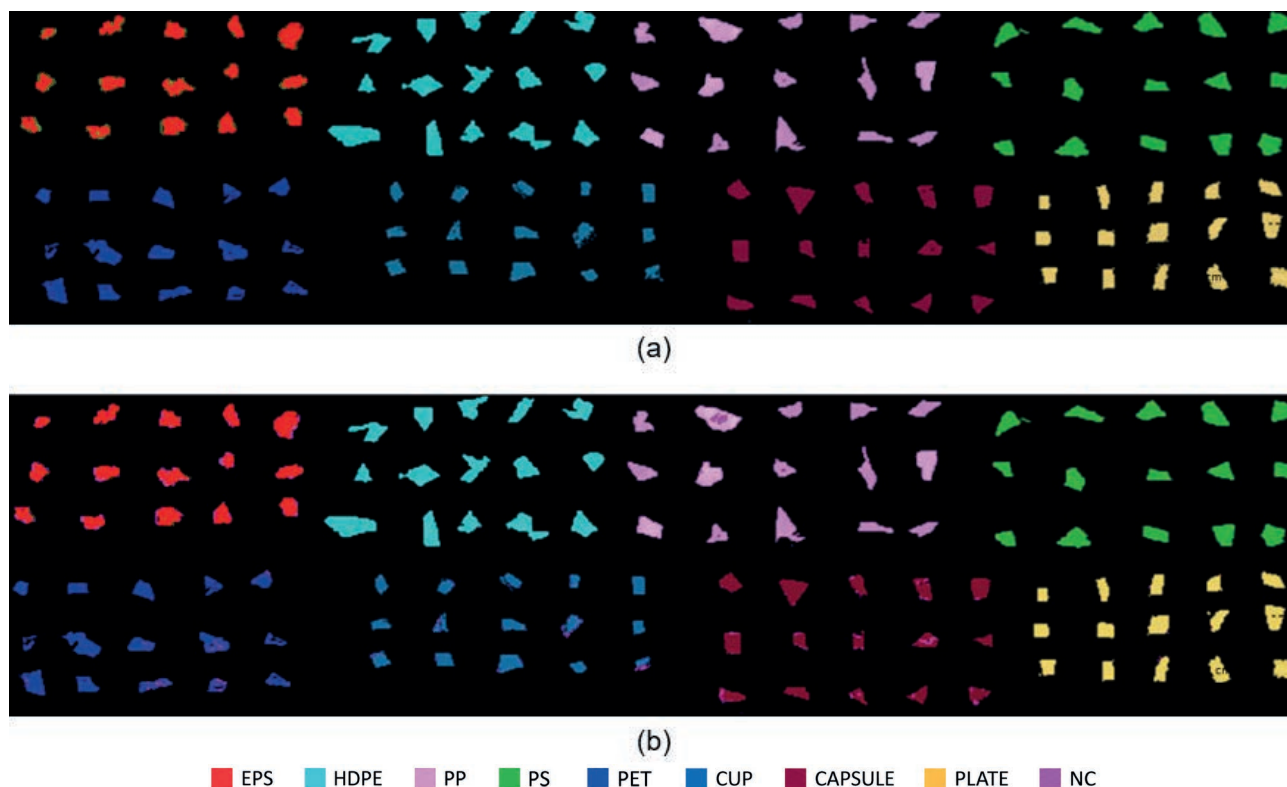


FIGURE 5: Validation dataset with (a) the expected classes and (b) the predicted classes obtained by Hi-PLS-DA. NC = Not Classified.

TABLE 1: Statistical parameters of calibration dataset from Rule 1 to Rule 5, in calibration (Cal) and cross-validation (CV) phases.

Rules	Classes	Sensitivity (Cal)	Specificity (Cal)	Sensitivity (CV)	Specificity (CV)
RULE 1	EPS/PS/PET/HDPE/PP	0.99	0.99	0.99	0.99
	CUP/CAPSULE/PLATE	0.99	0.99	0.99	0.99
RULE 2	EPS/PS/PET	1.00	1.00	1.00	1.00
	HDPE/PP	1.00	1.00	1.00	1.00
RULE 3	EPS	0.99	0.99	0.99	0.99
	PS	0.98	0.99	0.98	0.99
	PET	1.00	0.99	1.00	0.99
RULE 4	HDPE	0.99	0.99	0.99	0.99
	PP	0.99	0.99	0.99	0.99
RULE 5	CUP	0.99	0.97	0.99	0.97
	CAPSULE	0.98	0.98	0.98	0.98
	PLATE	0.99	0.99	0.99	0.99

phases. The results achieved for each rule are reported in the following.

Rule 1 provided high discrimination between PLA-based bioplastics and fossil-based plastics, with sensitivity and specificity values of 0.99 in both Cal and CV. Rule 2 achieved perfect classification (sensitivity and specificity = 1.00 in Cal and CV) for the discrimination between the two fossil-based macro-groups (HDPE/PP vs PS/EPS/PET). Rule 3, focused on the discrimination among EPS, PS, and PET, also showed very high performance, with sensitivity and specificity values from 0.98 to 1.00 in Cal and CV. Rule 4 achieved sensitivity and specificity values of 0.99 in both Cal and CV for the discrimination between HDPE and PP. Rule 5, related to the classification of PLA-based bioplastics (CUP, CAPSULE and PLATE), also exhibited high performance in Cal and CV, with sensitivity values between 0.98 and 0.99 and specificity between 0.97 and 0.99.

The prediction results obtained on the independent validation dataset (Table 2) further confirmed the robustness and generalization capability of the proposed Hi-PLS-DA model. Sensitivity values ranged from 0.96 to 1.00, while specificity values varied between 0.99 and 1.00. PET achieved perfect sensitivity (1.00), whereas PS showed the lowest sensitivity (0.96), although maintaining a specificity of 0.99. The remaining polymer classes exhibited sensitivity and specificity values equal to or higher than 0.98 and 0.99, respectively, demonstrating the excellent predictive

performance of the proposed hierarchical classification strategy.

Overall, the prediction results confirmed the capability of the proposed hierarchical Hi-PLS-DA model to accurately discriminate both fossil-based plastics and PLA-based bioplastics, as demonstrated by the predicted hyperspectral maps of the independent validation dataset and the corresponding statistical parameters.

4. CONCLUSIONS

This study demonstrated the feasibility of combining SWIR-HSI (1000-2500 nm), PCA-guided preprocessing optimization, and Hi-PLS-DA model for the discrimination of fossil-based plastics and PLA-based bioplastics in plastic waste flakes. The hierarchical classification strategy, designed according to the progressive spectral separability identified by PCA, enabled accurate polymer discrimination while maintaining high classification performance throughout the hierarchical decision process.

Although conceived as a proof of concept, the proposed methodology addresses an emerging challenge associated with the increasing diffusion of bioplastics in conventional plastic recycling streams. Reliable identification of these materials is becoming increasingly important to prevent contamination of fossil-based plastic recycling streams and preserve the quality of secondary raw materials from plastic packaging waste. In this context, the proposed workflow represents a promising methodological basis for the future development of optical sensor-based sorting strategies capable of managing increasingly heterogeneous plastic waste streams. This study focused on PLA-based bioplastic packaging products and did not cover the full range of commercially available biopolymers. Nevertheless, the high discrimination capability achieved among compositionally related PLA-based samples demonstrates the sensitivity of SWIR-HSI to subtle spectral differences associated with formulation, additives, and product-specific characteristics. These results provide a sound basis for extending the proposed approach to a broader range of commercially available biopolymers in future recycling-oriented sorting applications. Furthermore, this evidence

TABLE 2: Statistical parameters of validation dataset in prediction (Pred) phase.

Classes	Sensitivity (Pred)	Specificity (Pred)
EPS	0.99	0.99
PS	0.96	0.99
PET	1.00	0.99
HDPE	0.98	0.99
PP	0.99	0.99
CUP	0.99	1.00
CAPSULE	0.99	0.99
PLATE	0.99	0.99

suggests that SWIR-HSI, especially when combined with multivariate and hierarchical classification strategies, may represent a promising tool for extending the identification of biopolymer-based materials in recycling-oriented sorting applications.

Future work will focus on expanding the spectral library to include a wider range of commercial fossil-based polymers and bioplastic formulations, colors, additives, fillers, ageing conditions, surface contamination and real post-consumer materials. The evaluation of the proposed methodology under representative industrial sorting conditions will also be essential to assess its robustness and practical applicability, supporting the production of high-quality secondary raw materials by reducing cross-contamination between conventional plastics and PLA-based bioplastics during optical sorting.

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HOUSEHOLD AWARENESS AND PARTICIPATION IN E-WASTE MANAGEMENT IN NOVI SAD, SERBIA

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ABSTRACT

The rapid growth of waste electrical and electronic equipment (WEEE) poses a significant challenge for sustainable management, particularly in developing countries. Households play a key role in waste management as major consumers of electrical and electronic equipment and generators of e-waste. This study examines household awareness, practices, and willingness to participate in organized e-waste management in Serbia. An online questionnaire survey was conducted in Novi Sad. The results show that, although most respondents are aware of the hazardous nature of e-waste and the need for special treatment, regular participation in formal recycling remains limited. Storing old devices at home is a common practice, mainly due to insufficient information and a lack of accessible collection infrastructure. Despite this, a high willingness to participate in organized e-waste collection systems was identified. Household income significantly influences the willingness to financially support e-waste management, while age and education show no significant effect. The findings highlight the need for improved collection systems, strengthened awareness campaigns, and appropriate economic incentives to support e-waste management and circular economy objectives.

1. INTRODUCTION

Waste electrical and electronic equipment (WEEE) represents the fastest-growing waste stream worldwide, with an average annual growth rate of 6.5% between 2010 and 2019 (Bachér et al., 2017). The rapid spread of digital technologies has significantly changed the way people live, work, learn, communicate, and conduct business. With the growing use of electronic devices and improved connectivity in both urban and remote areas, the amount of electrical and electronic equipment (EEE) placed on the market has continued to rise (Baldé et al., 2024).

The rapid expansion has been accompanied by a significant increase in e-waste generation, which contains both hazardous substances and valuable secondary raw materials. In 2022, global e-waste generation reached a record of 62 billion kg, equivalent to an average of 7.8 kg per capita per year, while only 22.3% of this volume was formally collected and recycled in an environmentally sound manner. Over the same period, the amount of EEE placed on the market grew from 62 billion kg in 2010 to 96 billion kg in 2022, and it is projected to reach 120 billion kg by 2030 (Baldé et al., 2024). Although some progress has been made in improving formal collection and recycling

systems, the rapid growth of e-waste continues to exceed these efforts, underscoring the urgent need for more effective and sustainable WEEE management strategies.

E-waste is defined as electrical equipment that is no longer useful to the end-user and is discarded as waste. On the one hand, it can be considered a potential source of valuable base metals, such as iron, copper and aluminium and precious and rare earth elements (gold, silver, palladium and platinum) that can significantly contribute to material recovery and resource efficiency (Abdulaziz, 2022; Berežni, 2021). On the other hand, it also contains hazardous substances such as heavy metals, ozone-depleting substances, halogenated compounds and brominated flame retardants that pose a serious risk to human health and the environment if not properly managed (Banaszkie-wicz et al., 2022). Therefore, e-waste management needs to be prioritized.

The issue represents a serious and growing challenge in many developing countries where insufficient policies and environmental management systems, as well as inadequate infrastructure, limit the effective regulation of this waste stream. In the absence of sustainable waste management systems, landfilling remains one of the most widely used disposal practices. Hence, the collection, uti-

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lization, disposal and recycling of e-waste require a coordinated, multilevel approach where all stakeholders need to be involved. In this context, households play a crucial role, as they are directly involved in both consumption of electronic products and the generation of e-waste, making their awareness and participation essential for effective management strategies (Wang et al., 2017; Lim-Wavde et al., 2017).

Despite their critical role, household awareness and knowledge regarding proper e-waste handling remain limited in many developing countries. Accurate data on the quantities of e-waste generated are often unavailable and professional e-waste operators face significant challenges due to low public participation and unreliable collection systems. Household involvement is therefore a key factor in improving both the volume of e-waste collected and the overall efficiency of recycling programs. Understanding consumers' behaviour and attitudes toward e-waste disposal can provide valuable insights for enhancing recycling rates and optimizing the performance of e-waste recycling centres. Studies indicate that increasing consumer awareness has a direct positive effect on willingness to participate in recycling programs. Moreover, even in contexts where awareness is low, households in developing countries have demonstrated a willingness to pay for effective and environmentally sound e-waste disposal (Kitila et al., 2020; Borthakur & Govind, 2017).

The Waste Management Program of the Republic of Serbia for 2022-2031, as published in the Official Gazette of the Republic of Serbia (No.30/18), aims to reduce environmental pollution by minimizing waste generation and promoting the development of the circular economy. Managing e-waste remains a significant challenge and a key barrier to achieving circular objectives in Serbia (Waste Management Program of the Republic of Serbia 2022–2031). Improper e-waste disposal by consumers is still common and e-waste often ends up mixed with municipal waste. According to data from the Serbian Environmental Protection Agency from 2021 to 2023, the total amount of e-waste generated was 68,000 t, 81,000 t and 84,200 t, respectively. Of this, e-waste collected formally and recycled or reused amounted to 30,316 t, 34,532 t and 35,373 t for the corresponding years (SEPA, 2024), while the amount of informally collected e-waste is estimated at around 15,000 t per year (NALED, 2018). These figures suggest that a large portion of e-waste remains outside the formal system, potentially being disposed of improperly or untracked.

E-waste generated by households, businesses and public entities is collected by both formal and informal channels and transported to treatment facilities. While collection from businesses and public institutions is generally well-organized, there is no established system for household e-waste collection, leading to uncontrolled disposal and underscoring the importance of household participation in proper e-waste handling. Households' knowledge and awareness, as well as their behaviours in using, storing, disposing, repairing, and recycling electronic products play a key role in the effectiveness of e-waste management systems. Despite extensive research, significant gaps remain

in understanding household practices and their impact on circular economy outcomes. Raising public awareness and promoting responsible e-waste management at the household level can significantly improve recycling rates, increase material recovery, and mitigate the environmental impact of e-waste (Ofori & Mensah, 2022; ILO, 2025).

In this regard, this study focuses on analysing household behaviour, knowledge, and awareness regarding e-waste in Serbia. It examines the patterns of use of electronic devices, and the level of household understanding regarding the proper disposal and recycling of e-waste. In addition, the study explores the willingness of households to participate in e-waste collection and management initiatives, with the aim of identifying opportunities to improve recycling rates, enhance material recovery, and strengthen the overall efficiency of the e-waste management system.

2. STUDY AREA, MATERIALS, AND METHODS

This survey was conducted among households in Novi Sad. The city of Novi Sad is the second-largest city in Serbia with a population of over 300,000 inhabitants, and after Belgrade it represents the centre of economic development in the country. The structure of the economy is shaped by the existing industries mainly including trade, transport, and the processing industry. Although municipal waste collection coverage in Novi Sad is relatively high, the management of specific waste streams such as electrical and electronic waste remains underdeveloped. Increasing consumption of EEE, population growth and the absence of a proper collection system, combined with limited research on household awareness and practices regarding WEEE disposal in Europe make Novi Sad a relevant case for investigation.

This survey aimed to investigate knowledge and awareness levels related to e-waste and related issues among households in Novi Sad. Considering various survey methods and techniques, the authors decided to conduct the questionnaire online, due to the prevailing political circumstances and public protests in Novi Sad during that period. The questionnaire was administered online during the summer of 2025, and out of 209 received responses, 159 were complete and included in the analysis, resulting in a response rate of 76%. To ensure clarity and comprehension, the survey was carried out in Serbian, and the collected data were subsequently translated into English for analysis.

The questionnaire was developed based on previously published studies investigating household behaviour and awareness related to e-waste management and adapted to local conditions in Novi Sad (Borthakur & Govind, 2017; Banaszkiewicz et al., 2022).

The questions that made up the questionnaire were grouped into sections related to (a) demographic and socio-economic characteristics of respondents, (b) practices related to e-waste, (c) knowledge and awareness of e-waste and related environmental and health issues, and (d) willingness to participate in organized recycling models. The questionnaire consisted of 15 questions covering the four thematic areas described above. The questions

included closed-ended formats, such as yes/no and a multiple-choice questions, as well as multiple-response questions where respondents could select more than one option. The average time required to complete the questionnaire was approximately 10 minutes.

The collected data were stored and processed using Microsoft Excel. Descriptive statistical analysis was applied to summarize the demographic and socio-economic characteristics of the respondents, as well as their practices, knowledge and awareness related to electrical and electronic waste management. In addition, inferential statistical analysis was performed using the chi-square (χ^2) test to examine potential associations between selected categorical variables. The chi-square test was used to assess relationships between socio-demographic characteristics (such as age group and educational level) and household practices related to e-waste disposal, as well as respondents' willingness to participate in organized e-waste management. A significance level of $p < 0.05$ was used when analysing the data, and the results are presented in tables.

3. RESULTS AND DISCUSSION

3.1 Demographic and socio-economic features of study participants

Table 1 provides a summary of the demographic data of respondents. Of 159 respondents, 59% ($n=94$) were men while 41% ($n=65$) were women. The largest group in

terms of age was between 41-50 (31%), followed by those between 31-40 (28%). Participants aged 51-60 years accounted for 16%, while the youngest (21-30) and the oldest (above 60) were least represented, each comprising 13%. Most of the respondents were educated at the university level (79%, $n=126$), while 17% ($n=27$) had completed secondary education. Only a few study participants had primary education (4%, $n=6$).

As illustrated in Table 2, the majority of respondents were employed (91%, $n=144$), while smaller proportions were pensioners, students and unemployed. Regarding income, the largest share of respondents reported monthly incomes above €2,000 (34%, $n=54$), followed by those earning between €1,500 and €2,000 (28%, $n=45$) and between €1,000 and €1,500 (19%, $n=31$). Lower income categories were less represented, with 6% ($n=9$) reporting monthly incomes between €800 and €1,000 and 4% ($n=6$) reporting incomes below €800. Additionally, 9% of respondents ($n=14$) did not want to report their income.

The socio-demographic structure of the sample should be considered when interpreting the subsequent findings. In particular, the high proportion of respondents with university education may have influenced the observed levels of knowledge and awareness regarding e-waste. At the same time, the predominance of highly educated respondents indicates that the sample may not fully reflect the educational structure of the wider population of Novi Sad. Therefore, the socio-demographic characteristics of the re-

TABLE 1: Demographic profile of respondents ($n=159$).

Variable	Category	Frequency	Percentage (%)
Gender	Male	94	59%
	Female	65	41%
Age	Less than or equal to 30 years	20	13%
	31-40 years	44	28%
	41-50 years	49	31%
	51-60 years	26	16%
	Above 60 years	20	13%
Educational level	Primary	6	4%
	Secondary	27	17%
	University or above	126	79%

TABLE 2: Socio-economic profile of respondents ($n=159$).

Aspects	Components	Frequency	Percentage (%)
Employment status	Employed	144	91%
	Unemployed	3	2%
	Student	5	3%
	Retired	7	4%
Income	Below €800	6	4%
	€800 - €1,000	9	6%
	€1,000 - €1,500	31	19%
	€1,500 - €2,000	45	28%
	Above €2,000	54	34%
	Didn't want to answer	14	9%

spondents should be taken into account when interpreting the findings presented in the following sections.

3.2 Knowledge and awareness regarding e-waste

Figure 1 shows the results regarding the different sources of information about the collection and recycling of e-waste at the household level in Novi Sad. Respondents were allowed to select multiple sources. Among the various sources of information, internet was the most frequently mentioned (58%, n=93), followed by social media and friends (19% each, n=31 and n=30). The predominance of the internet and social media as sources of information suggests that digital communication channels may represent an effective tool for increasing public awareness regarding e-waste management. A notable proportion of respondents (33%, n=52) reported that they do not receive any information about e-waste.

Although 33% of respondents reported that they do not receive any information regarding e-waste, a majority demonstrated awareness of its management and associated risks. Specifically, 129 participants indicated that they are aware that it is prohibited to dispose of e-waste with other types of household waste, while 30 stated that they were not. Furthermore, 92% (n=146) reported that they are aware that e-waste contains toxic substances, while 88% (n=140) recognized the potential health and environmental risks arising from improper handling and disposal of e-waste. Finally, when asked whether e-waste requires special treatment before disposal, 125 agreed, while 34 disagreed. These findings suggest that despite gaps in information access, many participants demonstrate a reasonable level of knowledge regarding the safe management of e-waste (Table 3).

Overall, these findings indicate a relatively high level of general awareness of the potential risks associated with e-waste among the surveyed households. However,

awareness was somewhat lower regarding the need for special treatment and the prohibition of disposal together with household waste than regarding the presence of hazardous substances and associated environmental and health risks. This difference suggests that general knowledge about the harmful characteristics of e-waste does not necessarily imply equally strong knowledge of appropriate disposal requirements. Therefore, future awareness-raising activities should not focus only on communicating the hazardous nature of e-waste, but should also provide clear and practical information on appropriate disposal methods and available collection options.

3.3 Current practices and storage of electronic devices

The results indicate varying levels of engagement in e-waste recycling among participants (Table 4). Only 16% of participants reported that they always recycle electronic devices, while the majority (51%) stated that they do it occasionally. Moreover, the fact that 33% of the participants reported never handling electronic devices for recycling suggests that regular participation in formal recycling programs remains limited.

Figure 2 shows various alternatives that participants selected for handling and disposing of electrical and electronic devices. The same percentage of respondents reported storing their e-waste at home and/or repairing their devices (40%). It is important to note that respondents could select multiple options, indicating that individuals often use a combination of disposal methods. Donation of e-waste to others was also common (34%), with 30% giving it to informal collectors and 21% to authorized collectors. Discarding e-waste together with household waste was reported by 27% of respondents, while the least common practice was returning devices in retail stores (7%).

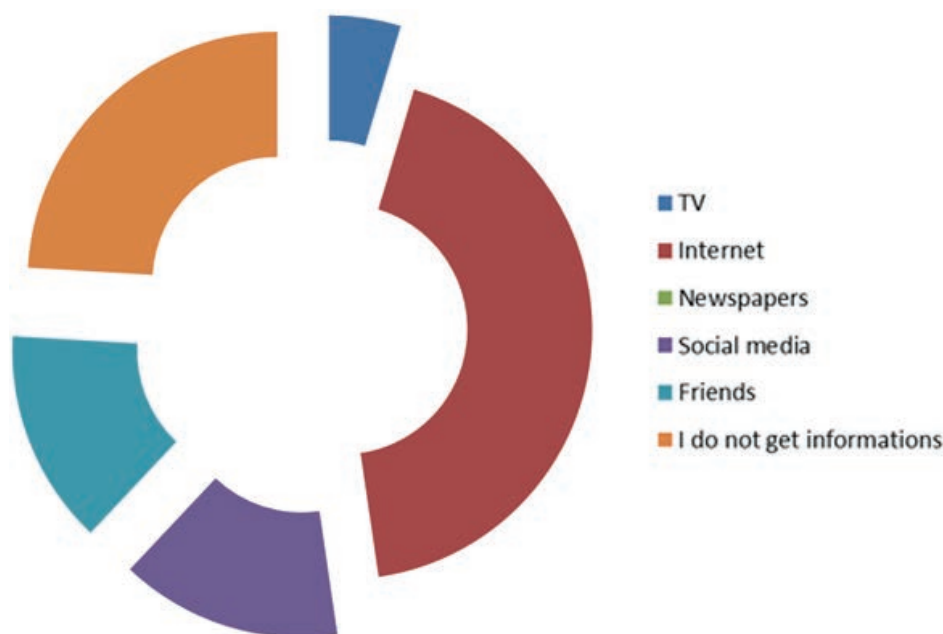


FIGURE 1: Sources used by respondents for information about e-waste.

TABLE 3: Statements on e-waste awareness among the study respondents (n=159).

Statements	No	Yes
Are you aware that it is prohibited to dispose of e-waste with other types of household waste?	30 (19%)	129 (81%)
Do electrical and electronic products contain hazardous substances?	13 (8%)	146 (92%)
Are you aware that e-waste requires special treatment before disposal?	34 (21%)	125 (79%)
Are there health and environmental risks associated with improper handling and disposal of e-waste?	19 (12%)	140 (88%)

TABLE 4: Statement on e-waste recycling.

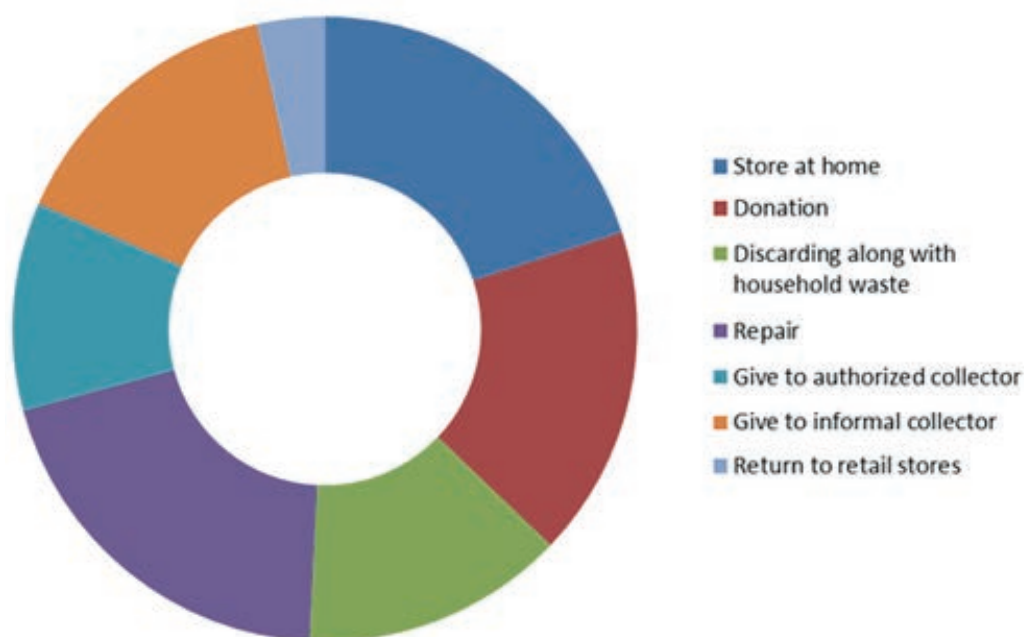
Statement	Always	Sometimes	Never
Do you recycle your electronic devices?	25 (16%)	81 (51%)	53 (33%)

The relatively high proportion of respondents reporting device repair and giving devices to others highlights the importance of life-extension strategies in household e-waste management. Repair can extend the useful lifetime of electrical and electronic equipment and delay its transition to the waste stream, while handing functional devices down to family members, friends or other users can support reuse. From a circular economy perspective, repair and reuse are important alternatives to immediate disposal and recycling because they preserve the functional value of products for a longer period and may reduce the demand for new electrical and electronic equipment. Therefore, recycling should not be considered the only desirable management option, as repair and reuse may represent preferable pathways when devices remain functional or can be restored.

However, storing unused devices at home may represent different underlying behaviours. Temporary storage may be associated with intentions to repair a device, use it

again in the future, or pass it on to another user. In contrast, prolonged storage may delay the recovery of valuable materials and keep devices outside formal reuse and recycling pathways. In the present study, the main reported barriers to disposal were insufficient information about where to take e-waste and the lack of nearby disposal points, suggesting that home storage may often result from limited access to convenient collection options rather than representing an intentional long-term management strategy.

An important finding is that 27% of respondents reported disposing of electronic devices together with household waste. This practice represents an incorrect disposal pathway and is particularly relevant given that the majority of respondents were aware that e-waste contains hazardous substances and may pose environmental and health risks. The results therefore suggest a potential gap between knowledge and actual disposal behaviour. Environmental awareness alone may not be sufficient to ensure appropriate e-waste management when households lack convenient collection options or clear information about available services. The improper disposal of e-waste through the municipal waste stream may result in hazardous components entering inappropriate waste treatment or disposal pathways, potentially contributing to environmental contamination and human exposure. This finding highlights

**FIGURE 2:** Methods used by households in handling and disposing of e-waste.

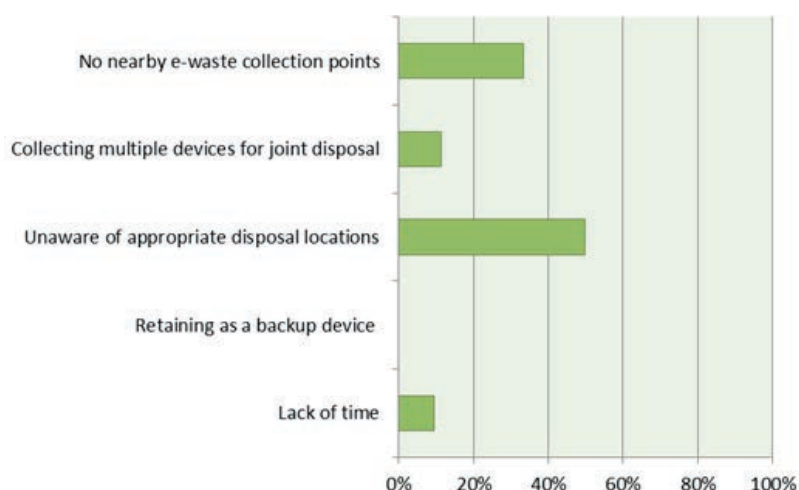


FIGURE 3: Reasons for not disposing of old devices.

the importance of combining awareness-raising activities with accessible and convenient household collection systems.

Storing e-waste at home may be driven by limited access to information and disposal infrastructure, according to the reasons respondents gave for not disposing of their e-waste (Figure 3). With the option to select multiple answers, 50% of respondents reported a lack of information on where to take e-waste as the main barrier to disposal. A significant proportion (33%) indicated that there are no nearby disposal points, while 11% reported that they are collecting devices to dispose of them together. Only 9% mentioned lack of time as a reason, and none of the respondents reported keeping devices as backups. These findings suggest that storing e-waste at home may be largely driven by limited awareness and inadequate access to formal disposal options.

Taken together, these findings suggest that household e-waste management practices are influenced not only by environmental awareness, but also by the accessibility and convenience of disposal options. The reported lack of information on where to dispose of e-waste and the absence of nearby collection points may help explain why some households continue to store obsolete devices or dispose of them through inappropriate channels. Improving access to clear information and convenient collection infrastructure could therefore facilitate the transition from temporary storage and informal disposal practices toward formal collection, reuse and recycling.

3.4 Households' willingness to participate in e-waste management

In addition to existing knowledge and current household practices related to e-waste, the survey also explored respondents' willingness to participate in and financially support organized e-waste management systems. Table 5 presents the willingness of study participants to hand over electrical and electronic devices for recycling if an appropriate system were established. The survey results indicate a high level of willingness among the respondents (94%), although the motivation for participation varied. While 66% stated they would participate free of charge, 16% indicated they would participate if offered a voucher or discount for a new device, and 12% if financial compensation were provided, suggesting that economic incentives could further encourage participation.

Respondents were also asked to evaluate different potential e-waste collection models. The results indicate that the most preferred option among households was scheduled monthly collection at the household address, suggesting that regular and convenient services may significantly improve participation. Recycling yards located at a moderate distance from households were also considered an acceptable option by many respondents. Collection on request by contacting an operator was similarly evaluated, indicating that flexible but slightly more demanding systems could still achieve moderate participation. The least preferred option was the placement of containers for small devices near residential buildings, which may reflect con-

TABLE 5: Willingness of study participants to participate in e-waste recycling if a collection system is established (n = 159).

Statement	Response	Percentage
Would you hand over electrical and electronic devices for recycling if an appropriate collection system were available?	Yes, free of charge	105 (66%)
	Yes, with financial compensation	19 (12%)
	Yes, with a voucher or discount for a new device	25 (16%)
	No	10 (6%)

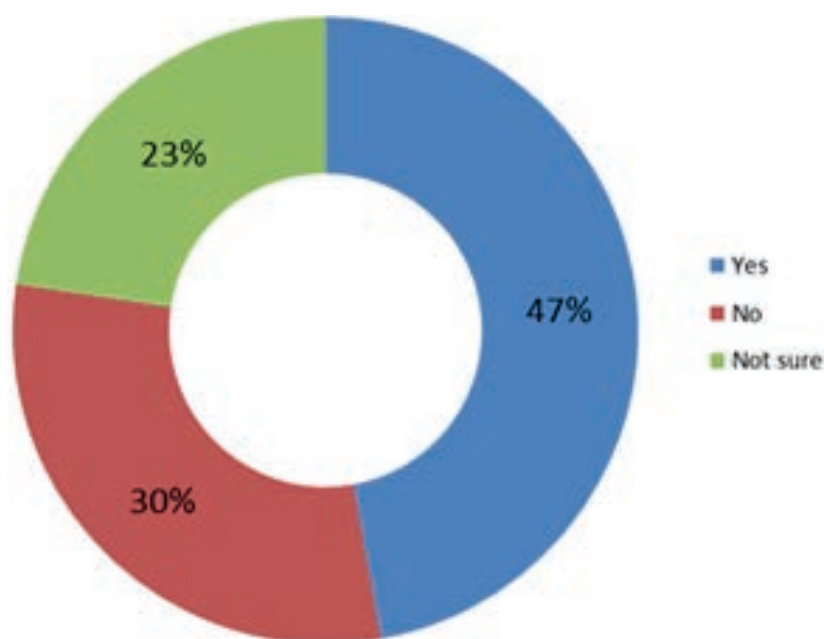


FIGURE 4: Participants' willingness to pay for e-waste management services.

cerns related to accessibility, safety, or limited capacity for handling different types of e-waste.

Regarding financial support for e-waste management, the survey revealed a moderate willingness to pay for such services. Specifically, 47% of respondents expressed readiness to pay a fee for an e-waste management system, while 30% were unwilling to pay, and 23% were uncertain (Figure 4).

Transparent communication regarding the allocation and use of collection fees is essential to build public trust and enhance participation. Providing clear information on how the funds will support the operation and maintenance of e-waste management programs can reassure households that their contributions are effectively utilized. Additionally, implementing flexible payment options or incentives such as discounts on new appliances or integration with existing municipal waste fees may increase overall engagement and support for long-term, sustainable e-waste management.

More broadly, the high willingness to hand over e-waste indicates considerable potential for increasing household

participation if an appropriate collection system is available. The fact that most respondents would participate without financial compensation suggests that convenience and accessibility may be more important incentives than direct economic benefits for many households. The interpretation is also supported by the preference for monthly household collection, which requires minimal additional effort from residents. These findings highlight the importance of designing collection systems that are simple, accessible, and adapted to household needs, as willingness to participate may not necessarily translate into actual behaviour if collection options are inconvenient or difficult to access.

3.5 Statistical analysis of socio-demographic factors and e-waste practices

Table 6 shows the results from chi-square tests performed to examine the relationship between sociodemographic characteristics and behaviours related to e-waste management. The significance level was set at $\alpha = 0.05$.

TABLE 6: Chi-square tests on the willingness to participate in e-waste management.

Variable	Groups	χ^2 calculated	df	p-value	Significance
Education vs. Willingness to recycle	Primary, Secondary, University ¹	0.46	2	0.79	Not significant ($p > 0.05$)
Age group vs. Giving devices for recycling	≤ 30 , 31-40, 41-50, 51-60, above 60 ²	0.21	8	1.00	Not significant ($p > 0.05$)
Income vs. Willingness to pay	Low, Middle, High ^{3,4}	9.91	2	0.007	Significant ($p < 0.05$)

Notes: ¹ Response categories: Yes, No - ² Response categories: Always, Sometimes, Never - ³ Response categories: Willing, Not willing/Uncertain - ⁴ Income categories were grouped for statistical analysis as follows: Low = below €1,000; Middle = €1,000 - €2,000; High = above €2,000. Significance level $\alpha = 0.05$

The analysis revealed no statistically significant differences in willingness to recycle electronic devices across different education levels or between age groups and the practice of giving devices for recycling.

In contrast, a statistically significant association was observed between household income and willingness to pay for organized e-waste management. Middle-income households (€1,000 - €2,000) showed the highest willingness to pay, whereas respondents from the high-income group (> €2,000) more frequently reported unwillingness or uncertainty. These findings suggest that income level influences households' readiness to financially support the e-waste management system, but does not necessarily increase with higher income.

Overall, these findings suggest that socio-demographic characteristics may not influence all aspects of household e-waste behaviour in the same way. The absence of statistically significant associations between education and willingness to recycle, as well as between age and device disposal practices, indicates that these behaviours may be shaped by factors beyond basic demographic characteristics, such as the accessibility of collection services, available information, and convenience. In contrast, the significant association between household income and willingness to pay suggests that economic considerations may play a more important role when participation involves a direct financial contribution. This distinction is relevant for the design of e-waste management policies, as measures aimed at increasing general participation may require different approaches from those involving household payment for collection services.

4. CONCLUSIONS

In this survey, the authors investigated household awareness, knowledge and behaviours regarding the management of electrical and electronic waste in Novi Sad, Serbia. The results showed that, while most respondents demonstrated awareness that e-waste contains toxic substances and requires special treatment, regular participation in formal recycling programs remained limited. Only 16% of households reported always recycling their electronic devices, while 51% recycled them occasionally, and 33% never participated in formal recycling programs. Storage of e-waste at home and repair of old devices were common, highlighting both limited access to convenient disposal options and the influence of behavioural habits. While repair and reuse can extend the useful lifetime of electrical and electronic equipment and support circular economy objectives, prolonged home storage may delay the recovery of valuable materials when devices are no longer functional. These findings highlight the need to distinguish between life-extension practices and the accumulation of unwanted devices resulting from limited access to convenient collection and recycling options.

Regarding the socioeconomic factors, household income was found to be a significant determinant of financial support for organized e-waste management, with middle-income households exhibiting the highest willingness to pay. In contrast, demographic factors, such as age and

education level showed no statistically significant effect on willingness to participate in e-waste collection and recycling, suggesting that economic factors play a more decisive role.

This study has several limitations that should be considered when interpreting the results. The survey was conducted online, which may have influenced the demographic structure of respondents, particularly the high share of participants with university education. As a result, the sample may not fully represent the educational structure of the general population of Novi Sad, which may limit the generalizability of the findings. In particular, the high level of education within the sample may have influenced the observed levels of awareness and knowledge regarding e-waste and its environmental and health impacts. Therefore, these findings should be interpreted with caution when extrapolating them to the wider population. Nevertheless, education level was not significantly associated with willingness to recycle in the present study. Although the survey included questions on incorrect disposal practices, it did not specifically investigate illegal dumping or littering of e-waste in public spaces. Therefore, the extent and environmental and health implications of these specific forms of improper disposal cannot be assessed based on the present data. Future research could include larger and more diverse samples, as well as longitudinal studies to better understand behavioural changes over time.

Given the limited current infrastructure for household e-waste collection, the study emphasizes the need for a coordinated approach involving local authorities, private operators, and community stakeholders. Implementing adequate collection systems may help reduce informal disposal and home storage of e-waste. Public awareness campaigns should be strengthened to improve knowledge of proper e-waste handling, including collection points and disposal methods. Additionally, offering flexible incentives, such as vouchers, discounts, or integration of e-waste fees into municipal services, may further improve participation. Ensuring transparency regarding the allocation and use of collected funds is crucial to building public trust and long-term engagement.

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SPECTROSCOPY AND CHEMOMETRICS FOR RAPID CLASSIFICATION OF CONSTRUCTION AND DEMOLITION WASTE AS A POTENTIAL APPLICATION IN POST-EARTHQUAKE WASTE MANAGEMENT

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ABSTRACT

Construction and demolition waste (C&DW, chapter 17 of the European Waste Catalogue: EWC) is highly heterogeneous, and its rapid characterization is important for safe handling, sorting, recycling and appropriate waste management. These challenges become particularly critical in emergency and post-earthquake scenarios, where large quantities of mixed construction materials may be generated and rapidly require preliminary screening and routing. This study proposes a spectroscopy-chemometrics framework based on visible-short-wave infrared (Vis-SWIR, 350–2500 nm) reflectance measurements, acquired with an ASD FieldSpec 4 full-range spectroradiometer, to classify earthquake-generated C&DW according to EWC codes, main material categories and hazard status. Representative samples of major C&DW material groups, including concrete and mortar, bricks and ceramics, natural aggregates, insulation materials and potentially contaminated components, were characterized in reflectance mode and labelled according to their assigned EWC code, material macro-class, and hazardous/non-hazardous status. Partial Least Squares-Discriminant Analysis (PLS-DA) models were developed in hierarchical mode focusing on the binary distinction between pre-defined hazardous and non-hazardous classes and on the classification of EWC codes. The hierarchical PLS-DA approach achieved high prediction accuracy, demonstrating the potential of Vis-SWIR spectroscopy and multivariate analysis as a rapid screening and decision-support tool for C&DW classification and EWC-based sorting, with relevance to post-earthquake waste management.

1. INTRODUCTION

Construction and demolition waste (C&DW) represents one of the largest and most complex waste streams generated worldwide. In many regions, construction and demolition waste (CDW) accounts for a substantial proportion of municipal solid waste, ranging from 30% to 46% (Huang et al., 2018; Wan et al., 2026). Approximately 60% of this waste is generated by residential and commercial construction activities (Huang et al., 2018; Sirimewan et al., 2024).

A commonly cited definition distinguishes between demolition waste, consisting of materials generated from the dismantling of structures, and construction waste, which includes residues arising from construction, renovation, and repair activities in residential, commercial, and infrastructure projects (Chileshe et al., 2019; Tchobanoglous

et al., 1993). Due to the diversity of materials involved and the variability of construction practices, C&DW is inherently heterogeneous and often difficult to characterize accurately. Beyond its substantial volume, this waste stream carries considerable environmental consequences, including the depletion of natural resources, significant greenhouse gas emissions from material extraction and production processes, and the potential release of hazardous substances when materials are mismanaged or improperly disposed of (Sakthibala et al., 2025). Effective waste management could minimize landfill disposal and supports resource recovery, reducing the demand for virgin materials (Chien et al., 2023; Su, 2020). Consequently, improving the characterization and classification of C&DW is a key step toward enhancing recycling efficiency and supporting the transition to a circular economy in the construction sector.

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To address these challenges, the European Union introduced the Waste Framework Directive 2008/98/EC (WFD), which provides a legislative framework for sustainable waste management (Directive, E.C., 2008) prioritizing prevention, reuse, and recycling ahead of disposal. It sets a target of recovering 70% of non-hazardous C&DW by 2020 and continues to encourage Member States to implement measures such as selective demolition. These practices support the safe removal of hazardous materials, enable higher-quality recycling, and help reduce overall waste generation. The WFD plays a central role in guiding construction and demolition waste management and in promoting more sustainable practices within the construction sector.

