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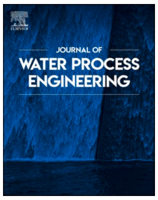

Decentralised treatment versus integrated biorefinery recovery of polyhydroxyalkanoates and struvite from urban and organic waste: A life cycle assessment approach

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ABSTRACT

Despite being a well-known alternative for the valorisation of organic wastes, anaerobic digestion needs to evolve toward the synthesis of higher-value products ensuring higher organic matter yield and economic profits. Large-scale implementation and robust environmental assessments of such integrated systems remain limited. This study compares two waste management scenarios for the Lombardy region (Italy): the current decentralised system (*Actual Scenario*) and a novel centralised biorefinery configuration (*Biorefinery Scenario*) designed to recover polyhydroxyalkanoates (PHA), struvite, heat and electricity. Following Life Cycle Assessment principles, the Product Environmental Footprint method was applied to quantify environmental impacts and identify key contributors to system performance. The results show that implementing a biorefinery at the Italian facility can reduce climate change (CC) impacts by 22 %. However, these benefits depend strongly on the PHA extraction method: only mechanical disruption and sodium hydroxide extraction keep CC impacts below those of the *Actual Scenario* (177.8 kg CO_2eq/t input waste). Biogas purification, sludge incineration and struvite recovery are identified as major hotspots requiring optimisation. Reducing energy demand (responsible for 31 % of CC impacts) and improving the management of direct emissions from biogas combustion are key priorities for enhancing environmental performance. Overall, this study provides one of the first integrated MFA–LCA assessments of a regional biorefinery simultaneously treating sewage sludge, agri-food residues and OFMSW using real operational data. By demonstrating both the potential and the critical limitations of multi-output resource-recovery systems, the work offers new scientific evidence to support the design, optimisation and policy development of future circular biorefineries.

Glossary

AD	Anaerobic digestion
BOD	Biochemical oxygen demand
CC	Climate change
CHP	Combined heat and power
COD	Chemical oxygen demand
EU	European union
EWC	European waste code
FE	Freshwater eutrophication
FRS	Fossil resource depletion
IPPC	Intergovernmental Panel of Climate Change
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LU	Land use
MFA	Material flow analysis
OFMSW	Organic fraction of municipal solid waste
PE	Person equivalent
PEF	Product environmental footprint
PHA	Polyhydroxyalkanoate
PMF	Particulate matter formation
SBR	Sequencing batch reactor
SS	Sewage sludge
TA	Terrestrial acidification
TN	Total nitrogen
TP	Total phosphorus
TS	Total solids
TSS	Total suspended solid

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(*continued*)

TVS	Total volatile solids
VFA	Volatile fatty acid
VS	Volatile solids
VSS	Volatile suspended solids
WC	Water consumption
WW	Wastewater
WWTP	Wastewater treatment plant

1. Introduction

The sustainable management of organic waste streams such as sewage sludge (SS), agri-food waste, and the organic fraction of municipal solid waste (OFMSW) is a growing challenge across Europe because of increasing waste disposal, stricter environmental rules, and the need to reduce landfilling and greenhouse gas emissions while recovering resources [1,2]. These types of waste are typically rich in organic matter and nutrients, offering significant potential for valorisation. For instance, recent studies on secondary sludge treatment have demonstrated that, when appropriately pre-treated or biologically converted, such residues can be transformed into a broad spectrum of value-added products, including short-chain fatty acids (SCFAs), biogas/methane, polyhydroxyalkanoates (PHAs), and nutrient-rich fertilisers, thus supporting circular economy strategies [3,4]. However, current management practices predominantly rely on decentralised treatment systems with suboptimal recovery efficiencies and environmental burdens [5]. It is important to acknowledge that the current debate in wastewater and resource-recovery planning increasingly considers decentralised configurations as a means to enhance resilience and reduce water and energy demand associated with long-distance pumping [6]. However, decentralisation is not universally advantageous. Recent regional analyses show that centralised “resource-recovery hubs” can outperform decentralised schemes, owing to higher process efficiencies, better quality control and economies of scale, particularly in contexts with fragmented infrastructure and stringent regulatory requirements [7]. For regions such as Lombardy, where sewage sludge, agri-food residues and OFMSW exhibit strong variability in composition and origin, evaluating a multifunctional centralised biorefinery is therefore essential to determine whether integration can unlock recovery efficiencies that decentralised systems cannot achieve.

In recent years, the development of integrated biorefineries for converting organic waste into high-value products has attracted increasing interest [8,9]. Depending on the composition of the feedstocks and the technologies considered, these biorefineries can produce a wide range of bio-based products, including bioplastics, biofertilisers, and biofuels, as widely demonstrated in recent studies on integrated waste-to-resource systems [10]. Among the available technologies, anaerobic digestion (AD) remains one of the most established and cost-effective methods for processing large volumes of organic waste, with the added benefit of generating renewable energy in the form of biogas [11]. To improve both economic and environmental performance, recent innovations have focused on directing AD processes toward fermentation pathways that enhance the production of volatile fatty acids (VFAs). These intermediates can serve as chemical building blocks for synthesizing higher-value compounds, such as polyhydroxyalkanoates (PHAs) [11]. In addition to the production of energy carriers and chemicals, the solid and liquid fractions of digestate represent valuable sources of nutrients, particularly nitrogen and phosphorus, which can be recovered and reused in agriculture. Among nutrient recovery technologies, the recovery of phosphorus through technologies such as struvite crystallisation from digester effluents is considered an alternative of closing nutrient loops and reducing reliance on mineral fertilisers [12]. These bio-based products can be further processed by industries producing fertilisers (from struvite), chemicals (from VFA), and bioplastics (from PHA) [13,14]. Such approaches align with the EU circular economy objectives and its Zero Pollution Action Plan, both of which promote resource-efficient systems that minimize environmental impacts and reduce dependence on fossil-based inputs [15,16].

Despite these promising developments, the large-scale implementation of integrated biorefineries for the treatment of mixed organic waste streams remains limited. Some relevant pilot and demonstration-scale experiences have been developed t in Europe, such as the PHARIO project, which successfully demonstrated the recovery of high-quality PHAs from municipal sludge [17] and the SMART-Plant project [18], which showcased the integration of PHA production, cellulose recovery, and struvite crystallisation in municipal wastewater treatment plants. While these initiatives represent important milestones, they have typically focused on individual valorisation pathways or specific types of waste. In contrast, the present study targets the integrated recovery of multiple resources such as VFAs, PHAs and struvite from complex, mixed organic waste streams under realistic operating conditions, advancing holistic and scalable circular solutions.

Major challenges include the heterogeneity and traceability of bio-based feedstocks, as well as regulatory and infrastructural limitations [19]. In this context, EU-funded projects, such as CIRCULAR BIOCARBON [20] and BioReCer (Biological Resources Certification Schemes) [21], are currently working to certify bio-based value chains. Given the complexity of these systems and their potential environmental trade-offs, rigorous and holistic evaluation methodologies are essential.

Life Cycle Assessment (LCA) is widely recognised as a robust and standardised approach for assessing the environmental impacts of emerging technologies across their entire life cycle. Recent studies confirm the relevance of LCA for evaluating sludge management and resource recovery systems in both emerging and established technological contexts [22,23]. Although numerous LCA studies have assessed particular waste-to-resource technologies, including struvite recovery from digestate or PHA production from organic residues, most are narrow in scope, differ in system boundaries and functional units, and generally focus on single waste streams [24–28]. This lack of standardisation complicates meaningful comparison and hinders informed decision-making. A recent study by Castro-Fernandez et al. [29] provides a notable exception, offering a holistic environmental assessment of a large-scale system for VFA production from sewage sludge and food waste. While this represents an important step forward in the environmental assessment of multi-waste biorefineries, no studies to date have assessed a system that simultaneously treats sewage sludge, agri-food waste, and OFMSW in a centralised facility while recovering both PHA and struvite, thereby capturing the full potential of mixed-waste valorisation within a circular economy framework.

To address this gap, the present study applies LCA to compare the environmental impacts of two alternative scenarios for organic waste management within the metropolitan area of Milan (Italy): (i) the current decentralised treatment model (based on operational data from 2016 to 2022), in which waste streams are managed separately across seven wastewater treatment plants operated by CAP Holding SpA; and (ii) a proposed centralised biorefinery model located in Sesto San Giovanni, which integrates the treatment of all organic feedstocks at a single facility to maximise resource recovery. This comparative assessment aims to quantify the potential environmental benefits of integrated waste treatment and resource valorisation, providing scientific evidence to support urban waste policies and the transition toward circular biorefineries. At the same time, critical environmental impacts were identified within the biorefinery, highlighting areas where improvement strategies should be proposed.