C&DW can generally be classified into three main categories (Bonifazi et al., 2025c). The first includes materials that may have value for construction applications, typically consisting of about 40-85% hardened concrete, 10-25% ceramics, and 20-25% bricks and tiles; these fractions can potentially be recycled and reused, for example, as cementitious precursors. The second category comprises easily recyclable materials, such as glass and metals, which usually represent less than 10% of the total waste stream. The third category includes hazardous waste, which may involve items such as lighting equipment, paints, and coatings, and in some cases, asbestos-containing materials (ACM) (Osmani, 2011); (Radica et al., 2024). Beyond conventional C&DW streams, increasing attention has recently been devoted to debris generated by earthquakes and other natural disasters. Post-seismic C&DW often consists of a highly heterogeneous mixture of structural materials, damaged building components, and potentially hazardous substances released during building collapse (Bonifazi et al., 2026). As a result, this waste stream poses significant challenges for rapid classification, safe handling, and efficient recycling, owing to both its compositional variability and the emergency conditions under which it is typically managed (Bonifazi et al., 2025a). Among the hazardous constituents that may be encountered, particular concern is associated with anthropogenic asbestos-containing materials, which, although banned in most countries, are still produced and used in some regions (Bonifazi et al., 2025b).

Proper assignment of European Waste Catalogue (EWC) codes is essential to enable high-quality recycling, distinguishing hazardous from non-hazardous waste, thus ensuring regulatory compliance. This task becomes particularly challenging in the case of “mirror entries”, where visually similar waste fractions may be classified as hazardous or non-hazardous depending on their chemical composition. In such cases, analytical evidence is required to support classification decisions. It should be noted that the regulatory determination of hazardousness cannot be based on Vis-SWIR spectroscopy alone. Spectral reflectance measurements do not directly provide the complete information required for regulatory assessment, such as the concentrations of specific hazardous substances, comparison with applicable concentration limits, or the determination of all relevant hazardous properties. Therefore, in the present work, the hazardous/non-hazardous labels

are considered as pre-established classes associated with the investigated materials and their EWC classification. The proposed spectroscopy-chemometrics approach is intended to provide rapid screening and decision-support information that can complement, rather than replace, conventional chemical characterization and regulatory assessment.

The EWC organizes waste types into six-digit codes grouped by industrial sector and origin. Within this system, some codes are defined as mirror entries, meaning that the same waste stream can receive two alternative codes depending on whether hazardous substances are present above regulatory thresholds. The correct attribution of these codes is therefore crucial not only for regulatory compliance but also for determining appropriate treatment, transport, and recycling pathways.

Traditional characterization approaches for C&DW rely on visual inspection, manual sorting and laboratory-based chemical analyses. While accurate, these methods are often time-consuming, costly, and poorly suited for rapid decision-making in operational environments such as recycling plants or demolition sites. Consequently, there is a growing interest in fast, non-destructive, and potentially automated techniques capable of supporting waste classification directly in the field. In this context, reflectance spectroscopy in the visible to short-wave infrared (Vis-SWIR) range has emerged as a promising tool for material identification. Spectral measurements in this range are sensitive to composition and surface characteristics of materials. When combined with advanced data analysis techniques, such as chemometrics, spectroscopy can represent a powerful tool for the classification of complex and heterogeneous materials. Previous studies have demonstrated the potential of spectroscopy-chemometrics frameworks for waste sorting and material discrimination (Bonifazi et al., 2015); however, their application to the hierarchical classification of C&DW according to hazard status and EWC codes remains relatively limited.

The present study aims to address this gap by proposing an integrated spectroscopy-chemometrics framework for rapid classification and screening of representative construction and demolition waste fractions. Samples spanning major material families, including concrete and mortar, bricks and ceramics, natural aggregates, insulation materials, and potentially contaminated components, were analyzed after appropriate spectral pre-processing and labelled according to their assigned EWC codes and pre-established hazardous/non-hazardous status under current EU legislation. Classification models were developed at two hierarchical levels: EWC code grouping and discrimination between hazardous and non-hazardous classes represented in the investigated dataset.

The overarching objective is to evaluate the capability of Vis-SWIR spectroscopy coupled with chemometrics to provide a reliable, rapid, and scalable decision-support information for C&DW sorting, preliminary screening and routing, while complementing the chemical and regulatory assessment required for definitive waste classification.

2. MATERIALS AND METHODS

2.1 Analyzed samples

Reflectance spectra in the Vis-SWIR range (350-2500 nm) were acquired from representative samples of major C&DW material families. In total, 167 independent physical items (i.e. the term “item” refers to a single physical sample: an individual debris fragment or material piece) were collected and analyzed from renovation, demolition, and post-earthquake sites across Italy.

These included mineral-based materials (e.g., concrete, cement, bricks, ceramics, and aggregates), soil and stone fractions, gypsum-based materials (gypsum and plasterboard), organic materials such as wood and plastics, metals, as well as potentially contaminated or hazardous materials, including bituminous mixtures containing coal tar and asbestos-containing materials. Overall, the dataset comprises multiple waste categories associated with specific European Waste Catalogue (EWC) codes and classified according to their hazardous or non-hazardous status.

For each material class, between 2 and 60 items were collected. For each item, at least 20 spectra were acquired to capture intra-sample variability.

The complete list of analyzed materials, together with the corresponding EWC codes, hazard classification, and the number of analyzed spectra (spectra considered excessively noisy or identified as outliers were excluded from the analyses), is reported in Table 1. Analyzed spectra were in total 3834, corresponding to measurements (except outliers) acquired on these 167 independent physical samples. Multiple spectra originating from the same item were always treated as measurements of the same

sample and were not considered independent observations.

2.2 Methods

2.2.1 Portable spectrophotoradiometer

Reflectance spectra were collected using a FieldSpec® 4 Standard-Res field-portable spectroradiometer (ASD Inc., Boulder, Colorado, United States). This instrument provides a spectral resolution of 3 nm at 700 nm and 10 nm at 1400/2100 nm and it can acquire spectra in the Vis-SWIR ranges (350 - 2500 nm) (Inc., 2015).

The spectroradiometer consists of a detector unit and a fiber-optic cable connected to a contact probe, controlled by a computer. The detector unit integrates three separate sensors equipped with different holographic diffraction gratings: a VNIR detector (512 element silicon array: 350-1000 nm), a SWIR 1 detector (Graded Index InGaAs. Photodiode, Two Stage TE Cooled; 1001-1800 nm), and a SWIR 2 detector (Graded Index InGaAs. Photodiode, Two Stage TE Cooled; 1801-2500 nm). A halogen lamp provides illumination with a colour temperature of 2901 +/- 10% °K. The contact probe spot is 10 mm in size. The ASD RS3 software was used for data collection and calibration procedures (ASD Inc., 2008). The spectroradiometer was calibrated by referencing the dark current calibration file and acquiring a standardized white Spectralon® ceramic material, spectrum is then acquired, and reflectance computed.

The ASD ViewSpec Pro (Ver. 6.2.0) was used to stack the spectroradiometer spectra “.asd” data files into an ASCII text file. An ad hoc written routine was used to import the converted data into the MATLAB environment (MATLAB R2019a; The Mathworks, Inc., Natick, Massachusetts,

TABLE 1: List of analyzed CDW materials, with the corresponding EWC codes and their classification according to waste hazard status.

Name	Code	Status	Number of analyzed spectra
Aggregates	17 01 07 - Mixtures of concrete, bricks, tiles and ceramics other than those mentioned in 17 01 06*	non-hazardous	60
Bituminous mixtures	17 03 01* - Bituminous mixtures containing coal tar (hazardous)	hazardous	60
Brick	17 01 02 - Bricks	non-hazardous	140
Ceramic and tile	17 01 03 - Tiles and ceramics	non-hazardous	120
Plastics	17 02 03 - Plastic	non-hazardous	312
Gypsum	17 08 02 - Gypsum-based construction materials other than those mentioned in 17 08 01	non-hazardous	60
Wood	17 02 01 - Wood	non-hazardous	160
Concrete	17 01 01 - Concrete	non-hazardous	60
Plasterboard	17 08 02 - Gypsum-based construction materials other than those mentioned in 17 08 01	non-hazardous	60
Asbestos Containing Material (AMC)	17 06 05* - Construction materials containing asbestos (hazardous)	hazardous	1161
Soil + ACM	17 06 03* - Soil and stones containing hazardous substances (hazardous)	hazardous	900
Soil + Cement	17 01 07 - Mixtures of concrete, bricks, tiles and ceramics other than those mentioned in 17 01 06*	non-hazardous	139
Cement	17 01 01 - Concrete	non-hazardous	19
Soil	17 05 04 - Soil and stones other than those mentioned in 17 05 03	non-hazardous	100
Marble (ornamental stone)	17 05 04 - Soil and stones other than those mentioned in 17 05 03	non-hazardous	340
Metals	17 04 05 - Iron and steel	non-hazardous	143

United States). Imported data files were analyzed in the MATLAB environment using PLS_toolbox (Ver. 8.2., Eigenvector Research, Inc., Manson, Washington, United States).

2.2.2 Spectral data acquisition and preprocessing

Spectra were cut to exclude the visible (VIS) region, retaining only the 1000-2500 nm interval for following analysis. The dataset was then pre-processed to minimize noise. Specifically, Multiplicative Scatter Correction (MSC), Generalized Least Square Weighting (GLS-W) and Mean Center (MC) algorithms were applied (Gasbarrone et al., 2018; Rinnan et al., 2009).

2.2.3 Hierarchical classification procedure

A hierarchical approach based on Partial Least Squares - Discriminant Analysis (PLS-DA) was implemented to achieve the classification. Classification techniques are designed to develop models that assign objects to specific classes using a set of descriptors. Among the classification algorithms, PLS-DA is a supervised classification method, combining the properties of partial least squares regression with the discriminating ability of a classification technique (Ballabio & Consonni, 2013).

The hierarchical model (Figure 1) is based on three main decision rules (model-based), each designed to discriminate between different levels of waste classification.

- **Rule 1:** Discrimination of pre-defined hazardous and non-hazardous classes. The first rule discriminates between samples belonging to the hazardous and non-hazardous classes represented in the investigated dataset. The corresponding labels were assigned a priori

according to the EWC classification adopted for the analyzed materials (this classification step serves as a spectral screening of pre-defined waste classes, rather than an independent regulatory determination of hazardousness).

- **Rule 2:** Classification of hazardous waste categories. Samples identified as hazardous are further classified according to the main hazardous EWC codes included in the dataset.
- **Rule 3:** Classification of non-hazardous waste categories. Samples identified as non-hazardous are assigned to the corresponding non-hazardous EWC groups, including concrete, bricks, tiles and ceramics, mixed mineral waste, wood, plastics, metals, soil and stones, and gypsum-based materials.

The hierarchical structure allows the model to first determine the hazard status of the waste and then refine the classification according to the corresponding EWC code groups. Samples not matching any of these classes are labelled as "NC". Models were calibrated by using the spectral information contained in the training sets and cross-validated by the Venetian Blinds (VBs) algorithm to assess the optimal complexity of the models. The VBs scheme was applied at the individual-spectrum level, i.e. spectra from the same physical sample could be distributed across different folds.

Classifier performance was assessed by computing Sensitivity, Specificity, Precision, and Accuracy from the confusion matrix (Ballabio et al., 2018; Fawcett, 2006) according to the following formulas:

$$\text{Sensitivity} = \text{TP} / (\text{TP} + \text{FN}) \quad (1)$$

$$\text{Specificity} = \text{TN} / (\text{FP} + \text{TN}) \quad (2)$$

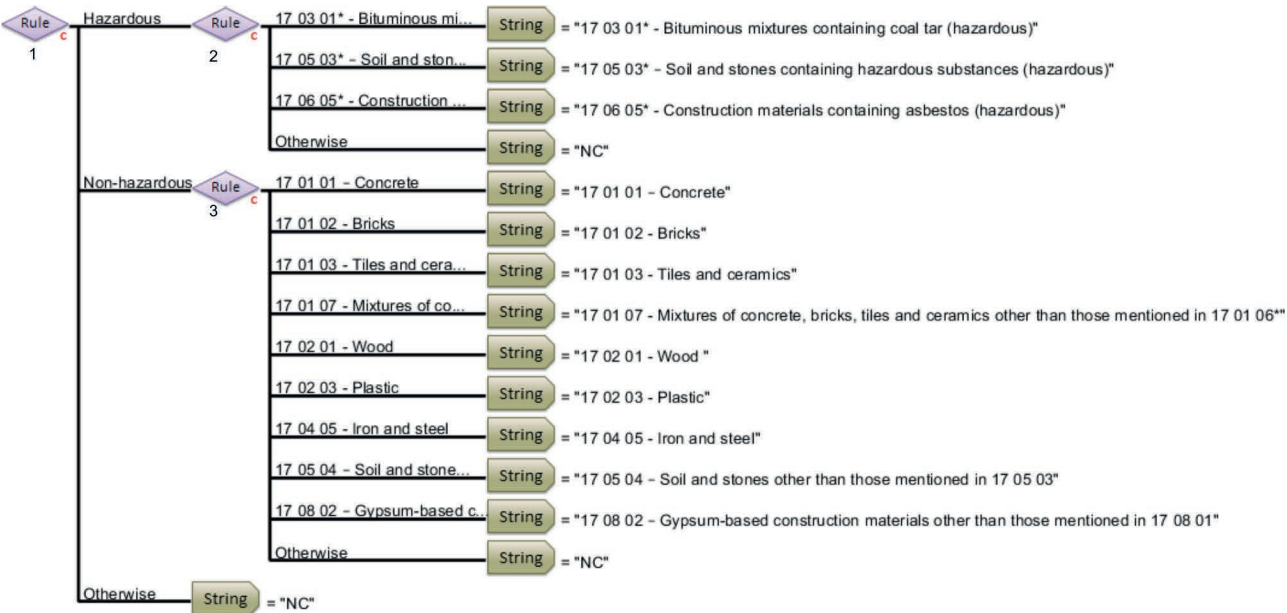


FIGURE 1: Hierarchical classification scheme for construction and demolition waste (C&DW) samples. The first decision rule separates hazardous from non-hazardous waste classes. Subsequent rules assign samples to the corresponding European Waste Catalogue (EWC) codes, including bituminous mixtures containing coal tar, soil and stones containing hazardous substances, asbestos-containing materials, concrete, bricks, tiles and ceramics, mixed mineral waste, wood, plastics, iron and steel, soil and stones, and gypsum-based construction materials. Samples not assigned to any of the predefined classes are labelled as NC (not classified).

$$\text{Precision} = \text{TP} / (\text{TP} + \text{FP}) \quad (3)$$

$$\text{Accuracy} = (\text{TP} + \text{TN}) / (\text{TP} + \text{TN} + \text{FP} + \text{FN}) \quad (4)$$

In these equations, TP (True Positive) is a positive instance that is classified as positive; FN (False Negative) is a positive instance that is classified as negative; TN (True Negative) is a negative instance that is classified as negative, and FP (False Positive) is a negative instance that is classified as positive.

3. RESULTS AND DISCUSSION

Raw reflectance spectra used to calibrate the hierarchical classification model are shown in Figure 2. These spectra highlight the variability among the analyzed materials and provide the initial spectral information used to build the classification models. The observed differences in spectral patterns suggest that the SWIR spectral range contains relevant features for discriminating among the considered waste categories. Specific preprocessing techniques were then applied for each rule, as defined in the hierarchical model. The corresponding pre-processed spectra are shown in Figure 3. The preprocessing stage plays a key role in reducing noise, minimizing scattering effects, and enhancing the spectral features relevant for classification.

Sensitivity and Specificity in calibration, cross-validation and validation are shown in Table 2 for the Rule 1, Table 3 for Rule 2 and Table 4 for Rule 3. These performance indicators allow a comprehensive evaluation of the classifier reliability, highlighting its capability to correctly identify both positive and negative instances for each class.

Concerning Rule 1, which focuses on the discrimination between the pre-defined hazardous and non-hazardous waste represented in the dataset, the model achieved very high performance, with sensitivity, specificity, and accuracy

values equal or very close to 1 in both calibration and cross-validation. This result indicates that the spectral information captured by the model is highly discriminative for the investigated hazardous and non-hazardous material classes. However, this result should be interpreted as evidence of the potential of Vis-SWIR spectroscopy for rapid screening of the investigated classes rather than as a demonstration that spectroscopy alone can establish the regulatory hazardous status of an unknown waste stream. Moreover, the hazardous and non-hazardous groups comprise different material matrices and material types. Therefore, the observed discrimination may reflect differences in the overall spectral characteristics of the material matrices and cannot be attributed exclusively to the presence of hazardous constituents. For Rule 2, concerning the classification of hazardous waste categories, the obtained results also show excellent performance. Most classes present sensitivity and specificity values equal or very close to 1 during both calibration and cross-validation. This confirms that once the hazard status has been correctly identified, the model is able to further distinguish among hazardous EWC classes with a high level of reliability.

The built hierarchical model was then applied to the entire dataset of spectra, and the obtained results are in Table 5. The results confirm the overall effectiveness of the hierarchical approach, with high accuracy and very low error rates for most of the considered EWC classes. The lower sensitivity observed for some non-hazardous classes in the final hierarchical model can be related to the intrinsic spectral characteristics and variability of these materials.

The sensitivity for EWC 17 04 05 classes reached 0.755, despite the very high specificity (1.000), which may be associated with the relatively low and spectrally flat reflectance response of metallic materials in the spectral

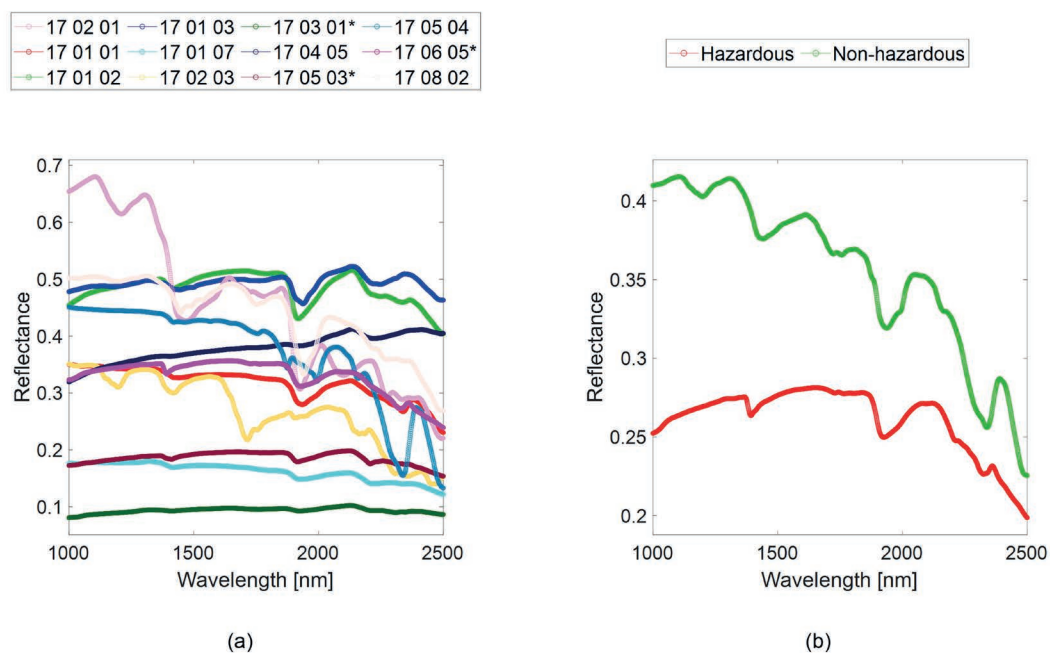


FIGURE 2: Raw reflectance spectra of samples classified according to the EWC code (a) and the hazard status (b).

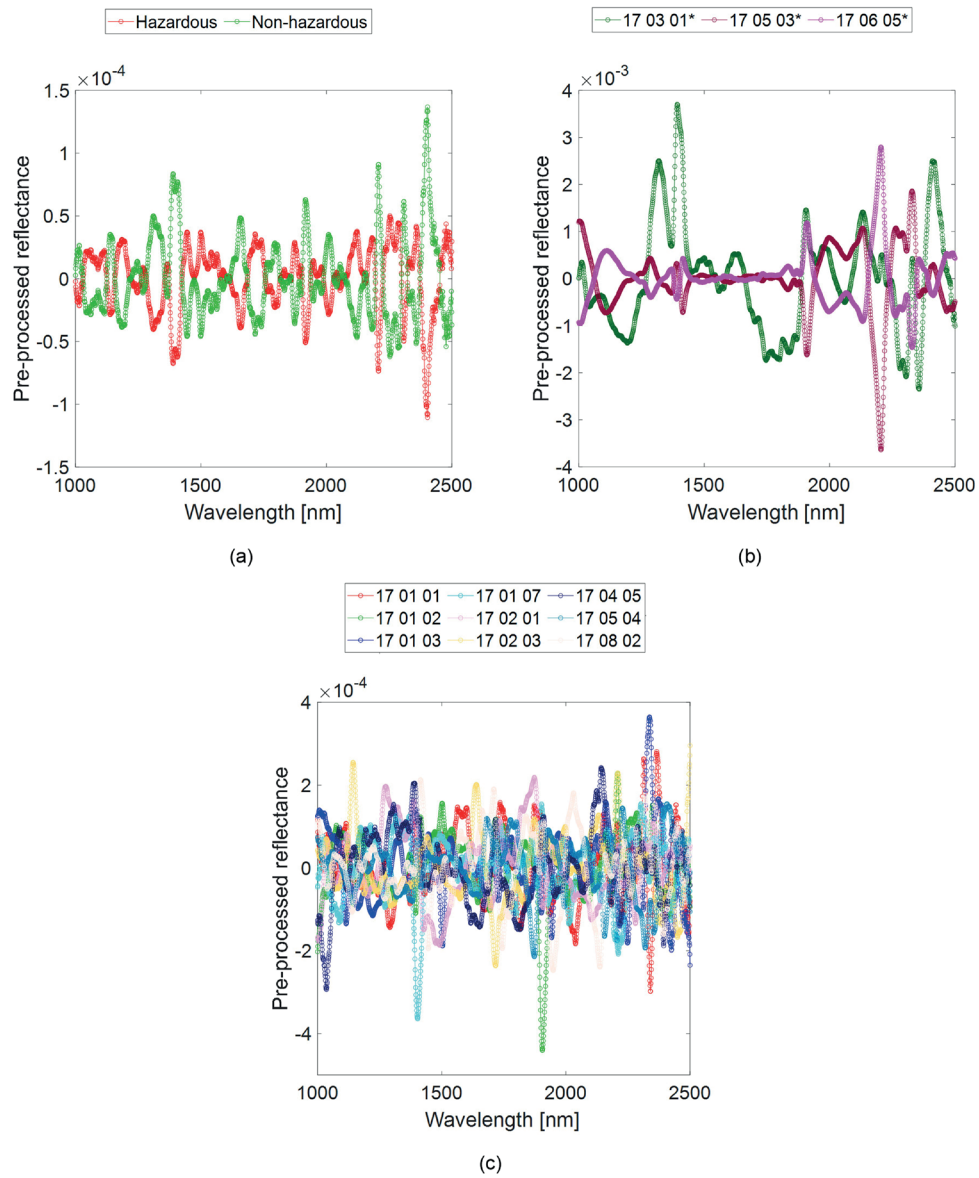


FIGURE 3: Preprocessed spectra corresponding to Rule 1 (a), Rule 2 (b), and Rule 3 (c) of the hierarchical classification model.

TABLE 2: Sensitivity and specificity in calibration and cross-validation for Rule 1.

Model phase	Class	Sensitivity	Specificity	Number of spectra	Precision	Accuracy
Calibration	Hazardous	1.000	1.000	2121	1.000	1.000
	Non hazardous	1.000	1.000	1713	1.000	1.000
Cross-validation	Hazardous	1.000	1.000	2121	1.000	1.000
	Non hazardous	1.000	1.000	1713	0.999	1.000

TABLE 3: Sensitivity and specificity in calibration and cross-validation for Rule 2.

Model phase	Class	Sensitivity	Specificity	Number of spectra	Precision	Accuracy
Calibration	17 03 01*	1.000	1.000	60	1.000	1.000
	17 05 03*	0.997	1.000	900	1.000	0.999
	17 06 05*	1.000	0.997	1161	0.997	0.999
Cross-validation	17 03 01*	1.000	1.000	60	1.000	1.000
	17 05 03*	1.000	1.000	900	1.000	1.000
	17 06 05*	1.000	1.000	1161	1.000	1.000

TABLE 4: Sensitivity and specificity in calibration and cross-validation for Rule 3.

Model phase	Class	Sensitivity	Specificity	Number of spectra	Precision	Accuracy
Calibration	17 01 01	1.000	0.999	79	0.975	0.999
	17 01 02	1.000	1.000	140	1.000	1.000
	17 01 03	0.983	1.000	120	1.000	0.999
	17 01 07	1.000	1.000	199	1.000	1.000
	17 02 01	1.000	1.000	160	1.000	1.000
	17 02 03	1.000	1.000	312	1.000	1.000
	17 04 05	1.000	1.000	143	1.000	1.000
	17 05 04	1.000	1.000	440	1.000	1.000
	17 08 02	1.000	1.000	120	1.000	1.000
Cross-validation	17 01 01	1.000	0.997	79	0.940	0.997
	17 01 02	1.000	1.000	140	1.000	1.000
	17 01 03	0.925	1.000	120	1.000	0.995
	17 01 07	1.000	1.000	199	1.000	1.000
	17 02 01	1.000	1.000	160	1.000	1.000
	17 02 03	1.000	0.999	312	0.994	0.999
	17 04 05	0.986	1.000	143	1.000	0.999
	17 05 04	1.000	1.000	440	1.000	1.000
	17 08 02	1.000	0.997	120	0.968	0.998

TABLE 5: Performance metrics of the hierarchical model approach.

Class	Sensitivity	Specificity	Number of spectra	Error rate	Precision	Accuracy
17 01 01	0.911	0.999	79	0.002	0.973	0.998
17 01 02	1.000	1.000	140	0.000	1.000	1.000
17 01 03	0.983	1.000	120	0.001	1.000	0.999
17 01 07	1.000	1.000	199	0.000	1.000	1.000
17 02 01	1.000	1.000	160	0.000	1.000	1.000
17 02 03	0.869	1.000	312	0.011	1.000	0.989
17 03 01*	1.000	1.000	60	0.000	1.000	1.000
17 04 05	0.755	1.000	143	0.009	1.000	0.991
17 05 03*	0.997	1.000	900	0.001	1.000	0.999
17 05 04	1.000	1.000	440	0.000	1.000	1.000
17 06 05*	0.947	0.999	1161	0.017	0.997	0.983
17 08 02	1.000	1.000	120	0.000	1.000	1.000

region used for the classification. A similar, although less pronounced, effect was observed for plastics (EWC 17 02 03) with a sensitivity of 0.869. This may be related to the variability of polymeric materials and to partial overlap of their spectral responses with those of other waste fractions. Concrete (EWC 17 01 01) also showed a low sensitivity (0.911), which can be reasonably associated with the compositional heterogeneity of this class.

It should be noted that the very high cross-validation metrics must be interpreted as indicators of internal consistency under a spectrum-level cross-validation scheme, rather than as definitive evidence of fully transferable performance. Because spectra from the same physical sample may occur in both calibration and validation folds, the reported figures are likely to overestimate the true generalization capability. Future work will therefore prioritize sam-

ple- or site-level cross-validation and external validation on independent datasets to obtain more realistic performance estimates.

4. CONCLUSIONS

This study demonstrates that a Vis-SWIR spectroscopy-chemometrics framework can effectively support the automated, hierarchical classification of construction and demolition waste (C&DW) according to European Waste Catalogue (EWC) codes and associated hazard status. By combining reflectance spectra with multivariate modelling, the proposed approach enables rapid and objective material identification, addressing key limitations of conventional, laboratory-based characterization and visual inspection in complex waste streams.

The hierarchical PLS-DA model achieved excellent classification performance for the pre-defined hazardous and non-hazardous classes represented in the investigated dataset. However, because these classes comprise different material matrices, the high performance of Rule 1 does not prove that the model specifically detects hazardous constituents independently of the underlying matrix. Controlled paired comparison using specific material matrix with and without specific contaminants are required to verify this capability, and further studies will be needed to validate the model true detection limits. On the other hand, hazardous EWC classes were correctly identified with similarly high figures of merit (Rule 2). For non-hazardous categories (Rule 3), the model maintained overall high accuracy across most classes, with slightly reduced sensitivity for the most heterogeneous or spectrally overlapping materials, such as certain plastic and metal fractions.

These results confirm Vis-SWIR reflectance spectroscopy can serve as a rapid, non-destructive and scalable screening technology to support EWC-oriented sorting and routing of the investigated C&DW classes. In particular, the proposed approach showed strong capability to discriminate between the pre-defined hazardous and non-hazardous classes represented in the dataset and to further classify these materials according to their associated EWC groups. However, Vis-SWIR spectroscopy should not be considered a stand-alone method for the definitive regulatory determination of hazardousness or for the resolution of mirror entries where chemical composition and concentration thresholds must be assessed. Rather, its potential lies in providing rapid preliminary information that can support operational decision-making and indicate materials or fractions requiring further analytical and regulatory assessment. Accordingly, the proposed methodology is best regarded as a complementary decision-support tool within a broader waste-characterization workflow, in which spectroscopic screening can be followed, where required, by targeted chemical analyses and regulatory assessment. This combined approach could be particularly valuable in post-earthquake scenarios, where a rapid screening of potentially hazardous fractions may help prioritize sampling, handling and subsequent analytical characterization.

Future work should prioritize external validation on larger and more diverse datasets, including additional construction typologies and contamination patterns, to further assess model robustness and transferability. Particular attention should also be given to reducing the imbalance among the investigated classes by increasing the number of spectra for the less represented materials, such as cement and some mineral-based fractions. This would provide a more balanced assessment of classification performance and further improve the robustness and transferability of the proposed hierarchical model. Moreover, integration with field-deployable systems (e.g. portable devices, conveyor-mounted sensors, or hyperspectral imaging units) and coupling with digital decision-support tools would enhance practical uptake, contributing to circular-economy strategies by maximising material recovery, limiting landfill disposal and improving the environmental sustainability of construction and demolition activities.

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A SIMPLE METHOD FOR DIFFERENTIATING HAZARDOUS FROM NON-HAZARDOUS SOLID MEDICAL WASTE CONTAMINATED WITH PATHOGENS

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ABSTRACT

Solid medical waste generated during patient care and contaminated with pathogens is generally classified as hazardous. It must be managed in accordance with a strict legal framework, including special packaging and mandatory destruction by incineration. In this paper, we focus on the potential health impact of this medical waste on employees who handle it. Using a simple algorithm based on pathogen properties, we describe a flexible method for distinguishing hazardous from non-hazardous medical waste and conclude on the risk to employees. The procedure involves constructing a two-dimensional coordinate system, where the x-axis represents the WHO scoring system, ranging from I to IV for disease severity and where the y-axis represents a quantitative score for pathogenicity. This score is obtained by answering and quantifying a sequence of questions, only if the pathogen survives outside the host: transmission of the disease linked to the pathogen through body fluids, mode of entry into a potential victim, and infectious dose. The resulting coordinates of each pathogen enable an objective assessment of its risk to waste handlers. By applying rational threshold values, the approach allows for data-driven classification of waste as either equivalent to household waste or genuinely hazardous. Implementing this method could significantly reduce the volume of hazardous waste without compromising the health of waste handlers.

1. INTRODUCTION

Many established operational protocols in the healthcare sector were severely challenged during and after the COVID-19 pandemic. Even in countries with highly developed healthcare systems, which are usually of excellent quality, the systems were unprepared for the massive influx of COVID-19 patients and nearly collapsed (Blumenthal, Fowler, Abrams, & Collins, 2020; Filip, Puscaselu, Anchidin-Norocel, Dimian, & Savage, 2022; Sachs et al., 2022). Likewise, the pandemic exposed severe weaknesses in medical waste management systems, particularly regarding the volume of pathogen-contaminated waste in hospitals (Anand et al., 2022; Fraeyman et al., 2022; Kanwar et al., 2023). Alarming reports contributed to a panic-like mindset among many people, and waste management was not guided by rational approaches. It was concluded that waste management systems needed to be adapted (Ranjbari et al., 2022), even beyond the exceptional conditions of a pandemic. The WHO

explicitly stated that there is “an urgent need to improve waste management systems” (<https://www.who.int/news/item/01-02-2022-tonnes-of-covid-19-health-care-waste-expose-urgent-need-to-improve-waste-management-systems>). Concerns over health issues related to medical waste management were extended to municipal waste, as waste produced through home healthcare could also pose a risk to waste handlers (Wankhede & Wanjari, 2021).

Medical waste is an enigmatic waste stream. Compared to the volume of household waste, it is negligible and accounts for only 1-3% of the total hazardous waste volume. However, medical waste carries an image of danger due to the presence of medical devices (sharps) and bodily fluids, such as blood or urine, which may be contaminated with infectious pathogens. It has an ethical component, suffice to refer to amputated limbs, preterm born dead babies, placentas or lumps of tissues, eventually cancerous, handled as waste. All this has led to a simple distinction between non-patient hospital waste, comparable to house-



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hold waste, and patient-related waste, which, as a whole, is considered hazardous. Both types of medical waste are incinerated by law; the main difference between them is the type of containers or plastic bags used for transport or collection, as well as the cost of destruction.

According to European regulations, solid medical waste is classified as either non-hazardous (EWC/Eural code 180104) or hazardous/contagious (EWC/Eural code 180103*), requiring specific UN3291-certified containers for collection and transportation.

There is general agreement that approximately 80% of hospital waste is indistinguishable from household waste, while about 20% is hazardous. One of the earliest mentions appears in the WHO Blue Book (1999), with additional references in sources such as Eker & Bilgili (Eker and Bilgili, 2011). This figure is reiterated in the second edition of the Blue Book (2013), on the WHO website in 2018 (<https://www.who.int/news-room/fact-sheets/detail/health-care-waste>), and is cited in reputable documents such as the United Nations General Assembly report of 2011 (https://www2.ohchr.org/english/bodies/hrcouncil/docs/18session/a-hrc-18-31_en.pdf), the Red Cross report of 2011 (<https://www.icrc.org/en/doc/assets/files/publications/icrc-002-4032.pdf>), and in almost all scientific literature (Janik-Karpinska et al., 2023).

Waste containing used needles or sharps, certain toxic pharmaceutical compounds such as cytostatics and biologicals, as well as ambulatory radioactive tracers, is unequivocally classified as hazardous. However, the classification of waste generated through daily medical care of patients infected with pathogens is less clear. The European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR) includes a "list A" of pathogens considered hazardous that require special precautions for handling, storage, etc. For all other pathogens not on "list A", there are no specific regulations to determine whether waste from handling patients infected with these pathogens is hazardous; decisions on this are often based on gut feeling (Janik-Karpinska et al., 2023). In practice, waste from these "non-list A" pathogens is almost always regarded as hazardous by default. The question remains whether this assumption is justified and supported by scientific evidence.

In this manuscript, we examine the risks associated with individuals handling medical waste produced in hospitals during the diagnosis, treatment, and daily care of patients with infectious diseases. We outline a semi-quantitative approach based on known pathogen characteristics, using a straightforward algorithm to enable an objective decision on whether this waste should be classified as hazardous. As a result, guidelines for selecting and handling the waste can be adjusted accordingly.

2. METHODOLOGY

2.1 People at risk

This paper focuses on the people who handle medical waste in a hospital setting, excluding healthcare workers directly involved in patient care (see assumptions). It includes: (1) hospital employees who collect waste from

the ward and transport it to the central storage area on campus; (2) personnel responsible for preparing the waste for transport, which involves stacking UN-certified bins and compacting plastic bags containing medical waste in waste compactors; (3) drivers who transport the waste from the hospital to incineration plants; (4) (eventually) employees at the incineration plants who handle the waste; and (5) (eventually) employees at the plant who analyze the waste before incineration. This manuscript does not consider individuals who collect household waste.

2.2 Assumptions

The methodology is feasible provided the following assumptions are met. (1) The individuals involved (see "People at risk") are in good health. Those with weakened immunity, for example, due to medical interventions, are not permitted to perform this task. (2) The individuals involved have access to suitable personal protective equipment, including gloves, aprons, masks, and other necessary items. The responsible managers within the hospital are aware of the importance of using these materials. (3) In case of accidents involving waste, such as during transport, or leakage from the containers due to incorrect filling or sealing of UN-certified containers, it is assumed that the organization has an appropriate protocol to manage the consequences of such incidents, in addition to standard waste handling procedures. (4) The procedure for collecting and sorting solid waste at the patient's bed has been established, is known to the relevant staff, and is subjected to strict oversight. (5) Typically, healthcare personnel (nurses, aides, paramedics) collect waste from patients' rooms and transport it to a designated temporary storage area. The waste is then collected by other employees not involved in direct patient care. The staff handling waste in the hospital do not enter the room of the patient, consequently, direct infection with airborne pathogens from patients is avoided. The likelihood of waste handlers being directly infected by patients is considered very low, if not zero.

2.3 Risk analysis

The risk for waste handlers to come into contact with, for example, blood was calculated using the following model. Hazardous waste is collected in UN3291-designated bins, which are sealed when properly closed and remain sealed irreversibly. The bin and its contents are incinerated without opening. In daily practice, we observe that not all bins are correctly closed; therefore, assuming body fluids such as blood are present in the bin, and considering that during handling, the bin might fall on its side, blood or other bodily fluids could leak out and potentially infect the waste handler. An unannounced count was conducted over 10 working days at a university hospital to determine the total number of UN3291 bins and the number that were not correctly closed. On average, 164 ± 45 bins were observed per day, with 1.7 ± 1 not properly closed—about 1% of the total bins. Recalculation of the total number of hospital beds and the average bed occupancy suggests that, assuming all bins could contain waste from infected patients (worst-case scenario), roughly one bin every two working days could pose an infection risk to handlers. Under these cau-

tious assumptions, the risk of handler infection from improperly closed bins remains low but is not zero. Wearing protective gear, especially suitable gloves, helps minimize exposure, making the risk very low and nearly negligible.

2.4 Legal obligations

Within Europe, the legal obligations related to waste management are summarized in <https://eur-lex.europa.eu/EN/legal-content/summary/eu-waste-management-law.html>. These obligations include rules for collecting the waste, separating different streams of waste (e.g., sharps, cytostatic drugs, etc), storage in the appropriate containers with specified UN numbers and incineration in a certified plant as the only valid destruction method. The implementation of EU rules may vary slightly among EU countries, but the general layout remains very similar (Mahnik, Hoffmann, Fraeyman, & Komilis, 2023).

2.5 Definition of pathogens, commensals as pathogens

Pathogens are (micro)organisms that can cause disease in humans and/or animals and include viruses, bacteria, fungi, various parasites, and prions (Mims et al., 2004). The bacteria in the enteric system, the microbiome, defined as commensals, do not cause diseases in everyday situations but might become (opportunistic) pathogenic in less favourable conditions, such as increased vulnerability due to e.g. reduced immunity after organ transplantation or during intensive cytostatic drug treatment (Athanasopoulou, Adamopoulos, & Scorilas, 2023; Sorboni, Moghaddam, Jafarzadeh-Esfehani, & Soleimanpour, 2022). As a consequence, commensals present in regular waste are harmless but may pose a danger to workers handling the waste if those workers are immunocompromised. As described in “assumptions”, these types of employees are not accepted to do the work.

2.6 Operational definition of pathogens, construction of the algorithm

Generally, pathogens are identified based on their pathogenicity and virulence. Pathogenicity is the capacity to cause disease; it is a dichotomous variable, meaning it has only two possible outcomes: yes or no. Virulence is a continuous variable that quantifies a pathogen’s degree of

pathogenicity (Shapiro-Ilan, Fuxa, Lacey, Onstad, & Kaya, 2005). Among the properties contributing to virulence are cell attachment, survival within and outside the host, the infective dose, and resistance to immune attacks, among others. See also <https://www.nature.com/scitable/topicpage/pathogenicity-microbial-virulence-763161/> and <http://www.differencebetween.net/category/science/health/>. (Leggett, Cornwallis, Buckling, & West, 2017; Martinez, 2014; Schmid-Hempel & Frank, 2007).

The operational definition used in this manuscript, referred to as pathogenicity, comprises two variables: the disease associated with the pathogen and an estimate of the risk that waste handlers will contract the disease.

For the disease parameter, the WHO classification on severity of diseases was chosen: class I: no to minimal body burden, class II: a distinct disease with measurable body burden and with evidence-based cure, class III, a severe disease with heavy body burden and with evidence-based cure and class IV, deadly disease with no or hardly any effective treatment.

The risk approximation is a tiered assessment. The first question is whether the pathogen is viable outside the host. If the answer is “yes”, three consecutive variables: transmission mode, body entry, and infectious dose, as described for the pathogen, were further quantified using an arbitrary score ; the scoring system’s numeric values are shown in Table 1.

Comments to Table 1:

- A. The pathogen could spread via aerogenic transmission, but direct infection of waste handlers through contact with the patients is unlikely (see methodology). The possibility of infection is nevertheless retained through indirect contact between waste handlers and, e.g. nurses.
- B. The possibility of formation of fomites, i.e. biofilms on the surfaces of inanimate recipients such as cell phones, doorknobs, keyboard, tables....) has been described. If these objects are disposed of as medical waste, this might pose an increased risk, since the waste Handlers might come into contact with them.
- C. The pathogen could spread through contact of the skin with blood. The risk analysis (see methods) concludes that the risk is non-relevant. Depending on the institutional organization (e.g. presence or absence of disas-

TABLE 1: Scoring system for pathogen calculation. nr: not relevant.

pathogen characteristics		arbitrary score	comment	max. value
Mode of transmission	aerogenic	2	A	2
	fomites	1 or 2	B	2
	body liquids	nr		
Body entry	skin	2	C	2
	others	nr	D	
Infection dose	<100 particles	4	E	4
	100-10000 particles	2	F	
	> 10000 particles	1	G	

ter treatment protocols – see assumptions), a value of 2 is acceptable.

- D. The spread of the pathogen through other body fluids (salivary or oral), having a possible effect on waste handlers, is considered non-relevant
- E. The lowest infective dose is the most contagious and gets the highest score
- F. The intermediate value represents intermediate infectivity
- G. The lowest score represents the highest infective dose and weakest infectivity

The final score is obtained by multiplying all variables mentioned in Table 1. In case the pathogen survives outside the patient, a score can be calculated:

The score is calculated as $A * B * C * E$ (or $* F$ or $* G$).

Max. Score is $A(=2) * B(=2) * C(=2) * E(=4) = 32$

Based on the procedure and the numerical values shown in Table 1, a pathogenicity score is obtained for each pathogen. This value constitutes the y-axis in a Coordinate system. The x-as in this system is the WHO class for the particular pathogen. The result is presented in Figure 1.

Theoretically, four zones can be distinguished in Figure 1: zones A and B on the left side of the graph represent relatively mild diseases for which evidence-based treatments are available (eventually including vaccination), while zones C and D stand for serious, potentially deadly diseases. Conversely, zones A and C indicate low pathogenicity, while zones B and D indicate highly infectious pathogens. The (x-y) coordinates of each pathogen allow the positioning of the pathogen in zones A, B, C, or D. The grey zone for pathogenicity indicates the possibility of choosing the boundary between low and high pathogenicity (see discussion).

Pathogens included in the ADR regulation's A-list, as well as those capable of causing diseases in WHO class IV, are consistently regarded as hazardous. Their calculated pathogenicity values according to the algorithm are sufficiently high to place them within zone D of the coordinate system. In situations where empirical data are unavailable

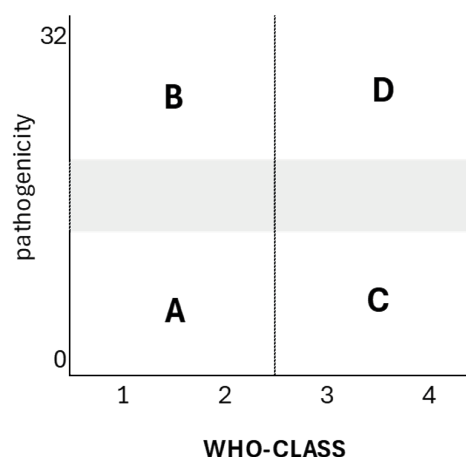


FIGURE 1: Matrix for pathogenicity allocation. WHO-class 1, 2, 3 and 4 correspond to disease severity as defined by the WHO; this is explained in the text.

or pathogens are unidentified, a worst-case assessment is applied, assigning them to zone D.

3. RESULTS

The entire procedure is illustrated for two pathogens that have recently caused concern: the coronavirus (Table 2) and the monkeypox virus (Table 3).

3.1 Coronavirus

Fraeyman et al. (2022) demonstrated that survival duration varies by author. Fraeyman et al. (2022) found no viral particles on hospital solid materials relevant to solid medical waste. Other literature reports the presence of fomites on various hospital materials. Here, we assume the “worst-case principle” and consider the virus viable outside the host. Hence, pathogenicity can be calculated.

Comment to Table 2:

The table illustrates how literature data are utilized to finalize the risk analysis and construct the algorithm. The

TABLE 2: Variables related to the COVID-19 virus. Data are obtained from WHO ([https://www.who.int/news-room/fact-sheets/detail/coronavirus-disease-\(covid-19\)](https://www.who.int/news-room/fact-sheets/detail/coronavirus-disease-(covid-19))) and the Mayo Clinic (<https://www.mayoclinic.org/diseases-conditions/coronavirus/symptoms-causes/syc-20479963>).

Variable	Rationale	Score	
Transmission	The well-documented aerogenic transmission of the virus is relevant for healthcare workers who come into close contact with patients, but not for waste handlers. The possibility of fomite transmission remains, although it is considered a low risk. Here, we assume the “worst-case principle” and consider the virus viable outside the host. Infection through blood contact or other body fluids is considered as less important.	2	
Entry into the victim	The only relevant entry route is through the skin, whether or not damaged. The worst-case scenario, i.e. contact with blood from patients, is retained. Other possible entry routes are considered irrelevant, as discussed in Table 1.	2	
Infection dose	In one paper, the infective dose, expressed as particles, is reported to be between 300 and 2000, which, according to the authors, is comparable to the infective dose of influenza (Prentiss, Chu, & Berggren, 2022). Both figures are retained, resulting in a double score. Score for low infectivity Score for high infectivity	2	4
Total score		8	16

TABLE 3: Variables related to the monkeypox virus. Data were obtained from the WHO (<https://www.who.int/news-room/questions-and-answers/item/monkeypox>) and from CDC (<https://www.cdc.gov/poxvirus/mpox/if-sick/transmission.html>). nr: not relevant.

Variable	Rationale	Score	
Transmission	Infection usually occurs through the bite of an infected animal or after close contact with the animal's blood or body fluids of patients. Human-to-human transmission happens via aerosolization or contact with the patient's skin lesions. Transmission via fomites is possible but considered less likely. During the 2022 outbreak, the virus was mainly spread through sexual contact. These transmission routes are not relevant to the management of solid medical waste. Transmission via blood contact is possible but less relevant. Transmission through other body fluids are not relevant.	nr	
Entry into the victim	The only relevant entry route is through the skin, whether or not damaged. The worst-case scenario, i.e. contact with blood from patients, is retained. Other possible entry routes are considered irrelevant, as discussed in Table 1.	2	
Infection dose	The infective dose for humans is unknown. The infective dose in animals using the Congo Basin monkeypox virus is from 100 to 10.000 particles. Two figures for infectivity are retained leading to the double score. Score for low infectivity Score for high infectivity	2	4
Total score		4	8

information for some variables is disparate. In this case, the worst-case scenario (fomites) is chosen, or both possibilities are retained (infective dose), leading to two possible total scores: 2*2*2 or 2*2*4.

3.2 Monkeypox virus

Similar to the result with the coronavirus: two infectivity-dose scores are retained, leading to two possible total scores: 2*2 or 2*4.

The same reasoning was applied to a large number of bacteria, viruses, moulds, and fungi. The numeric values for viruses and bacteria are provided in the Additional Results section. A representative example of viruses is shown

in Figure 2. The Figure is intended for illustrative purposes only; not all viruses are shown due to layout constraints.

Nearly all viruses listed in ADR list A are located in zone D of the Figure, indicating that the corresponding diseases are severe and highly pathogenic.

4. DISCUSSION

To the best of our knowledge, we present the first rational approach to an objective and usable judgment of the risk for disease transmission of a pathogen when present in medical waste. Thomas and Elkinton (Thomas & Elkinton, 2004) attempted to quantify virulence using LD50 or

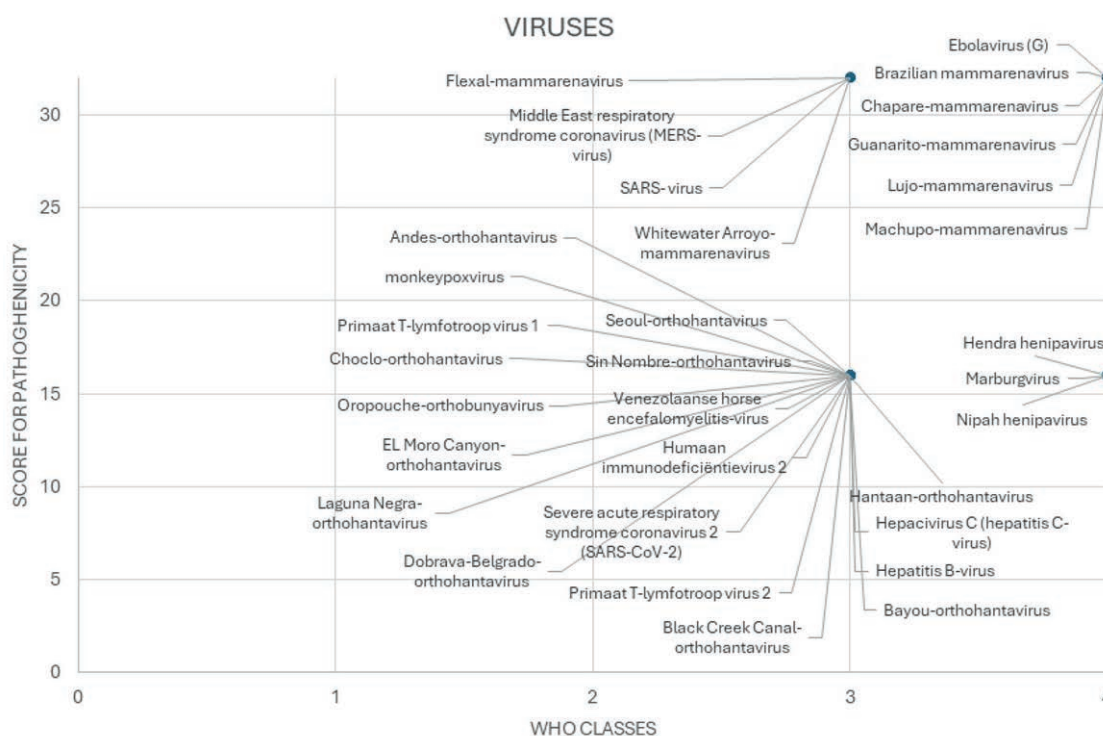


FIGURE 2: Matrix for viruses. WHO classes refer to diseases as explained in the text. Score for pathogenicity is calculated according to the algorithm shown in Table 1.

LC50-values in invertebrates as a criterion, and although these values are valuable in characterizing the pathogen, it is not helpful in the context of waste management. To translate our reasoning into practice, we adopted an operational definition of a pathogen that combines its biological properties with the disease it causes upon infection. This resulted in a representative figure for each pathogen and its position in a two-dimensional coordinate system. From this, some decisions for waste management are possible.

The figures in Table 1 reflect the authors' interpretations and are illustrative rather than definitive. For example, the weight of the infection dose in the algorithm is considered more significant than the mode of entry into the body, since if waste handlers correctly use their protective equipment (i.e., gloves) and the waste is stored appropriately, infection through the skin is virtually impossible. Similarly, the theoretical division of the four zones in Figure 1 is arbitrary. We classified diseases in Classes I and II as minor, easily treatable, and often vaccine-preventable. Conversely, diseases in Class III and definitely Class IV are regarded as severe and difficult to treat. Furthermore, the risk assessment that defines zones B/C and A/D, representing low and high infection potential, respectively, is arbitrary. Any decision about the risk to waste handlers depends on the chosen thresholds; in our model, pathogens with x-y coordinates corresponding to zones A, B, and C are deemed non-hazardous. The advantage of our system is that any responsible waste management professional in a hospital may adjust these thresholds according to their own judgment. For instance, the boundary between diseases of type II and III could be shifted to that between types I and II and the possibility of choosing a discriminating level of pathogenicity is illustrated by the grey zone in Figure 1. Clearly, any choice will affect the volume of medical waste and the procedures for handling it. All pathogens on list A in ADR are located in zone D of the x-y coordinate system, which is compatible with the legal requirements.

The algorithm uses data from the scientific literature, i.e., peer-reviewed papers or generally accepted and scrutinized databases. However, this information is not available for all pathogens. When information is insufficient or an unknown pathogen is involved, the precautionary principle applies, and a worst-case scenario is assumed.

The key point in this discussion is that the way a pathogen is transmitted during daily bedside patient care differs from its transmission during the handling of solid waste by waste handlers. Several examples clearly demonstrate this distinction. Malaria is caused by a mosquito bite, but the malaria patient cannot spread the parasite to bystanders, except through blood transfusion, organ donation, or from mother to baby during birth. These transmission routes are not relevant for waste handling. The virus responsible for severe diseases like dengue and Zika can be transmitted through blood contact in patients, but this is less significant during waste handling, as discussed in the "risk analysis" section. A pathogen with limited ability to survive outside the body, such as *Rickettsia*, may infect the healthcare worker treating the patient, but is unlikely to pose a risk to waste handlers, although the WHO classifies the diseases

caused by such infections as class III. Complex transmission routes are also possible; for example, the Coronavirus can survive outside the body as a fomite on materials that waste handlers might come into contact with (Fraeyman et al., 2022). Therefore, it is essential to consider not only the properties of the pathogen but also to conduct a thorough risk analysis to identify potential adverse effects.

5. CONCLUSIONS

Taken together, adopting the highest standard of safety for pathogens in solid medical waste would mean treating all waste as if it were hazardous, and this is unnecessary. The authors' opinion is that the discussion should strike a balance between safety, ecological, and economic benefits. The method outlined in this document at least provides a framework for considering how to reduce the approximately 80% of medical waste that is incorrectly regarded as hazardous. In cases of uncertainty, safe solutions have to be chosen.

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LIFE CYCLE ASSESSMENT AND INTEGRATED SUSTAINABILITY EVALUATION OF COAL-SLUDGE CO-FIRING POWER GENERATION

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ABSTRACT

The co-firing of municipal sewage sludge in coal-fired power plants is considered a viable waste-to-energy pathway for sludge disposal and low-carbon transition, yet comprehensive sustainability evaluations under China's dual-carbon goals remain limited. This study fills this gap by quantifying the environmental, economic, and integrated performance of a typical 2×330 MW co-firing plant in northern China using a cradle-to-gate life cycle assessment (LCA), life cycle costing (LCC), and the analytic hierarchy process (AHP). The results show that global warming potential dominates the total environmental impact (82.3%). Co-firing reduces internal costs by 1.1% while slightly increasing external costs by 0.8%. The integrated sustainability score of the co-firing scenario (0.5021) is statistically indistinguishable from that of conventional coal power (0.4979; bootstrap 95% CI of the difference [-0.008, +0.016]), indicating that co-firing does not compromise overall sustainability while providing the additional function of sludge disposal. Dynamic life cycle assessment further reveals that while centennial-scale GWP is nearly equivalent, co-firing exhibits an ~80% higher short-term (20-year) climate impact under time-resolved biogenic carbon accounting, underscoring the need to distinguish long-term carbon neutrality from near-term climate penalties in policy formulation. The evidence indicates that coal-sludge co-firing represents a viable transitional co-processing solution that should be supported through waste-disposal subsidies rather than carbon credits, without a significant net increase in centennial-scale climate burdens.

1. INTRODUCTION

Global climate change has intensified, with the past decade being the warmest on record (IPCC, 2021). China, as the world's largest energy producer and consumer, has committed to peaking carbon dioxide emissions by 2030 and achieving carbon neutrality by 2060 (State Council, 2021). Thermal power, which constitutes roughly 63% of China's total electricity generation (China Electricity Council, 2024), persists as the principal source of carbon emissions and air pollution. Therefore, promoting the low-carbon transformation of the thermal power industry is critical for achieving the dual carbon goals.

Meanwhile, China's annual municipal sludge production has exceeded 60 million tons (80% moisture content) with an annual growth rate of 5-8% (Dai et al., 2022). Traditional sludge disposal methods such as landfilling (38%) and land application (22%) face increasing environmental constraints due to land scarcity, groundwater contamination risks, and odor pollution (Zhou et al., 2022). Coal-sludge co-firing power generation utilizes existing coal-fired power plant facilities to co-combust dewatered sludge with coal,

achieving the harmless disposal of sludge, volume reduction, and energy recovery simultaneously. This technology has attracted widespread attention due to its low incremental investment, high treatment capacity, and compatibility with existing power generation infrastructure (Chen et al., 2019).

Life cycle assessment (LCA) is a systematic methodology for evaluating the environmental impacts of products or processes throughout their entire life cycle, from raw material extraction to final disposal (ISO 14040, 2006). It has been widely applied in the power industry to assess the environmental performance of different generation technologies. Previous studies have conducted LCA on conventional coal-fired power plants (Kommalapati et al., 2018; Li et al., 2020), biomass co-firing (Kommalapati et al., 2018), and renewable energy systems (Li et al., 2020). However, research on coal-sludge co-firing remains limited and fragmented. Most existing studies focus on combustion characteristics and pollutant emission control (Huang et al., 2021), while few have conducted comprehensive cradle-to-gate LCA studies covering all life cycle stages.

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Furthermore, most LCA studies only consider environmental impacts, ignoring economic costs and social benefits. A holistic sustainability evaluation that integrates environmental, economic, and social dimensions is essential for evidence-based policy-making regarding the promotion of coal-sludge co-firing technology. Recent studies (Ren et al., 2025; Wang & Zhu, 2023) have highlighted the need for multi-criteria decision analysis to balance trade-offs between different sustainability dimensions.

This study aims to fill these research gaps by conducting a comprehensive life cycle assessment and integrated sustainability evaluation of coal-sludge co-firing power generation. The specific objectives are: (1) to establish a cradle-to-gate LCA model for coal-sludge co-firing and quantify its environmental impacts; (2) to conduct sensitivity analysis to identify key parameters affecting environmental performance; (3) to evaluate life cycle costs including both internal operational costs and external environmental costs; (4) to develop an integrated AHP-based evaluation system and compare the comprehensive sustainability of co-firing and conventional coal-fired power generation. The findings of this study will provide quantitative evidence for policy makers and power plant operators to make informed decisions regarding sludge co-firing promotion.

2. MATERIALS AND METHODS

2.1 Goal and scope definition

The primary goal of this study is to evaluate the environmental impact, economic cost, and comprehensive sustainability of coal-sludge co-firing power generation compared to conventional coal-fired power generation. The functional unit is defined as 1 kWh of net electricity delivered to the grid, which is the standard functional unit for power generation LCA studies (ISO 14067, 2018).

The system boundary follows a cradle-to-gate approach, encompassing four consecutive stages:

- Raw material acquisition: Extraction and processing of coal, limestone, urea, hydrochloric acid, sodium hydroxide, and sludge collection/dewatering.
- Transportation: Transportation of all raw materials to the power plant via railway and road.
- Power generation: Combustion of coal-sludge mixture, electricity generation, and flue gas treatment (desulfurization, denitrification, dust removal).
- By-product recycling: Comprehensive utilization of boiler slag, fly ash, and desulfurization gypsum as construction materials.

Within the power generation stage, the coal-sludge blend undergoes pulverization in coal mills, preheating with combustion air, and subsequent combustion in the pulverized-coal boiler at approximately 1,400°C. The resulting flue gas passes sequentially through selective catalytic reduction (SCR) for NO_x removal, electrostatic precipitators for dust removal, and limestone-gypsum wet flue gas desulfurization for SO₂ removal before being discharged through the stack.

In the conventional coal-fired power generation baseline scenario, the same annual quantity of municipal sludge

(75,000 t, 80% moisture content) is assumed to be generated but is disposed of independently via sanitary landfilling. Consistent with the cut-off principle of attributional LCA (ISO 14040:2006, Section 4.3.1), the environmental burdens of sludge landfilling—including landfill gas emissions, leachate generation and treatment, and land occupation—are excluded from the system boundary of the power generation baseline. This exclusion rests on the rationale that, under attributional LCA, a product system is responsible only for the environmental interventions directly attributable to its own function (electricity generation); the post-use disposal of sludge, which would occur regardless of whether the sludge is co-fired or landfilled, constitutes an independent waste management system with its own functional unit (tonnes of sludge treated). Including landfill burdens in the power generation baseline would confound the functional units of two distinct product systems.

This conservative methodological choice has the following consequence: co-firing receives no credit for the avoided landfill methane emissions that would result from diverting sludge away from landfill disposal. The magnitude of this uncredited benefit is estimated in the Supplementary Materials (Table S8): depending on landfill gas management conditions, avoided methane emissions could provide a GWP credit of 0.003–0.008 kg CO₂ eq/kWh, which, if credited to co-firing, would reduce its net GWP below that of conventional coal power by approximately 1–3%. The main-text comparison therefore represents a conservative lower bound of co-firing's relative climate performance (Figure 1).

The construction and decommissioning stages of the power plant are excluded from the system boundary, consistent with the majority of power generation LCA studies, on the grounds that their contribution per unit of electricity generated is typically small relative to the operational phase over a 30-year service life (Malode et al., 2023). However, it is acknowledged that the co-firing scenario required retrofit modifications—specifically, the installation of a sludge receiving and storage facility, a sludge dewatering unit (centrifuge), a closed sludge conveying system, and modifications to the coal feeding system to accommodate the blended fuel—that would not be necessary for a conventional coal-fired plant of equivalent capacity. The environmental impacts of manufacturing and installing this retrofit equipment are not separately quantified in this study. They are assumed to be partially captured within the auxiliary power consumption data (Section 2.3) and the sludge pre-treatment inventory, though this assumption may underestimate the actual cradle-to-gate environmental burden of the co-firing configuration. The magnitude of this potential underestimation should be quantified in future work through a dedicated capital-equipment LCA of the retrofit components. From a life cycle cost perspective, the capital expenditure for the sludge co-firing retrofit (approximately 35–50 million yuan for the sludge receiving, dewatering, and conveying systems, per the plant's engineering procurement records) is amortized over the 30-year remaining service life of the host plant. The annualized retrofit cost, normalized to the functional unit, is approximately 0.0004–0.0006 yuan/kWh (< 0.2% of the internal cost), and

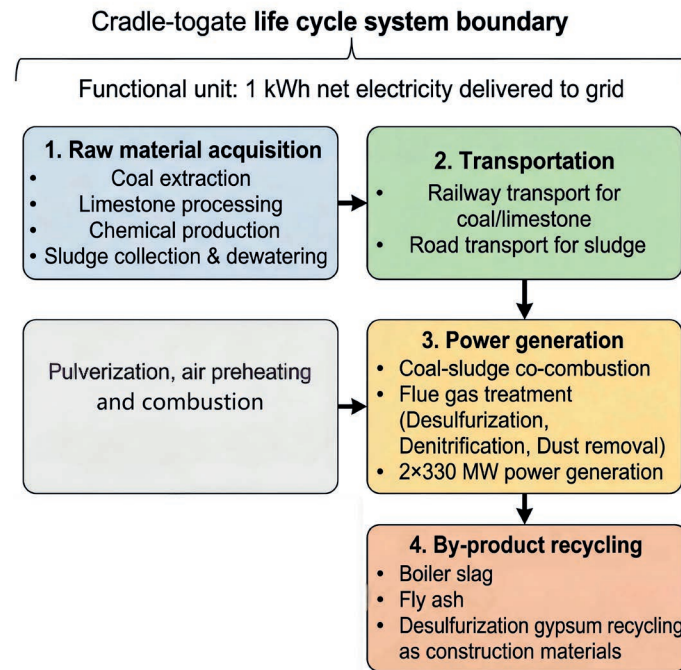


FIGURE 1: System boundary of coal-sludge co-firing power generation system.

is therefore not separately itemized in the life cycle cost analysis. This assumption is valid for the retrofit-of-existing-plant scenario studied here; a greenfield co-firing plant would require a full capital-cost LCA, beyond the scope of this work. Electricity transmission and distribution are also excluded as they are identical for both co-firing and conventional coal-fired power generation.

2.2 Co-product allocation for the CHP system

The studied power plant is a combined heat and power (CHP) system producing two co-products: net electricity (3.01×10^9 kWh/year) and heat (6.132×10^6 GJ/year). In accordance with ISO 14040:2006, Section 4.3.4.2, which requires that allocation in multi-functional systems reflect underlying physical relationships, the energy allocation method was adopted—the most widely recommended allocation approach for CHP systems in the LCA literature. The allocation coefficient for electricity (a_e) was calculated as:

$$a_e = E_e / (E_e + E_h) \quad (1)$$

where E_e is the annual net electricity output expressed in energy units (3.01×10^9 kWh $\times$ 3.6 MJ/kWh = 1.0836×10^7 GJ) and E_h is the annual heat output (6.132×10^6 GJ). This yields $a_e = 0.6386$ (63.86%) for electricity and $a_h = 0.3614$ (36.14%) for heat. All plant-level input and output data were first compiled as total annual quantities, then partitioned using these coefficients, and finally normalized to the functional unit of 1 kWh net electricity. The detailed allocation factors and the resulting electricity-attributed shares of key inventory flows are summarized in Supplementary Table S1.

This transparent reporting of the allocation methodology and coefficients enables full reproducibility and allows readers to recalculate results under alternative allocation assumptions.

2.2.1 By-product recycling allocation method

The system expansion approach (also termed the avoided burden method) was adopted to account for the environmental credits associated with by-product recycling, consistent with the ISO 14044:2006 recommendation for multi-functional processes where system expansion is feasible. Under this approach, the recycled by-products—boiler slag, fly ash, and desulfurization gypsum—are assumed to substitute equivalent quantities of primary materials in their respective markets: natural gravel (for boiler slag used as road base aggregate), Portland cement (for fly ash used as supplementary cementitious material in concrete production), and natural gypsum (for desulfurization gypsum used in wallboard manufacturing). The environmental burdens avoided by not producing these primary materials are credited to the co-firing system.

As shown in Table 2, recycling credits are allocated to ADP, GWP, and HTP, reflecting the primary environmental mechanisms of material substitution: ADP credits arise from avoided extraction of limestone, clay, and natural gypsum; GWP credits arise from avoided process-related CO₂ emissions during cement clinker production and gypsum calcination; and HTP credits arise from avoided heavy metal and particulate releases associated with mining and quarrying operations. No recycling credits are assigned to POCP, AP, and EP because the avoided production of natural gravel, cement, and gypsum generates negligible reductions in photochemical oxidant formation, acidification, and eutrophication relative to the dominant contributions from coal combustion and upstream fuel processing. The substitution ratios adopted are as follows: 1 kg of fly ash displaces 0.85 kg of Portland cement (CEM I 42.5), reflecting the loss-on-ignition-based quality adjustment for Class F fly ash; 1 kg of desulfurization gypsum displaces 0.90

kg of natural gypsum, accounting for the slightly higher free moisture content of FGD gypsum relative to mined gypsum; and 1 kg of boiler slag displaces 1.0 kg of natural gravel on a mass basis. The avoided environmental burdens per unit of displaced primary material were obtained from Ecoinvent 3.9 using the following background processes: “Portland cement, strength class CEM I 42.5 {GLO} market for | Cut-off, U” for cement; “Gypsum, mineral {GLO} market for gypsum | Cut-off, U” for natural gypsum; and “Gravel, crushed {GLO} market for gravel | Cut-off, U” for natural gravel. The substitution factors and their data sources are documented in Supplementary Table S7. This conservative approach avoids overstating the environmental benefits of by-product recycling and is consistent with the material-specific substitution logic applied in previous power generation LCA studies.

2.3 Life cycle inventory analysis

Primary inventory data were collected from a typical 2×330 MW subcritical coal-sludge co-firing CHP plant in northern China. The plant’s key technical specifications are presented in Table 1. The sludge co-firing ratio is approximately 5% (by mass), with sludge sourced from local municipal wastewater treatment plants. Heavy metal and trace pollutant emission data (mercury, cadmium, lead, arsenic, chromium, copper, nickel) were obtained from the plant’s Continuous Emission Monitoring System (CEMS), with sampling and analytical methodologies conforming to China’s GB 13223-2011 “Emission Standard of Air Pollutants for Thermal Power Plants.” Dioxin emissions were

TABLE 1: Main technical parameters of the coal-sludge co-firing power plant.

Parameter	Value	Unit
Installed capacity	2×330	MW
Annual operating hours	4600	h
Annual net electricity output	3.01×10 ⁹	kWh
Annual heat output	6.132×10 ⁶	GJ
Annual coal consumption	1.60×10 ⁶	t
Annual sludge consumption	7.5×10 ⁴	t
Sludge co-firing ratio	5	%
Auxiliary power consumption rate	7.12	%
Desulfurization system	Limestone-gypsum wet FGD	-
Denitrification system	SCR	-
SO ₂ net emission intensity	0.23	g/kWh
NO _x net emission intensity	0.33	g/kWh
Particulate matter net emission intensity	0.07	g/kWh

Note: Desulfurization and denitrification efficiencies are presented as technical background. SO₂, NO_x, and dust emission values adopt the ultra-low emission limits specified in GB 13223-2011 (35 mg/Nm³, 50 mg/Nm³, and 10 mg/Nm³, respectively) and are converted to emission intensity per kWh using a typical flue gas volume of 6.5 Nm³/kWh for a 300 MW-class coal-fired unit. Actual plant CEMS-monitored annual average emissions are lower than these regulatory limits; the GB 13223-2011 values are used here as conservative estimates in the absence of continuous annual CEMS data across the full assessment period.

estimated using US EPA AP-42 emission factors (Chapter 1.1: Bituminous and Subbituminous Coal Combustion) for modern coal-fired utility boilers equipped with activated carbon injection and baghouse filtration systems. Secondary data for upstream processes (coal mining, limestone production, etc.) were obtained from the Ecoinvent 3.9 database and the Chinese national life cycle database (CLCD). The specific background processes used were: (1) Coal production: corresponding process from Ecoinvent 3.9, representing Shanxi bituminous coal mining; (2) Limestone production: corresponding process from the CLCD database; (3) Urea and chemical production: corresponding Chinese national average processes from the CLCD. Transportation distances were determined based on the actual supply chain of the power plant: coal is transported 630 km by railway from Shanxi Province, limestone 370 km by railway and 97 km by road, and sludge 50 km by road from local wastewater treatment plants. SO₂, NO_x, and dust emission concentrations were obtained from the plant’s CEMS. For the life cycle inventory, these concentrations were converted to emission intensity per unit of net electricity output (g/kWh) using the plant’s annual average flue gas volume of 6.5 Nm³/kWh. Where annual average CEMS data were unavailable over the full assessment period, the ultra-low emission limits specified in GB 13223-2011 were adopted as conservative estimates.

The complete foreground life cycle inventory dataset, comprising all input and output flows normalized to the functional unit of 1 kWh net electricity, is documented in Supplementary Table S2. The aggregated inventory flows are also summarized in Supplementary Table S2, and the disaggregated SimaPro model output is available from the corresponding author upon reasonable request.

The life cycle inventory data for each stage, after energy allocation and normalization to the functional unit, are summarized in Supplementary Table S2. All values are reported to 2-3 significant figures, consistent with the precision of the underlying measurement and estimation methodologies.

2.4 Life cycle impact assessment

The CML-IA baseline method (Guinée et al., 2002) was selected for life cycle impact assessment, which is one of the most widely used midpoint impact assessment methods in environmental LCA studies.

Six environmental impact categories were considered based on their relevance to coal-fired power generation:

- Abiotic Depletion Potential (ADP): Measures the depletion of non-renewable resources.
- Global Warming Potential (GWP): Measures the contribution to climate change over a 100-year time horizon.
- Human Toxicity Potential (HTP): Measures the potential harm to human health from toxic substances.
- Photochemical Ozone Creation Potential (POCP): Measures the formation of ground-level ozone.
- Acidification Potential (AP): Measures the potential to cause acid rain.
- Eutrophication Potential (EP): Measures the potential to cause nutrient enrichment in water bodies.

Characterization and normalization calculations were performed using SimaPro 9.0 software.

Normalization factors were based on the CML-IA baseline 2000 global average per capita environmental impacts, as provided in the SimaPro 9.0 software package (Guinée et al., 2002). These factors represent the total environmental impact per person per year globally, and are widely used in international LCA studies to convert absolute impact values into comparable dimensionless values, enabling cross-category comparison of environmental burdens. The use of standardized global normalization factors ensures the reproducibility of the results and allows direct comparison with other LCA studies using the same methodology.

Supplementary analyses using the ReCiPe 2016 midpoint (H) and endpoint (H) methods were also conducted to test the robustness of the CML-IA baseline results. The ReCiPe results, reported in Section 3.5 and Supplementary Table S5, are not intended to replace the primary CML-IA analysis but to provide a cross-validation of the impact category ranking.

2.5 Life cycle cost analysis

Life cycle cost (LCC) analysis was conducted to evaluate the economic performance of the co-firing system. LCC includes both internal costs (borne directly by the power plant operator) and external costs (borne by society due to environmental pollution and ecological damage).

Internal costs include raw material costs, transportation costs, operational costs, and by-product revenues. Cost data were obtained from the power plant's financial records and 2024 market prices in China. Sludge has a negative cost as the power plant receives a treatment fee of 200 yuan/ton from local governments.

External costs were calculated by monetizing the environmental impact results using China-specific marginal environmental damage factors, following the methodological framework of the Ministry of Ecology and Environment of China (MEE, 2021). The monetary factors assigned to each impact category were as follows: for ADP, 9.56×10^{-3} yuan/kg Sb eq; for GWP, 0.102 yuan/kg CO₂ eq; for HTP, 0.317 yuan/kg 1,4-DB eq; for POCP, 4.34 yuan/kg C₂H₄ eq; for AP, 5.05 yuan/kg SO₂ eq; and for EP, 14.92 yuan/kg PO₄⁻³ eq. The GWP monetary factor was derived from a synthesis of provincial-level social cost of carbon estimates for China (Wang et al., 2022). The monetary factors for ADP, HTP, POCP, AP, and EP were calculated using the damage cost approach with willingness-to-pay parameters recommended by MEE (2021) and updated with recent valuation studies (Ren et al., 2025). The full set of monetary factors and their sources are documented in Supplementary Table S3.

The monetary factors employed in this study should be interpreted as order-of-magnitude estimates rather than definitive damage costs. Monetization of environmental impacts in LCA remains an evolving field, and valuations can vary substantially depending on the chosen methodology (e.g., abatement cost vs. damage cost approaches, geographic scope, discount rate assumptions). The factors used here represent China-specific estimates from the published literature and are applied consistently to both the co-firing and conventional coal-fired scenarios, there-

by enabling a relative comparison. Absolute external cost figures should be treated as indicative and interpreted with appropriate caution.

2.6 Integrated sustainability evaluation

An integrated sustainability evaluation system was developed using the Analytic Hierarchy Process (AHP) (Saaty, 1980). The system consists of three hierarchical levels:

- Target layer: Comprehensive sustainability of power generation technology
- Criterion layer: Environmental impact, economic impact, social impact
- Indicator layer: 11 specific indicators covering the three dimensions, including sludge disposal capacity (75,000 t/year) and reduced landfill demand (75,000 t/year).

It is acknowledged that the inclusion of plant technical staff (8 of 15 experts) introduces a potential source of bias toward favorable evaluations of co-firing technology. To assess the robustness of the AHP results with respect to panel composition, a subgroup analysis using only independent academic and regulatory experts ($n = 7$) was conducted, with full results reported in Section 3.7 (Figure 2).

The weights of each indicator were determined through expert scoring. A total of 15 experts with more than 5 years of relevant work experience were recruited: 8 senior technical staff from the power plant, 5 researchers from universities specializing in environmental engineering and energy economics, and 2 policy makers from the local ecological and environmental bureau. The consistency ratio (CR) of all judgment matrices was less than 0.1, indicating acceptable consistency of the expert judgments. The full judgment matrix and detailed weight calculation process are provided in the Supplementary Materials.

The weights derived from the AHP expert scoring process are as follows. At the criterion layer: environmental impact, 0.6483; economic impact, 0.2297; and social impact, 0.1220 (CR = 0.0036). Within the environmental sub-criteria: HTP, 0.4033; GWP, 0.1645; AP, 0.1645; EP, 0.1645; POCP, 0.0683; and ADP, 0.0349 (CR = 0.0198). Within the economic sub-criteria: internal cost, 0.8000; and external cost, 0.2000 (CR = 0). Within the social sub-criteria: public health risk, 0.6370; community acceptance, 0.2583; and corporate reputation, 0.1047 (CR = 0.0370). The complete judgment matrices and consistency ratios are provided in the Supplementary Materials.

2.7 Sensitivity and uncertainty analysis

Sensitivity analyses were performed to evaluate the influence of four key operational parameters on the environmental performance of the co-firing system:

- Auxiliary power consumption rate: varied from the plant's measured baseline of 7.12% to an industry best-practice target of 6.0%. This range corresponds to the efficiency gain achievable through the adoption of variable-frequency drive technology and combustion optimization, as reported in the China Electricity Council's 2024 annual development report.

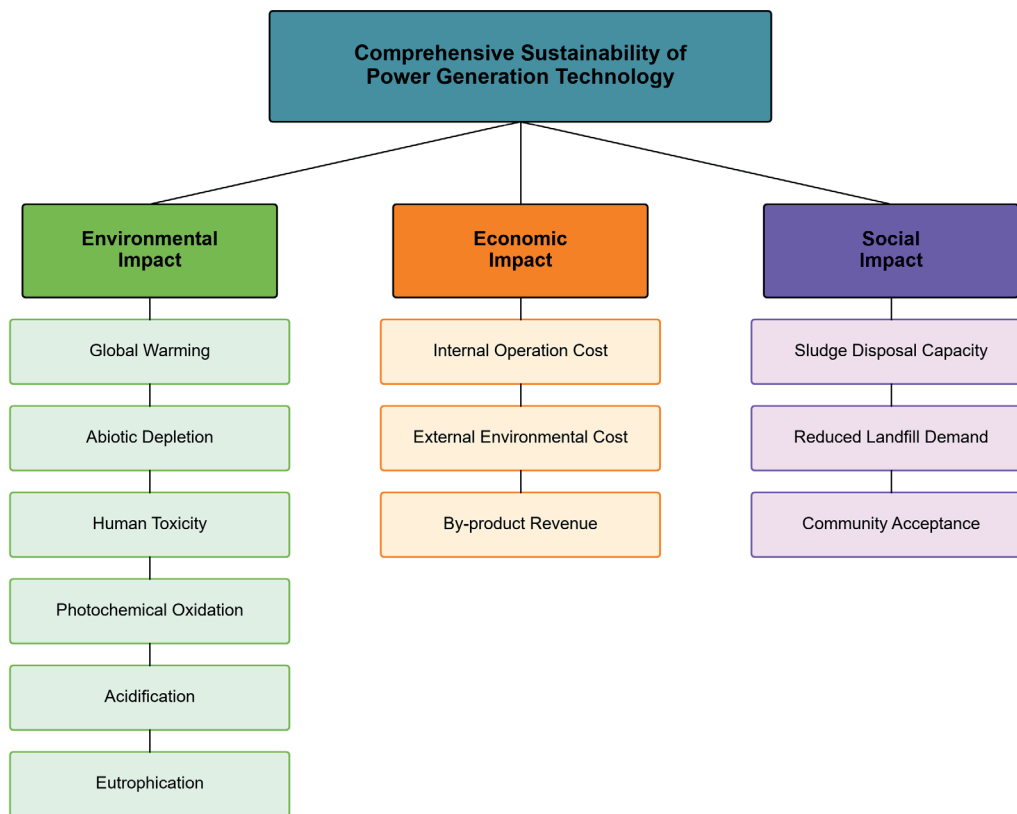


FIGURE 2: Integrated sustainability evaluation index system.

- Desulfurization efficiency: varied from the plant's design range of 99.4%-99.9% (representing optimal operation of the limestone-gypsum wet FGD system) to a degraded condition of 90% (the minimum compliance threshold specified in GB 13223-2011 for existing coal-fired units). This range captures the performance decline that may occur due to absorber spray nozzle fouling and limestone slurry quality variation over an operating cycle.
- Denitrification efficiency: varied from the plant's design value of 95% (representing optimal SCR operation with fresh catalyst) to a degraded condition of 85%. The lower bound corresponds to the performance decline observed after approximately 16,000-24,000 hours of SCR catalyst operation, per the plant's maintenance records and the typical catalyst deactivation rate of 0.5-1.0 percentage points per 1,000 operating hours for coal-fired SCR systems.
- Transportation mode: varied by shifting 50% of road transport tonne-kilometers to railway, reflecting the modal shift target of China's "Road-to-Rail" policy for bulk commodity transport (State Council, 2021). The 50% shift is consistent with the China Railway Corporation's medium-term target for coal and mineral freight corridors.

A supplementary sensitivity analysis of the sludge treatment subsidy was conducted by varying the subsidy level from 100 to 300 yuan per tonne of dewatered sludge (baseline: 200 yuan/t), covering the full range currently observed across Chinese provinces.

3. RESULTS AND DISCUSSION

3.1 Environmental impact characterization results

The characterization results of the coal-sludge co-firing power generation system are presented in Table 2. The findings indicate that the raw material acquisition and power generation stages are the primary contributors to most environmental impact categories. Human toxicity potential (HTP), photochemical ozone creation potential (POCP), acidification potential (AP), and eutrophication potential (EP) are predominantly influenced by the raw material acquisition stage. In contrast, global warming potential (GWP) and abiotic depletion potential (ADP) are dominated by the power generation stage, with the power generation stage accounting for approximately 66.4% of the total ADP. The raw material acquisition phase contributes approximately 13.3% of the total GWP, mainly stemming from upstream coal mining, limestone production, and chemical reagent manufacturing. The by-product recycling stage yields quantifiable environmental benefits via resource substitution, partially offsetting the impacts of the upstream and operational stages. Detailed stage-by-stage characterization results for all six impact categories are provided in the Supplementary Materials (Table S2).

3.2 Normalization results

The normalization results are shown in Figure 3. GWP has the highest normalized value (1.81×10^{-13}), accounting for 82.3% of the total environmental impact, followed by EP (4.44×10^{-14} , 20.2%) and AP (3.63×10^{-14} , 16.5%). ADP has the

TABLE 2: Characterization results of coal-sludge co-firing power generation (per kWh).

Impact category	Total value	Raw material	Transport	Power generation	By-product recycling
ADP (kg Sb eq)	2.74×10^{-7}	1.52×10^{-7}	1.2×10^{-8}	1.99×10^{-7}	-7.8×10^{-8}
GWP (kg CO ₂ eq)	9.07×10^{-1}	1.21×10^{-1}	6.2×10^{-3}	7.86×10^{-1}	-1.2×10^{-3}
HTP (kg 1,4-DB eq)	1.03×10^{-1}	7.82×10^{-2}	3.1×10^{-3}	2.36×10^{-2}	-1.8×10^{-3}
POCP (kg C ₂ H ₄ eq)	6.64×10^{-5}	5.41×10^{-5}	1.2×10^{-6}	1.11×10^{-5}	0
AP (kg SO ₂ eq)	1.02×10^{-3}	6.47×10^{-4}	2.1×10^{-5}	3.52×10^{-4}	0
EP (kg PO ₄ ⁻³ eq)	5.86×10^{-4}	5.14×10^{-4}	1.3×10^{-5}	5.9×10^{-5}	0

lowest normalized value (3.24×10^{-15} , 1.5%). This indicates that global warming is the most significant environmental challenge for coal-sludge co-firing power generation, consistent with the characteristics of fossil fuel-based power generation.

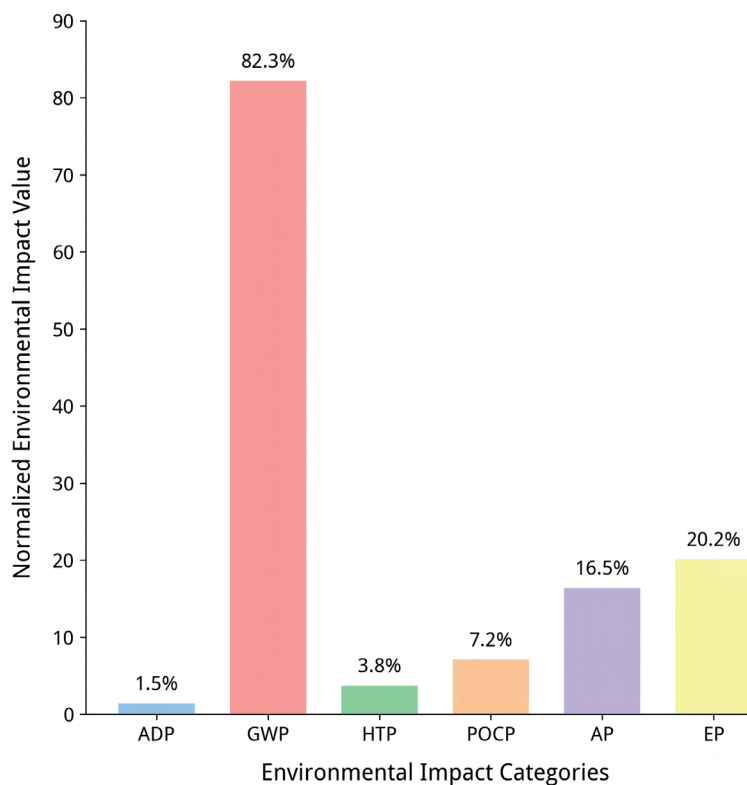
3.3 Comparison with conventional coal-fired power generation

The environmental impact comparison between coal-sludge co-firing and conventional coal-fired power generation is shown in Figure 4. The results demonstrate that the two technologies have very similar environmental profiles. Co-firing increases ADP by 5% and HTP by 3%, mainly due to additional energy consumption for sludge dewatering and transportation. However, GWP remains almost unchanged (0.17% increase) as the carbon in sludge is considered biogenic and not included in fossil carbon accounting. AP and EP increase slightly by 0.56% and 0.43%, respectively, which is effectively mitigated by the plant's high-efficiency flue gas treatment systems.