2. Methodology and methods

The Horizon Europe project BioReCer is designed to enhance the added value, efficient utilisation, and social acceptance of biological feedstocks and the bio-based products derived from them within the framework of the European bioeconomy. One of the core objectives of the project is to validate the environmental performance and traceability of biological feedstocks across the entire value chain of bio-based systems, thereby supporting the transition toward more transparent, sustainable, and circular industrial models.

In the context of BioReCer, an innovative biorefinery system integrated into a wastewater treatment plant (WWTP) within the metropolitan area of Milan (Italy) was evaluated. This biorefinery is designed to valorise secondary raw materials from both urban and industrial sources, particularly SS, agri-food waste and OFMSW. Accordingly, this study started with the quantification and characterisation of the currently managed wastes, carried out through a comprehensive Material Flow Analysis (more information in Section 2.1). All these wastes will be eligible to be fed in the biorefinery (Section 2.2.2), as a substitute management strategy to the one already implemented in the Italian region (Section 2.2.1). In this context, the environmental impacts of the facility, estimated using the LCA methodology (Section 2.3.) are adapted to the specific operation according to the composition of the original mixed feedstock.

2.1. Material flow analysis

The quantitative data for the MFA were obtained through extensive review and analysis of operational documents provided by CAP Holding SpA, covering the period from 2016 to 2022. These documents include records of waste generation, handling, and treatment associated with the wastewater treatment infrastructure operated by the company. In parallel, qualitative data were gathered to describe the chemical and physical characteristics of each waste stream, including parameters such as moisture content and nutrient concentrations. This characterisation relied on waste acceptance documentation issued by CAP Holding SpA and was further supplemented with values and ranges reported in relevant scientific and technical literature [30–33]. The scope of the analysis encompasses several WWTPs, which vary in terms of treatment capacity and wastewater flows. Table 1 summarises the WWTPs included in this study, showing their design capacities, average wastewater flows, and the annual quantities of waste managed over the six-year study period (wet mass). For regulatory and operational consistency, all waste streams considered in this study (not only for Table 1 but also for others such as Table 2) are classified according to the European Waste Catalogue (EWC), also known as the European List of Waste [34]. Each waste type is identified by a six-digit EWC code, which provides precise information about the nature and origin of the waste, complemented by its respective two- and four-digit chapter headings. This classification framework ensures consistency in traceability, compliance, and reporting. The list of waste types assessed in the Italian case study, along with their corresponding EWC codes, is detailed in Table S1.

Subsequently, Tables 2 and 3 present the detailed compositions of the agri-food waste and OFMSW, respectively. These datasets form the basis for subsequent modelling steps within the LCA and are critical for assessing the environmental implications of integrating waste valorisation technologies into existing treatment infrastructures.

2.2. Description of the scenarios

Two distinct scenarios were analysed in this study in order to evaluate and compare the environmental performance of alternative organic waste management strategies within the metropolitan context of Milan. The "*Actual Scenario*" reflects the decentralised treatment approach currently adopted by CAP Holding SpA, in which different waste streams are treated separately across multiple WWTPs located throughout the region. These facilities apply conventional technologies primarily oriented toward waste stabilisation and disposal, with limited integration or resource recovery. As such, this scenario serves as the baseline reference. The "*Biorefinery Scenario*" is a prospective, full-scale scenario that explores the potential of transitioning to a centralised and integrated biorefinery model. It is based on the conceptual design of a facility located in Sesto San Giovanni, where all relevant organic waste streams (previously managed in a decentralised manner) would be co-treated in an optimised site. The scenario assumes the valorisation of waste fractions through the production of high-value bio-based products, including VFAs, struvite and PHAs.

By comparing these two scenarios using LCA, the study aims to quantify the potential environmental benefits of process integration and resource recovery and to provide evidence-based insights to guide strategic planning and policy development in the field of organic waste valorisation.