3.3.1 Sensitivity analysis of biogenic carbon accounting

Given the ongoing methodological controversy regarding biogenic carbon accounting in sludge energy utilization (Cherubini et al., 2011; Guest et al., 2013), a dedicated sensitivity analysis was conducted to assess how different carbon accounting frameworks affect the global warming potential (GWP) results. Three scenarios were defined, all maintaining identical system boundaries, functional units, and inventory data:

- Baseline Scenario (BS): Followed ISO 14067:2018 guidelines, treating sludge carbon as biogenic and excluding it from fossil carbon emissions (the default assumption used throughout this study).
- Sensitivity Scenario (SS): Conservative fossil carbon equivalence assumption, where all carbon in sludge is treated as fossil carbon, reflecting the upper bound of potential climate impact.
- Dynamic Scenario (DS): Adopted a dynamic LCA approach (Levasseur et al., 2010) that accounts for the temporal mismatch between biogenic carbon emissions

**FIGURE 3:** Normalization results of environmental impact categories.

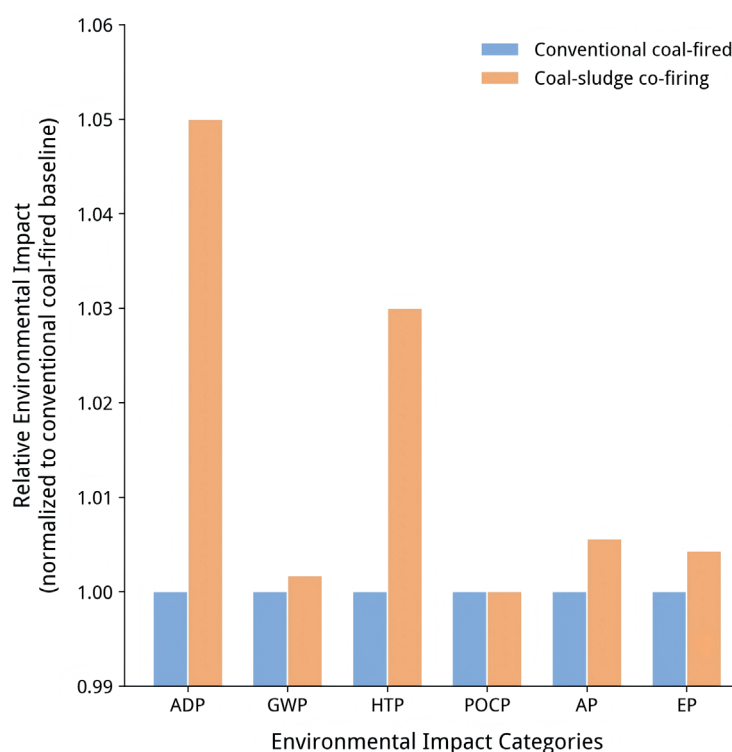


FIGURE 4: Environmental impact comparison between co-firing and conventional coal-fired power generation.

and carbon sequestration. This scenario uses a 20-year time horizon (relevant for China's 2030 carbon peaking goal) and applies a time-dependent emission weighting factor of 1.8, consistent with the dynamic LCA framework of Levasseur et al. (2010) and its application to short-lived climate forcing.

Table 3 summarizes the GWP results under the three accounting frameworks, compared to the conventional coal-fired power generation baseline. This analysis only examines methodological uncertainty from carbon accounting frameworks. Parameter uncertainty (including sludge carbon content measurement error $\pm 5\%$, combustion efficiency fluctuation $\pm 3\%$, and background emission factor variability $\pm 10\%$) was assessed via Monte Carlo simulation, which yielded a 95% confidence interval of $\pm 6.4\%$ for GWP results. This parameter uncertainty is significantly smaller than the systematic bias introduced by switching carbon accounting methods (ranging from $+1.2\%$ to $+80.0\%$).

It should be emphasized that the Sensitivity Scenario is designed as an extreme methodological counterfactual, not as a recommendation that sludge carbon be classified under fossil carbon accounting. Its purpose is to bracket the range of possible GWP outcomes under alternative carbon accounting conventions and to highlight the sensitivity of climate impact rankings to this methodological choice. It should be noted that the baseline GWP comparison presented above is a conservative estimate. If avoided landfill methane emissions resulting from sludge diversion (equivalent to $0.003\text{--}0.008 \text{ kg CO}_2 \text{ eq/kWh}$, per IPCC Tier 1 methodology) were credited to the co-firing scenario, the net GWP of co-firing would be approximately $0.3\text{--}0.9\%$ lower than that of conventional coal power, as detailed in Supplementary Table S8.

The results demonstrate that biogenic carbon accounting is among the most influential parameters determining the climate impact ranking of coal-sludge co-firing. Under the standard ISO 14067 framework, co-firing has nearly

TABLE 3: Sensitivity of GWP results to biogenic carbon accounting methods (per kWh net electricity).

Scenario	GWP (kg CO ₂ eq/kWh)	Change from baseline scenario	Comparison with pure coal baseline	Key assumptions
Baseline Scenario (BS)	0.907	-	0.1% higher	Biogenic carbon neutral (ISO 14067:2018)
Sensitivity Scenario (SS)	0.918	+1.2%	1.3% higher	All sludge carbon treated as fossil carbon
Dynamic Scenario (DS, 20-year horizon)	1.633	+80.0%	80.2% higher	Dynamic LCA time weighting factor = 1.8

Note: The Baseline Scenario follows ISO 14067:2018 biogenic carbon neutrality convention. The Sensitivity Scenario is a methodological counterfactual upper bound, not a recommended accounting approach. The Dynamic Scenario applies time-dependent weighting factors from Levasseur et al. (2010) with a 20-year time horizon.

identical GWP to conventional coal power. However, under the conservative fossil carbon assumption, co-firing exhibits a small but measurable climate penalty. Most strikingly, the dynamic LCA scenario reveals that sludge co-firing could have a substantially higher short-term climate impact than pure coal combustion, due to the immediate release of biogenic carbon that would otherwise be sequestered in landfills over decades. This finding provides a quantitative reference for waste-to-energy LCA methodology: while most previous co-firing LCA studies have typically adopted the biogenic carbon neutrality convention, the evidence here quantifies the systematic bias that this convention introduces when projected against China's 2030 carbon peak timeline, thereby providing a concrete reference point for the ongoing debate on how to handle biogenic carbon in waste-to-energy LCA.

To evaluate the sensitivity of the DS result to the choice of the dynamic weighting factor, the factor was varied from the baseline value of 1.8 (Levasseur et al., 2010) to 1.5 and 2.0. At a weighting factor of 1.5, the DS GWP is approximately 1,440 kg CO₂ eq/MWh, representing a 59% increase over the Baseline Scenario. At a factor of 2.0, the DS GWP is approximately 1,740 kg CO₂ eq/MWh, representing a 92% increase. While the absolute GWP magnitude is sensitive to the choice of weighting factor, the qualitative conclusion—that the short-term climate impact of co-firing

is substantially greater than that indicated by the static ISO 14067 framework—remains robust across the tested range of 1.5-2.0.

3.4 Sensitivity analysis results

The rationale and literature basis for each parameter range are detailed in Section 2.7. Sensitivity analysis was conducted to evaluate the influence of key operational parameters on the environmental performance of the co-firing system. The results are summarized in Figure 5.

Figure 5 presents the sensitivity results as a tornado diagram. Each horizontal bar represents the percentage change in an environmental impact category resulting from the variation of a single operational parameter while all other parameters are held at their baseline values. The four parameters and their variation ranges are: (i) auxiliary power consumption rate, from the plant's actual 7.12% to an industry best-practice target of 6.0%; (ii) desulfurization efficiency, from the plant's design value of 99.4% to a degraded condition of 90%; (iii) denitrification efficiency, from the plant's design value of 95% to a degraded condition of 85%; and (iv) transportation mode, shifting 50% of road transport to railway (the "road-to-rail" policy scenario).

Auxiliary Power Consumption Rate. Reducing the auxiliary power consumption rate from 7.12% to 6% resulted in a systematic decrease in all environmental impact cate-

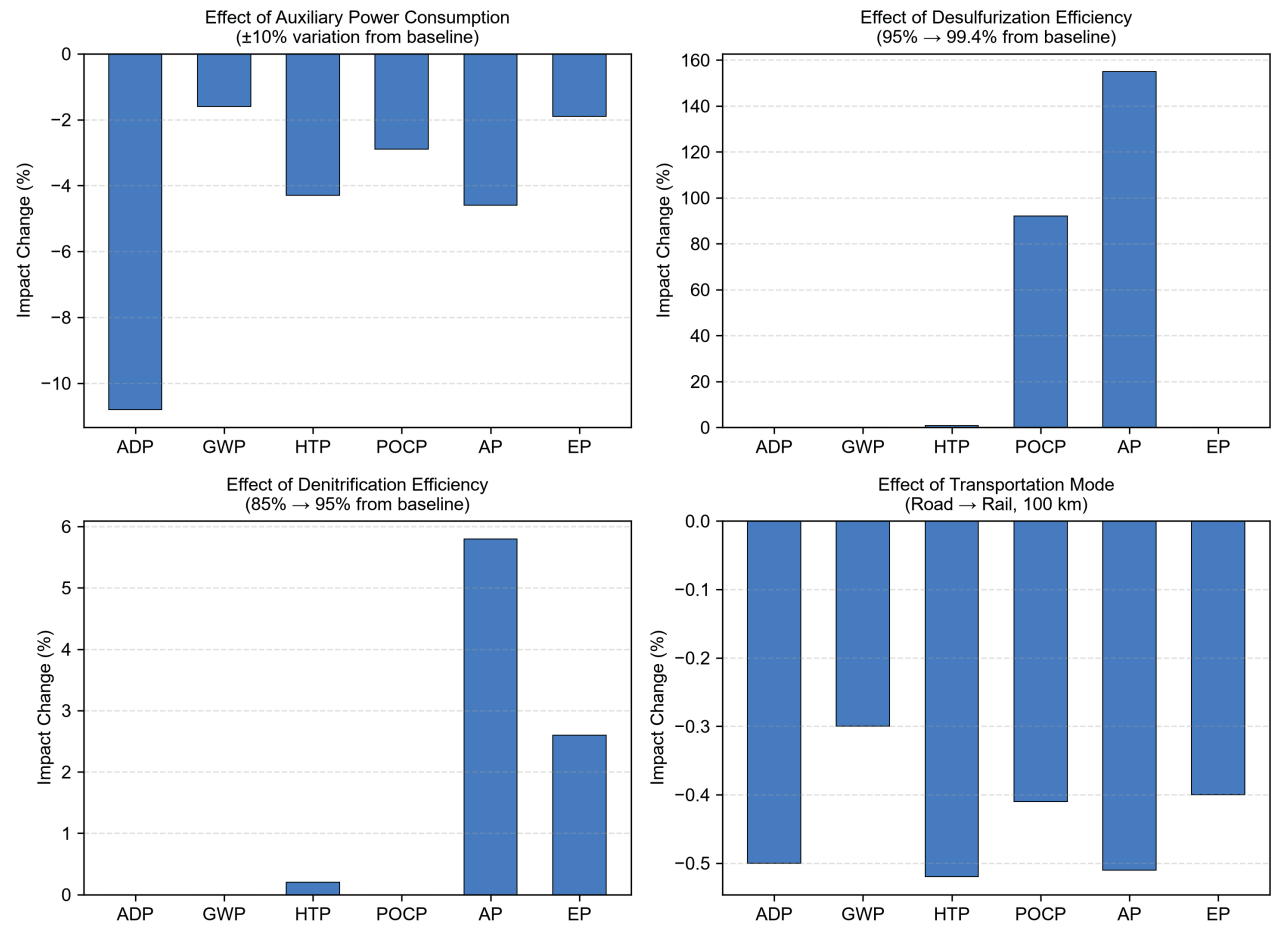


FIGURE 5: Sensitivity analysis results of key parameters.

gories. ADP decreased the most by 11%, followed by HTP (4.5%), AP (4.4%), GWP (1.2%), POCP (2.7%), and EP (1.7%). This is because lower auxiliary power consumption directly reduces coal consumption, thereby decreasing both resource depletion and pollutant emissions.

Desulfurization Efficiency. Reducing desulfurization efficiency from 99.4% to 90% had a dramatic effect on AP and POCP. AP increased by 152.6%, and POCP by 92.5%, while other impact categories changed by less than 2%. This highlights the critical importance of maintaining high desulfurization efficiency to control acidification and photochemical smog formation.

Denitrification Efficiency. Reducing denitrification efficiency from 95% to 85% increased AP by 5.81% and EP by 2.64%, as NO_x is a precursor for both acid rain and eutrophication. Other environmental impact categories were not significantly affected.

Transportation Mode. Implementing the “road-to-rail” policy (shifting 50% of road transportation to railway) resulted in a slight but consistent improvement in all environmental impact categories. ADP, HTP, and AP decreased by approximately 0.5%, while GWP decreased by 0.3%.

Sensitivity of External Costs to Monetary Valuation Factors. Recognizing that the monetary valuation factors carry inherent uncertainty, a supplementary sensitivity analysis was conducted in which the GWP monetary factor (base value: 0.102 yuan/kg CO_2 eq), AP monetary factor (base value: 5.05 yuan/kg SO_2 eq), and EP monetary factor (base value: 14.92 yuan/kg PO_4^{3-} eq) were each independently varied by $\pm 50\%$. The total external cost of the co-firing scenario ranged from 0.073 to 0.153 yuan/kWh under these perturbations, representing a variation of -32% to $+42\%$ relative to the base case (0.108 yuan/kWh). The GWP monetary factor was the dominant driver of this variability, contributing approximately 57% of the total external cost variance. Despite this sensitivity, the relative comparison between co-firing and conventional coal-fired generation remained stable: the co-firing external cost premium was consistently within the range of 0.6–1.0% across all scenarios. This stability supports the robustness of the policy conclusions drawn from the life cycle cost analysis.

3.5 Uncertainty analysis results

The Monte Carlo simulation results confirmed the overall robustness of the LCA conclusions. All key impact categories exhibited coefficients of variation below 5.3%. GWP demonstrated the lowest uncertainty ($\text{CV} = 3.2\%$), reflecting the relatively well-characterized nature of CO_2 emission factors and coal consumption data. The mean GWP value was 9.07×10^{-1} kg CO_2 eq/kWh, with a 95% confidence interval of $[8.50 \times 10^{-1}, 9.64 \times 10^{-1}]$. ADP showed a mean of 2.74×10^{-7} kg Sb eq/kWh and a CV of 4.2%. HTP exhibited a mean of 1.03×10^{-1} kg 1,4-DB eq/kWh with a CV of 4.0%. POCP and AP displayed CVs of 4.8% and 4.1%, respectively, while EP exhibited the highest variability ($\text{CV} = 5.3\%$, 95% CI $[5.25 \times 10^{-4}, 6.47 \times 10^{-4}]$ kg PO_4^{3-} eq/kWh), attributable to the combined uncertainties in fuel sulfur and nitrogen content, removal efficiencies, and background characterization factors. For all impact categories, the 95% confidence intervals are substantially narrower than the observed dif-

ferences between the co-firing and conventional coal-fired scenarios, confirming the statistical reliability of the comparative conclusions. The full Monte Carlo output distributions—including mean values, 95% confidence intervals, and coefficients of variation for all six impact categories—are documented in Supplementary Table S4.

Supplementary ReCiPe 2016 midpoint and endpoint analyses were also conducted to test the robustness of the CML-IA results. The ReCiPe analysis confirmed the same ranking of impact categories, with GWP remaining the dominant contributor (81.9% of the total endpoint score). These results are presented in Supplementary Materials (Table S5).

3.6 Life cycle cost results

The life cycle cost analysis yielded three principal findings. The internal cost of coal-sludge co-firing stands at 0.270 yuan/kWh, which is 1.1% lower than the 0.273 yuan/kWh of conventional coal-fired power generation—a difference attributable to the combined sludge-related benefits (direct subsidy and avoided disposal cost), of which the direct government subsidy contributes 0.005 yuan/kWh at 200 yuan/t. The external environmental cost, however, is 0.8% higher for co-firing (0.108 yuan/kWh) than for conventional coal power (0.107 yuan/kWh), driven mainly by increased HTP and AP impacts. Aggregating the two components, the total life cycle cost of co-firing reaches 0.378 yuan/kWh, marginally below the 0.380 yuan/kWh of the conventional route. The complete breakdown of internal, external, and total costs for both scenarios is provided in Supplementary Table S6.

The sensitivity of internal cost to the sludge treatment subsidy is as follows. The total sludge-related cost benefit (0.015 yuan/kWh) comprises two components: the direct government treatment subsidy (0.005 yuan/kWh at 200 yuan/t) and the avoided cost of alternative sludge disposal (0.010 yuan/kWh). At the baseline subsidy of 200 yuan/t, the internal cost of co-firing (0.270 yuan/kWh) is 1.1% lower than that of conventional coal power (0.273 yuan/kWh). If the subsidy were reduced to 100 yuan/t—the lower bound currently observed in some Chinese provinces—the internal cost of co-firing would rise to approximately 0.2725 yuan/kWh, narrowing the cost advantage to approximately 0.2%. At a subsidy of 300 yuan/t, the cost advantage would widen to approximately 2.0%. Linear interpolation identifies the break-even subsidy level as approximately 80 yuan/t, at which the internal costs of the two scenarios are equal. This break-even value lies well below the 100–300 yuan/t range currently implemented across Chinese provinces, indicating that co-firing remains economically viable under prevailing policy conditions.

These figures gain further context when benchmarked against China's dominant sludge disposal alternatives. Landfilling, which currently accounts for approximately 38% of China's sludge disposal, carries a typical cost of 150–300 yuan per ton of dewatered sludge, while dedicated sludge mono-incineration, an increasingly adopted alternative in large cities, costs approximately 300–600 yuan per ton (Havukainen et al., 2022). At the sludge treatment fee of 200 yuan per ton received by the co-firing plant in this

study, co-firing is cost-competitive with landfilling and significantly cheaper than dedicated sludge incineration, while providing the added benefits of coal displacement and energy recovery without requiring separate incineration infrastructure. The cost comparison between the two generation scenarios is illustrated in Figure 6.

3.7 Integrated sustainability evaluation

The integrated AHP evaluation was conducted following the three-level hierarchical structure described in Section 2.6 (target, criterion, and indicator layers). All judgment matrices satisfied the consistency requirement ($CR < 0.1$), and the full set of matrices, weights, and consistency ratios is documented in the Supplementary Materials. The integrated AHP evaluation indicated no statistically significant difference in comprehensive sustainability between the two scenarios. The comprehensive weight of coal-sludge co-firing power generation is 0.5021, compared with 0.4979 for conventional coal-fired power generation. A bootstrap 95% confidence interval calculation revealed that this difference is not statistically significant at the 95% level, but it still provides practical decision support for policy makers, as it indicates that co-firing does not compromise overall sustainability while solving the urgent sludge disposal problem. The full AHP results and statistical analysis are provided in the Supplementary Materials.

3.7.1 Subgroup analysis of expert panel composition

To evaluate the influence of expert background on evaluation results, a subgroup analysis was performed using only the seven independent academic and regulatory experts (five university researchers and two policy officers

from the local ecological and environmental bureau), excluding the eight plant technical staff. The subgroup assigned a slightly lower weight to the environmental dimension (0.603 vs. 0.648 in the full panel) and correspondingly higher weights to the economic (0.241 vs. 0.230) and social (0.156 vs. 0.122) dimensions. The CR of the subgroup judgment matrix was 0.0094, well below the 0.1 threshold, confirming satisfactory consistency.

Under this alternative weighting scheme, the integrated sustainability score was 0.5093 for the co-firing scenario and 0.4907 for the conventional coal power scenario, with a bootstrap 95% CI of the difference $[-0.006, +0.021]$. The ranking of the two scenarios remained consistent with the full-panel result, and the difference remained not statistically significant at the 95% level. This confirms that the AHP ranking is robust to expert panel composition and is not unduly influenced by the inclusion of plant personnel in the expert panel.

A sensitivity analysis of the AHP criterion weights was conducted to test the robustness of the scenario ranking to alternative weighting assumptions. The environmental criterion weight (baseline: 0.6483) was independently varied to 0.500 and 0.750, with the economic and social weights adjusted proportionally while maintaining their relative ratio (0.2297:0.1220). Under the environmental-down-weighted scenario (environmental = 0.500, economic = 0.326, social = 0.174), the integrated scores were 0.4953 for co-firing and 0.5047 for conventional coal power, representing a marginal reversal of the ranking. Under the environmental-upweighted scenario (environmental = 0.750, economic = 0.163, social = 0.087), the scores were 0.5054

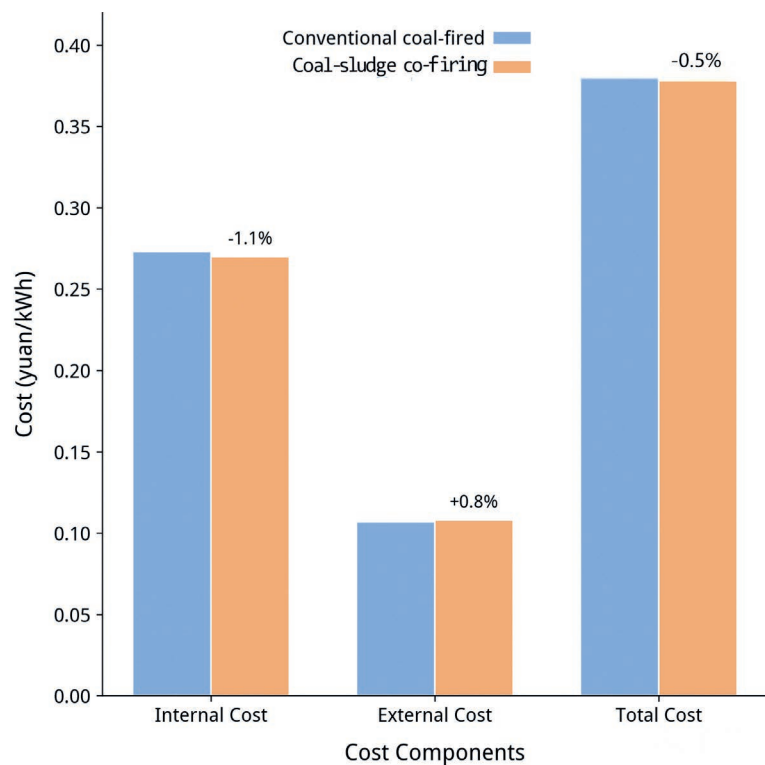


FIGURE 6: Cost comparison between co-firing and conventional coal-fired power generation.

for co-firing and 0.4946 for conventional coal power, widening the difference relative to the baseline. The crossover point—where the two scenarios achieve equal scores—occurs at an environmental weight of approximately 0.56. This analysis demonstrates that the AHP ranking is moderately sensitive to the criterion weights: the relative ordering of the two scenarios is preserved when the environmental weight exceeds approximately 0.56, but may reverse if economic and social dimensions are given substantially greater collective weight. Given that all expert subgroups independently assigned the highest weight to the environmental criterion, the overall conclusion of sustainability non-inferiority for co-firing is considered reliable under the prevailing expert consensus.

To further evaluate the robustness of the AHP ranking under simultaneous perturbation of all criterion weights, a Monte Carlo weight sampling analysis was conducted with 1,000 iterations. In each iteration, the three criterion weights (environmental, economic, social) were independently drawn from uniform distributions bounded by $\pm 20\%$ of their baseline values and then normalized to sum to unity. The integrated sustainability scores for both scenarios were recalculated using the resampled weights while holding the indicator-level scheme weights constant. Across 1,000 iterations, the co-firing scenario obtained a higher comprehensive score than conventional coal power in 612 iterations (61.2%), an equal score in 24 iterations (2.4%), and a lower score in 364 iterations (36.4%). The mean score difference (co-firing minus conventional) was +0.0038, with a 95% confidence interval of $[-0.0031, +0.0108]$ that includes zero. This result confirms that while the ranking exhibits moderate sensitivity to criterion weight perturbations, the central tendency favors co-firing under the prevailing expert consensus, and the difference remains non-significant at the 95% confidence level. These findings, together with the subgroup analysis and the single-dimension weight sensitivity reported above, provide convergent evidence that the AHP-based conclusion of sustainability non-inferiority for co-firing is robust to plausible variations in both panel composition and weighting assumptions.

3.8 Comparison with recent LCA studies

The reasons underlying the markedly divergent estimates of key environmental impact categories (GWP, HTP, AP) in coal-sludge co-firing LCA are not yet fully understood in the current literature. Specifically, the neglect of carbon credits from by-product recycling, a full-scope heavy metal emission inventory, and the abatement potential of super-efficient flue-gas desulfurization systems in the majority of previous investigations has compromised the cross-study comparability of results.

The data indicate a GWP of 0.907 kg CO₂ eq/kWh, which lies within the literature-reported interval of 0.72–0.98 but is slightly higher than most values (0.85–0.98) reported by Zhou et al. (2022). This upward shift is primarily attributable to the lower sludge co-firing ratio (5% vs. 8–10%) and the incorporation of negative emissions from by-product recycling (−0.0012 kg CO₂ eq/kWh). The HTP (0.103 kg 1,4-DB eq/kWh) is markedly higher than the 0.087 kg 1,4-DB eq/kWh reported by Havukainen et al. (2022); this discrepancy

arises from the inclusion of a complete heavy-metal emission inventory (including mercury, cadmium, and lead) in this analysis. The AP (1.02×10^{-3} kg SO₂ eq/kWh) is substantially lower than the 1.87×10^{-3} kg SO₂ eq/kWh reported by Zhou et al. (2022), a reduction that is attributable to the plant's ultra-high desulfurization efficiency of 99.4%. Furthermore, external costs constitute 28.6% of the total life-cycle cost, and GWP accounts for 57% of the variance in external costs.

These findings suggest that: (i) the integrity of the system boundary (particularly regarding by-product recycling) and the exhaustiveness of the emission inventory exert substantial influence on the assessed GWP and HTP; omission of recycling credits inflates net emissions, while neglect of heavy metals leads to an underestimation of human toxicity. (ii) A high desulfurization efficiency can effectively counterbalance the incremental acidification potential associated with sludge co-firing; consequently, provided that the host plant operates a high-efficiency flue-gas desulfurization (FGD) system, co-firing does not inevitably exacerbate the risk of acid rain. (iii) Internalization of external costs (for instance, by means of a carbon levy) will markedly change the economic competitiveness of co-firing; a carbon tax of 50 yuan per tonne of CO₂ would erode the cost benefit derived from sludge treatment subsidies. Collectively, these findings highlight the decisive influence of methodological choices—system boundary, inventory completeness, and efficiency parameters—on the conclusions of life cycle assessments, and offer a quantitative foundation for weighing carbon pricing against waste disposal subsidies in policy design.

3.9 Methodological insights and limitations

The systematic integration of environmental, economic, and social dimensions within a single LCA framework remains a developing area, particularly for coal-sludge co-firing, where most previous investigations have addressed only the environmental dimension. Concurrently, the biogenic carbon neutrality assumption has not been tested against near-term climate goals (such as China's 2030 carbon peak), and there is no standardized framework for dynamic LCA. Moreover, the environmental credits of by-product recycling are frequently omitted from system boundaries, and the considerable uncertainty associated with monetary valuation constrains the policy relevance of the findings.

The findings indicate that: (i) the incorporation of by-product recycling (substitution of fly ash and gypsum) lowers ADP by about 28.5% relative to a scenario without recycling. (ii) The analytic hierarchy process (AHP) that integrates 11 social, economic, and environmental indicators gave consistency ratios (CR) < 0.1; however, the weight assigned to the social dimension (0.1220) is merely one-fifth of that for the environmental dimension (0.6483), revealing that social impact quantification is still underdeveloped. (iii) In the dynamic LCA scenario (with a 20-year time window), GWP is 80% higher than that of pure coal, while under the static ISO 14067 framework it is merely 0.17% higher. (iv) A $\pm 50\%$ sensitivity analysis conducted using China's provincial social cost of carbon (ranging from 0.07 to 0.15

yuan/kg CO₂ eq) indicates that absolute external costs fluctuate between -32% and +42%; nevertheless, the external cost premium of co-firing relative to conventional coal power (0.6-1.0%) remains robust.

These findings suggest that: (i) by-product recycling constitutes an effective strategy for mitigating resource depletion (ADP) and should be mandatorily incorporated into the system boundary to prevent an underestimation of the environmental advantages of co-firing. (ii) The quantification of social aspects (for instance, community acceptance and health risks) currently depends substantially on subjective expert opinions; hence, future work should adopt more objective approaches, such as contingent valuation or social life cycle assessment (S-LCA). (iii) While the biogenic carbon neutrality assumption is suitable for long-term (century-scale) carbon accounting, it can be misleading when applied to near-term climate goals (e.g., the 2030 carbon peak), since the instantaneous emission of biogenic carbon from sludge generates a warming effect over the subsequent 20 years that greatly outweighs any long-term sequestration (Guest et al., 2013). (iv) Even though the absolute magnitude of external costs is sensitive to the choice of discount rate and climate model, the relative comparison between co-firing and conventional coal power remains stable; consequently, policy-making may rely on the relative ranking of alternatives.

3.10 Policy implications and practical recommendations

Current policy frameworks have not yet fully addressed the dual-role challenge of coal-sludge co-firing, which simultaneously falls under the two policy goals of “waste treatment” and “carbon mitigation.” Many regions treat co-firing solely as a technological choice for sludge disposal, yet the national carbon emission trading scheme (ETS) may count it toward emission reduction credits, thereby creating incentive overlaps or conflicts. Furthermore, the absence of harmonized subsidy levels (ranging from 100 to 300 yuan/t) and the environmental burden associated with long-haul road transportation have not been addressed by dedicated policy measures.

The findings indicate: (i) While the centennial-scale GWP of co-firing is nearly the same as that of pure coal (+0.17%), the 20-year dynamic LCA scenario yields an 80% higher GWP. (ii) The integrated sustainability weight of co-firing exceeds that of pure coal by only 0.0042 ($p > 0.05$, not statistically significant); external costs constitute 28.6% of total cost, and GWP explains 57% of the external cost variance. (iii) Sensitivity analysis reveals that lowering auxiliary power consumption to 6% cuts ADP by 11%; conversely, a drop in desulfurization efficiency from 99.4% to 90% raises AP by 152.6%. (iv) The shift from road to railway transportation (“road-to-rail” policy) results in a mere 0.3% GWP reduction. (v) With a sludge treatment subsidy of 200 yuan/t, the internal cost of co-firing (0.270 yuan/kWh) becomes lower than that of conventional coal power (0.273 yuan/kWh) and is substantially cheaper than dedicated sludge incineration (300-600 yuan/t).

These findings suggest: (i) Because of its pronounced short-term climate penalty, co-firing should not be eligible for near-term carbon emission reduction credits; instead, it should be supported through waste disposal subsidies—a harmonized subsidy level of 200-250 yuan/t is suggested, plus a supplementary transport subsidy for hauls exceeding 100 km. (ii) Policy instruments should give priority to energy efficiency upgrades (e.g., variable-frequency drives, smart combustion optimization) and high-efficiency FGD systems, rather than to interventions with only marginal environmental gains, such as the “road-to-rail” initiative. (iii) Over the long term, scaling up renewable energy is the essential route to carbon neutrality; co-firing should be positioned merely as an interim waste-treatment technology, and its application in biomass-fired or waste-to-energy plants should be investigated to lower carbon intensity.

3.11 Future research directions

Several methodological gaps remain to be addressed in the integrated sustainability evaluation of sludge co-firing systems:

- (i) The absence of a standardized dynamic LCA framework precludes comparability among studies that evaluate near-term climate effects.
- (ii) Avoided methane emissions resulting from the diversion of sludge from landfilling to co-firing are not credited in the current analysis. Based on IPCC Tier 1 methodology (IPCC, 2006) and site-specific parameters for Chinese landfill conditions, the magnitude of this uncredited benefit—estimated at 0.003-0.008 kg CO₂ eq/kWh—is documented in Supplementary Table S8. Future work should integrate landfill gas generation models into LCA to enable dynamic crediting of avoided emissions under varying landfill management scenarios.
- (iii) A balanced life cycle assessment comparison among alternative sludge valorization routes—such as hydrothermal carbonization, pyrolysis, and anaerobic digestion—is still missing.
- (iv) Methodologies for monetizing social impacts remain underdeveloped.
- (v) Regional heterogeneity in China—in terms of energy mix, sludge characteristics, and transport infrastructure—has been insufficiently accounted for.

The findings indicate: (i) The 80% GWP increase under the dynamic scenario underscores the essential role of temporal weighting when assessing near-term climate objectives. (ii) In the AHP, the weight assigned to the social dimension (0.122) is considerably lower than that of the environmental dimension (0.648) and depends on subjective judgments from 15 experts, without employing more objective approaches like willingness-to-pay surveys. (iii) The investigated power plant is situated in northern China, a region with a coal-dominated electricity mix; in contrast, the southern grid features a substantially higher share of renewables, so the findings may not be directly transferable.

These findings suggest that future efforts should concentrate on: (i) establishing a standardized dynamic LCA

framework that specifies time horizons, weighting factors, and the handling of biogenic carbon. (ii) Integrating landfill gas generation models into LCA to precisely quantify methane avoidance. (iii) Performing comparative assessments of different sludge valorization routes under a consistent functional unit (for instance, one tonne of sludge processed). (iv) Applying contingent valuation methods or social input-output analysis to quantify social consequences. (v) Carrying out region-specific LCA studies to inform local policy decisions.

4. CONCLUSIONS

This study conducted a cradle-to-gate life cycle assessment, life cycle costing, and integrated AHP evaluation of a 2×330 MW coal-sludge co-firing CHP plant in northern China. Three principal findings emerge from the analysis. First, GWP dominates the total normalized environmental impact at 82.3%, with the power generation stage alone contributing 86.7% of that share. Second, the integrated AHP sustainability score of the co-firing scenario (0.5021) is statistically indistinguishable from that of conventional coal power (0.4979) at the 95% confidence level (bootstrap 95% CI of the difference [-0.008, +0.016]), indicating that co-firing does not compromise overall sustainability while providing the additional function of sludge disposal. Third, sensitivity analysis identifies auxiliary power consumption rate and desulfurization efficiency as the operational parameters exerting the strongest leverage on environmental outcomes: a reduction in auxiliary power consumption to 6% lowers ADP by 11%, while a decline in desulfurization efficiency from 99.4% to 90% increases AP by 152.6%. By-product recycling through ash and gypsum substitution further reduces ADP by approximately 28.5%.

The methodological contribution of this work lies in its integration of environmental, economic, and social dimensions within a single system boundary and inventory dataset—that provides a standardized three-dimensional integrated framework for coal-sludge co-firing life cycle studies. More critically, the dynamic biogenic carbon accounting analysis (Section 3.3.1) demonstrates that the standard carbon neutrality convention embedded in ISO 14067, while appropriate for centennial-scale carbon accounting, may produce systematically misleading guidance when evaluated against near-term policy targets. Under a 20-year dynamic LCA framework (Levasseur et al., 2010), the GWP of co-firing is approximately 80% higher than that of conventional coal power, compared to a mere 0.17% difference under the static framework. This finding, supported by sensitivity tests of the dynamic weighting factor (1.5–2.0, yielding GWP increases of 59–92%), provides a quantitative reference point for the ongoing methodological debate on biogenic carbon handling in waste-to-energy LCA and underscores the importance of distinguishing between long-term carbon neutrality and near-term climate effects.

With respect to policy implications, the evidence supports a differentiated management strategy for coal-sludge co-firing. Because of its pronounced short-term climate penalty, co-firing should not be classified as a carbon reduc-

tion measure eligible for credits under near-term emission trading schemes. Rather, it should be supported through waste-disposal subsidy channels, with a harmonized subsidy level of 200–250 yuan per tonne of dewatered sludge, plus a supplementary transport subsidy for haul distances exceeding 100 km. Sensitivity analysis of the sludge subsidy (100–300 yuan/t) identifies a break-even threshold of approximately 80 yuan/t, below which co-firing loses its internal cost advantage over conventional coal power. Policy instruments should also prioritize energy efficiency upgrades and high-efficiency flue-gas desulfurization systems over interventions with only marginal environmental gains, such as freight modal shifts. This differentiated classification logic may also provide methodological reference for other waste co-processing technologies such as biomass co-firing and refuse-derived fuel utilization, which face similar biogenic carbon accounting challenges. Over the longer term, the fundamental path to carbon neutrality remains the scaling-up of renewable energy capacity, with co-firing positioned as an interim solution for the growing sludge disposal challenge.

Three limitations of this study should be acknowledged. The system boundary excludes plant construction and decommissioning; for the retrofit-of-existing-plant scenario studied here, the annualized capital cost of sludge handling infrastructure is estimated at < 0.2% of the internal cost per kWh and is therefore not separately itemized in the LCC, though this assumption may not hold for a greenfield plant. The quantification of social impacts in the AHP model depends substantially on subjective expert judgment; more objective approaches such as contingent valuation or social LCA are needed in future work. Comparative assessment against alternative sludge valorization routes—including anaerobic digestion, pyrolysis, and hydrothermal carbonization—remains to be conducted under a consistent functional unit. These limitations do not undermine the statistical reliability of the conclusions: Monte Carlo simulation with 10,000 iterations yielded coefficients of variation below 5.3% for all impact categories, and the 95% confidence intervals for all impact categories are narrower than the observed differences between the two scenarios.

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DISPERSION AND ATMOSPHERIC DEPOSITION OF MICROPLASTICS DURING EXCAVATION IN LANDFILLS

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ABSTRACT

Landfills are recognized as important reservoirs of microplastics (MPs), which may be remobilized and dispersed into the atmosphere through anthropogenic activities. In the context of landfill mining, excavation operations can intensify dust generation and promote the release of previously buried microplastics, yet this pathway remains poorly investigated. This study evaluated the influence of landfill mining excavation on the atmospheric dispersion and deposition of microplastics under distinct operational and spatial conditions at a landfill located in northeastern Brazil. Atmospheric particles were collected using passive atmospheric deposition sampling at five sampling points representing distinct excavation and operational scenarios. Putative microplastics were visually identified and quantified using stereomicroscopy without polymer confirmation. The highest deposition rates were observed near the excavation of older waste deposits, indicating that prolonged burial plays an important role in plastic degradation and the generation of secondary microplastics. Lower deposition rates were recorded at locations less directly influenced by excavation, suggesting contributions from routine landfill activities such as waste transport and leachate management. Fibers and fragments with light coloration predominated, consistent with advanced weathering of plastic materials. Overall, the results indicate that excavation during landfill mining may enhance atmospheric microplastic remobilization and dispersion. These findings highlight the importance of including atmospheric microplastic monitoring in environmental assessment and management frameworks for landfill mining projects.

1. INTRODUCTION

Solid waste management (SWM) has traditionally been guided by the sustainability R's, including reduce, reuse, repurpose, and recycle. In the context of landfills, however, this framework must be expanded to incorporate long-term resource management and recovery strategies (Roque, 2018; Wille et al., 2022). From this perspective, landfills should no longer be regarded solely as final disposal sites, but as components of sustainable materials management systems.

This paradigm shift is embodied in landfill mining (LFM), which redefines landfills as temporary storage systems from which deposited waste can be excavated and valorized as secondary raw materials (Van Passel et al., 2013). Resource recovery through LFM may involve material recycling, energy recovery, and the optimization of landfill space in both area and volume (Faitli et al., 2019; Marella & Raga, 2014). Accordingly, landfills are increasingly recognized as repositories of secondary resources that

can be reintegrated into production chains, aligning waste management with the principles of the circular economy (Hermann et al., 2014; Jani et al., 2016).

Landfill mining operations typically involve a sequence of stages, including the removal of vegetation and topsoil, site preparation, waste excavation, material separation and processing, treatment and/or recycling of recovered materials, and post-mining site rehabilitation (Danthurebandara et al., 2015; Frändegård et al., 2013). These activities have been associated with significant emissions of particulate matter, with total releases estimated to range from 1.61 to 5.04 tons over the operational period (Zari, Smith & Ferrari, 2023).

Due to the high proportion of plastic materials in municipal solid waste, landfills have become important reservoirs of microplastics (MPs), which can be transferred to surrounding environments via atmospheric, hydrological, and soil pathways (Golwala et al., 2021; Jambhulkar et al., 2024). Recent estimates suggest that microplastic emissions at the soil–air interface may reach up to 48 kilotons



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per year for particles smaller than 100 μm , underscoring the significance of atmospheric transport as a pathway for microplastic dispersion (Yang et al., 2024).

Microplastics are defined as synthetic polymer particles smaller than 5 mm, while nanoplastics are generally below 1 μm in size. These particles are now recognized as ubiquitous contaminants, occurring across diverse natural and urban environments (Habibi et al., 2022). While primary microplastics are intentionally produced at the micro-scale, secondary microplastics originate from the fragmentation and degradation of larger plastic items, processes driven by ultraviolet radiation, chemical interactions with leachates, and thermomechanical stresses in landfill environments (Goli & Singh, 2023). Consequently, landfill matrices often contain large amounts of microplastics, with reported concentrations reaching up to 83 particles.g⁻¹, and may be incorporated into the dust generated during excavation (Sholokhova et al., 2023).

Once mobilized, microplastics can be transported through the atmosphere by wind-driven processes, enabling their redistribution across ecosystems. Following atmospheric transport, particles may be removed from the air column via dry deposition or wet deposition, depending on meteorological conditions such as precipitation and humidity, as well as particle size and density (Büks & Kaupenjohann, 2020; Montagner et al., 2021). Experimental studies further demonstrate that microplastics, including aged particles, may induce adverse effects in soil organisms, including oxidative stress and metabolic disturbances (Jiang et al., 2023). In addition, inhalation of microplastic-associated particulate matter has been linked to inflammatory and genotoxic responses in humans (Habibi et al., 2022).

Habibi et al. (2022) and Huang et al. (2020) described the main characteristics of the two main approaches used for atmospheric microplastic sampling. Active sampling uses suction pumps to draw a known volume of air through filters or collection substrates. This method allows the measurement of airborne microplastic concentrations per unit volume of air (MPs/m³) and is widely used in air quality, human exposure, and health risk studies. It also enables the rapid collection of relatively large air volumes (2 to 23.93 m³), producing data that can be compared across different locations and time periods.