2.2.1. Actual scenario

In the *Actual Scenario*, the management of organic waste streams (including SS produced at WWTPs, agri-food waste generated by nearby industries from the food and beverage sector, and the OFMSW from surrounding municipalities) is carried out through a decentralised treatment configuration. The management of sewage sludge and agri-food waste predominantly involves either incineration or land application. Sewage sludge, agri-food waste, and OFMSW are either treated separately or co-treated within the sludge treatment lines of several WWTPs in the metropolitan area. The primary treatment technology applied is AD, which facilitates the recovery of biogas. This biogas is

Table 1
Characteristics of the waste processed in CAP HOLDING SPA between 2016 and 2022.

WWTP name	Facility capacity (PE)	Average WW influent (m^3/d)	Type of feedstock	EWC	Quantity (t/y)	Timeframe (y)
Sesto San Giovanni	138,488	24,135	Sewage sludge (TS = 24 %)	19 08 05	3443	2016–2021
			Agri-food waste (TS = 3.4 %)	02 03 04	32	2021
			Agri-food waste (TS = 3.4 %)	02 05 01	188	2019–2021
			OFMSW (TS = 13 %)	20 01 08	121	2022
Robecco sul Naviglio	340,000	99,335	Sewage sludge (TS = 26 %)	19 08 05	7293	2016–2022
			Agri-food waste (TS = 3.4 %)	02 03 04	47	2021–2022
			Agri-food waste (TS = 3.4 %)	02 07 01	7	2021–2022
San Giuliano Milanese Ovest	30,000	10,700	Sewage sludge (TS = 90 %)	19 08 05	2957	2016–2022
			Agri-food waste (TS = 3.4 %)	02 02 01	661	2021–2022
			Agri-food waste (TS = 3.4 %)	02 02 04	720	2022
			Agri-food waste (TS = 3.4 %)	02 03 01	430	2021–2022
			Agri-food waste (TS = 3.4 %)	02 03 05	27	2022
			Agri-food waste (TS = 3.4 %)	02 06 01	540	2022
			Agri-food waste (TS = 3.4 %)	02 07 01	1277	2021–2022
Canegrate	151,800	29,340	Sewage sludge (TS = 23 %)	19 08 05	3261	2016–2021
Pero	620,600	150,250	Sewage sludge (TS = 25 %)	19 08 05	9488	2016–2021
Rozzano	340,000	99,335	Sewage sludge (TS = 22 %)	19 08 05	3440	2016–2021
Bareggio	64,800	13,215	Sewage sludge (TS = 24 %)	19 08 05	1567	2016–2021

Note: EWC: European Waste Code; PE: Person Equivalent; TS: Total Solids; WW: Wastewater; WWTP: Wastewater Treatment Plant.

Table 2
Agri-food waste composition (waste approvals).

EWC	COD (mg/L)	BOD_5 (mg/L)	TN (mg/L)	TP (mg/L)	TSS (mg/L)	TVS/TS (−)	TS (%)	Density (kg/m^3)
02 03 01	4800	1928	96	48	1961	0.13	0.98	
02 02 04	17,725	10,870	1228	126	732	0.47	4.85	
02 03 05	82,124	55,547	465	59	49,098	0.62	3.70	1043
02 06 03	65,562		546			0.74	3.53	1010
02 03 04	50,572		519		144,650	0.88	7.00	992.5
02 02 01	15,131	4697	99.7	18	32,370	0.95	3.68	
02 07 01	3765		173		293	0.67	1.50	
02 06 01	71,134	19,533	168	62	16,250	0.88	3.50	

Note: BOD: Biochemical Oxygen Demand; COD: Chemical Oxygen Demand; EWC: European Waste Code; TN: Total Nitrogen; TP: Total Phosphorus; TS: Total Solids; TSS: Total Suspended Solids; TVS: Total Volatile Solids. The EWC codes are shown in Table S1.

Table 3
Composition of the organic fraction of municipal solid waste (waste approvals). Total monitored waste = 126.9 kg.

European Waste Code 20 01 08	Average of 15 samples (%)
Compostable material	85.48
Non-compostable material	8.14
Organic waste	86.46
Compostable bag	2.06
Internal bioplastic	0.90
Herbaceous waste	0.36
Lignocellulosic waste	0.00
Paper and cardboard	2.07
Wooden packaging	0.02
Plastic bags	1.27
Plastic	1.97
Glass	0.33
Metals	0.26
Inert material	0.22
Natural stones litter	0.68
Diapers	1.00
Other	2.40

subsequently converted into thermal and electrical energy through a combined heat and power (CHP) system and sold externally. In this scenario, both outputs were estimated following the approach developed by Omer [35]. The resulting digestate requires further treatment, which varies according to the waste source and the specific treatment plant. Depending on the digestate characteristics and regulatory or operational constraints, three main strategies are considered: direct land application of digested sludge, fertiliser production, or incineration.