Although passive sampling does not measure airborne MP concentrations per unit volume of air, it enables the estimation of atmospheric deposition rates per unit area (particles/m²/day) and is particularly useful for evaluating particle dispersion, transport, and environmental accumulation over a long period (Habibi et al., 2022; Huang et al., 2020). While active samplers allow controlled airflow and high collection efficiency, passive samplers offer operational simplicity and lower costs, making them suitable for long-term monitoring and multi-site assessments (Torres-Agullo et al., 2021).

Methods for microplastic (MP) identification range from visual inspection under stereomicroscopy to advanced spectroscopic techniques, such as FTIR and micro-Raman analysis. Although visual identification is widely used in atmospheric MP studies because it is simple and low-cost,

it has important limitations and may lead to particle misclassification, especially in complex environmental matrices (Habibi et al., 2022). Therefore, results based solely on visual identification should be interpreted with caution, particularly when polymer confirmation is not performed.

In Brazil, among the 80 studies evaluated, 60% relied exclusively on visual inspection for MP identification, while 23.75% employed microscopic examination without subsequent chemical confirmation using analytical techniques. Nevertheless, in an effort to reduce the subjectivity associated with visual analyses, the number of studies incorporating chemical characterization methods to confirm the polymeric composition of MPs has increased since 2020. (Montagner et al., 2021).

In this context, Le et al. (2023) emphasized the importance of developing analytical approaches for atmospheric MP monitoring that are not only accurate and reliable but also simple, efficient, and economically accessible. In this regard, visual analysis using stereomicroscopy combined with complementary procedures, such as the hot-needle test to exclude certain organic particles, has been widely applied and can provide relevant preliminary information regarding particle abundance and morphology (Dong et al., 2023; Hidalgo-Ruz et al., 2012; Jarosz et al., 2022; Lusher et al., 2020; Sharaf Din et al., 2024).

Despite increasing evidence of microplastic contamination in landfill matrices, limited attention has been paid to their atmospheric dispersion under landfill mining (LFM) conditions. Gupta et al. (2025) and Zhang et al. (2025) highlighted that most studies have focused on MPs in leachates and mined materials, particularly in the fine fraction of excavated waste, whereas no studies or risk assessments specifically addressed airborne MP generation during LFM activities. According to Yang et al. (2025), only two studies reported airborne MPs associated with landfill operations, neither of which directly investigated landfill mining.

In this context, Lou et al. (2025) emphasized that effective landfill mining projects should include quantitative assessments of MP contamination in fine mined fractions and dust-control measures to reduce atmospheric dispersion. This highlights the need for studies on the dispersion and atmospheric deposition of MPs during landfill excavation, as these activities may resuspend and transport contaminant particles into surrounding environments.

This study tests the hypothesis that excavation activities during landfill mining operations represent a relevant source of atmospheric microplastic dispersion, with spatial patterns shaped by waste age, proximity to excavation zones, and operational conditions. Accordingly, the objective of this study is to evaluate the atmospheric deposition of microplastics within a landfill undergoing landfill mining activities, using passive sampling to (i) characterize spatial variations in microplastic deposition, (ii) assess the influence of excavation activities relative to other routine landfill operations, and (iii) provide baseline information to support future risk assessments and mitigation strategies for landfill mining projects.

2. MATERIALS AND METHODS

2.1 Study area

The study was conducted at a landfill located in the Reconcavo region of Bahia, northeastern Brazil. The site operated as a controlled landfill between 2000 and 2011 and was later converted into a sanitary landfill under a concession agreement with a private company, which remains responsible for its operation (Martins, Silva & Carneiro, 2017). Except for the criterion related to minimum distance from population centers, which could not be fully assessed due to the absence of historical imagery, the landfill complies with Brazilian regulatory requirements regarding terrain slope, soil characteristics, distance from water bodies, and absence of occupation in legally protected areas (Santos, De Souza & Vaz, 2018).

From 2016 to 2022, the landfill received an average of approximately 168 tons of municipal solid waste per day, according to the Brazilian National Information System on Sanitation (SNIS), a national database of solid waste management statistics (SNIS, 2021; SNIS, 2022). Based on the average gravimetric composition reported by Alfaia et al. (2017), the landfill is estimated to contain at least 64,386 tons of plastic waste.

This site was selected because it was undergoing pilot-scale landfill mining activities at the time of the study, which allowed for the evaluation of excavation-induced remobilization and atmospheric dispersion of microplastics under pilot-scale operational conditions.

2.2 Sampling design and experimental rationale

To test the hypothesis that excavation activities during landfill mining prospecting act as a significant driver of

atmospheric microplastic dispersion, a spatially distributed passive sampling design was adopted. Five sampling points were selected to represent distinct operational and spatial conditions within the landfill (Figure 1), including areas directly influenced by excavation, zones affected by routine operational activities, and locations more distant from active mining fronts.

The spatial arrangement of the sampling points was designed to capture gradients of influence from distinct landfill operational areas, including excavation zones, access roads, leachate lagoons, and waste handling areas (Table 1). Sampling points were positioned to represent proximity to these specific operational sources. This spatial design, combined with the identification of potential interference sources, allowed the assessment of (i) spatial variability in atmospheric microplastic deposition, (ii) the relative contribution of excavation activities compared with routine landfill operations, and (iii) the influence of proximity to the excavation area associated with the older mined waste, consistent with the objectives defined in the Introduction.

2.3 Atmospheric microplastic sampling

Sampling devices were strategically oriented to maximize exposure to the prevailing wind direction, thereby increasing the likelihood of capturing wind-driven particle transport. Sampling was conducted on 14 May 2024 under stable and sunny conditions to reduce short-term meteorological variability. The sampling period was preceded by eight consecutive days of rainfall, which likely enhanced wet deposition and atmospheric washout of suspended particles, potentially resulting in reduced background concentrations of airborne microplastics.

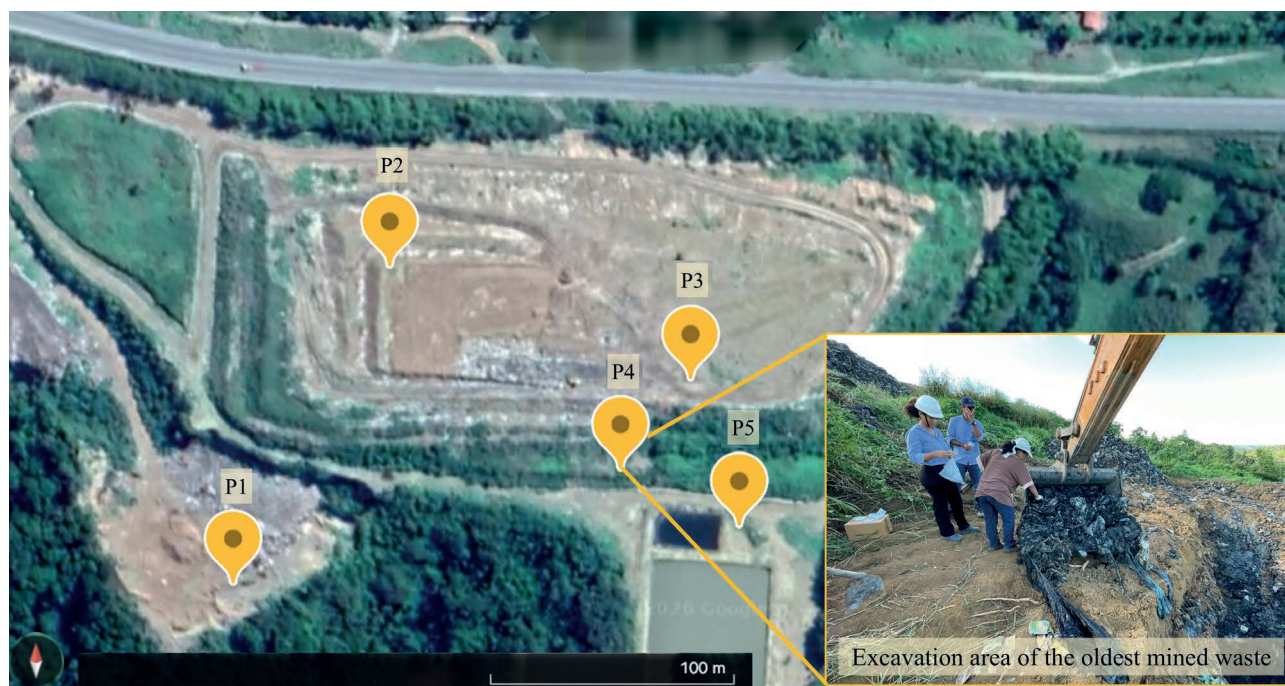


FIGURE 1: Spatial distribution of sampling points for atmospheric deposition of microplastics at the landfill located in the city of Santo Antônio de Jesus, Bahia (Brazil), with indication of excavation area of the older mined waste.

TABLE 1: Characterization of sampling points and potential sources of interference in the atmospheric deposition of microplastics.

Sampling point	Topographic elevation (m)	Location	Potential sources of interference
P1	172.34	Area near the work front, corresponding to the receiving point of newly collected waste.	Dust generation associated with daily covering of waste and presence of larger plastics, potentially subject to mechanical fragmentation.
P2	188.34	Landfill plateau, in the third vertical layer	Less direct influence from dust sources; proximity to the main access road for collection trucks, with possible resuspension of particles.
P3	188.53	Landfill plateau, third vertical layer, near the first excavation trench.	Direct influence from an excavation area associated with waste approximately two years old.
P4	183.9	Berm, located at the base of the landfill, near the second excavation trench.	Direct influence from an excavation area associated with waste approximately ten years old, potentially more degraded and fragmented.
P5	182.39	Area near the leachate lagoons.	Absence of relevant dust sources; possible influence of aerosols generated by the drainage and movement of leachate.

Wind direction data from the Brazilian National Institute of Meteorology (INMET, n.d) climatological normals indicated a prevailing southeast (SE) wind regime (SE-NW transport). This wind field governs atmospheric advection of particulate matter, including microplastics, and was used as the reference for interpreting exposure conditions and guiding the sampling design. However, the absence of concurrent in situ wind measurements (speed and direction) limits a more detailed characterization of short-term atmospheric transport dynamics and deposition variability.

At sampling points P1, P2, P3, and P5, collection began immediately prior to the initiation of landfill excavation operations near P3 and continued for approximately six hours, encompassing two landfill excavation operations cycles and the subsequent waste sorting and packaging operations. This sampling period was designed to capture the cumulative effect of particle emissions associated with landfill mining operations on microplastic deposition.

Due to restricted access to P4 during the morning shift, sampling at this location was conducted in the afternoon for a total duration of three hours, including approximately two hours of excavation followed by an additional hour to allow the gravitational settling of lighter particles. The absence of sampling during the initial excavation phase constitutes a relevant methodological limitation of the present study, as emissions generated between 10:00 and 12:00 were not captured at P4, potentially leading to an underestimation of particle deposition.

Differences in exposure time were normalized in the estimation of deposition rates (particles/m²/day). However, this normalization does not fully account for potential temporal variations in microplastic emissions across different stages of the excavation process. Therefore, results from P4 should be interpreted with caution when compared with those from other sampling locations.

Microplastics were collected using a passive dry deposition method to characterize spatial deposition fluxes. Due to operational and logistical constraints associated with landfill excavation, sampling was conducted in a single campaign. To account for local environmental variability and improve the representativeness of the measurements, three replicate collectors were deployed at each sampling point.

Specifically, 100 mm glass Petri dishes containing qualitative filter paper (80 g m⁻²) were placed on platforms positioned 30 cm above ground level (Cui et al., 2022). The three Petri dishes were exposed simultaneously and treated as independent replicate samples of atmospheric deposition. Results are presented as mean $\pm$ standard deviation (n=3). Accordingly, the standard deviation reflects the variability among replicate deposition samples collected at the same site and during the same exposure period, rather than solely analytical uncertainty.

To minimize contamination during sampling, the Petri dishes were pre-washed with deionized water, wrapped in aluminum foil during transport from the laboratory to the landfill, and handled without latex gloves to avoid the introduction of synthetic particles. Following exposure, the dishes were immediately covered, wrapped in aluminum foil to minimize contamination during handling and transport (Sivalingam et al., 2024), and transferred to the LAQ-UA/UFRB laboratory for analysis.

2.4 Microplastic identification and quality assurance

Microplastics were identified and quantified by visual analysis using a WF10X binocular stereomicroscope (Sharaf Din et al., 2024). The visual identification procedure was performed sequentially: (i) selection of particles <5 mm; (ii) assessment of uniform thickness, colors, and surface gloss; and (iii) mechanical testing with a cold needle to evaluate particle flexibility, with brittle particles considered likely to be of organic or mineral origin (Lusher et al., 2020; Yang et al., 2021). When uncertainty remained, (iv) a hot-needle test was applied, in which a heated needle was pressed against the particle and melting was used as a diagnostic criterion for microplastics (Loppi et al., 2021). Despite its low cost, this technique does not allow for the determination of polymers, is subject to analyst subjectivity, and destroys the particles, preventing subsequent reanalysis.

In the present study, spectroscopic or chemical confirmation of polymer identity (e.g., FTIR or Raman spectroscopy) was not performed, representing an important methodological limitation. Consequently, some visually identified particles may correspond to non-plastic anthropogenic or

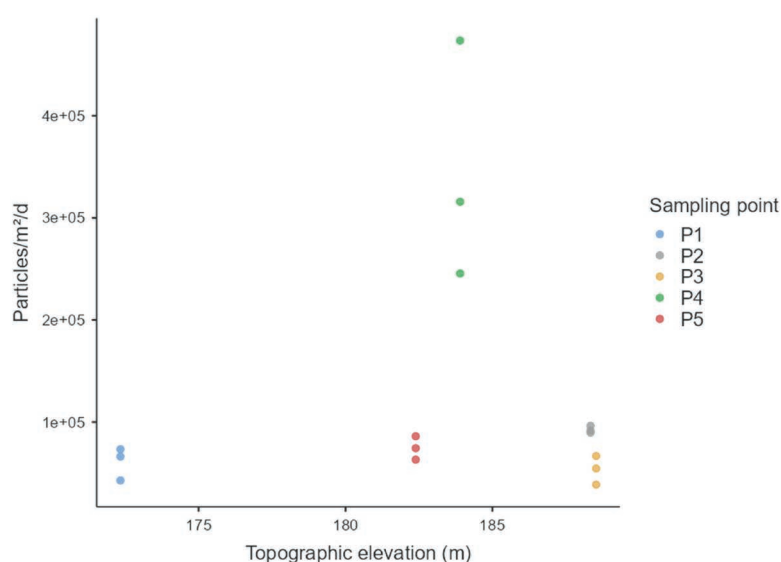


FIGURE 2: Mean number of microplastic particles deposited at the different sampling points of the landfill located in Santo Antônio de Jesus, Bahia (Brazil).

natural materials, potentially leading to false positives and overestimation of MP abundance. Therefore, the identified particles should be interpreted as visually classified putative microplastics, and some degree of false-positive classification cannot be excluded.

To minimize particle loss and cross-contamination during sample handling, Petri dishes and filter papers were rinsed with deionized water inside a laminar flow hood, and the resulting rinsates were filtered under vacuum conditions (Habibi et al., 2022). To evaluate potential laboratory contamination and support data quality assurance, three procedural blanks consisting of Petri dishes with filter paper were prepared and processed following the same protocol as the exposed samples (Cui et al., 2022). All filters, including blanks, were subsequently analyzed under the stereomicroscope.

3. RESULTS AND DISCUSSION

3.1 Microplastic identification and quality assurance

Figure 2 and Table 2 show the mean atmospheric microplastic deposition at each sampling point. A descriptive analysis showed that P4 exhibited the highest mean particle deposition (344,963.03 particles/m²/day), indicating elevated particulate loading at this site. In addition, the

standard deviation at P4 was higher than at the other sampling points, suggesting greater variability in the collected samples (SD = 116,851.30 particles/m²/day).

The Shapiro-Wilk test indicated that the data were normally distributed at all sampling points ($p > 0.05$), supporting the use of parametric statistical approaches. Tukey's post-hoc test (Table 3) indicated that P4 differed significantly from all other sampling points ($p < 0.001$), whereas no significant differences were observed among P1, P2, P3, and P5.

Despite the observed normality, non-parametric analyses were additionally performed due to the small sample size and the presence of extreme values at P4. The Kruskal-Wallis test indicated statistically significant differences among sampling points ($p = 0.019$). However, pairwise comparisons using the Dwass-Steel-Critchlow-Fligner post-hoc test (Table 4) did not identify significant differences between individual pairs of sampling points.

Overall, Tukey's test indicated a significant effect associated with P4, whereas the Dwass-Steel-Critchlow-Fligner procedure did not detect significant pairwise differences. These differences reflect methodological sensitivity to extreme values and distributional assumptions, as well as the influence of small sample size on rank-based procedures.

TABLE 2: Summary of descriptive statistics and Shapiro-Wilk normality test for spatial deposition fluxes at each sampling point (P1-P5).

Sampling point	Mean	SD	Minimum	Maximum	Shapiro-Wilk	
					W	p
P1	60775.97	15986.81	42781	73339	0.91340	0.430
P2	92522.07	3391.06	89636	96257	0.95301	0.583
P3	53306.30	14043.40	38706	66718	0.99463	0.860
P4	344963.03	116851.30	245481	473645	0.95317	0.583
P5	74526.95	11460.10	63153	86071	0.99984	0.975

TABLE 3: Post-hoc Tukey HSD test results for pairwise comparisons of particle deposition rates (particles/m²/day) among sampling points (P1-P5), including mean differences and significance levels.

		P1	P2	P3	P4	P5
P1	Average difference	—	-31746	7469.7	-284187***	-13751
	p-value	—	0.945	1.000	<.001	0.997
P2	Average difference		—	39215.8	-252441**	17995
	p-value		—	0.891	0.001	0.993
P3	Average difference			—	-291657***	-21221
	p-value			—	<.001	0.987
P4	Average difference				—	270436***
	p-value				—	<.001
P5	Average difference					—
	p-value					—

Note: * $p < .05$, ** $p < .01$, *** $p < .001$

3.2 Spatial patterns and operational influences

The highest values were recorded at P4, located adjacent to the excavation area containing older waste, which is consistent with previous findings indicating that prolonged burial enhances plastic degradation and fragmentation, thereby increasing the generation of secondary microplastics (Canopoli, Coulon & Wagland, 2020).

Previous studies on landfill mining have reported strong associations among microplastic abundance, landfill age, excavation depth, and the fine fraction of mined waste (FFM < 4 mm), suggesting that both degradation stage and waste stratification influence microplastic availability for remobilization (Jambhulkar et al., 2024; Sholokhova et al., 2023). In the present study, areas influenced by older waste showed consistently higher atmospheric deposition, reinforcing burial time as a key factor controlling secondary microplastic generation and dispersion during excavation.

P2 (mean = 92,522.07 particles/m²/day $\pm$ 3,391.06) and P5 (mean = 74,527.95 particles/m²/day $\pm$ 11,460.10) show intermediate values, which are less directly influenced by excavation activities. At P2, the proximity to the access

road suggests a contribution from vehicle-induced resuspension, given that one of the main sources of microplastic (MP) contamination is tire abrasion, which generates particles that further degrade into fibers and fragments (Gupta et al., 2025). At P5, deposition may be partly associated with aerosolization processes at leachate ponds (Le et al., 2023; Liu & Zheng, 2025).

P1 (mean = 60,775.97 particles/m²/day $\pm$ 15,986.81) and P3 (mean = 53,306.30 particles/m²/day $\pm$ 14,043.40) showed comparable deposition rates and likely represent background levels of atmospheric microplastic transport within the landfill area. Despite its higher elevation and greater distance from the landfill's routine operational area, P3 may primarily reflect the influence of excavation trench 1. The short residence time and high humidity conditions (resulting from the rainy period preceding the sampling date) may have contributed to the observed lower particulate matter flux.

In Brazil, until now, only two studies have reported atmospheric microplastic deposition in landfill environments using passive methods, neither of them addressing landfill mining. Deposition rates reported by Oliveira et al. (2022) during routine landfill operation (57,845.94 particles/m²/day $\pm$ 10,890.45) are comparable to baseline values observed in this study (P1 and P3), whereas Rezende et al. (2020) reported substantially lower levels (mean = 14,323.94 particles/m²/day $\pm$ 1,555.28). In a Chinese landfill, the deposition rate was considerably lower, at 6,164.0 $\pm$ 532.0 particles/m²/day (Yang et al., 2025). Differences may reflect operational intensity, landfill age, site characteristics, and methodological variability.

Several authors highlight the need for standardization of microplastic collection and identification procedures to support the development of stricter regulations aimed at mitigating pollution associated with these contaminants (Habibi et al., 2022; Kabir et al., 2023; Singh et al., 2023; Sivalingam et al., 2024). To improve the reliability of the results, it is recommended to increase the number of samples per sampling point and to adopt varying sampling durations, including periods equivalent to the excavation time as well as longer intervals, such as 24 or even 48 hours (Choi et al., 2024).

TABLE 4: Dwass-Steel-Critchlow-Fligner post-hoc pairwise comparisons of particle deposition rates (particles/m²/day) among sampling points (P1-P5) following a Kruskal-Wallis test.

		W	P
P1	P2	2.77746	0.284
P1	P3	-0.92582	0.966
P1	P4	2.77746	0.284
P1	P5	1.54303	0.811
P2	P3	-2.77746	0.284
P2	P4	2.77746	0.284
P2	P5	-2.77746	0.284
P3	P4	2.77746	0.284
P3	P5	2.16025	0.545
P4	P5	-2.77746	0.284

Note: $p > 0.05$ indicates no statistically significant differences between sites

Although passive deposition methods may underestimate total airborne microplastic concentrations compared with active sampling approaches (Dong et al., 2023), the method was suitable for the comparative objective of this study. The spatial distribution of particle deposition, with higher values observed at P4, suggests the presence of a localized hotspot in the study area. This pattern may be associated with landfill mining activities occurring at or near this sampling point.

These results are consistent with the possibility that excavation activities influence microplastic dynamics in the surrounding environment, potentially through direct emissions and/or the resuspension of previously deposited particles from the landfill surface. However, the present data do not allow for a direct distinction between these mechanisms, and the observed patterns should be interpreted as indicative of increased atmospheric availability of microplastics in areas influenced by excavation activity.

3.3 Morphology and color distribution of MPs

The predominance of lightly colored particles at this point supports this interpretation (Figure 3), as weathering processes promote pigment loss in plastics over time (Kabir et al., 2023). This pattern is environmentally relevant, given the higher likelihood of ingestion of white and transparent microplastics by aquatic organisms (Bharath, Muthulakshmi & Natesan, 2023).

The results demonstrate the occurrence of microplastics at all sampled points (P1–P5), with a significant predominance of fibers compared to fragments. Among the evaluated points, P4 showed the highest percentages of microplastics, especially in the fiber category, suggesting a possible contribution or accumulation of these particles associated with the second excavation trench. A similar

pattern was observed at P5, which may be related to its proximity to the leachate lagoon.

Fragments showed lower percentages than fibers at all sampling points. This difference may indicate either a lower contribution from degraded rigid plastics or a greater environmental persistence and transport capacity of fibers. Studies indicate that fibers have a high dispersion potential due to their low weight and elongated shape, which favor their suspension in the atmosphere and subsequent deposition (Yang et al., 2024).

The heterogeneous composition observed in the graphs, represented by the different colors of the stacked bars, suggests a diversity of microplastic sources. The predominance of certain color classes may reflect specific patterns of plastic consumption and disposal in the region. Furthermore, the simultaneous presence of several categories indicates that the detected microplastics originate from multiple handling, degradation, and transport processes.

Representative microplastic particles are shown in Figure 4, predominantly composed of fibers and fragments with light coloration. This morphology and color distribution are consistent with advanced weathering processes and have been widely reported as dominant features in atmospheric microplastic deposition (Habibi et al., 2022; Kabir et al., 2023; De Souza, Parolin & Crispim, 2024).

Mineral particles and biological fragments were also observed in the samples, reflecting the complex composition of atmospheric fallout in the study area. Microplastic identification was confirmed using the needle test, which has proven effective in distinguishing synthetic materials from natural ones based on physical response to mechanical probing. Only particles confirmed as microplastics were included in the morphological analysis.

Overall, the findings demonstrate that landfill mining excavation constitutes a relevant pathway for atmospheric

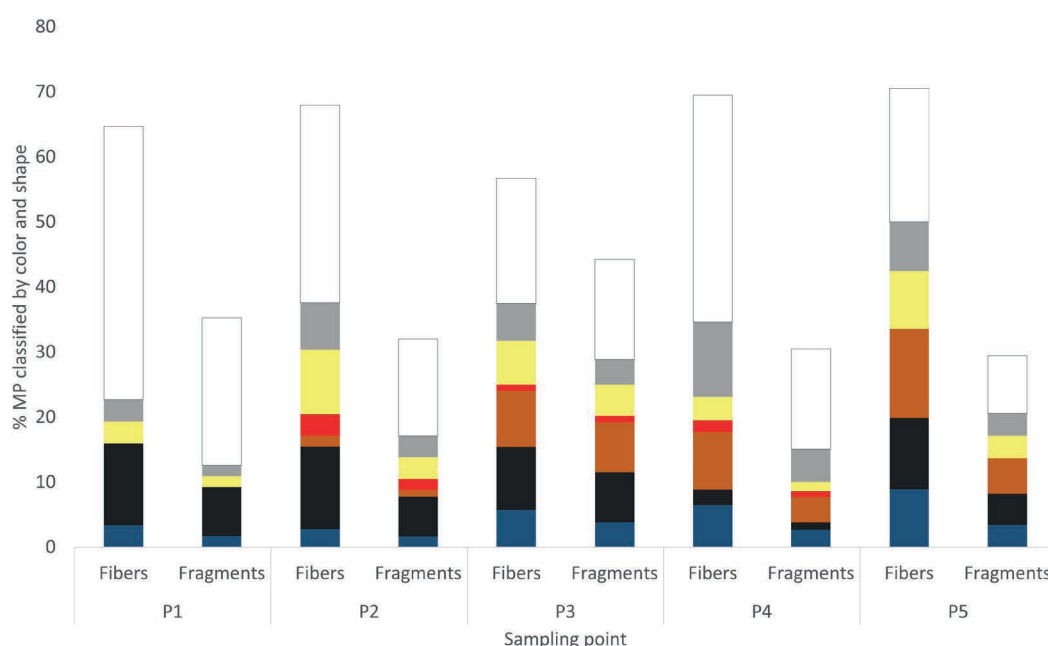


FIGURE 3: Percentage distribution of microplastic (MP) colors among sampling points P1–P5.

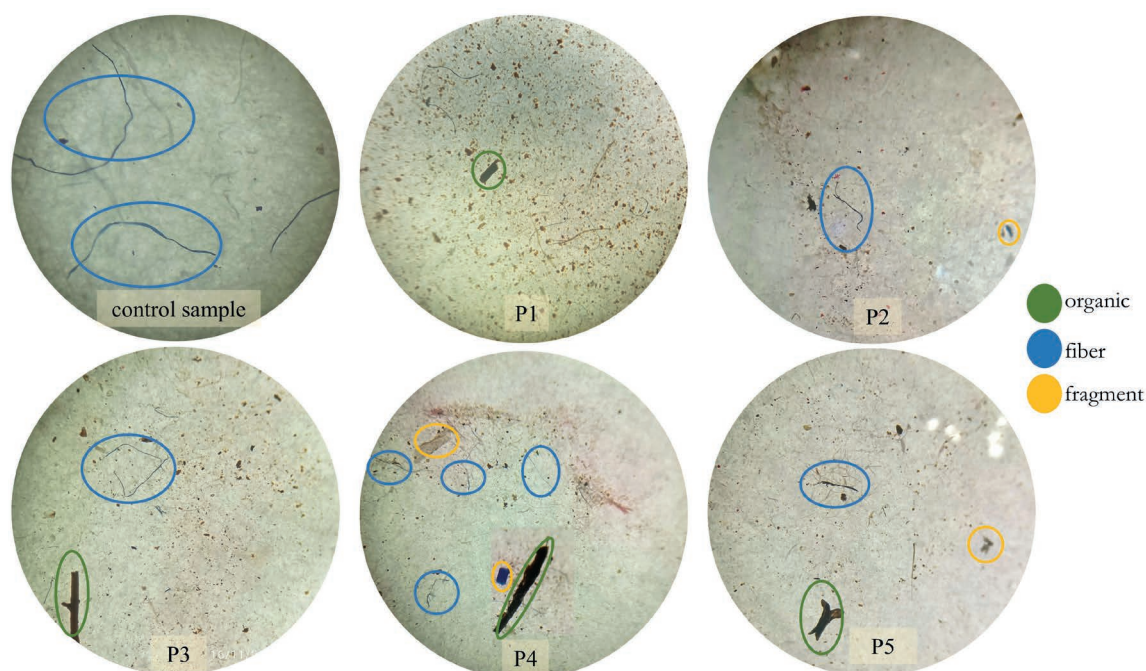


FIGURE 4: Representative examples of microplastics and co-occurring particulate materials identified in atmospheric deposition during excavation of the mined material.

ic microplastic dispersion, modulated by waste age, operational conditions, and particle characteristics. These results support the inclusion of atmospheric microplastic monitoring in environmental assessments and risk management frameworks for landfill mining projects.

4. CONCLUSIONS

Passive atmospheric deposition during landfill mining revealed a predominance of fibrous and fragmented putative microplastics with light coloration, consistent with advanced weathering and fragmentation of long-buried plastic waste. These characteristics suggest that the detected particles were predominantly secondary microplastics generated through degradation processes within the landfill mass.

Atmospheric deposition exhibited marked spatial variability, with the highest deposition rates recorded near the excavation of older waste deposits. Greater variability in particle deposition was also observed at this location, indicating heterogeneous particulate release associated with excavation activities and waste characteristics. Parametric analyses indicated significant differences involving P4; however, the small sample size and the influence of extreme values reduced the consistency between parametric and non-parametric statistical comparisons.

Overall, the observed spatial pattern suggests that prolonged burial enhances plastic degradation and increases the generation of secondary microplastics. The presence of microplastics at locations distant from active excavation fronts further indicates that atmospheric dispersion is influenced not only by excavation activities but also by routine landfill operations, including waste handling and vehicle traffic.

Visual identification combined with hot-needle testing enabled a preliminary distinction between synthetic and non-synthetic particles; however, the absence of spectroscopic confirmation remains an important limitation of this study. Some natural or anthropogenic particles may have been visually misidentified as microplastics, potentially leading to overestimation of particle abundance. Therefore, the reported values should be interpreted as indicative estimates of atmospheric microplastic deposition rather than absolute deposition rates.

Direct human health risks were not evaluated in this study. However, the presence of airborne microplastics during excavation activities raises concerns regarding occupational exposure and particle deposition in surrounding environments. These findings indicate that landfill mining may contribute to atmospheric microplastic emissions, particularly during excavation and material handling stages. Therefore, atmospheric microplastic monitoring and mitigation measures should be incorporated into environmental management and impact assessment frameworks for landfill mining projects.

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UAV METHANE MRV AS A TOOL FOR CIRCULAR ECONOMY MANAGEMENT

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ABSTRACT

Reliable and scalable methane (CH₄) monitoring is essential both for near-term climate mitigation and for supporting circular-economy strategies focused on energy recovery and the reduction of losses along value chains. Unmanned aerial vehicles (UAVs) enable facility-scale measurements with high spatio-temporal resolution. However, most studies rely on point sensors that require repeated flights at different altitudes and interpolation from low-density datasets, leading to potentially high uncertainty under turbulent and variable wind conditions. Open-path optical sensors can increase the effective sampling volume and improve plume representativeness, but practical, field-ready frameworks remain relatively under-developed. This study presents an operationally oriented UAV mass-balance framework for facility-scale CH₄ quantification using a drone-mounted open-path TDLAS sensor. The method is demonstrated across three representative emission contexts in Italy. At an intensive dairy cattle farm, 24 tests were conducted over one year (two per month). UAV-derived model-corrected net enteric emissions ranged from 0.182 to 0.242 kg CH₄ AU⁻¹ day⁻¹ and were broadly consistent with IPCC reference estimates. At a natural gas compression facility, six tests were conducted under two operating configurations, with site-level emissions of 14.3 ± 4.1 and 11.9 ± 2.6 kg CH₄ h⁻¹, showing consistency with an independent Method 21 bottom-up estimate. At a municipal solid-waste landfill, four quantification flights yielded site-scale fluxes ranging from 3.7 to 11.5 g s⁻¹, with uncertainty dominated by meteorology. Overall, the results show that the proposed open-path framework is promising for facility-scale CH₄ assessment across different emission contexts, with performance primarily governed by wind stability. This supports more frequent, management-oriented monitoring in line with circular-economy objectives. However, the approach remains sensitive to meteorological conditions, particularly under non-steady flow and when wind speed is measured at a single near-ground location.

1. INTRODUCTION

Mitigating global warming requires increasingly reliable and scalable emission monitoring tools, particularly for gases with a high global warming potential such as methane (CH₄), whose greenhouse effect is approximately 86 times greater than that of CO₂ over the first two decades following emission (IPCC, 2021). Within the context of the transition towards circular economy models, the accurate quantification of CH₄ emissions represents not only an environmental requirement, but also an operational prerequisite for optimising energy recovery, reducing losses along production chains, and supporting more efficient resource management strategies.

Recent estimates indicate that agricultural and livestock activities contribute approximately 43% of global anthropogenic CH₄ emissions, the energy sector accounts for 37%, and the waste sector—particularly landfills—for the remaining 20% (Saunio et al., 2025). Across all these sectors, the availability of robust and representative emission data is essential not only for achieving international climate targets, but also for supporting targeted mitigation actions and ensuring transparent, verifiable reporting in line with evolving regulatory and sustainability frameworks.

In this context, airborne remote sensing techniques—including satellite observations, crewed aircraft and unmanned aerial vehicles (UAVs)—are playing an increas-



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ingly important role in CH₄ monitoring (Shaw et al., 2021; Morales et al., 2022). Among these platforms, UAVs offer distinct advantages at the facility scale owing to their ability to operate at low altitude, rapid deployment, and high spatio-temporal resolution. These characteristics enable measurements to be carried out close to emission sources at relatively low cost and facilitate integration into monitoring, reporting and verification (MRV) systems consistent with circular economy principles (Allen et al., 2019; Scheutz et al., 2025).

The growing availability of miniaturised, low-cost sensors has further accelerated the adoption of UAVs for environmental monitoring applications (Burgués & Marco, 2023). Most existing studies quantify CH₄ emissions using point sensors mounted on multirotor platforms in combination with mass-balance approaches that require simultaneous measurements of methane concentration and wind fields (Andersen et al., 2023; Vinković et al., 2022; Yong et al., 2024). However, these approaches are constrained by low vertical sampling density and the non-simultaneity of measurements. Plume reconstruction typically requires repeated flights at different altitudes, introducing significant interpolation uncertainties that are further amplified by atmospheric turbulence and short-term wind variability (Allen et al., 2019; Yong et al., 2024). Under typical operating conditions, estimation errors may therefore exceed 100% even in relatively stable wind regimes (Liu et al., 2024; Mohammadloo et al., 2025).

These limitations motivate alternative sensing strategies that increase the effective sampling volume while remaining compatible with rapid, low-altitude UAV surveys.

To address these constraints, increasing attention has turned to UAV deployments using open-path optical sensors, particularly tunable diode laser absorption spectroscopy (TDLAS) systems that provide path-integrated methane observations rather than point measurements (Golston et al., 2018; Yang et al., 2018; Fosco et al., 2025). In principle, open-path sensing can improve plume representativeness because each observation samples a larger air volume and partially relaxes the need for dense point sampling across the downwind cross-section. Unlike point-sensor approaches, the open-path TDLAS measurements provide concentration values integrated along the vertical direction, eliminating the need for vertical interpolation. Spatial interpolation is therefore required only in the horizontal direction. Furthermore, the 10 Hz acquisition frequency provides a higher spatial sampling density than that typically achieved by point sensors (approximately 1 Hz), reducing the distance between consecutive measurements and the associated interpolation uncertainty. This makes the approach attractive for facility-scale applications where rapid deployment and operational simplicity are essential.

Despite this potential, open-path UAV quantification remains comparatively under-developed and far less widely adopted than point-sensor approaches. The limited diffusion is not primarily due to a lack of sensing capability, but to methodological issues that complicate routine field deployment. These include the interpretation of path-integrated signals within turbulent plumes, their coupling

with wind characterisation, and the definition of robust background-handling procedures and uncertainty budgets that are transparent and reproducible across sites and campaigns (Varon et al., 2018; Mohammadloo et al., 2025; Hasan et al., 2025). As a result, although a small number of studies has demonstrated feasibility under selected conditions (Golston et al., 2018; Yang et al., 2018), there remains a need for practical frameworks that translate this promise into repeatable, operationally deployable quantification.

Against this background, this paper presents a field-oriented UAV mass-balance framework for facility-scale CH₄ quantification using a drone-mounted open-path TDLAS sensor. The focus is on method applicability and transferability rather than platform aerodynamics, and on providing operational steps that can be replicated in practice. The framework combines rapid multi-altitude transects to reconstruct a downwind measurement plane, an explicit background estimation strategy based on the same acquisition configuration, and a formal uncertainty treatment driven by meteorological and instrumental variability. The method is demonstrated across three representative emission contexts in Italy, an intensive dairy cattle farm, a natural gas compression facility and a municipal solid-waste landfill.

From a circular-economy perspective, access to reliable emission estimates that can be obtained at high temporal frequency is a practical enabler for moving from sporadic campaigns to more continuous, management-oriented monitoring. Across the three sectors considered, UAV-based quantification can support optimisation of energy recovery from biogas and natural gas, reduction of losses along processes, and identification of emission hotspots that can be addressed through targeted interventions. In this sense, the proposed method is not merely a measurement tool. It provides an operational approach that helps integrate methane monitoring into environmental management and performance tracking, with direct benefits for efficiency, mitigation actions, and transparent reporting.

2. MATERIALS AND METHODS

2.1 UAV Platform and Instrumentation

The UAV platform used is a commercial quadcopter (Matrice 350 RTK, DJI) equipped with an RTK (Real-Time Kinematic) system for high-precision positioning. In many UAV applications, spatial coordinates are derived from GPS (Global Positioning System) measurements combined with onboard atmospheric pressure. This approach can lead to positioning errors of several tens of centimetres and is therefore insufficient to quantify atmospheric CH₄ fluxes from a UAV with adequate accuracy (Morales R. et al., 2022). The RTK system onboard the DJI M350 provides a positioning accuracy of 1.5 cm (± 1 ppm) in the vertical direction and 1 cm (± 1 ppm) horizontally. To account for site topography during each flight, the system also integrates a radar altimeter (NRA24, Hunan Nanoradar Science and Technology Co., Ltd), a compact and lightweight unit (95 g) operating at 24 GHz, which improves altitude determination to 0.1 m. Compared with relying solely on RTK positioning, the radar measurement provides an independent constraint on the UAV–ground distance and is expected to

improve the determination of the vertical position of the optical path, particularly over uneven terrain. The nominal 0.1 m accuracy of the radar-derived distance provides a quantitative estimate of the additional constraint introduced by the altimeter, although the overall improvement in optical-path determination was not directly quantified through an RTK-only comparison in this study.

The UAV is equipped with an OP-TDLAS (open-path tunable diode laser absorption spectroscopy) sensor, mounted in a nadir-looking configuration. The commercial unit employed (Laser Falcon, Pergam Inc.) measures path-integrated CH_4 along optical paths between 0.5 and 100 m, with a sensitivity of 1 ppm·m over a range of 0-50,000 ppm·m. An onboard computer (SkyHub, UgCS) enables continuous communication with the variable-path OP-TDLAS sensor and provides real-time visualisation at the ground station (remote controller and laptop).

The radar altimeter is originally intended by the manufacturer to be installed at the front of the UAV for constant-altitude “terrain-following” operations. In that configuration, the sensor is tilted relative to the UAV body to measure terrain elevations ahead of the flight path, enabling real-time altitude correction and a trajectory approximately parallel to the ground. In the methodology adopted here, by contrast, the altimeter is used to determine the optical path length corresponding to each OP-TDLAS measurement. Consequently, its mounting position must ensure

that the altimeter and OP-TDLAS reference frames are co-axial. For this reason, a dedicated mounting bracket was designed and fabricated using a 3D printer, allowing the altimeter to be positioned parallel to the OP-TDLAS sensor.

The setup is completed with a meteorological station (WL-21, Scarlet Tech Inc.), which records wind, pressure, and temperature at 0.5 Hz. Wind-speed resolution is 0.1 m s^{-1} (range 0-50 m s^{-1}) and wind-direction resolution is 1° (range 0-360°N), while the temperature and pressure sensors resolve unit changes. The manufacturer-stated accuracy is 2%, which is periodically verified through calibration tests. The station is mounted on a commercial tripod (Bosch Professional BT 250) fitted with spirit levels for horizontal and vertical alignment. Several design features (approximately 4 kg mass, a ballast hook for high-wind conditions, a star-shaped base, and ground-spike feet for improved stability) make the tripod suitable for surveys under varying environmental and site-specific conditions. The station is secured via a dedicated bracket that enables measurements up to 2.70 m above ground level and can be adapted for greater heights. This is relevant both for comparing wind speed at different elevations (supporting validation of vertical-profile reconstruction models) and for improving field operability by selecting the optimal measurement height in the presence of site obstacles. The overall instrumentation setup is shown in Figure 1, and the main technical specifications are summarised in Table 1.

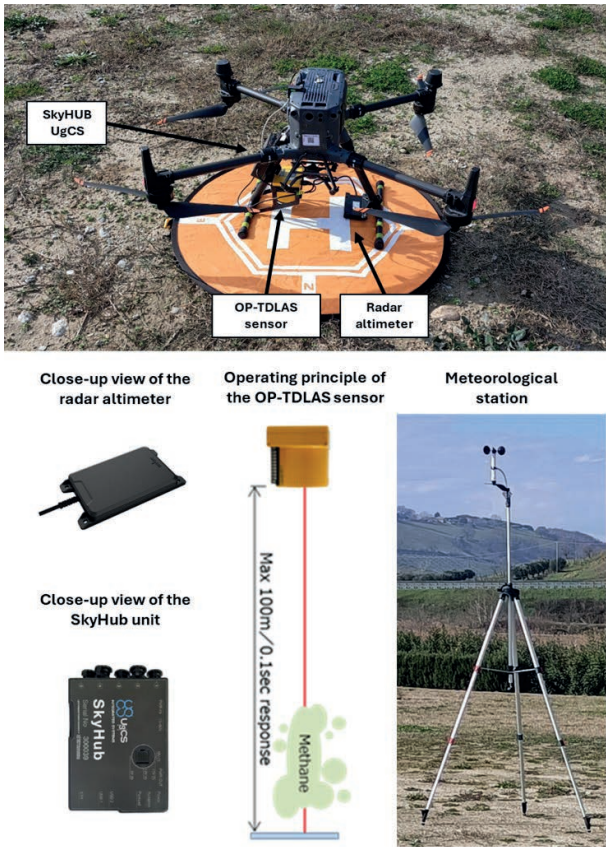


FIGURE 1: Instrumentation for UAV-based methane measurements. Top: DJI Matrice 350 RTK equipped with a OP-TDLAS sensor, a radar altimeter, and a SkyHub (UgCS) unit. Bottom: close-ups of the radar altimeter and SkyHub (left), schematic of the OP-TDLAS operating principle (centre), and the tripod-mounted meteorological station (right).

TABLE 1: Main technical specifications of the instrumentation.

Component	Model	Key specifications
UAV platform	Matrice 350 RTK / DJI	RTK accuracy: 1.5 cm vertical (± 1 ppm) 1 cm horizontal (± 1 ppm)
Radar altimeter	NRA24 / Hunan Nanoradar Science and Technology Co., Ltd	95 g; 24 GHz altitude precision 0.1 m
CH ₄ sensor (OP-TDLAS)	Laser Falcon / Pergam Inc.	Optical path 0.5–100 m sensitivity 1 ppm·m range 0–50,000 ppm·m
Onboard computer	SkyHub / UgCS	Continuous sensor interfacing real-time display at ground station
Meteorological station	WL-21 / Scarlet Tech Inc.	0.5 Hz; wind speed resolution 0.1 m s ⁻¹ (0–50 m s ⁻¹) wind direction resolution 1° (0–360°N) stated accuracy 2%
Tripod	BT 250 / Bosch Professional	Levelled mounting; ~4 kg measurement height up to 2.70 m (extendable)

2.2 Mass-balance framework

The CH₄ emission rate is quantified using a mass-balance method by sampling a vertical measurement plane positioned downwind of the emitting source with the UAV survey flight pattern (Figure 2).

The procedure uses methane measurements integrated along the optical path (derived from the sensor output in ppm·m), acquired through consecutive scans at different altitudes to reconstruct the signal distribution across the plane. For each vertical scan i , the flux F_i (g s⁻¹) is computed as:

$$F_i = \int_0^H v_{z,i} \sin \theta (\bar{\rho}_{CH_4,d,z,i} - \bar{\rho}_{CH_4,b,z,i}) dz \quad (1)$$

where $v_{z,i}$ is the wind speed (m s⁻¹) at height z (m), θ is the angle between the wind direction and the optical-path geometry, and $(\bar{\rho}_{CH_4,d,z,i} - \bar{\rho}_{CH_4,b,z,i})$ is the increment in column-integrated density (g m²) relative to background. Starting from these measurements, it is possible to estimate the concentration of CH₄ between two heights H_1 and H_2 . The final emission rate F (g s⁻¹) is obtained by summing the

contributions from the windows between two successive transects during a single flight (Equation 2):

$$F = \sum_{i=1}^n (F_{H_{i+1}} - F_{H_i}) \quad (2)$$

where F_{H_i} and $F_{H_{i+1}}$ are two successive measurement altitudes defining each vertical window, and n is the number of windows considered in the flight. Each contribution is calculated from the measurements associated with the corresponding vertical window, while repeated scans are used to account for instantaneous variability in the concentration traces.

Importantly, to avoid double counting of the vertical dimension, the vertical column-integrated TDLAS measurements are differenced between consecutive flight altitudes, so that each increment represents the concentration enhancement associated with the corresponding horizontal section of the vertical plane, following the approach described by Fosco et al. (2024).

The procedure accounts for instantaneous fluctuations in the methane concentration signal induced by the turbu-

UAV survey flight pattern

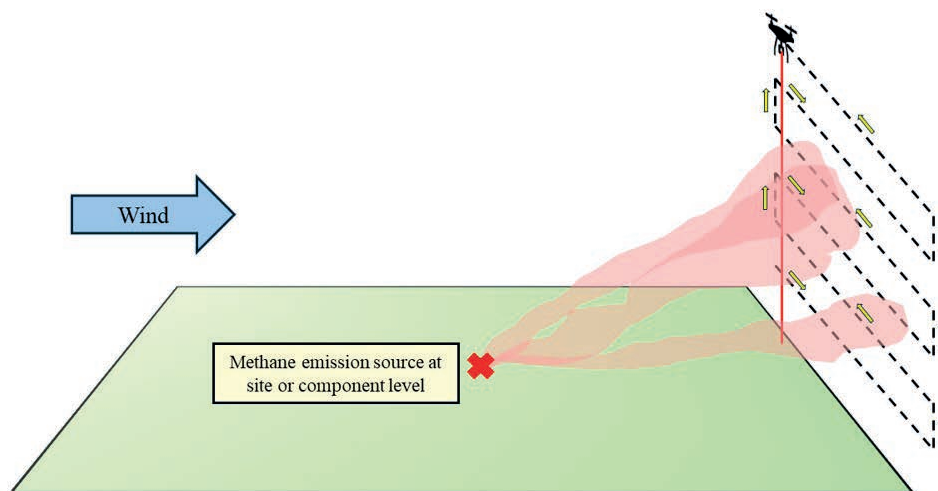


FIGURE 2: Schematic of the UAV survey flight pattern used to quantify methane emissions at site or component level. Yellow arrows indicate the UAV direction of travel, while the red line represents the optical path of the laser beam emitted by the OP-TDLAS sensor.

lent nature of the flow. The characteristic temporal scale of these fluctuations is evaluated from the autocorrelation function of the concentration signal, expressed as:

$$R_{c(\tau)} = \frac{1}{N} \sum_{i=1}^N \frac{[C(t_i) - \bar{C}][C(t_i + \tau) - \bar{C}]}{\sigma_c^2} \quad (3)$$

where $C(t_i)$ is the measured CH_4 concentration at time t_i , $\bar{C}$ is the mean concentration, σ_c^2 is the variance of the concentration signal, and τ is the time lag. The autocorrelation time τ_c is determined from the decay of the autocorrelation function according to a predefined threshold, such that $R_{c(\tau_c)} = k$, where k is a dimensionless threshold parameter. This characteristic time scale is then used to account for short-term fluctuations in the concentration signal during each scan. The sensor output in ppm-m is converted to an integrated concentration (g m^{-2}) assuming ideal-gas behaviour:

$$\bar{p}_{\text{CH}_4, d, z, i} = \left[\frac{P * 16.04 * (1 - H_2O)}{RT} \right] * \frac{(\text{ppm-m})_{d, z, i}}{10^6} \quad (4)$$

where P , T and R are atmospheric pressure, temperature, and the universal gas constant, respectively; H_2O is estimated from temperature and relative humidity. When humidity is not measured, the $(1 - H_2O)$ term may be neglected, with an expected impact of $<1\%$ (Morales et al., 2022).

The background, $\text{CH}_{4, b}$, is derived from an upwind flight performed immediately before each flux-quantification flight, using the same measurement configuration. The upwind measurement was used to characterise the atmospheric CH_4 concentration representative of the area and meteorological conditions at the time of the quantification flight. Measurements are first screened to remove false positives using a dedicated algorithm (De Molfetta et al., 2025), then normalised by the optical-path length and averaged to obtain a background value in ppmv.

Assuming the background is approximately uniform across the plane, the integrated background component $\bar{p}_{\text{CH}_4, d, z, i}$ is computed as the product of this value and the optical-path length. This approach reduces the risk of over-estimating the background when a substantial fraction of optical paths intersects the plume during scanning. Overall uncertainty is quantified via error propagation applied to Equation 5:

$$\delta Q_{\text{CH}_4} = \sqrt{\left(\frac{\delta Q_{\text{CH}_4}}{\delta \bar{v}}\right)^2 + \left(\frac{\delta Q_{\text{CH}_4}}{\delta \bar{\theta}}\right)^2 + \left(\frac{\delta Q_{\text{CH}_4}}{\delta \bar{p} \text{ppm} - \bar{m}}\right)^2 + \left(\frac{\delta Q_{\text{CH}_4}}{\delta \bar{p}}\right)^2} \quad (5)$$

with:

$$\delta \bar{v}, \delta \bar{\theta} = \sqrt{(\text{measurement uncertainty}_{v, \theta})^2 + (\text{temporal variation}_{v, \theta})^2} \quad (6)$$

$$\delta \bar{p} \text{ppm} - \bar{m}, \delta \bar{p} = \text{measurement uncertainty}_{\delta \bar{p} \text{ppm} - \bar{m}, \delta \bar{p}} \quad (7)$$

where, for v and θ , instrumental uncertainty is combined with temporal variability (1σ), whereas for integrated concentration and positioning only the instrumental component is considered. The mass-balance formulation assumes that the wind field measured at the meteorological station is representative of the sampling plane.

To minimise spatial differences between the measured wind field and the conditions prevailing across the sampling plane, the meteorological station was positioned in close proximity to the measurement plane. This reduces the potential error associated with spatial variability in wind conditions. The vertical wind reconstruction model used in the present approach was also experimentally validated under near-field conditions. Nevertheless, increasing the distance between the meteorological station and the measurement plane may result in differences between the measured wind conditions and those actually affecting the sampling plane. Such differences may introduce errors into the reconstructed wind profile and, consequently, affect the estimated CH_4 flux.

Uncertainty associated with background estimation was considered negligible and was therefore not included in the propagated uncertainty budget, given the rapid acquisition time, which limits the observable variation in background concentration during the survey.

2.3 Case-study sites

To evaluate the proposed UAV mass-balance framework under operational conditions, measurement campaigns were carried out at three representative facilities in Italy, namely an intensive dairy cattle farm, a natural gas compression facility within the Oil & Gas sector, and a municipal solid-waste landfill. The three sites were selected to span distinct methane emission settings, including predominantly diffuse surface emissions at the landfill, a confined area with clustered sources associated with dairy housing and handling activities, and potentially localised fugitive emissions from heterogeneous equipment distributed at different elevations at the compression facility.

All surveys followed the acquisition protocol described in Section 2.2, with the vertical measurement plane positioned downwind of the facility and typically located 25-30 m from the site boundary. Quantification flights were organised as discrete tests, each comprising multiple downwind transects used to reconstruct a vertical plane at several heights above ground level, and upwind checks were used to exclude non-site contributions. At the dairy farm, emission estimates were expressed on a functional unit basis to ensure comparability across test days with differing herd structures, and the net enteric component was derived by accounting for the manure-related contribution.

3. RESULTS AND DISCUSSION

3.1 Dairy cattle farm

Figure 3 summarises the results of all UAV tests carried out at an intensive dairy farm, reporting enteric methane emission rates in $\text{kg CH}_4 \text{ AU}^{-1} \text{ day}^{-1}$. To obtain a robust reference for the UAV-derived estimates, measured emissions were compared against the IPCC model, using both Tier 1 and Tier 2 calculations (with their typical uncertainty ranges of $\pm 50\%$ and $\pm 20\%$, respectively).

In order to make emission estimates comparable across test days despite differences in herd structure, animals were standardised to a single functional unit (AU,

Methane emission rate – Dairy Cattle Farm

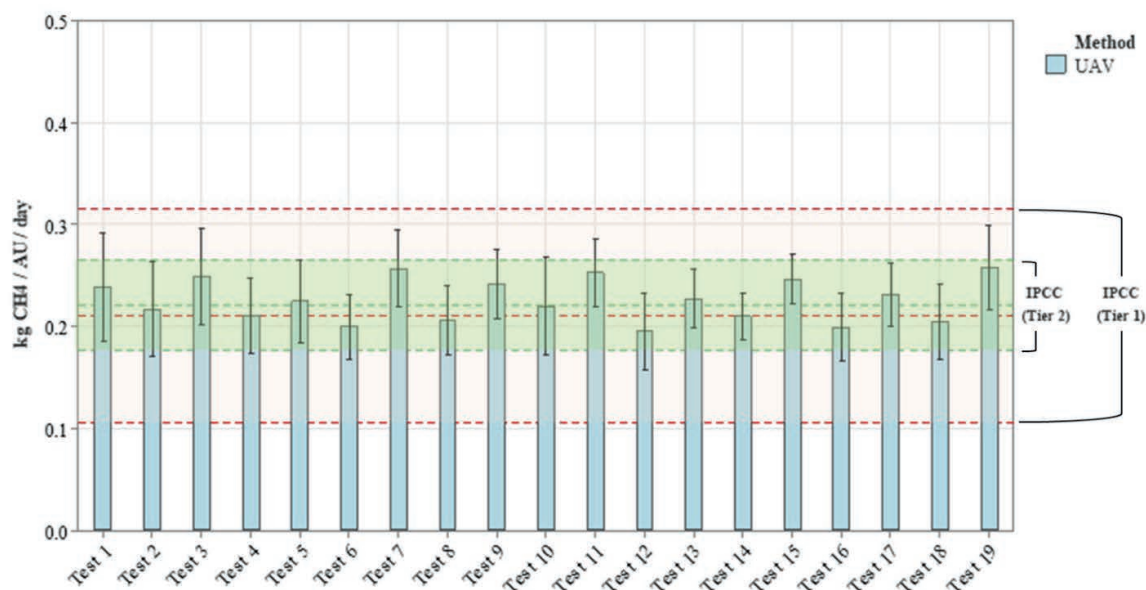


FIGURE 3: UAV-based enteric CH₄ emission rates in an intensive dairy farm compared with IPCC Tier 1 and Tier 2 estimates. The red band represents the Tier 1 uncertainty ($\pm 50\%$), while the green band indicates the Tier 2 uncertainty range ($\pm 20\%$).

equal to 500 kg live weight) by converting non-lactating categories into lactating-cow equivalents. Dry cows were assumed to emit 39% less CH₄ than lactating cows (ISPRA, R398/2024), while heifers/young stock (6-24 months) were assumed to emit 75% less (Vinković et al., 2022). Because the UAV quantifies the total CH₄ flux through the down-wind sampling plane (enteric plus manure-related contributions), the manure component was estimated using the IPCC Tier 2 approach and subtracted, so that the values reported represent net enteric emissions.

Across the campaign, UAV-derived enteric emissions ranged from 0.182 to 0.242 kg CH₄ AU⁻¹ day⁻¹, showing consistency with the IPCC reference estimates. Given the uncertainty associated with the IPCC inventory approaches, this comparison is intended to demonstrate consistency between the UAV-derived estimates and the reference values rather than to provide direct validation of the proposed methodology. The maximum relative deviation from Tier 1 was 0.54%, and the mean relative deviation from Tier 2 was 4.32%, remaining consistent with expected Tier 2 uncertainty and indicating that the UAV approach yields estimate comparable to inventory-based modelling under operational conditions.

The residual discrepancies are plausibly explained by the intrinsic short-term variability of enteric CH₄ production (e.g., daily dynamics and peaks after feeding; Rodrigues et al., 2024) and by sensitivity to microclimatic and nutritional drivers, since temperature/heat stress can reduce animal activity and emissions (Ngwabie et al., 2011; Saha et al., 2014), and diet composition (particularly higher fibre and lower fat) is generally associated with increased methanogenesis (Benaouda et al., 2019), meaning that snapshot UAV measurements may deviate from model estimates representing averaged conditions.

3.2 Natural gas compression station

The UAV-based method was applied at several facilities within the Oil & Gas sector. This section reports the results of a test carried out at a natural gas compression facility under two different operating configurations (hereafter referred to as A and B). On average, configuration B exhibited higher wind speeds than configuration A (+33%), a condition consistent with improved plume representativeness and a reduced uncertainty in the inferred emission flux.

At the site scale, the UAV-based approach yielded an emission rate of 14.3 kg CH₄ h⁻¹ (uncertainty ± 4.1 kg h⁻¹, ~29%) for configuration A and 11.9 kg CH₄ h⁻¹ (± 2.6 kg h⁻¹, ~22%) for configuration B (Figure 4).

In parallel, an independent bottom-up assessment based on Method 21 was performed as a reference. At the site level, the bottom-up approach returned 15.8 kg CH₄ h⁻¹ for configuration A and 13.5 kg CH₄ h⁻¹ for configuration B, assuming an overall uncertainty of $\pm 51\%$ (Table 3.2-1). The relative difference between the UAV-based and bottom-up estimates was 9.4% (configuration A) and 11.6% (configuration B), which falls within the maximum tolerance specified by the applicable standard, Regulation (EU) 2024/1787, for comparisons between top-down and bottom-up methodologies ($\pm 20\%$).

The uncertainty analysis for the UAV-based method indicates that wind speed is the dominant contributor to the total variance, whereas wind direction provides a secondary contribution (on the order of a few percentage points). This is consistent with standard error-propagation formulations for mass-balance approaches and with experimental evidence under low-wind conditions.

Under such conditions, the method may underestimate the flux when the plume does not retain sufficient momentum across the measurement plane, or overestimate it

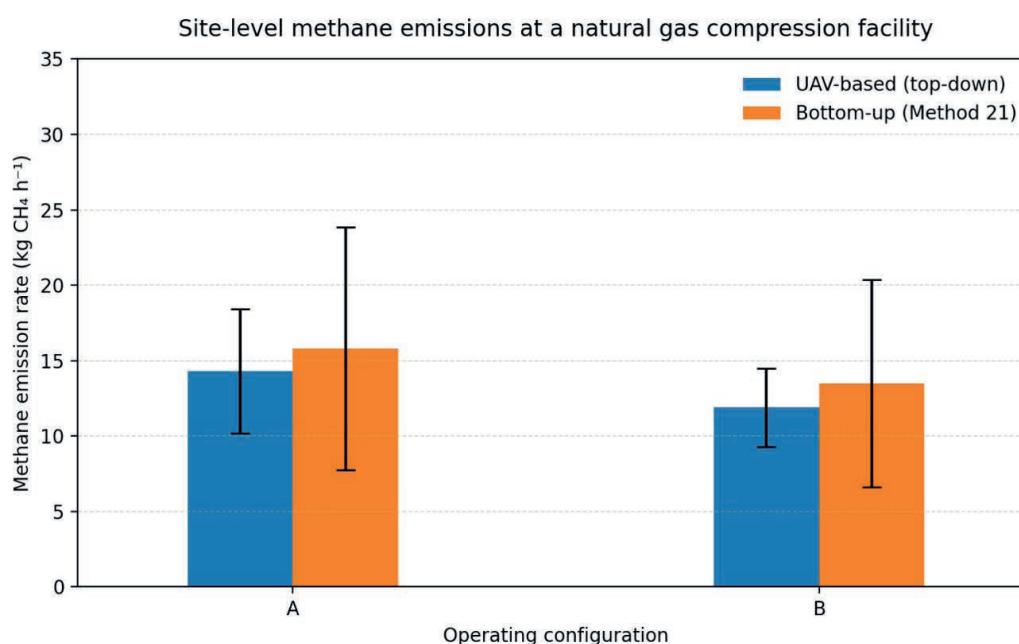


FIGURE 4: Site-level methane emission rates estimated at a natural gas compression facility using the UAV-based approach and the bottom-up Method 21 for two operating configurations (A and B). Error bars indicate the reported uncertainties (UAV-based: ± 4.1 and ± 2.6 kg CH₄ h⁻¹ for A and B, respectively; bottom-up: $\pm 51\%$ of the estimate).

when parts of the plume become quasi-stationary and undergo local recirculation due to turbulence, thereby increasing the observed integrated concentration. Consequently, in future campaigns, reductions in UAV-related uncertainty should be pursued primarily through (i) the selection of meteorological windows characterised by more stable winds and (ii) increased replication of transects within the same window, leveraging rapid data acquisition to improve statistical robustness.

3.3 Municipal solid waste landfill

The UAV method was applied at a municipal solid-waste landfill in Italy (area ≈ 4.2 ha) that had been closed to waste acceptance and was equipped with temporary capping and an active landfill-gas collection system. During two tests conducted between July and September 2024, each comprising two quantification flights, the engine and flare had been switched off approximately two weeks before the measurements as part of the landfill's operating conditions, independently of the UAV measurement campaign. Dedicated upwind flights ruled out any CH₄ contributions not attributable to the site. Fugitive emissions were quantified by reconstructing, downwind, a vertical measurement plane consisting of four horizontal transects at 10, 20, 30 and 40 m above ground level (AGL), extended 30 m beyond the lateral projection of the landfill footprint on both sides to ensure full plume interception. However, the possible extension of portions of the plume beyond the surveyed limits represents a limitation of the measurements.

For Test 1, despite comparable mean wind speeds (4.96 ± 1.15 and 4.77 ± 1.17 m s⁻¹), wind-direction variability differed markedly ($294 \pm 107^\circ$ vs $305 \pm 21^\circ$). The estimated CH₄ fluxes were 11.52 g s⁻¹ and 8.54 g s⁻¹, corresponding to 987 ± 392 and 732 ± 117 mg CH₄ m⁻² h⁻¹ (Table 3), with

total uncertainties of ± 4.57 g s⁻¹ (39.6%) and ± 1.37 g s⁻¹ (16%), respectively. Uncertainty propagation shows that the error budget is dominated by meteorology, with wind speed contributing 60.0–68.7% and wind-direction variability 25.1–34.8%, whereas instrument-related uncertainty is $\sim 6\%$ and positioning contributes $<1\%$, consistent with what is typically reported for airborne mass-balance implementations.

In Test 2, the two flights yielded specific emissions of 320 ± 280 and 578 ± 385 mg CH₄ m⁻² h⁻¹ (Table 3), equivalent to a site-level mass emission rate between 3.7 and 6.7 g s⁻¹.

For an independent comparison at the same case study site, a flux-chamber survey based on 140 points was carried out, with areal integration using the Sinclair approach and the Sichel estimator, resulting in an integrated flux of 2.87 g s⁻¹ (the corresponding specific emission reported in Table 3 is 224 mg CH₄ m⁻² h⁻¹). Relative to Test 2, the flux chambers underestimate the UAV-derived fluxes by $\sim 30\%$ (vs Flight 1) and $\sim 61\%$ (vs Flight 2). This discrepancy is consistent with evidence that chambers, sampling very small surface areas, require substantial spatial upscaling over highly heterogeneous landfill covers and may therefore under-represent hotspots and inaccessible zones.

A tendency towards underestimation has been widely documented (Borjesson et al., 2000; US EPA, 2018) and is exacerbated when sampling density is limited (Babilotte, 2011; Levy et al., 2012; Wong, 2018). In the present case, the sampling density was 18.2 points ha⁻¹, higher than in other Italian chamber studies (Di Bella et al., 2011; Folino et al., 2024), which plausibly explains the good agreement in terms of order of magnitude with the UAV estimates.

Moreover, the chamber–airborne discrepancy is comparable, and often smaller, than that reported in the liter-

ature for faster, higher-altitude airborne platforms. For example, Yeşiller et al. (2022) found flux-chamber estimates to be up to an order of magnitude lower than aerial mass-balance measurements, whereas in this study the estimates remain within the same order of magnitude, consistent with reduced spatio-temporal uncertainty achievable with low-altitude UAV surveys.

Part of the observed differences may also be related to the different measurement durations of the two approaches. The flux chamber survey required approximately two hours to complete, whereas each UAV flight lasted only a few minutes. This difference in sampling duration may result in discrepancies between the two methods because methane emissions can fluctuate during the chamber survey, while the UAV measurement represents a much shorter temporal snapshot of the emission conditions (Table 2).

Finally, comparisons with modelling approaches reported in the literature indicate that models can, in some cases, overestimate emissions relative to measurements (Di Bella et al., 2011; Di Bella et al., 2024), partly because coefficients calibrated under ideal steady-state conditions may overpredict biogas generation (Cossu et al., 1996).

3.4 Implications for the oil & gas, livestock and waste management sectors

In Europe, Regulation (EU) 2024/1787 on methane emission reductions in the energy sector requires companies to measure, monitor, report and verify emissions in line with high monitoring standards. It is also the first legal instrument to explicitly allow the use of drones for site-level monitoring. Operators must submit an annual CH₄ emissions report, subject to independent verification, to the competent authorities of the Member States in which the sites are located. The relatively low cost of UAV-based methods may encourage rapid uptake, provided that

quantification achieves sufficient accuracy and precision. In this respect, drone-mounted open-path laser sensors appear promising, and the error associated with using column-averaged wind data can be substantially reduced, by up to about 50 per cent, when the column is subdivided and averaged across multiple segments. Further momentum is provided by the common framework introduced by Regulations (EU) 2019/945 and (EU) 2019/947, which harmonise drone rules across Member States, although some outstanding issues still require national action. Protocol standardisation also improves the reproducibility of tests across different countries. From an organisational perspective, companies will need to integrate UAV monitoring into environmental management systems, train staff in data interpretation, and align reporting with verification requirements. Beyond compliance, UAV monitoring can enhance transparency, reduce reputational risk, and identify emission hotspots for targeted action, shifting methane monitoring from a regulatory obligation to a management tool.

In the livestock sector, Denmark is considering the introduction of a tax on farm CH₄ emissions from 2030, as part of an agreement aimed at reducing greenhouse gas emissions by 70 per cent relative to 1990. The effectiveness of this measure is debated because reliable and accessible technologies for measuring and mitigating enteric methane at farm scale are still lacking. Conventional methods, including respiration chambers and tracer-gas techniques, remain constrained by cost, complexity and practical applicability. In this context, open-path laser sensors mounted on UAVs could support more accurate farm-scale quantification, with high-frequency measurements and broader spatial coverage. This would be useful both for assessing mitigation measures such as feed additives and for supporting monitoring, reporting and verification systems. From a management perspective, such data can

TABLE 2: Average specific methane emissions from different Italian landfills.

Study	Operating conditions	Average specific CH ₄ emission [mg CH ₄ m ⁻² h ⁻¹]	Method
Di Bella et al., (2011) Landfill 1 (Bellolampo)	Active – temporary capping	1368 ± 4104 5123 4840	Flux chamber LandGEM model Erhig model
Brilli et al., (2024) Landfill 1 (Giugliano) Landfill 2 (Case Passerini)	Closed – final capping Closed – final capping	250 ± 238 29 ± 25	Eddy Covariance Eddy Covariance
Folino et al., (2024) Landfill 1 (Fossetto) 2022 2021 2020 2019	Active – temporary capping	720 ± 1086 628 ± 954 403 ± 730 573 ± 1704	Flux chamber
This study Landfill 1 Test 1 Flight #1 Flight #2 Test 2 Flight #1 Flight #2	Closed – temporary capping	987 ± 392 732 ± 117 320 ± 280 578 ± 385 224	UAV Mass Balance UAV Mass Balance UAV Mass Balance UAV Mass Balance Flux chamber

inform farm decision-making, support compliance, and improve communication with stakeholders, helping to prioritise cost-effective mitigation options.

For waste management, estimating fugitive CH₄ emissions from landfills remains challenging. Although several techniques exist, there is no internationally recognised reference standard, and application is still limited to a small number of countries. The main difficulties stem from extreme spatial and temporal variability. Fluxes can vary by orders of magnitude over distances of only a few metres, and hotspots can account for more than half of total emissions while occupying a small fraction of the surface. Atmospheric conditions, including pressure and wind, can also influence emissions on hourly and sub-hourly timescales. Accumulation chambers, while widely used, tend to underestimate emissions because they do not adequately represent emission distributions and often miss contributions from wells, vents and inaccessible areas. More advanced methods such as DIAL and tracer approaches can perform well at site scale, but they are costly and difficult to deploy for extended periods. In this setting, UAVs equipped with open-path sensors enable high-frequency surveys over large areas, provide denser spatial coverage, and access hazardous or otherwise unreachable zones. They can support management by delivering timely hotspot information that allows operators to prioritise actions, optimise gas capture and flaring, strengthen compliance and improve transparency.

It is emphasised that CH₄ monitoring is not a circular-economy activity in itself, but can support circular-econ-

omy objectives by identifying resource losses and supporting improved recovery and management of CH₄.

A summary of the key advantages of UAV-based methane monitoring across the three sectors is presented in Figure 5.

4. CONCLUSIONS

This study developed and tested a UAV-based mass-balance framework for quantifying methane emissions using a drone-mounted open-path TDLAS sensor, supported by centimetre-level RTK positioning and radar altimetry to improve geometric accuracy of the optical path. The methodology reconstructs a downwind vertical measurement plane through repeated horizontal transects at multiple heights, applies background correction derived from dedicated no-emission acquisitions, and quantifies uncertainty via formal error propagation that combines instrumental errors with the temporal variability of wind speed and direction.

Field deployments at three representative methane settings in Italy demonstrate that the approach is effective at both site and sector-relevant scales. At the intensive dairy farm, UAV-derived net enteric emissions ranged from 0.182 to 0.242 kg CH₄ AU⁻¹ day⁻¹ and showed close agreement with IPCC references, with a maximum deviation of 0.54% relative to Tier 1 and a mean deviation of 4.32% relative to Tier 2, remaining consistent with the expected Tier 2 uncertainty envelope. At the natural gas compression facility, site-level UAV estimates of 14.3 ± 4.1 kg CH₄ h⁻¹ and 11.9 ± 2.6 kg CH₄ h⁻¹ for two operating configurations were



FIGURE 5: Overview of sector-specific benefits for the Oil & Gas, Livestock and Waste Management sectors, highlighting the potential of drone-mounted open-path laser sensing to deliver cost-effective, high-resolution measurements, improved quantification, and support for monitoring, reporting and verification (MRV).

consistent with an independent Method 21 bottom-up assessment within 9.4–11.6%, which is within the tolerance commonly adopted for top-down versus bottom-up comparisons. At the municipal solid-waste landfill, site-scale fluxes spanned 3.7–11.5 g s⁻¹ across tests and flights, with uncertainty dominated by meteorology. A flux-chamber survey provided the same order of magnitude but underestimated UAV-derived fluxes by approximately 30–61%, consistent with known limitations of point sampling over highly heterogeneous covers and hotspot-driven emission patterns.

Across all case studies, the results highlight that the dominant limitation of UAV mass-balance quantification is meteorological sensitivity, particularly under low-wind or highly variable wind-direction conditions. Wind speed was consistently the primary driver of the propagated uncertainty, with wind-direction variability providing a secondary contribution.

These findings indicate that improved quantification can be achieved by prioritising measurement windows characterised by relatively stable atmospheric conditions and wind speeds between 1 and 6 m s⁻¹, while avoiding periods of atmospheric instability. In addition, increasing transect replication and ensuring an appropriate measurement-plane design can strengthen the statistical robustness and reliability of the estimates. Overall, the results indicate the potential of the UAV-based approach for CH₄ emission assessment, while further testing and validation are required to assess its broader applicability.

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LIFE-CYCLE RESOURCE CONSUMPTION OF HYDROPONIC GREEN ROOF SYSTEMS

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ABSTRACT

The research focuses on assessing the circularity, in terms of life-cycle resources embodied, of a hydroponic system installed on a building roof in Southern Italy, used for producing food in soilless conditions. The analysis of the entire system is performed by applying the Life Cycle Assessment methodology and adopting a “from cradle to gate” approach, which includes all the life-cycle steps from the raw materials supply to the system assembly. The selected categories to quantify the impact on circularity are: land use, water use, use of minerals and metals resources, use of non-renewable energy sources, and use of renewable energy sources. The results reveal the materials and components of examined system that are mainly responsible for these impacts. In particular, for almost all the impacts water tank and platform are the main hot-spots influencing the results and should be further investigated to improve the circularity of the hydroponic system.

1. INTRODUCTION

Promoting sustainable food production and resilient agricultural practices are the main goals of the Sustainable Development Goal 2 – Target 2.4 of the Agenda 2030 for Sustainable Development (United Nations, 2015). To date, food production processes are neither resilient nor sustainable at global level. The effects due to climate change, including extreme weather, drought and flooding, make agri-food production vulnerable by disrupting crop yields, reducing water and soil availability, and increasing the frequency of supply chain disruptions. Furthermore, the food sector contributes significantly to environmental degradation, biodiversity loss, greenhouse gas emissions, and resource consumption (Food and Agriculture Organization of the United Nations, 2021). Together with housing, it accounts for about 72% of the European material footprint, which represents the materials extracted from nature to manufacture or provide goods and services for European citizens. Specifically, these two sectors are responsible for consuming approximately 80% of non-metallic minerals and biomass, 50% of fossil energy materials, and 44% of metal ores (European Environment Agency, 2024).

Thus, identifying new practices to ensure food security, environmental protection and a transition towards circular, resource efficient and less resource intensive processes is fundamental.

Producing food with soilless systems can be considered a potential innovative solution to current agricultural processes, to be applied especially in the urban context, for facing challenges related to food supply such as increasing population, climate change and extreme events, reduced availability of soil for agriculture, etc. (Rapisarda et al., 2024). This new strategy for urban food production has to be efficient concerning the food yield and it needs to be performed in a sustainable way, with a reduced environmental and energy footprint, low costs, and social benefits.

In this context, the present study develops a Life Cycle Assessment (LCA) study to quantify the circularity of hydroponic systems by assessing the resources embodied throughout their entire life cycle.

Circularity is considered from an environmental resource-efficiency perspective, focusing on the extent to which the hydroponic system relies on the consumption and depletion of natural resources throughout its life cycle. Although circularity is a multidimensional concept

encompassing material flows, resource efficiency, waste prevention, reuse, recycling, and the extension of product and material lifetimes, reducing the demand for primary and non-renewable resources represents a relevant environmental dimension of circular systems.

The innovative contribution of this paper with respect to the state-of-the-art is double:

- Existing LCA studies of hydroponic systems have mainly focused on the production in greenhouses (Mofatteh et al., 2024; Nadeem et al., 2024; Srinivasan and Yadav, 2024; Paturu and Varadarajan, 2024; Martínez et al., 2024) or commercial and large-scale vertical farming systems (Gargaro et al., 2024; Martin et al., 2023; Casey et al., 2022; Martin et al., 2019a; Romeo et al., 2018). Other studies have examined plant factories and combinations of greenhouse and vertical farming systems (Maynard et al., 2023; Blom et al., 2022), while rooftop hydroponic applications have been considered at large scales (Rufi-Salís et al., 2020; Sanyé-Mengual et al., 2015). In addition, some studies have addressed theoretical or human-powered hydroponic configurations (Grigas et al., 2023; Casamayor et al., 2024). The innovative aspect of the present study is that it investigates a small-scale hydroponic system specifically designed for installation on flat residential rooftops and intended to support food production for household consumption. To the authors' knowledge, among the studies identified in the literature, Sanyé-Mengual et al. (2015) represent the closest reference to the present work, as they assessed hydroponic cultivation in a rooftop farming context focusing on a community rooftop garden of 250 m². The small scale of the system examined in this paper and intended application for individual households or small residential buildings represent a key novelty of the present work.
- Previous LCA studies have generally considered a limited selection of resource consumption indicators. Several studies have focused primarily on fossil-resource or abiotic-resource depletion (Mofatteh et al., 2024; Gargaro et al., 2024; Nadeem et al., 2024; Paturu and Varadarajan, 2024; D'Amico et al., 2023; Grigas et al., 2023; Chen et al., 2020; Rufi-Salís et al., 2020; Martin et al., 2019a; Romeo et al., 2018), while others have focused mainly on water use (Maynard et al., 2023; Sanyé-Mengual et al., 2015) or cumulative energy demand (Sanyé-Mengual et al., 2015). The present study provides a broader resource consumption assessment by simultaneously considering land use, water use, mineral and metal resource depletion, and cumulative energy demand (renewable and non-renewable). This allows the resource profile of a household-scale rooftop hydroponic system to be characterized across a wider range of dimensions than those commonly reported in previous studies.

2. CASE STUDY

The case study is a Hydroponic Green Roof System (HGRS) (Figure 1), involving an alternative cultivation tech-

nique that does not use soil.

In detail, in a HGRS system the plant roots are immersed in a well-oxygenated and nutrient-rich water, through a substrate of expanded clay. In this system, the plants do not need to extend their roots much because they do not need to consume energy in search of nutrients as it is normally done on land.

The advantage of HGRSs is that vegetables grow in a controlled environment and the possibility to be exposed to pests or weed species is reduced. As a result, there is less or no use of pesticides and harmful chemicals, helping to produce healthier and safer food for human consumption. Furthermore, the installation of hydroponic systems on building rooftops offer numerous benefits, such as thermal insulation, reduction of urban heat islands, and stormwater management. This system can improve the efficiency of urban space use, contribute to environmental sustainability, and provide fresh food in urban settings. The most important characteristics of the system are the following:

- Water: the roots are immersed in water, allowing the plants to constantly absorb the nutrients and water they need;
- Oxygenation: since the roots are immersed in water, it is essential that the solution is well-oxygenated to prevent the plants from suffocating. This is achieved using an air pump and a porous stone that create air bubbles in the solution;
- Nutrients: the solution contains all the necessary nutrients for plant growth, replacing soil;
- The system includes rapid plant growth and relatively low maintenance once set up.

The examined HGRS is installed on the roof of the building housing the Department of Engineering of the Universi-



FIGURE 1: The examined hydroponic green roof system.

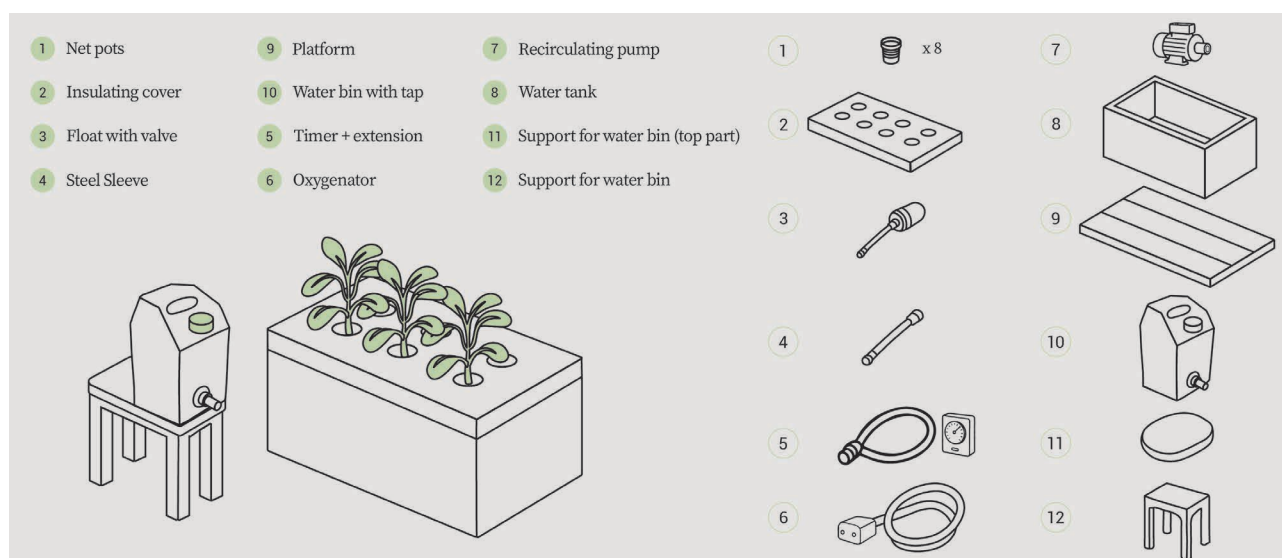


FIGURE 2: System components.

ty of Palermo. At the core of the hydroponic system (Figure 2) is a polyethylene cultivation tank that provides an efficient growing environment. This tank, with a capacity of 200 litres, is covered by an external polystyrene shell, which serves as thermal insulation to maintain stable water temperature and minimize fluctuations that could affect plant development. The dimensions of the tank (104.5 cm in length, 69.5 cm in width, and 34.5 cm in height) allow adequate space to accommodate a variety of plants while ensuring ease of maintenance and monitoring. Supporting the cultivation tank is a robust platform made from a combination of wood and extruded polystyrene, which provides stability and ensures the tank remains securely positioned.

An insulating cover made of extruded polystyrene is placed on the top, featuring eight circular openings, designed to hold the polyethylene terephthalate net pots, allowing the plants to be suspended in the nutrient-rich water while ensuring proper aeration and roots support. Within the tank, a floating valve mechanism ensures a consistent water level is maintained. This float is hydraulically connected via a durable steel sleeve to a 20-liter plastic water bin equipped with a tap, which facilitates easy refilling of water as needed. The container itself is supported by a sturdy aluminium table, whose top surface is also made of extruded polystyrene, further contributing to the insulation and structural integrity of the system. To support an optimal growth environment, the system incorporates both a 10 W recirculation pump and a 6 W oxygenator, powered by electric current and housed respectively in protective cases, made of mixed materials for the pump and ABS for the oxygenator. The oxygenator plays a crucial role in preventing root rot by continuously enriching water with oxygen, thereby enhancing nutrient absorption and promoting healthy plant growth. These components are automated via a timer, which activates the system for 10 minutes every hour, ensuring a balanced and efficient water circulation cycle. The crops to be introduced in the system are cultivated in PET net pots. Before being trans-

ferred to these pots, the young plants undergo an initial growth phase in small polypropylene trays, which are later discarded as waste. Each net pot is equipped with a specialized strap that functions as a wicking material, drawing water and nutrients from the tank to the plant roots. This capillary action ensures that the plants remain consistently hydrated and well-nourished. To provide additional support, expanded clay is used as the growing substrate within the net pots, offering both anchorage and aeration to the developing roots.

3. MATERIALS AND METHODS

The circularity of the hydroponic system was evaluated from a resource-efficiency perspective, by assessing the following life-cycle resources consumption indexes (Damiani et al., 2022; Frischknecht et al., 2015):

- Land use (unit of measure “pt”): it is a soil quality index describing the transformation and use of soil for human activities (e.g. agriculture, roads, etc.). It is calculated as an aggregated impact taking into consideration loss of species, organic matter, soil, filtration capacity, permeability;
- Water use (unit of measure “m3 worldeq”): it represents the depletion of available water calculated with the use of weights that consider the local water scarcity and the water needs for humans and ecosystems;
- Use of minerals and metals resources (unit of measure “kg Sbeq”): referred to the abiotic resources –ultimate reserves, it takes into account the non-renewable resource depletion and the deprivation for future generations;
- Use of non-renewable energy sources (unit of measure “MJeq”): this index includes the use of fossil fuels (such as coal, oil, and natural gas), nuclear energy and non-renewable biomass sources, which are organic materials that can be used as fuel but are not sustainably replenished;

- Use of renewable energy sources (unit of measure “MJeq”): including the consumption of biomass sources (such as sustainably harvested wood or agricultural residues), wind, solar, and geothermal, energy from hydropower.

The above indexes provide information on the depletion of key natural resources associated with the system over its life cycle. Such information support a circularity-oriented assessment because minimizing the use of virgin, non-renewable, and scarce resources and improving resource efficiency are key environmental objectives associated with circular systems.

The calculation of the above resource consumption indexes was made by applying the LCA methodology, developed according to the international standards of the ISO 14040 series (ISO 14040, 2021; ISO 14044, 2022). In general, this approach enables the evaluation of circular aspects in terms of resource consumption throughout the life cycle of a product or service.