At the wastewater treatment plants of Bareggio, Pero, Canegrate, and Rozzano, the stabilised sludge produced is directly applied to agricultural land, in line with regulatory requirements and agricultural practices. The organic fraction of municipal solid waste is digested at the Sesto San Giovanni facility, and the resulting digestate is delivered to a fertiliser manufacturing company for further valorisation. In the case of agri-food waste, co-digestion with SS is performed at the WWTPs located in Robecco sul Naviglio, Sesto San Giovanni, and San Giuliano Milanese Ovest. The digestate produced in these facilities is not reused but is instead sent for incineration, due to the lack of viable alternatives for its recovery.

This scenario illustrates a fragmented and non-integrated waste management system, with heterogeneous treatment strategies and variable levels of resource recovery. The differences in processing routes limit the overall circularity and environmental efficiency of the current model. A schematic representation of the actual scenario, including waste flows (as dry matter), treatment pathways, and final destinations, is presented in Fig. 1a-c.

2.2.2. *Biorefinery scenario*

The *Biorefinery Scenario* represents a more complex and integrated valorisation pathway compared to the *Actual Scenario*. It incorporates multiple treatment and recovery processes, including fermentation, PHA recovery and extraction, phosphorus recovery, anaerobic digestion, and biogas purification. In this scenario, all organic waste streams considered (i.e., SS, agri-food waste, and OFMSW) are assumed to be valorised in a biorefinery facility located at the Sesto San Giovanni WWTP. To ensure comparability between scenarios and to avoid scale-related biases, the biorefinery was sized to treat exactly the same total annual quantity of waste processed in the *Actual Scenario*. Such a level of integration is technically realistic, as it is consistent with the scale of regional sludge-hub models currently being implemented in Europe, such as Uisce Éireann's Regional Sludge Hub Centres [54]. This centralised configuration aims to enhance resource recovery by producing high-value bio-based products, including biofertilisers and bioplastics, thus supporting the development of circular economy strategies.

The biorefinery configuration assessed in this case study has a total processing capacity of around 35,500 t/y and is composed of eight interconnected processing units (Fig. 1d). These units include a fermentation reactor, a thickening unit for solid-liquid separation, a phosphorus recovery section for the crystallisation of struvite, a storage tank for VFAs, a biomass selection and nitritation reactor, a PHA accumulation unit, a PHA extraction section, an anaerobic digestion reactor, a biogas purification (recently introduced at the sludge line of Sesto San Giovanni WWTP) and a dewatering system for the final treatment of residual sludge.

The process begins with the dilution of the incoming waste streams from 57 % TS (total solids) to reach an optimal solid content of approximately 5 % TS for fermentation. Once homogenised, the mixture is fed into the fermentation reactor at about 35 °C, where microbial activity converts organic matter into VFAs. The fermented mixture is then directed to the thickening unit, which separates the solid and liquid fractions. The supernatant, rich in VFAs, represents about 1/3 in flowrate of the fermented stream and is sent to the phosphorus recovery unit, where struvite is precipitated. This mineral compound ($MgNH_4PO_4 \cdot 6H_2O$) is subsequently collected and can be supplied to the fertiliser industry as a sustainable phosphorus source (12.62 % in dry pure weight). The remaining VFA-rich liquid is stored temporarily before being transferred to the biomass selection and nitritation unit, where microbial communities are conditioned and optimised for PHA accumulation.

In the subsequent step, the activated biomass enters the PHA accumulation reactor, where conditions are controlled to maximise intracellular PHA synthesis, resulting in sludge enriched with bioplastics precursors (0.3 g PHA/gVSS). After this stage, the residual fermented sludge is subjected to anaerobic digestion to generate biogas. This biogas is subsequently converted into thermal and electrical energy through a CHP system and sold externally. The digestate is then processed through a final solid-liquid separation step. The liquid fraction resulting from this phase is reused within the system to dilute incoming waste, contributing to water and nutrient recirculation.