The study aims at assessing the resource consumption associated with the manufacturing of the hydroponic green roof system, with particular emphasis on identifying the main components and materials contributing to the overall resource demand. The assessment focused on the environmental burdens associated with the production and assembly of the system, in order to identify the environmental hot-spots and suggest some qualitative eco-design strategies.

The hydroponic system, including all its components and materials, was selected as reference for the indexes evaluation, thus it represents the functional unit of the study that is the quantified performance of the product system to which the input and output flows must be linked (ISO 14040, 2021). This choice is consistent with the goal of the study, which was to quantify the resource consumption associated with the realization of the hydroponic system, rather than the vegetable production. Therefore, the results were expressed per complete hydroponic system. A production-based FU (e.g., kg of vegetables produced) would be more suitable for assessing the environmental performance of the agricultural production phase; however, this was outside the scope of the present study.

A “from cradle to gate” approach was adopted, including the following steps:

- Extraction and processing of raw materials;
- Transport of the raw materials from the site of extraction to the site where the system components are produced;
- Manufacturing of the system components, including energy consumption and ancillaries;
- Manual assembly of the hydroponic system: step directly examined during the installation process.

The end-of-life phase was excluded from the study, based on the material composition of the hydroponic system and the approach adopted for recycling processes. Specifically, the recyclability was estimated by analysing the mass composition of all system components and classifying the materials according to their potential for mate-

rial recovery. Metals, wood, most of the plastic materials and electrical cables were considered recyclable, whereas materials for which material separation and recovery are particularly challenging, such as XPS/polystyrene, PVC, silicone, mixed materials and air stones, were not conservatively considered recyclable and are potentially destined for landfill or incineration.

Based on this material-by-material assessment, the mass of potentially recyclable materials was estimated at about 20 kg, corresponding to about 87% of the total mass of the system. An alternative, less conservative classification, in which XPS/polystyrene, PVC and silicone were also considered potentially recoverable, would result in a recovery rate of 98.89%. The conservative value of 87% was adopted in the present study.

The recycling process was subsequently excluded by adopting a cut-off approach, that is the assumption that the benefits and burdens of recycling are attributed to the new product system that will use the recovered materials.

Since most of the materials are modelled with a cut-off approach, it is assumed that the remaining 13% that is landfilled or incinerated as a negligible impact with respect to the other examined life-cycle stages.

Transport-related impacts from the manufactory site to the installation site were excluded from this analysis, in order to obtain results that are not affected from the distance between the sellers of the hydroponic system and the installation site.

The analysis started with the collection of primary and secondary data. In particular, primary data related to the components of the hydroponic system (materials used and masses) were collected during the assembly step through a weighting process and using the datasheets of these components (Table 1). Then, for each input, secondary data were selected in the environmental database Ecoinvent (Wernet et al., 2016), in order to describe the inputs supply chains in a life-cycle perspective. The application of LCA allowed calculating a list of environmental indicators related to raw materials consumption. These indicators were grouped into the resource consumption indexes listed above. In detail, the grouping method applied for the consumption of energy sources was the Cumulative Energy Demand (Frischknecht et al., 2015), while the other indexes were assessed by applying the Environmental Footprint method (European Commission, 2021). All the calculations were performed by using the LCA software Simapro (Prè, 2024).

Primary data were collected with direct measurements (Figure 3) and analysis of datasheets related to system components.

4. RESULTS AND DISCUSSION

The results of the analysis, related to the calculation of the resource consumption indexes, are reported in Table 2.

Focusing on the contribution of the different inputs of hydroponic systems, previous LCA studies have highlighted the importance of energy and material requirements as key contributors to environmental impacts, although the dominant processes vary substantially depending on

TABLE 1: Collected primary data.

Component	Material	Mass (kg)	Length (m)
Water tank - Inner part	Polyethylene	10.90	
Water tank - Outer Part	Polystyrene	0.84	
Insulating cover	Polystyrene	0.65	
Platform	Wood	4.70	
	Polystyrene	0.70	
Water bin	HDPE	0.90	
Tap	Brass	0.10	
Pump	Mixed materials	0.20	
Pump (electric cable)			1.45
Oxygenator	ABS	0.05	
	Copper	0.08	
	Steel	0.08	
	PVC	0.04	
	Air stones	0.06	
	Silicone	0.03	
Oxygenator (electric cable)			1.37
Timer	Polycarbonate	0.03	
	ABS	0.16	
Timer (electric cable)			2.93
Water bin support	Aluminium	2.05	
	Polystyrene	0.20	
Float	HDPE	0.03	
Valve	Stainless steel	0.17	
Net Pots	PET	0.15	
Steel sleeve	Stainless steel	0.20	
Substrate	Expanded clay	0.15	

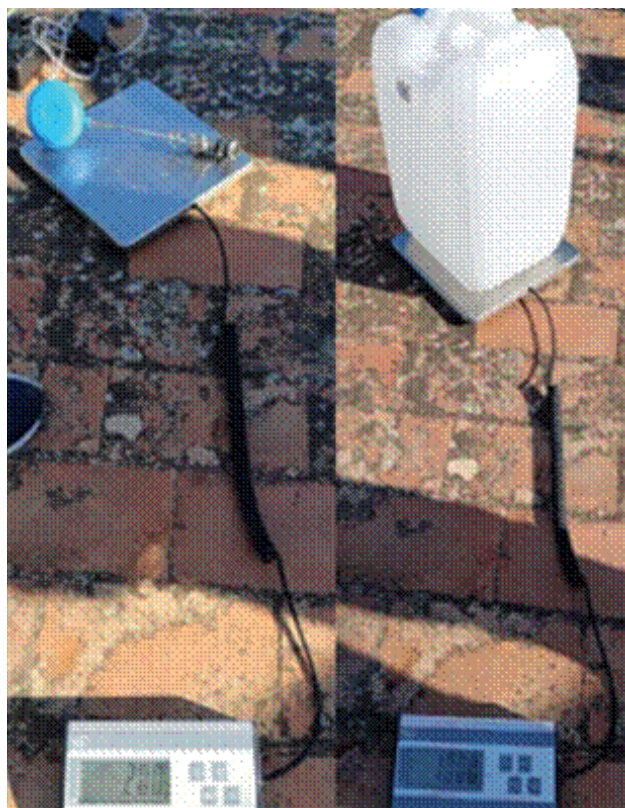


FIGURE 3: Weighting process of the system components..

TABLE 2: Results of the analysis.

Resource consumption index	Unit of measure	Quantity
Land use	pt	8.66E+02
Water use	m3 worldeq	4.58E+01
Use of minerals and metals resources	kg Sbeq	2.93E-03
Non-renewable, fossil	MJeq	1.66E+03
Non-renewable, nuclear	MJeq	1.57E+02
Non-renewable, biomass	MJeq	3.17E-02
Renewable, biomass	MJeq	1.30E+02
Renewable, wind, solar, geothermal	MJeq	3.17E+01
Renewable, water	MJeq	5.75E+01

system configuration, scale, and technology. In particular, studies on vertical farming and plant-factory systems have frequently identified energy demand associated with controlled cultivation conditions as a major environmental hotspot, whereas studies on greenhouse and rooftop hydroponic systems have reported a greater relevance of cultivation infrastructure, water management, and pumping requirements (Romeo et al., 2018; Martin et al., 2019a; Casey et al., 2022; Gargaro et al., 2024; Sanyé-Mengual et al., 2015).

A dominance analysis of the environmental impact assessment obtained in this study (Figure 4) identified some critical hotspots across the examined impact categories. In detail:

- Land use: the platform had a substantial impact on land use (62.78%), with a value of 5.43E+02 pt, indicating significant land occupation and transformation. Water tank also contributed to the land use impact, accounting for 17.74% of the total. Sustainable land use practices and minimizing land disturbance during production are critical. Implementing land restoration projects and optimizing land use efficiency can help mitigate these impacts.
- Water use: the production of the water tank required a relevant amount of water, resulting in significant water scarcity impact, with a total water deprivation value of about 20.97 m³eq, corresponding to 45.76% of the overall water use impact. Additionally, the water directly used within the system for the initial filling also contributed notably, accounting for 20.67% of the total. These findings underscore the need for water-efficient manufacturing processes and the adoption of sustainable water management practices to mitigate resource depletion and reduce pressure on freshwater availability.
- Use of minerals and metals resources: the timer, water bin, and oxygenator demonstrated a significant contribution to resource use related to minerals and metals. Among these, the timer (and in particular cables) was the most impactful component, with a quantified value of 6.13E-04 kg Sbeq, representing 25.62% of the total impact. The water bin and oxygenator followed closely, contributing 25.07% and 17.40%, respectively. The critical inputs of water bin emerging as significant hotspot for this impact category, is brass, while for oxygenator

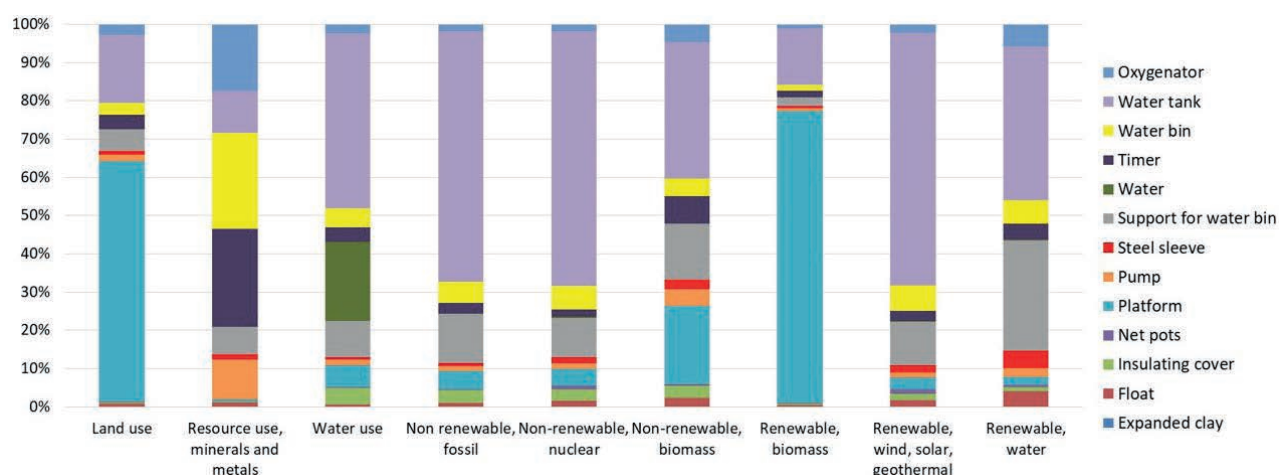


FIGURE 4: Dominance analysis of the results.

the main responsables of the impact are cables and copper. To mitigate these impacts, it is essential to adopt recycling strategies and explore the use of alternative, less resource-intensive materials. Furthermore, embracing circular economy principles and promoting the use of secondary raw materials can significantly reduce the depletion of mineral and metal resources.

- Non-renewable, fossil: this category represents the most significant contribution to the energy consumption, totaling about 81.5% of the primary energy consumption. The majority of this value is attributable to the water tank, which accounts for about 65% of the total fossil energy demand. In particular, the internal part of the water tank, made of polyethylene, is identified as the most critical hotspot. This highlights the high-energy intensity associated with the tank's production, likely due to petroleum-based plastic materials and energy-intensive manufacturing processes. The support for water bin is the second-highest contributor (12.8%).
- Non-renewable, nuclear: nuclear energy contributes to about 7.7% to the overall energy demand. Once again, water tank is the largest single contributor with approximately 67% of the total in this category. This confirms the water tank's significant role in the energy balance. Other components, including the platform, float, pump, and timer, contribute to a lesser extent.
- Non-renewable, biomass: this category has a very limited impact, lower than 0.002% of the total. Thus, the individual contributions from components are negligible in quantitative terms, indicating a minimal role of non-renewable biomass in the system's life-cycle.
- Renewable, biomass: the contribution from renewable biomass is about 6.4%, with the platform being the dominant component, accounting for 76.4% of the total. This result highlights the significant renewable energy demand involved in the platform supply chain, mainly due to the feedstock energy embodied in the wood used for this component.
- Renewable, wind, solar, geothermal: this category contributes to 1.5% of the total, with the water tank again being the main contributor (66.2%). This suggests that,

along the supply chains, part of the energy used in the tank's production comes from renewable electricity sources such as solar or wind power.

- Renewable, water: renewable energy from hydropower accounts for 2.8% of the total primary energy consumption, with the water tank again leading at 40.3%, and support for water bin at 28.8%.

Considering the existing literature studies, given the differences in system configuration, scale, and functional characteristics among the hydroponic systems investigated, a direct quantitative comparison with most previous LCA studies is not straightforward. In particular, the majority of published studies concern commercial greenhouses, vertical farms, or plant factories, which differ substantially from the household-scale rooftop system considered in this study. The study reported by Sanyé-Mengual et al. (2015) represents, to the authors' knowledge, the closest study in terms of application to rooftop, as authors assessed hydroponic cultivation in a rooftop farming context in Bologna, Italy. Their study compared nutrient film, floating hydroponic, and soil-based cultivation in a 250-m² community rooftop garden and applied LCA to the production of different crops. However, their assessment was performed using 1 kg of crop as the functional unit and therefore incorporated the productivity of the cultivation systems into the environmental results. In contrast, the present study focuses on the burdens associated with the production of the household-scale hydroponic system itself, without extending the assessment to crop production and without defining the functional unit in terms of mass of crop produced. Therefore, a direct quantitative comparison of the LCA results with those reported by Sanyé-Mengual et al. (2015) would not be methodologically appropriate. Further developments of the present study will extend the assessment to the cultivation phase, including the evaluation of crop productivity, in order to obtain results referred to a mass-of-product basis and to have the possibility to compare them with previous LCA studies. Such a comparison will also need to account for the influence of local climatic conditions on system operation and crop produc-

tivity, which may affect the environmental performance of rooftop hydroponic cultivation.

5. SENSITIVITY ANALYSIS

The LCA study was developed by using a from cradle-to-gate approach, consistently with its goal of assessing the resources consumed during the system realization. However, a sensitivity analysis was performed to evaluate the potential relevance of the operational phase.

The operational requirements of the system were estimated based on the annual consumption of water, electricity and fertilizer. Specifically, the system requires 600 l of water (excluded the 200 l used in the initial filling) for the first year and 800 l/year in the next years, 24 kWh of electricity and 100 mL of fertilizer per year. Since the service life of the system can vary depending on the durability of its individual components, three reference service-life scenarios were considered: 5, 10 and 15 years. These scenarios were selected to represent short-, medium- and long-term operation and are consistent with the range of service lives reported for components of hydroponic and soilless cultivation systems, which vary according to the type of component and its operating conditions (Martin et al., 2019b; IUCN, 2023; Pennisi et al. 2019).

The results of the sensitivity analysis, showed in Table 3, highlighted that resource use minerals and metals is dominated by the cradle-to gate impacts even if the use phase is included, with a contribution going from 65% to 85% when the service life of the system decrease from 15 to 5 years. Similarly for land use, for which the above stages accounts for 54% considering a 15-years of operation and increases at 78% when the service life has the minimum value.

The operational phase becomes the main contributor to the impacts on water use, representing from 81% (5-years service life) to 93% (15-years service life) mainly due to the use of water for plant growth. Moving to the energy indexes, the from cradle-to-gate stages remain relevant for biomass depletion (renewable and non-renewable), with a contribution higher than 53%, while operation represents the main hot-spot (higher than 66%) when other renewable energy sources (wind, solar, geothermal and water) are considered. This last result comes from the renewable share on energy in the electric mix used in the analysis (referred to

Italy). Focusing on non-renewable energy from fossil fuels and from nuclear, the incidence of operation increase from 28% to 54% (fossil) and from 39% to 65.5% (nuclear) when the service life increases.

The analysis revealed the importance to include the operational phase, which could substantially affect the magnitude and interpretation of the results obtained from the cradle-to-gate assessment.

6. POTENTIAL IMPROVEMENT STRATEGIES

The identification of the main environmental hotspots and a direct observation of the system layout provide useful information for defining qualitative eco-design solutions aimed at improving the resource-efficiency of the system, that can be applied not only for the system manufacturing but also for its operation. In particular, eco-design strategies can be oriented toward the reduction of materials/components, water and energy requirements and use of secondary raw materials:

- Use of secondary raw materials: the replacement of virgin materials with recycled or secondary raw materials provides an opportunity of improving the system performance in terms of circularity, particularly for components with a high material mass such as the water tank. For example, assuming similar characteristics, recycled polyethylene can be considered as an alternative to virgin polyethylene for the manufacturing of water tank. This substitution can result in important improvements in the resource-efficiency: for 10.9 kg of material (that is the weight of the water tank – inner part), using secondary polyethylene allows for a reduction of energy consumption of one order of magnitude, from 83.45 MJ to 9.37 MJ. Non-renewable energy sources are reduced of about 178%, while there is an increase of 67% of renewable energy sources. Land use, water use and depletion of minerals and metals resources decrease of about 84.5%, 91.9% and 91.7%, respectively.
- Reduction of the amount of materials used, with a specific focus on optimizing cable lengths. Careful components layout design, particularly for the timer, pump and oxygenator, can minimize cable routing distances. This relatively simple design choice can contribute to the overall sustainability of the system because the use

TABLE 3: Results of the sensitivity analysis.

Resource consumption index	Unit of measure	Cradle-to-gate	5 years oper.	10 years oper.	15 years oper.
Land use	pt	8.66E+02	2.48E+02	4.96E+02	7.44E+02
Water use	m3 worldeq	4.58E+01	1.93E+02	3.95E+02	5.97E+02
Use of minerals and metals resources	kg Sbeq	2.93E-03	5.25E-04	1.05E-03	1.57E-03
Non-renewable, fossil	MJeq	1.66E+03	6.39E+02	1.28E+03	1.92E+03
Non-renewable, nuclear	MJeq	1.57E+02	9.91E+01	1.99E+02	2.98E+02
Non-renewable, biomass	MJeq	3.17E-02	9.28E-03	1.86E-02	2.79E-02
Renewable, biomass	MJeq	1.30E+02	2.15E+01	4.30E+01	6.45E+01
Renewable, wind, solar, geothermal	MJeq	3.17E+01	1.59E+02	3.19E+02	4.78E+02
Renewable, water	MJeq	5.75E+01	1.11E+02	2.22E+02	3.33E+02

of shorter cables implies a reduced need for copper and insulating materials, resources whose extraction and processing have an environmental impact. For example, a reduction of 20% of cables length can reduce the impact on minerals and metals resources of about 6.6% and lower than 2% for the other examined categories.

- The current configuration of the system includes a 20-liter plastic water bin equipped with a tap, which facilitates easy refilling of water as needed. The water bin is put on a sturdy aluminium table, whose top surface is made of extruded polystyrene. An eco-design strategy, where technically and hydraulically feasible, would be to connect the hydroponic system directly to the building's water supply system, thus eliminating the water bin, the aluminium table and the top surface, thereby reducing the amount of material required for the overall system. This helps reducing the energy impacts of the system of about 17.8%, with a variation from 16% to 19% of non-renewable energy sources and from 4% to 35% of renewable energy sources. The resource consumption impacts are reduced from 9% (land use) to 32.4% (minerals and metals resources), with a water use reduction of 18.1%.
- Reduction of the water level: a possible strategy concerns the reduction of the water volume contained in the tank. In the current configuration, the tank contains 200 l of water, corresponding to a water height of about 27.5 cm. A reduction of the operating water level could be considered, provided that the minimum volume required to ensure adequate plant growth, hydraulic operation and oxygenation is maintained. For example, reducing the water height to 20 cm would decrease the water volume from 200 l to 145 l for each filling, that is from 800 l to 580 l per year, with a corresponding reduction in water demand during operation. This solution causes a reduction of the impacts due to water of the system of 27.5% during each year of operation. Considering one year of operation of the whole system (not only the water impact) a decrease of the impact lower than 2% can be obtained. However, it is important to outline that the impact on the category "water use" of the whole system can be reduced of about 23.4%.
- Reduction of electricity consumption during operation, that is associated with the pump and oxygenator. In the current configuration, the two components have a combined power of 16 W. They are connected to a timer and work for 10 minutes every hour, reaching a total of 4 hours per day. The annual consumption of the pump and oxygenator is 23.36 kWh (0.064 kWh per day). If the time of operation is changed and the two components work for 10 minutes every hour and a half, a total of 2.7 hours per day of working is obtained, with a consequent electricity consumption of 0.0432 kWh per day and of 15.77 kWh per year, and a reduction of about 32.5% of electricity consumption. In this case, a 32.5% reduction of the impacts due exclusively to electricity can be obtained.

Overall, the identified strategies suggest that improvements should primarily focus on the components and

flows responsible for the largest resource requirements. In particular, reducing the material intensity of the water tank and cables, increasing the use of secondary raw materials, optimizing water and electricity requirements, could contribute to improve the resource-efficiency performance of the system. These interventions should be considered as potential design options rather than as directly quantified improvement scenarios, since their actual effectiveness would depend on technical feasibility, structural and operational requirements, and the specific materials and technologies adopted.

7. CONCLUSIONS

This study proposes an evaluation of the circularity performance of a hydroponic green roof system, considering the life cycle resources embodied from raw material supply to system assembly. The results highlight that the system's circularity is strongly influenced by a limited set of components. In particular, the water tank and the platform emerged as the main hot-spots across multiple impact categories, with material composition playing a decisive role in their overall contribution. Other elements, such as the water bin, its support structure, the timer, and the oxygenator, also showed notable impacts.

These outcomes confirm the need to prioritize material selection and design optimization in order to improve the circularity of urban hydroponic systems.

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Extra contents

COLUMNS AND SPECIAL CONTENTS

This section comprises columns and special contents not subjected to peer-review

Environmental Forensics, Law and Policy

BIODEGRADABLE PLASTIC BAGS IN THE WASTE STREAM - PRACTICES, FAILURES, AND ENFORCEMENT CHALLENGES

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1. INTRODUCTION

Plastic packages have become one of the most visible symbols of the global waste and pollution problem. Their low production cost, lightweight nature, high flexibility, and water resistance have made them convenient and widely used packaging materials, including in food packaging, while also contributing to their persistent and ubiquitous presence as environmental contaminants. Plastic bags made from polyethylene or polypropylene may remain in the environment for decades or centuries, fragmenting into microplastics. In soil systems, compost, rivers, agricultural land, and marine environments, such fragments may contribute to ecological disturbance, reduced environmental quality, impaired plant growth, and long-term risks to environment and human health (Thompson et al., 2024).

Widely used applications for plastic materials are food packages, carrier and waste collection bags, that often enter organic waste streams in countries with separate collections. In response to these findings, several countries introduced bans on certain applications of plastics. As an alternative, plastic items made from biodegradable polymers are introduced, that need to fulfil certain degradation profiles approved by certifying bodies.

In Austria, a ban on conventional plastic carrier bags was introduced in 2020 under the Austrian Waste Management Act (BGBL, 2002). Among other exceptions from the ban, plastic shopping bags are allowed to be placed on the market if they are home-compostable and consist predominantly of renewable raw materials. Across the EU, regulations are not uniform, with some countries promoting the use of biodegradable materials, while others adopt more restrictive approaches. The advantages for mandating biodegradable packages and carrier and collection bags include facilitating the separate collection of organic wastes and improving collection rates in the urban areas, while reducing the pollution of the waste stream by plastics. On the other hand, waste managers and environmental groups are particularly concerned that allowing biodegradable plas-

tics in the waste stream may encourage improper disposal practices, which could subsequently extend to other types of plastics.

At the EU level, harmonized rules for food packaging have been mandated by the Packaging and Packaging Waste Regulation (PPWR), which identified items such as tea bags, coffee pods, and carrier bags as applications for which compostable plastics may be required in the future, given that these items are frequently disposed of with organic waste and cannot be effectively removed from such waste streams (COUNCIL, 2024b). In addition, the PPWR allows Member States, under specified conditions, to require certain packaging applications to use compostable materials at the national level. However, implementing such measures may be challenging in practice, as food packaging is generally produced for the broader EU market, with only labels and printed information being adapted to individual countries and languages. Nevertheless, this open component of the PPWR allows for other food packages to be made of biodegradable materials that cannot be currently recycled.

However, the practical effectiveness of such legislation depends not only on the existence of a legal prohibition, but also on market compliance, reliable certification, consumer trust, enforcement capacity, and the ability of waste management systems to distinguish between genuine biodegradable products and misleadingly labelled conventional plastics, which are far cheaper than the biodegradable alternatives.

Recent evidence from Austrian composting facilities and local markets indicate that a substantial number of bags labelled as “bio”, “biodegradable”, or “compostable” are in fact conventional plastic bags. These products imitate compliant packaging while avoiding the higher production costs and quality controls associated with certified biodegradable materials. The result is a combination of environmental damage, consumer deception, unfair competition, and regulatory enforcement difficulty.

This column examines the practical problem of falsified biodegradable plastic bags in Austria. Drawing on ob-

servations from composting facilities, market inspections, expert material analysis, and the perspectives of producers, waste managers, testing bodies, and public authorities, it discusses how fake “bio-bags” enter the market, why they are difficult to trace, how they affect compost quality and legitimate businesses, and what this case reveals about the broader governance challenges of biodegradable plastics.

2. BIODEGRADABLE BAGS AND THE REGULATORY TRANSITION

The Austrian prohibition of conventional plastic carrier bags created a dedicated market for biodegradable and compostable alternatives. Retailers and supermarkets adapted relatively quickly to the legal requirements. At supermarket checkouts, consumers now commonly encounter reusable cloth bags, paper bags, or certified compostable lightweight bags for fruit and vegetables. In principle, this regulatory transition was intended to remove persistent plastic carrier bags from everyday retail use and to reduce problems when these products enter the organic waste stream.

Their environmental performance depends on chemical composition, processing conditions, certification standards, and the actual waste treatment pathway. Genuine biodegradable or compostable bags are generally made from materials such as starch-based polymers, polylactic acid blends, or other biologically degradable compounds. Such products are designed to break down under appropriate composting conditions within a limited period and to be converted into biomass, carbon dioxide, water, and mineral residues, rather than persistent plastic fragments.

Certification is essential in distinguishing genuine compostable products from ordinary plastic. In Europe, consumers and regulators often rely on visual marks such as the “Seedling” logo or “OK compost” certification issued by recognized testing bodies such as TÜV Austria (EN13432, 2008; TÜV-Austria, 2012). These labels are not merely marketing symbols; they are intended to indicate that the product has been tested according to defined standards. The presence of a certification number enables verification of the producer or license holder in certification databases. This traceability is particularly important because biodegradable plastics cannot be reliably identified by the consumer through visual inspection alone.

In practice, however, the regulatory system relies heavily on truthful labelling, functioning supply chains, and effective enforcement. If conventional plastic bags are printed with misleading phrases such as “bio”, “biodegradable”, “compostable”, or even counterfeit certification marks, many consumers and small retailers may be unable to identify the deception. This creates a loophole in which illegal products can circulate in markets while appearing to comply with environmental law.

3. FAKE BIODEGRADABLE BAGS AS AN ENVIRONMENTAL AND ECONOMIC PROBLEM

The problem of falsified biodegradable bags becomes visible most clearly in composting facilities. Vegetable res-

idues, fruit waste, coffee grounds, garden waste, and other organic materials are decomposed by microorganisms under warm and moist conditions until they form a dark, fertile compost mass. Ideally, only biodegradable material should enter this process.

However, compost operators increasingly observe white, green, and colored plastic fragments in the organic waste stream. These fragments do not decompose together with the organic matter. Instead, they remain visible in the windrows at the end of the composting process. Larger fragments are removed mechanically by screening, but smaller fragments remain in the compost (Binner et al., 2026). According to operators, such plastic contamination has increased despite the Austrian plastic bag ban (Muel-ler, 2026).

This contradiction reveals the central governance failure: legal bans may remove compliant retailers from the conventional plastic market, but they do not automatically eliminate illegal or misleading products distributed through informal or poorly controlled supply chains. In municipal organic waste, bags labelled as biodegradable are often disposed of by consumers in good faith. If the bag is made from conventional polyethylene or polypropylene, it becomes a non-degradable contaminant that is transferred to the environment.

The environmental implications are substantial. Non-biodegradable plastic fragments can remain in compost and eventually enter agricultural soils. Over time, larger pieces may break into smaller particles, contributing to microplastic contamination (Zafiu et al., 2023). Research showed that carelessly disposed plastic carrier bags account for a substantial share of non-degradable impurities in biowaste (Weithmann et al., 2018). Microplastics from packaging residues may affect soil organisms, impair plant growth, influence root development, and compromise the quality of compost as a soil amendment. Unlike natural organic matter, these plastic particles are not fully mineralized under ordinary composting conditions.

The economic consequences are also considerable. Composting companies must invest additional labour, equipment, screening, and quality control to remove plastic impurities. Lightweight plastic fragments may be blown from composting areas, requiring further collection and cleaning to prevent environmental dispersion. If contamination levels exceed quality thresholds, compost may lose value or become unsuitable for certain uses. Thus, the cost of illegal or misleading packaging is shifted from the producers and distributors of the fake bags to waste managers, municipalities, farmers, consumers, and the environment.

Legitimate biodegradable plastics producers are also affected. Companies producing certified compostable bags face higher material costs, certification expenses, and quality assurance requirements. Conventional plastic bags are substantially cheaper to manufacture. If counterfeit producers sell ordinary plastic bags under green claims, they gain an unlawful price advantage. In addition, when consumers or compost operators encounter non-degrading “bio-bags”, they may blame genuine biodegradable producers, thereby damaging trust in certified products and undermining the market for sustainable alternatives.

4. IDENTIFICATION OF GENUINE AND FAKE BIODEGRADABLE BAGS

An important practical challenge is that fake biodegradable bags are often designed to appear environmentally compliant. Some are printed with recycling symbols, green circles, plant motifs, or falsified certification labels.

However, the presence of the word “bio” does not prove biodegradability. In several observed cases, bags with green “bio” labelling also carried the material abbreviation “PEHD” or “HDPE”, indicating that they are made of conventional petroleum-based plastics and are not biodegradable under composting conditions. Other samples displayed TÜV-like certification marks without a valid serial number. Without such a number, the certification cannot be traced to an approved manufacturer or product. In these cases, the symbol functions as a misleading imitation rather than a verifiable quality mark (Figure 1).

Experts can sometimes distinguish suspicious bags through touch and sound. Starch-based compostable bags often feel softer, silkier, or more flexible, whereas conventional polyethylene or polypropylene bags tend to be stiffer and produce a louder rustling sound. However, such sensory impressions are insufficient for legal or scientific certainty. Material analysis is required.

This demonstrates the importance of combining visual inspection, certification verification, and material analysis. While consumers may rely on labels, regulators and waste managers require more robust procedures to identify and document violations. Without such methods, enforcement remains dependent on uncertain visual impressions and inconsistent market supervision.

5. MARKET PATHWAYS AND SUPPLY CHAIN OPACITY

The circulation of fake biodegradable bags is facilitated by opaque supply chains. Small market vendors frequently

obtain bags from informal distributors, private contacts, or local wholesale suppliers. During an investigation in Vienna (Austria) with field observations, market traders often stated that they purchased the bags from acquaintances, foreign contacts, or an unidentified “bag man” who visits markets early in the morning and sells bags directly to stand operators. Many sellers were unable or unwilling to identify the original supplier (Mueller, 2026).

Two categories of supply pathways can be distinguished. The first involves established wholesale businesses supplying food service and market vendors. Such wholesalers may import or purchase plastic bags from changing sources in countries of the European Union or outside, depending on price and availability. The second involves informal distribution through individual intermediaries who sell bags directly to market traders without transparent documentation.

The price difference between certified biodegradable bags and fake alternatives is the major driver. Certified starch-based bags may cost several times more than conventional plastic bags carrying misleading green claims. For small vendors operating with tight margins, low-cost bags are attractive, especially where enforcement risk appears low, or when they are unaware of the offence.

Tracing the origin of such bags is difficult. Some products carry barcodes or product numbers, that are fictitious or are leading to other products. In such circumstances, administrative authorities, certification bodies, and affected companies face serious obstacles when attempting to identify the legally responsible entity.

6. LEGAL AND ENFORCEMENT CHALLENGES

In the Austrian case, the national legal framework prohibits conventional plastic carrier bags and permits only specific biodegradable alternatives. In principle, violations may result in administrative penalties. The competent ministry responsible for waste management may conduct

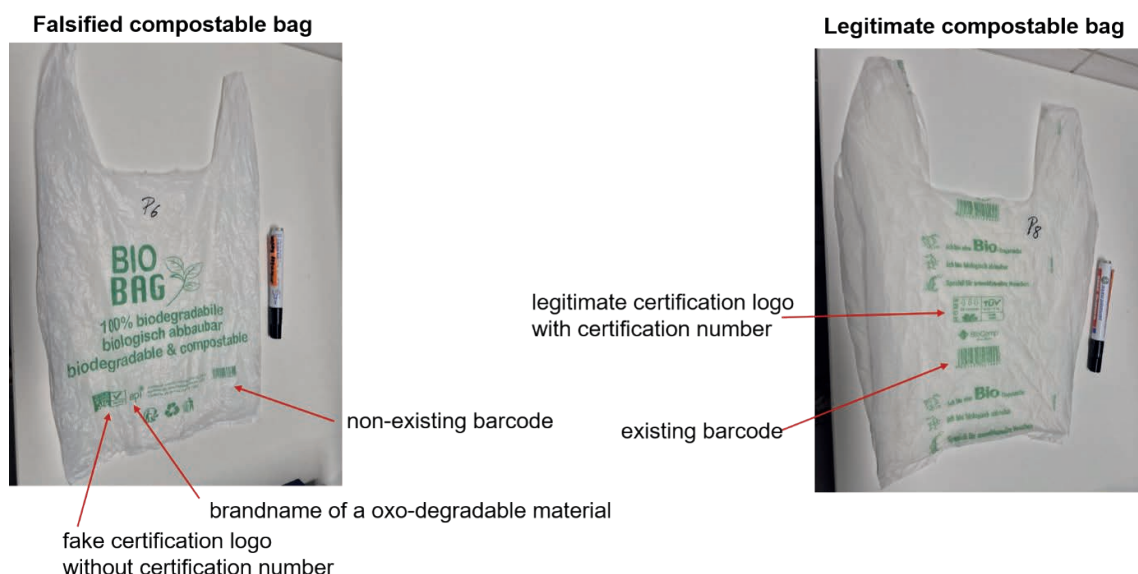


FIGURE 1: Hallmarks of falsified and legitimate compostable bags.

checks following public reports and refer violations to district administrative authorities. Fines may reach several thousand euros. However, enforcement is difficult in practice for several reasons. First, the number of small distribution points is high. Individual market stands, snack bars, food shops, and small wholesalers may all carry suspicious bags. Systematic inspection of every vendor would require substantial administrative resources. Authorities therefore tend to focus on larger distributors or major sources rather than individual stallholders. While this is understandable from an enforcement efficiency perspective, it may allow widespread small-scale circulation to continue.

Second, institutional responsibilities are fragmented. Waste management authorities may consider themselves responsible for the legal prohibition of plastic bags, while local market authorities may be responsible for general market supervision but not specifically for plastic bag compliance. In Vienna, the market authority indicated that it is responsible for many legal rules and ordinances, but not for waste management enforcement or technical bag inspection. Such institutional separation may create regulatory gaps in which products are visible in public markets but not effectively checked by the authority present on site.

Third, the technical distinction between legal and illegal bags is not always obvious. Inspectors require training to recognize certification labels, verify serial numbers, interpret material abbreviations, and identify suspicious claims. Without guidance, enforcement may be inconsistent. The planned development of informational material for market inspectors could therefore improve early detection, but it does not replace the need for laboratory confirmation in disputed cases.

Fourth, legal action by affected private parties is limited by the inability to identify defendants. TÜV Austria can act against misuse of certification marks if the producer or distributor is known. Similarly, legitimate producers may pursue legal claims for unfair competition, misleading labelling, or reputational harm only if the responsible party can be identified. Where the origin of the product remains hidden, enforcement shifts from ordinary civil litigation to investigative work.

Fifth, cross-border supply chains complicate jurisdiction. A bag may be produced in one country, printed in another, sold through a wholesaler in a third, and distributed informally in another country. If documentation is missing or fraudulent, the burden of investigation becomes disproportionate to the value of individual shipments. This creates an attractive environment for low-cost illegal products.

7. CERTIFICATION, CONSUMER TRUST, AND GREENWASHING

The fake biodegradable bag case is not merely a question of illegal plastic distribution; it is also a form of greenwashing. Greenwashing occurs when environmental claims are used to create the impression of sustainability without corresponding environmental performance. In this case, terms such as “bio”, “biodegradable”, “compostable”, or “100% degradable” are used to persuade consumers and

retailers that the product is environmentally responsible and legally compliant.

The damage caused by greenwashing is multi-layered. Consumers are misled into believing they are making an environmentally sound choice. Market vendors may be deceived into purchasing unlawful products. Composting operators receive contamination that consumers assumed to be biodegradable. Legitimate certified producers lose market share to cheaper fraudulent competitors. Certification bodies risk reputational harm if falsified logos circulate. Finally, policymakers may face public skepticism if a legal ban appears ineffective.

Certification systems are therefore central to market integrity. A credible biodegradable bag should display a recognized certification mark, a valid license or serial number, and clear information about the applicable composting conditions.

It is important to distinguish between industrial compostability and home compostability. A product certified for industrial composting may require higher temperatures and controlled conditions that are not present in ordinary garden compost. A product certified for home composting must meet more demanding degradation requirements under lower-temperature conditions. Consumers and vendors often do not understand these differences, which reinforces the need for clear labelling and public education (EN13432, 2008; TÜV-Austria, 2012).

However, certification alone cannot solve the problem if labels can be copied without verification. Enforcement agencies and retailers should therefore treat the absence of a valid certification number as a sign of warning. Public databases maintained by certification bodies can support verification, but only if inspectors and purchasers know how to use them.

8. IMPACTS ON COMPOSTING AND CIRCULAR ECONOMY OBJECTIVES

Composting is a key component of circular economy policy. Organic waste, when properly collected and treated, can be converted into compost and returned to soil as a nutrient-rich amendment. This reduces the need for landfill disposal, supports soil fertility, and closes biological material cycles. However, composting systems depend on input quality. If biowaste is contaminated with conventional plastics, glass, metals, or other impurities, the environmental value of compost is reduced (BMLFUW, 2001).

Fake biodegradable bags directly undermine the circular economy by introducing non-circular materials into biological cycles. Unlike genuine compostable materials, conventional polyethylene and polypropylene do not become part of the biological nutrient loop. Instead, they create persistent residues requiring removal, disposal, or, if not removed, eventual dispersion into soil systems.

This has practical implications for waste management operators. Composting facilities must invest in pre-treatment, screening, manual sorting, windrow monitoring, and post-treatment quality control. Even advanced screening systems may not remove all small plastic fragments. The smaller the fragments become, the harder they are to sep-

arate (Binner et al., 2026). Thus, prevention at the source is more effective than downstream removal.

The issue also reveals a tension in biodegradable plastics policy. Compostable bags can help collect organic waste and may reduce contamination from conventional plastic liners if they are genuinely compostable. However, the market presence of fake bags can lead waste operators to distrust all bags, including certified ones. Some composting facilities may prefer to exclude all plastic-like bags from biowaste streams because the practical burden of distinguishing certified from falsified products is too high. This could weaken the intended role of biodegradable bags in improving biowaste collection.

9. ADDRESSING THE CHALLENGE OF MISLABELLED BIODEGRADABLE BAGS

Several actors play a crucial role in removing falsified compostable plastic bags from the market (Figure 2). At the end of the product lifetime, falsified compostable plastic bags will be disposed of in bio bins and can be observed in composting plants by operators that can collect and report their occurrence. Compost operators process organic waste and need to maintain compost quality and prevent environmental contamination. They bear operational costs

caused by illegal products placed on the market as such products can compromise compost quality, causing the resulting compost to lose its product status and requiring its subsequent disposal. Their experience provides important evidence for regulators because repeated contamination in composting facilities indicates systemic market failure rather than isolated consumer error.

Scientific institutions can contribute with analytical expertise through material characterization, contamination studies, and waste stream analysis. Researchers can distinguish genuine biodegradable polymers from conventional plastics and quantify the share of non-degradable impurities in biowaste. The information generated by these actors can help to identify sources by waste forensic frameworks and aid enforcement, policy evaluation, and public communication.

Companies representing the compliant segment of the biodegradable packaging market are severely harmed by falsified products through unfair price competition and reputational damage. These companies invest large budgets in material design, testing, certification, quality assurance, and intellectual property rights to create a market for compliant products. Their experience demonstrates that environmental regulation can support innovation, but only if enforcement prevents illegal competitors from undermining the market.

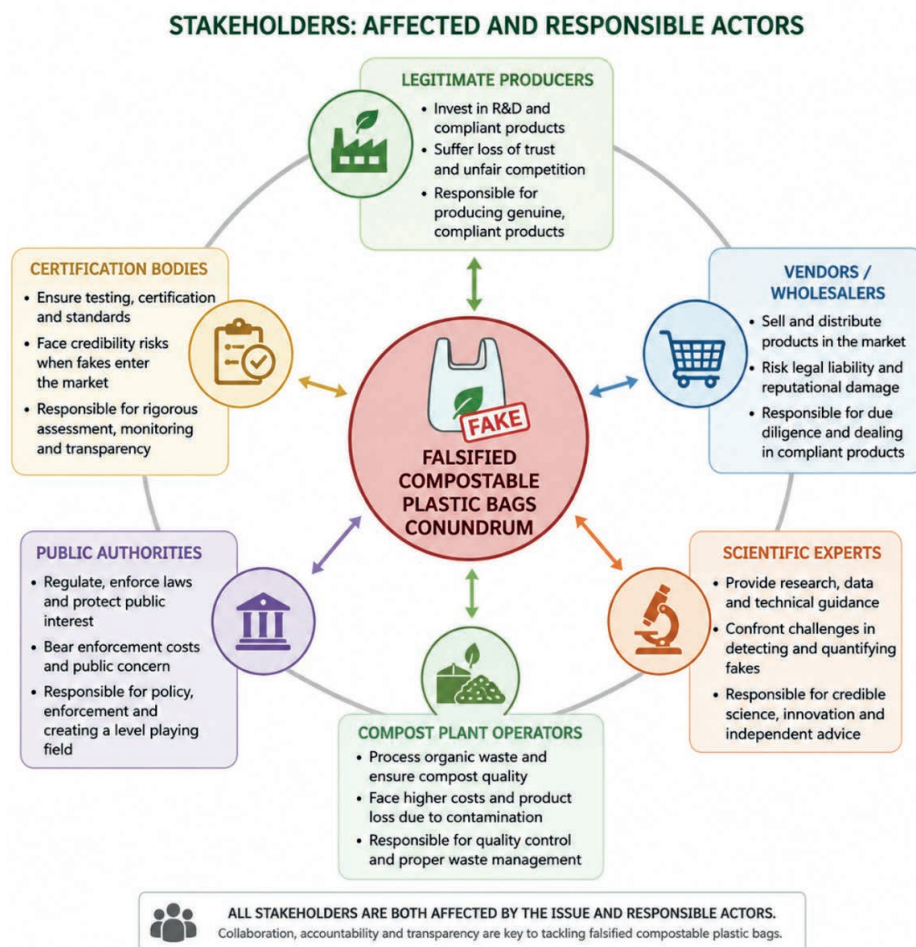


FIGURE 2: Stakeholders affected by and responsible for addressing the falsified compostable plastic bags conundrum.

Certification bodies provide certification, traceability systems and provide labels that allow consumers and authorities to identify compliant products. However, falsified certification logos weaken trust. Certification bodies can maintain public blacklists and pursue legal remedies, but their ability to act depends on identifying the responsible producer or distributor.

An important position is occupied by small vendors and wholesalers that distribute falsified products. Some may knowingly purchase cheap falsified bags, while others may be misled by suppliers and labels. In either case, they form the distribution network through which illegal products reach consumers. Their purchasing decisions are influenced by price, availability, lack of knowledge, and low perceived enforcement risk.

Public authorities are responsible for implementing and enforcing plastic bag regulations. They must balance limited resources, technical complexity, and fragmented institutional competencies. Effective governance requires cooperation between authorities of waste management, market, customs, certification bodies, environmental agencies, and possibly consumer protection.

The Austrian experience is particularly relevant considering broader European policy developments. As the European Union continues to restrict single-use plastics and strengthen circular economy legislation, biodegradable and compostable packaging will remain an important but contested product category. If regulation is not supported by strong verification and enforcement systems, markets may be flooded with misleading products that imitate environmental compliance and lead to a restriction of use of biodegradable products even if they offer in part a solution to environmental problems.

Recent discussions on green claims and environmental product labelling are therefore highly relevant. The misuse of terms such as “biodegradable” and “compostable” illustrates the need for stricter rules on environmental claims. Claims should be specific, evidence-based, verifiable, and linked to recognized standards. Vague green language should not be permitted as a substitute for certification, which is addressed by the EmpCo regulation (COUNCIL, 2024a).

In addition, the case suggests that regulatory requirements towards materials designed for certain End-of-life scenarios (e.g. compostability) should be closely coordinated with waste treatment infrastructure. A bag that is technically compostable under laboratory or industrial conditions may still create problems if it enters facilities that are not designed to process such materials or if it is indistinguishable from falsified bags. Therefore, product regulation, consumer information, and waste management practices must be aligned.

10. CONCLUDING REMARKS

The case of fake biodegradable plastic bags in Austria reveals a fundamental challenge of environmental regulation: a legal ban is only as effective as the enforcement, traceability, and market integrity mechanisms that support it. Austria’s prohibition of conventional plastic carrier bags

created an important regulatory signal and supported the development of legitimate biodegradable alternatives. However, it also created an economic opportunity for falsified products. By printing ordinary polyethylene or polypropylene bags with words such as “bio” or “compostable”, dishonest suppliers can exploit consumer trust, undercut certified producers, and shift environmental and financial costs onto composting facilities and the public.

The problem involves material science, waste management, consumer protection, certification governance, market surveillance, and environmental enforcement. Material analysis can identify fake products, even with portable devices. Publicly accessible certification databases can help to verify compliant products. Waste management facilities can reveal contamination hot spots. However, these tools must be integrated into a coherent enforcement strategy.

A central lesson is that biodegradable packaging requires credible traceability. Environmental claims must be verifiable, and certification marks must be protected against misuse. Products without valid certification numbers, transparent producers, and clear material declarations should not be treated as compliant. At the same time, consumers and small vendors cannot be expected to solve the problem alone. Responsibility should be directed toward the actors who manufacture, import, wholesale, and knowingly distribute misleading products.

If fake biodegradable bags continue to circulate, they will undermine public confidence in compostable materials and weaken circular economy policy. Conversely, if authorities, certification bodies, researchers, legitimate producers, and waste managers cooperate effectively, the Austrian case can become an example of how to close the gap between environmental law and market practice. The objective should not only be to remove illegal bags from markets, but to protect the integrity of organic waste management, ensure fair competition, and prevent persistent plastics from entering waste management facilities under the false promise of biodegradability.

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Grassroots Innovations in Solid Waste Management

FROM GRASSROOTS INVESTIGATION TO TREATY ADVOCACY: THE EVOLUTION OF PLASTIC WASTE TRADE ACTIVISM IN MALAYSIA

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1. INTRODUCTION

"The river is on fire."

My sister Noor tosses her words in the air, yee sang-like, nonchalance in tone, anxiety in the crease of her brow, eyes, weary, darting across the scene below. We perch on the edge of a longkang, monsoon drain, peering over the edge, our house around the corner. We wait for Maghrib to beckon our return, but we don't need Azan prayer calls blaring from speakers to know that evening creeps forth.

Amber retreating into charcoal, a sunset choked by smog. Black patches scrape the air. The bats are coming out. We are roadside, but traffic is distant now, rush hour discord diffused into background buzz.

Noor points at the river again.

Heaps of refuse clogs up a drainpipe-dirty containers, contaminated canisters of Allah-knows-what, stained fabrics, globular clusters of close-to-bursting plastic bags, an orgy of polyethylene and PVC, an accumulation of foam polystyrene, a dumpsite dotted with splotches of little flames here and there. It can be pretty dreary.

You can travel the world through a Malaysian dumpsite's unwanted-British food boxes, Canadian agricultural film, German tubing. Nowhere in the peninsula has there ever been a Walmart, but their old smiley face logo, American, flashes at us menacingly from crinkled plastic bags, snagged onto soda cans. Every day, after school walks weave themselves through, along the monsoon drains, where plastic waste ingrains itself into topographies of home, geographies of discard, discard from within the country, discard from outside, through the plastic waste trade and the country's imports.

In 2018, this practice saw a shift, when China, formerly the largest importer, implemented its National Sword Policy (NSP), a sweeping ban on plastic waste imports. Many Global North countries rerouted their exports of plastic scraps to Global South locations, feeding a dynamic of uneven waste processing infrastructure and capacity. Consequently, Malaysia became the world's largest importer of plastic waste (Wang et al, 2022). Between January and July 2018, Malaysia imported 456,000 tonnes of plastic waste compared with 316,000 tonnes imported in all of

the prior year signalling that though the import was a normative activity for Malaysia, the frequency and volume increase in the wake of NSP, was not (Latiff and Harris, 2019; Otsuka & Skrobe, 2019). The influx included contaminated shipments that could not be legally or technically recycled. The Malaysian government returned 254 containers containing 5,512 tonnes of plastic waste back to their country of origin (C4 Center, 2021). This surge contributed to open dumping, open burning, and illegal processing near communities such as Jenjarom, Klang, and Sungai Peetani in Malaysia (Greenpeace Malaysia, 2018).

The impacts of such a surge have been significant; large quantities of plastic waste have entered communities as unrecyclable residues, with 17,000 tonnes of it unloaded onto Jenjarom, a small town of around 30,000 residents (Tan 2019; Zulkefli, 2019). The impacts have been deleterious on health and the environment; sampling at Malaysian plastic waste processing and disposal sites found heavy metals and brominated flame retardants in soil and ash; surface waters near or downstream from some sites also contained solid waste and chemical contamination consistent with plastic dumping and processing activities; and the open burning as attempts to rid the waste accumulation sites rendered carcinogenic pollutants airborne (C4 Center, 2021; Greenpeace Research Laboratories, 2020; Oanh et al, 2025). As the imports continue to stream into the country, so do the health and environmental impacts of accumulating plastic waste. Even as the Malaysian government introduces interventions such as 2025's SIRIM and MITI permit approval for plastic waste imports, 26.4% of the country's plastic waste continues to be mismanaged (Bernama, 2026).

Though the government's initial enforcement directly following the increase in plastic waste imports was lauded, imports remain substantial with 478, 092 tonnes in 2020, a 43% increase from 2019, and 406,000 tonnes in 2023 (C4 Center, 2021; World Bank, 2025). 2024 data shows that the imports continue to play a significant role in Malaysia's plastic waste flows, with the country importing 332,080 tonnes of waste, parings, and scraps of polymers of ethylene in that year alone (World Bank, n.d.). But how have

people engaged and responded? People don't sit idly while plastic waste accumulates in their homes, choking air and polluting water supplies. Some take up activism.

How has plastic waste trade activism in Malaysia evolved since China implemented its National Sword restrictions in 2018? How have activists' repertoires, targets and relationships with state and non-state actors changed during this period?

2. CONCEPTUALIZING PLASTIC WASTE TRADE ACTIVISM

Responses to plastic waste and environmental activism, which plastic waste trade activism falls under, are not to be conflated with each other. Distinguishing the two is important for several reasons; the former, while there is overlap with the latter, focuses primarily on plastic waste as a pollutant or resource that is not necessarily tethered to notions of environmental justice nor systems challenging. For example, in 2025, a community plastic waste clean-up organized by the Global Environment Centre and the Petaling Jaya (a prominent Malaysian city) City Council, hosted 300 volunteers in picking up over 300 kilograms of waste. The focus of the initiative was on beauty and aesthetic. Activism, on the other hand, is grounded in intentional efforts to influence other actors, public opinion, policy, corporate conduct, or social arrangements (Stern, 2000). Activism itself is not a monolithic, static engagement, and can take multiple forms.

Conceptualizations generally characterize activism as intentional action directed toward achieving or resisting social, political, institutional, or cultural change (Corning & Myers, 2002; della Porta & Diani, 2020). Yes, environmental activism can be taken individually, but it frequently operates through collective identities, shared purposes, and claims directed towards actors they understand to be responsible for a particular harm (Snow et al., 2004; Tarrow, 2011; Tilly & Wood, 2013). Environmental activism can consequently be distinguished from private environmental behaviour and non-activist public participation by its explicit effort to influence collective decisions, organizations, policies, or broader social practices (Dono et al., 2010; Stern, 2000). In other words, there is an intent for systemic, social change and there is an articulation or expression of that intent.

In the Malaysian context, this conflation can sometimes occur with culturally rooted practices. A culturally specific concept within the Malaysian, Indonesian, and Singaporean contexts is the concept of 'gotong-royong', or 'collective community action', sometimes mutual aid and often in the contemporary sense, a community cleanup. The term, sometimes associated with activism, is etymologically Javanese, whereby gotong translates to 'to carry' and 'royong' meaning 'together', denoting communal mutual assistance practiced across the region (Yuhertiana et al., 2022). Historically, gotong-royong has deep cultural roots in Javanese communities, including diaspora, whereby post-independence state campaigns had co-opted its resonance with citizens for nationalist social engineering (Suwignyo, 2019). This co-optation is not intended to challenge the waste regimes that developed in the post-inde-

pendence landscape, but rather it repositions a pre-existing culturally ingrained community practice towards bolstering said waste regime. In this sense, although it is a collective action in response to waste, participation within the logistics of gotong-royong do not themselves constitute activism. Gotong-royong should not automatically be classified either as activism or as depoliticized community service. As an example, gotong-royong's classification depends on how organizers frame the activity, whether responsibility is assigned, and whether participants expressly articulate demands extending beyond removal of visible waste.

There is a difference and sometimes, disconnect, between 'doing activism' and 'being an activist' that challenges the assumption that collective action depends on alignment between personal and collective identity (Bobel, 2007). Importantly, many individuals and communities engaging in systems-change may not identify as activists. Incorporating this consideration, activism for the scope of this paper, concerns actions undertaken with the intent of systemic change, that an action is classified as 'activism' when it meets these criteria. With this logic, gotong-royong, a common community response to plastic waste accumulation, may not necessarily be considered as activism, unless it overlaps with expressed intent to systemic change. The systemic change in question may be brought about by an endogenous force, that is from within a system, or pressured from outside, that is, exogenous. Due to the fluid and heterogeneous nature of activism, and literature's proclivity of talking or writing about activism without explicitly defining it, I adopt Mathias' framing that argues activists are defined not by motion but by motive (Cabrera et. al., 2017; Mathias, 2026). Here then, motive is explicitly expressed as being aligned with systemic change. This is also adopted to avoid exonymic tendencies by researchers.

There are many forms activism can take. Social movement activism specifically involves collective, sustained, and organized extra-institutional efforts to bring about or resist change (Coley & Schachle-Gordon., 2025). Thomas and McGarty distinguish benevolent support like charitable giving from activist support like socio-political action, as qualitatively different forms of behaviour rather than degrees of the same behaviour, arguing the form of action is more descriptive than the person performing it (2017). They acknowledge that categories of people are multifaceted and fuzzy, whereas behaviours are specific, making action-based classification more precise. Neumayer and Svensson offer a typology of activism that argues that one individual or group can adopt different forms of activist participation (2016). Their activist types are neither static nor fixed and may differ depending on the political demand for which activists are fighting.

This is the way that plastic waste trade activism has unfurled within the Malaysian context, with community members developing into self-proclaimed activist roles, and collaborations with NGOs, government and corporate actors, in different phases of flux. How does this summation come into form? Through the examined corpus of publicly available reports on activities targeting the Malaysian plastic waste trade.

3. THE EXAMINED TEXTS

With this operational understanding of what constitutes activism, the body of text, or sometimes referred to as ‘corpus’, for examining plastic waste trade activism is constructed. Modelling after Bowen (2009), Braun and Clarke (2006), and Benford & Snow (2000), I combine qualitative document analysis and social movement framings to examine a purposefully selected corpus of materials, primarily news articles, on Malaysian plastic waste activism. Initial codes were informed by collective-action framing theory, identifying actors, type of actors, actions, type of actions, intended target of actions, and responses of targets. Analyses of selected Malaysian activist responses to plastic waste were carried out on a timeframe of 2018, the year that China implemented NSP, to the current year as of this writing, 2006. The purpose was to plot out geogra-

phies of plastic waste activism in a post-NSP landscape. Following Bowen (2009), publicly available documents were treated as sources through which activist organizations represent problems, strategies, objectives, and forms of action. Search engines on Google News, and Malaysian news platforms were utilized with variations of ‘activism’, ‘plastic waste’, ‘plastic waste trade’, ‘plastic import’, ‘protest’ and the Bahasa/Malay language counterparts, ‘plastik’, ‘sisa-sia plastik’, ‘protes’, entered as search inquiries. Bahasa, being my native tongue, renders the task straightforward, and though I reviewed translations through Google Translate, the results were not as accurate nor relevant as that of a native speaker’s. Figure 1 distills the aforementioned information into an accessible flowchart of the data sourcing and analysis process.

The same searches were also carried out in major NGOs such as Sahabat Alam Malaysia and Greenpeace Malay-

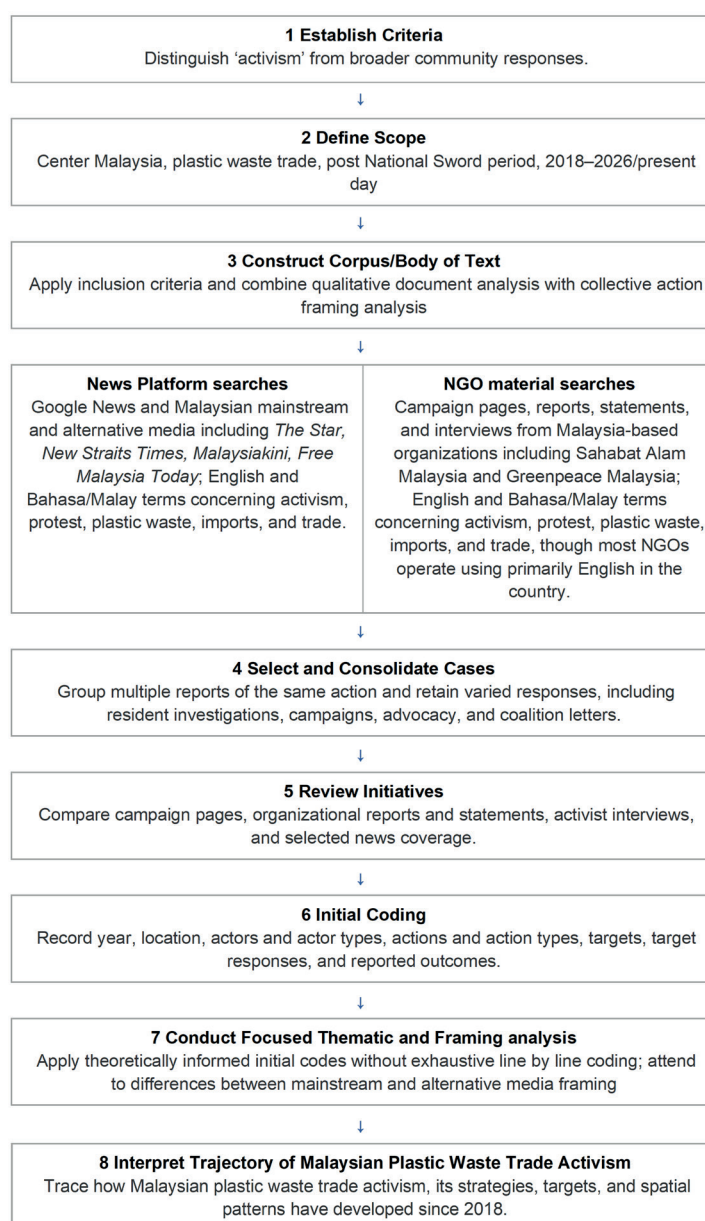


FIGURE 1: Method for examining Malaysian plastic waste trade activism.

sia. Multiple reports of an action were grouped together for ease of analysis, and a variation in activist responses were noted, such as the resident-led investigation carried out by Jnejarom, Klang Valley community members, and coalition letters addressing the Malaysian government in plastic waste advocacy. For each initiative, campaign pages, organizational reports or statements, activist interviews, and selected news coverage were reviewed. A structured extraction table was used to summarize each initiative's year, activities, types of activities, targets, and responses. I did not employ exhaustive line-by-line coding, but rather than comprehensive claims about Malaysian plastic waste trade activism, I seek to trace the trajectory and development of the aforementioned activism as it continues to unfold in real time, as Malaysia is party to the international Basel Convention currently attempting to forge a global plastics treaty.

Keeping in mind, prior framing analysis research on Malaysian media framing of waste has shown slight differences in information source and conflict-driven framing of the plastic waste crisis between mainstream news outlets and alternative platforms that stress just reporting in the face of biased state-controlled media (Ong and Diong, 2023). Given this slight difference, materials were drawn from across mainstream and alternative media.

My primarily conversational precedent is Dauvergne and Islam's examination of anti-plastics activism in Indonesia and Malaysia (2023). They combine a review of existing literature with interviews and less structured conversations with activists. Their analysis discusses the principal activities activists undertake, including education, recycling initiatives, clean-ups, advocacy for waste workers, lobbying, and campaigning within the backdrop of political constraints, but my focus differs in its narrower scope, that is, plastic waste trade activism and not the broader plastics activism that they explore. I also examined how grassroots participation changed across these dimensions, whether affected residents-initiated actions, produced evidence, formulated demands, or remained publicly visible as campaigns expanded through NGO, governmental, and transnational networks. Therein lies my scholarly contribution here.

4. ANALYSIS-PHASES OF MALAYSIAN PLASTIC WASTE TRADE ACTIVISM

Amidst the sea of information available, of different actors ebbing and flowing in their plastic waste trade-targeted actions, it can sometimes seem sporadic and reactionary. I rebuke this and assert that we can break down the events of activism around plastic waste into patterns of actors and actions. I propose four phases to better understand responses and engagement with the Malaysian plastic waste trade. Phases were derived by comparing changes across three dimensions-activist repertoires, targets, and scale. The phases do not imply that Malaysian activism developed in a linear or uniform manner, nor that one repertoire disappeared when another emerged. The key purpose here is to outline how activists engage in different forms of not just organizing, but solidarity-building and how their

actions, and targets of their actions are framed and articulated to different audiences. This information is built from publicly available data, that is, news reports and grey literature. In activist spheres, not every action is reported in news publications, whether oppositional or backed by the ruling party in the case of Malaysia, that would be Malaysiakini, Free Malaysia Today for the former and News Straits Times and The Star for the latter. This constitutes a limitation as not all forms of activism are reported, and they can be curated in ways that reduce their visibility (Wong, 2026). To slightly remedy this, I included NGO materials from Sahabat Alam Malaysia and Greenpeace Malaysia as they have worked together and with regards to a contested disposal site, publicly highlighted how Malaysian environmental reporting has contained inconsistencies (Sahabat Alam Malaysia, 2020). This approach aligns with scholarly recommendations aimed at addressing the biases and limitations of event-based and activism reporting in newspaper research (Earl et. al, 2024; Demarest & Langer, 2022)

The phases identified are:

- **Phase I: 2018-2020**
Frontline Resistance and Evidentiary Activism

The first phase emerged after China's National Sword restrictions redirected plastic waste shipments toward Southeast Asia as per the inclusion criteria. Malaysia's reported plastic waste imports rose from 316,600 tonnes in all of 2017 from its largest importers alone, to approximately 456,000 tonnes between January and July 2018; with other estimates covering a longer portion of 2018 are higher because they use different periods and datasets (Gunia, 2019; Ananthalakshmi & Chow, 2019). Malaysia, flooded with plastic waste, to send back some scrap to source. Reuters.). In Jenjarom and the surrounding Kuala Langat district of Selangor, close to Port Klang, residents encountered smoke, chemical odours, polluted waterways and nighttime burning as unlicensed recycling operations proliferated.

In this phase, activists mainly took the form of residents/community groups bringing light to the matter of illegal plastic waste facilities cropping up in the Klang Valley area. Chemist and community organizer Pua Lay Peng became a leading figure in the movement (Danowitz, 2023). She recruited other neighbours and residents in surrounding areas in tracking, monitoring, and investigating plastic waste reprocessing sites as they surfaced. Importantly, the racial dynamics of the plastic waste accumulation locations are predominantly in Chinese neighbourhoods.

Racial dynamics are an important, but often underlooked facet of plastic waste flows in the Malaysian context. This is despite a body of literature that traces the lineage of racial urban planning from British Empire land and waste management to modern nation state racially informed organizations of neighbourhoods. Jenjarom, where Peng is from, was historically used as a 'new village' or British concentration camp, as part of the Empire's Briggs Plan in 1951 (Hisham & Ling, 2025). A historically agricultural town nestled between rivers Sungai Langat and Sungai Semenyih, 54 kilometres from the nation's capital, Jenjarom's relegation as one of the 'new villages' saw the British corral predomi-

nantly Chinese residents in the Malay Peninsula, accusing them of being communists, starving, shooting at them in the process. This initiative, Malhi argues, reconstituted the resulting independent Malaysia as a racial state (2021).

That Jenjarom's Chinese majority makeup is not lost on the township's plastic waste organizers. Pua Lay Peng's parents were among the corralled in Jenjarom. Shared history informs how the activists steadily built their ranks, seeking out others in nearby ethnic Chinese townships that were also plagued by plastic fires. "“This (Jenjarom) is a nice Chinese village. We must have seemed perfect for them,” Pua has said of Jenjarom's designation as a plastic waste accumulation site (Winn, 2019). Along with other impacted residents, Pua then brought their evidence to the authorities, handing over binders of paper filled up with GPS coordinates and damning pictures.

Environmental NGOs like Greenpeace Malaysia would establish waste flow patterns through co-investigating with community organizers like Pua. Their action type combined community investigation, citizen monitoring, public complaints, documentation and transnational advocacy. Residents photographed and filmed burning, used drones to locate facilities, identified foreign packaging, contacted journalists and government officials, circulated evidence through social media, and worked with Greenpeace Malaysia on field investigations particularly in Jenjarom, Klang and Ipoh. Greenpeace Malaysia and community activists subsequently launched The Recycling Myth on 27 November 2018 and delivered it to Selangor's 56 state assembly representatives. Pua also travelled to confront one of the exporting countries, New Zealand, with evidence of how its

waste was being handled in Malaysia (Greenpeace Malaysia, 2018, 2019; Heng, 2021). The primary targets of activist actions were illegal factory operators, local and state regulators, Malaysia's federal government and waste-exporting countries.

The initial target response was substantial but incomplete. Malaysian authorities imposed a temporary freeze on plastic waste import permits in July 2018, announced an intended three-year phase-out of imports, raised import requirements, and closed approximately 30-33 illegal factories around Jenjarom. Despite this initially strong response, the proposed complete phase-out was not ultimately implemented, and imports continued (Parker, 2018; Rosengren & Pyzyk, 2018). The reported local outcome was a reduction in visible illegal operations and improved air conditions in Jenjarom, but through a follow-up, roughly 17,000 tonnes of abandoned waste reportedly remained, while activists documented dumping surfacing into Teluk Gong, Pulau Indah and as far north as Ipoh and Sungai Petani (C4 Center, 2021; Heng, 2019; The Malaysian Insight, 2019). A pattern in response was established, as Peng puts it “Those illegal factories, they would multiply by two times, three times. They can copy and paste so fast!” but the exact locations of where the factories would resurface remained difficult to predict. Figure 2 shows an accumulation site in Ipoh in the state of Perak, 234 kilometres north of Jenjarom. Figure 3 shows these locations on the Malay Peninsula.

The federal government also announced in May 2019 that it would return as much as 3,000 tonnes of contaminated waste to exporting countries and, by January 2020,



FIGURE 2: Plastic waste accumulation in Ipoh, Malaysia. Note. Photograph courtesy of Greenpeace. Copyright (2018) by Greenpeace. Reproduced with permission.



FIGURE 3: Locations of selected plastic waste accumulation sites in Malaysia. Note. The map identifies Jenjarom, Klang, Ipoh, and Sungai Petani in Malaysia. Map created by the author using Natural Earth raster administrative-boundary data.

reported sending 150 containers to 13 countries (Associated Press, 2020; Reuters, 2019). These developments are consistent with Chen et al.'s (2021) finding that Malaysia's plastic crisis involved fragmented governance, inadequate management capacity and weak enforcement, and with Ong and Diong's (2023) finding that post-National Sword Malaysian news frequently framed imported plastic as an international controversy. This framing sidelines or perhaps even occludes Malaysia's dual role as a leading producer of plastics and importer of plastic waste. Dauvergne and Islam (2023) identify the Jenjarom grassroots activism campaign as an important example of intensifying Malaysian anti-plastics activism, while cautioning that policy reform and plant closures do not by themselves demonstrate lasting control over plastic production, trade or regulatory evasion.

- **Phase II: 2019-2022**

- **Geographic Expansion and Widening Targets**

In the second phase, activists expanded their campaigns beyond Jenjarom and beyond the immediate target of illegal factory closure. This tracks with the revelation that plastic waste reprocessing facilities resurfaced in other places on the peninsular after being shut down. They would move. In Sungai Petani, Kedah, Ipoh, north of Jenjarom and Port Klang, where ensuing plastic waste accumulation sites surfaced, the organization, Persatuan Tindakan Alam Sekitar Sungai Petani (PTAS), organized residents concerned about factory emissions, fires from plastic waste incineration, and illegal dumping. Many of

the plastic waste processing facilities, accumulation, and incineration sites like Jenjarom and Sungai Petani, sited in close proximity with palm oil plantations, another adopted relic of the British Empire, monoculture farming, that has since been ballooned to national identity association (Liu, Ganesan, and Smith, 2020). Its action types included community health monitoring, petitions, meetings with officials and public demonstrations. An August 2019 protest reportedly involved approximately 150 participants, while about 250 people joined a peaceful rally at Kedah Halal Park on 21 September 2019 (C4 Center, 2021). PTAS associated periods of intense plastic burning with increased respiratory illness and hospital use, although its figures were community-produced rather than a controlled epidemiological study (Sahabat Alam Malaysia, 2021). Greenpeace Malaysia simultaneously documented new sites and fires in Sungai Petani and Pulau Indah, while its 2020 Recycling Myth 2.0 investigation (a follow-up to their 2018 publication) reported metals, brominated flame retardants and other contaminants in material sampled from burned or abandoned waste sites (Heng, 2019; Greenpeace Malaysia, 2020). The plastic issue consequently broadened from imported waste alone to include toxic burning, health, factory displacement, abandoned residues and proposed waste-to-energy incineration. Targets now included municipal and state regulators in Kedah and Selangor, federal permit authorities and advocates of incineration. The concern also expanded beyond the binary of legal/illegality into concerns over impacts of hosting the plastic waste reprocessing sites.

Activists also targeted the infrastructure and corporations enabling waste movements, a shift towards upstream accountability. Beginning in 2021, Sahabat Alam Malaysia (Friends of the Earth Malaysia), Greenpeace, the Basel Action Network, GAIA and dozens of international organizations wrote to nine major shipping companies, asking them to stop transporting plastic waste from richer OECD economies to countries with weaker processing and regulatory capacity. In June 2022, the Malaysia Stop Waste Trade Coalition directly requested that shipping company Maersk disclose plastic waste volumes and stop shipments into Malaysia (Sahabat Alam Malaysia, 2022). Maersk's eventual public response was this: in February 2023, it stated that it would not accept HS 3915 plastic waste imports into Malaysian ports and that this restriction had been in place since 26 October 2019 (A.P. Moller–Maersk, 2023).

Government enforcement also became more closely connected to international coordinated efforts, primarily the Basel Convention's Plastic Waste Amendments, effective in 2021. Malaysia had sought to return a US-origin container for violating the new rules in March 2021, but upon closer inspection, allowed it to enter, with the following month finding Malaysia returned 267 illicit containers since 2019, with another 81 being processed at the time (Reuters, 2021a; Chu & Ananthalakshmi, 2021). The reported outcomes of this phase were thus geographic mobilization, stronger community networks, greater scrutiny of shipping companies, expanded use of Basel rules and hundreds of returned containers, not the demanded termination of plastic waste imports. Research on the changing geography of waste trade supports the interpretation that the National Sword Policy redistributed, rather than eliminated trade, while receiving states continued to face regulatory, infrastructural and enforcement constraints (Wahab & Lim, 2022; Wang et al., 2022).

• **Phase III: 2022-2025**

Coalition-Building And Plastics-Treaty Politics

The third phase shifted the principal problem definition from mismanaged imported waste toward the entire plastic life cycle, from manufacturing to consumption to disposal. Key actors included the Malaysia Stop Waste Trade Coalition, Sahabat Alam Malaysia, the Consumers' Association of Penang, C4 Center, Greenpeace Malaysia, Zero Waste Malaysia, Environmental Protection Society Malaysia, Zero Waste Sabah and international Break Free From Plastic and Friends of the Earth networks. Their action types consisted of coalition formation, policy drafts, public education, exhibitions, opinion surveys, ministerial dialogues, international treaty interventions and advocacy against production growth and incineration. These organizations targeted plastic and petrochemical producers, consumer-goods companies, waste-to-energy proponents, Malaysian ministries and Malaysia's delegation to the UN Global Plastics Treaty negotiations.

Activists argued that cleanups and recycling could not keep pace with production. They demanded mandatory production reductions, removal of hazardous chemicals, extended producer responsibility, product transparency and accessible reuse systems. For example, in October

2024, a coalition of activists and NGOs organized a three-day Journey to End Plastic Pollution at Pavilion Bukit Jalil in Kuala Lumpur, using art, film, storytelling and a "People or Plastic?" discussion involving then-environment minister Nik Nazmi Nik Ahmad, human-rights representative Edmund Bon and SAM researcher Mageswari Sangaralingam (Consumers' Association of Penang, 2024; Sahabat Alam Malaysia, 2024). Greenpeace had also published Malaysian polling before INC-4 indicating that 87% of respondents supported reducing plastic production, turning public-opinion evidence into a lobbying resource (Greenpeace Malaysia, 2024).

The government response in this phase was dialogic but internally contradictory. Take Nik Nazmi for instance, who engaged with the 2024 event, but when questioned over the implementation of Malaysia Plastics Sustainability Roadmap 2021-2030 (MPSR), invoked the focal responsibility to individual Malaysian consumers for the increase in plastic packaging during the COVID-19 pandemic (Bernama, 2024). On the international stage, Malaysia participated in plastics treaty negotiations but generally favoured downstream waste management and national discretion over binding global production limits. This placed it closer to the lower-ambition group than to the parties demanding mandatory production caps, despite Malaysia's earlier diplomatic rhetoric against foreign dumping (Lee, 2025; Gomes & Tan, 2025).

From the articles analysed, reported outcomes include a durable multi-organization coalition, direct ministerial engagement as in the case of Nik Nazmi, greater public visibility for production reduction and human rights-framed arguments, as well as the delivery of a memorandum supported initially by more than 100-130 Malaysian organizations. No global treaty was concluded at Busan in 2024 or Geneva in 2025, however, and Malaysia did not adopt the coalition's proposed 75% production reduction. This mixed result accords with Dauvergne and Islam's (2023) conclusion that Malaysian activism is intensifying and can energize communities and pressure governments, while entrenched petrochemical and corporate power limits systemic change. It also reflects research showing that Malaysia simultaneously faces imported waste, high domestic plastic consumption, weak waste-management, recycling infrastructure capacity and a large plastics-manufacturing sector (Chen et al., 2021; Goh et al., 2025).

• **Phase IV: 2025-Present**

Implementation Watchdog Work And Organized Reuse

The fourth phase (so far, as this is an ongoing development) combined continued treaty advocacy with closer monitoring of enforcement and experiments in reuse. Actors included Greenpeace Malaysia, SAM, CAP, C4 Centre, Zero Waste Malaysia, Zero Waste Sabah, Environmental Protection Society Malaysia, genREuse volunteers, participating restaurants, public-health researchers and affected residents. Their action types included parliamentary lobbying, petitions, legal and trade monitoring, community-based research, and criticism of government negotiating positions. On 23 July 2025, coalition representatives delivered their plastics treaty memorandum to MPs in Par-

liament, asking them to convey its demands to the prime minister and responsible ministers before INC-5.2 in Geneva (C4 Centre, 2025; Sahabat Alam Malaysia, 2025a). Greenpeace's genREuse initiative recruited volunteers and restaurants to trial reusable dining systems, shifting part of the movement from opposition toward demonstration of alternative infrastructure. Meanwhile, in an overlap with prior phases, advocates continued targeting imported plastic, misleading recycling narratives, single-use food-service material, the petrochemical lobby and Malaysia's opposition to internationally binding production limits. The locations of action therefore encompassed a more varied range of scales, from local restaurants and affected communities to Parliament, federal ministries and the Geneva negotiating venue for ongoing plastics treaty formation.

The most concrete governmental action was the import regime effective 1 July 2025. The Malaysian government appointed SIRIM to assess and issue Certificate of Approvals for HS 3915 imports, partly to standardize a part of the plastic waste flow process. This restricted eligibility primarily to Basel Convention parties or countries covered by qualifying agreements, and introduced pre-approval, inspection and contamination requirements. Importantly, plastic waste imports from the United States are excluded for they are not part of the convention and continue to resist binding plastics proposals. Importantly, the US Census-based data shows continuing exports to Malaysia, and Basel Action Network recorded 1.6 million kg in July 2026, describing those imports as prohibited by Malaysia despite the SIRIM move, highlighting an enforcement or reporting gap (Basel Action Network, 2026). It was not a comprehensive ban on plastic waste imports from every country, but a noteworthy step (Ministry of Investment, Trade and Industry, 2025).

In response, Sahabat Alam Malaysia, and allied organizations welcomed the restriction but demanded transparent enforcement, stronger customs procedures, anti-corruption measures and prosecution of traffickers, showing the movement's transition into an implementation-watchdog role (Sahabat Alam Malaysia, 2025b). At INC-5.2, the Malaysian delegation still did not support the binding production cuts sought by activists, submitting no text under Article 6 on plastic production reductions, and the talks ended without agreement. Activists lauded an increase in a crackdown on plastic waste imports but expressed frustration at the failure of upstream treaty ambitions (Greenpeace Malaysia, 2025; King, 2025). In February 2026, Malaysia completely prohibited e-waste imports and considered, but had not yet adopted, a temporary plastic waste import moratorium, amid corruption investigations involving senior environmental officials and licensing for reprocessing facilities (Latiff, 2026). The reported outcomes of this phase are thus stronger import controls, exclusion of some exporting countries, increased parliamentary and media scrutiny, continued reuse experimentation and renewed attention to pollution around recycling facilities. Evidence of national reductions in plastic production, consumption or pollution has not yet been reported, making this an ongoing rather than completed phase (Table 1).

What do these phases mean for activist responses to Malaysian plastic waste trade?

Plastic Waste Trade Activism as Dynamic

The adaptiveness of Malaysian plastic waste trade activism must be lauded. While not romanticizing the circumstances, it is noteworthy that everyday citizens have formed coalitions with other actors and other activists, depending on their goals and targets. It may seem simple to offer that plastic waste trade activism changes because the plastic waste trade itself changes. The reality, from the information gathered and analysed, is that it changes in a way that a simple chronology of activism belies its dynamism-activists are not merely becoming more sophisticated over time, but rather, their repertoires change because their target of contestation moves. Like the closing-down-then-resurfacing-elsewhere movements of the plastic waste reprocessing facilities, activists are consequently expanding their networks and targets, scaling, shifting, moving as their targets move.

Plastic Waste Trade Activism as Expanding into Upstream Accountability

Another interesting and important note is the shift, or expansion, of targets towards upstream actors. Targeting illegal operators expands into exporting countries (the UK, US, Canada) and the federal government's waste governance instruments, towards shipping companies (Maersk), towards transboundary treaty negotiations (the Basel Convention). Documented in Greenpeace's 2019 recorded investigation show initial concerns of 'someone is illegally burning plastic waste near me'. Eventually, the problem becomes focused on 'why is so much plastic being produced or traded in the first place?' By Phase III, activists are making whole life cycle demands on production caps, chemicals, reuse, and petrochemical influence, where Phase IV adds monitoring of implementation and practical alternatives. Activists highlight their fatigue with mainstream recycling narratives that ignore final accumulation sites, the communities they affect, and larger systems of export/import and producer accountability. "For all these years developed countries relied on China to recycle their plastic, so they didn't care," activist, chemist, and Jenjarom resident Pua is quoted as saying "Now China is trying to take care of its pollution problem, so the burden is shifting to us. But recycling is a myth. The root cause of the problem is we are too dependent on plastic."

Plastic Waste Trade Activism and Social Dynamics

The story of plastic waste trade and its impacts in Malaysia is a story of race, ethnicity, class, ingrained dynamics that cannot be ignored when considering solutions. From Jenjarom's predominant Chinese make-up bearing the brunt of initial plastic waste accumulation to the informal waste labourers working for around 10 dollars a day, who are primarily Bangladeshi straddling different immigration categories, who have continuously faced stigma not just as waste labourers but as Bangladeshi residents (Bengali, 2018; Reza & Islam, 2026). They are racialized in the Malaysian context, often facing discrimination from the state and society. Their labour in the plastic waste repro-

TABLE 1: Phases of Malaysian plastic waste trade activism after implementation of China's 2018 national sword policy.

Years	Phase	Activist	Organizing Actions	Target of Actions
2018–2020	Frontline resistance and evidentiary activism	residents/community group, environmental NGO	Community investigations, drone mapping, complaints, journalist visits, exporter-country advocacy and chemical sampling.	Illegal operators; Malaysian authorities; exporting states
2019–2022	Scaling and target expansion	residents/community group, environmental NGO, multi actor coalition	Monitoring displaced factories, waste-colonialism framing, brand audits, anti-incineration organising and shipping-company pressure.	Exporters; brands; incineration advocates; shipping companies
2022–2025	Coalition and treaty politics	residents/community group, environmental NGO, multi actor coalition	Whole-life-cycle demands, production caps, chemical controls, reuse and scrutiny of petrochemical influence.	Malaysian negotiators; plastic and petrochemical producers; UN treaty process
2025–Present	Implementation watchdog and practical reuse	residents/community group, environmental NGO, multi actor coalition	Monitoring import-rule enforcement, challenging Malaysia's treaty position in the Basel Convention, piloting reuse and producing community-health evidence.	Enforcement agencies; treaty negotiators; restaurants and consumers

cessing facilities is mentioned in some articles and reports but not expanded upon. Interviews tended to focus on the owners and managers of the facilities with interviews focusing primarily on their employers and owners of businesses near the plastic waste accumulation sites. Despite evidence that migrants perform low-paid manual labour in Malaysia's plastic waste reprocessing economy, post-2018 waste-trade activism has rarely centred migrant workers as political actors or articulated demands concerning wages, immigration status, occupational exposure or labour rights (Bengali, 2018). Similarly, activism in historically racialized settlements such as Jenjarom and its Chinese residents, has principally framed imported waste through community health, illegality, governmental failure and waste colonialism rather than through an explicit analysis of race. Race and labour consequently constitute significant silences within the activism's publicly reported framing.

5. CONCLUSIONS

I love my home, Malaysia and it is frustrating to navigate its relationship to the plastic waste trade. Plastic waste trade activism spurs critical optimism though. The grassroots activism of early phases was not just a reactionary local engagement. Residents grew into activist roles, transforming embodied experiences of risk, of smoke, odour, illness, and environmental damage into evidence that travelled in directions that ran counter to plastic flows, where the latter moved downstream, activism expanded towards upstream accountability through the photographs, coordinates, packaging labels, drone footage, complaints, and chemical samples, some through citizen science, some via collaboration with NGOs, which in turn, established the evidentiary foundation upon which NGOs, journalists, and government officials subsequently acted. The dynamism of Malaysian plastic waste trade activism gives me hope that challenges the binary of success/failure in measuring actions and outcomes, that adaptiveness and coalition-building that has been unfurling since 2018 offers me, other Malaysians, and plastic waste trade activists at large

not only considerations for moving forward, but a reason to appreciate the progress made.

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DETRITUS & ART / A personal point of view on Environment and Art

by Rainer Stegmann



Is this art, or waste?

The reader immediately remarks that this is not the right question, since art can also be created from waste, as I have shown in many examples on my previous Detritus art Pages. The question should be whether this was created by an artist or simply happened. I saw this metal plate – I think it was metal – among partly discarded construction materials near an art school on the campus of a university in China. So, it could have been thrown away by an art student and become waste, or it could be construction material spotted with black paint.

The picture shows an abstract painting style with black areas, spots and lines. It reminds me a bit of the paintings of Jackson Pollock (1912-1956). Now, engaging a bit more with this plate, I tend to think it was created by an art student, though I am not sure. The art student may not have been satisfied with their work and may have discarded it among the other material at the construction site.

We may now start a discussion about what is art, but we will not find the answer.

Anyway, does it matter? I think the important question is whether I am attracted to it, regardless of whether it was created by an artist or by accident. The attraction may be triggered by its beauty, content and the kind of creation, or it may simply attract us without a clear explanation of why. In my view, art does not always need an explanation; it raises attention through feelings and emotions.

Whether painted or accidentally created as art from waste, it makes no difference once it is discarded. Maybe the plate will be recycled either as material or, as a whole, as a piece of art. In such cases, it would make sense to give people a chance to get it. In some countries, there are second-hand warehouses for all kinds of discarded products that can give them a second life. If someone buys this piece of art there, it would find its purpose in a second life.

*In the next issue of
DETRITUS, will tell
the story about this
bag ...*



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