The main outputs of the biorefinery are struvite and PHA-rich sludge. The PHA-rich sludge undergoes downstream extraction and purification processes to isolate the biopolymer, which can subsequently be used for the production of biodegradable materials. The key parameters used to

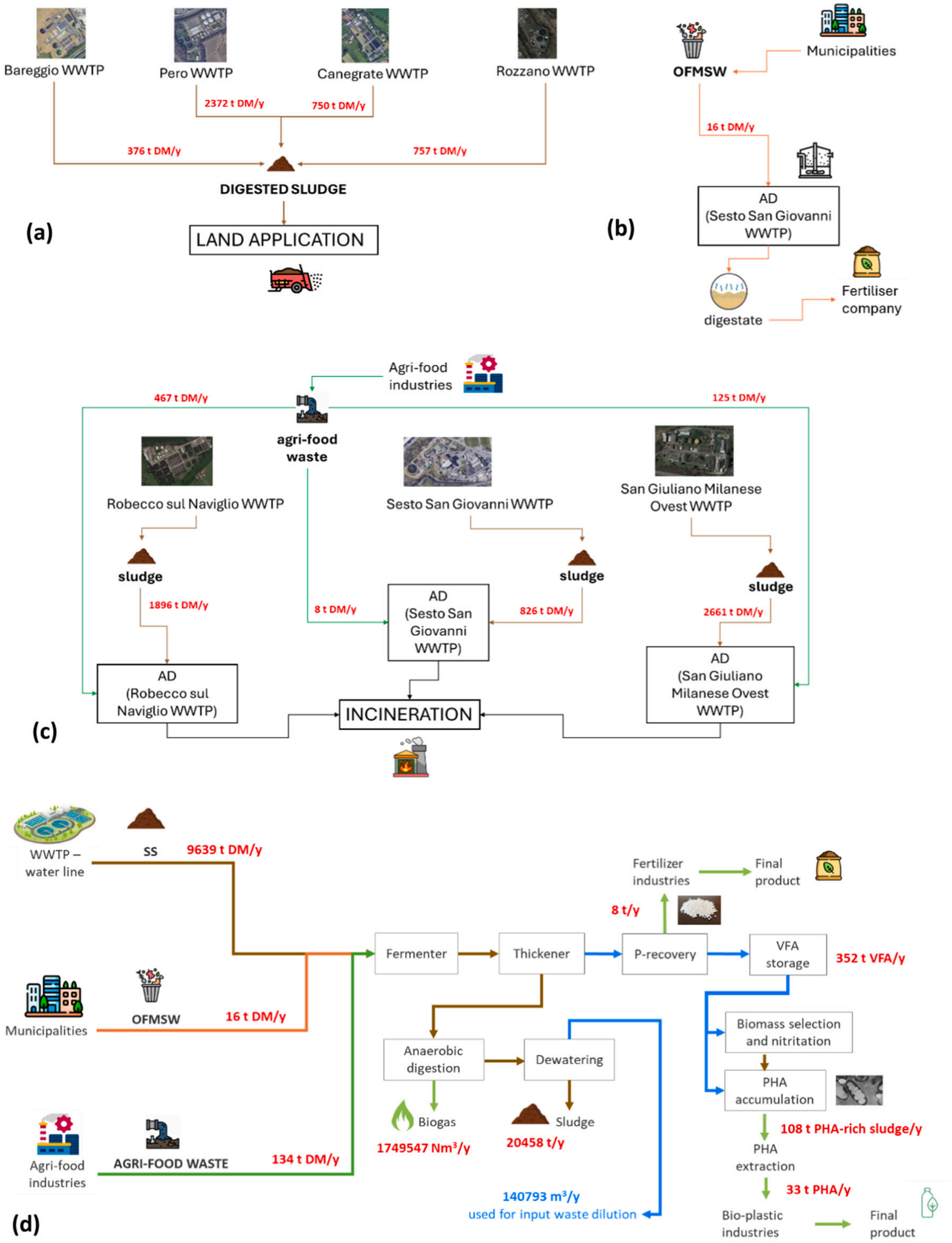

Fig. 1. Simplified process flow diagrams (including quantitative mass flows) of the *Actual Scenario* considering the valorisation of the sewage sludge digestate in the Italian wastewater treatment plants for direct land application (a), the treatment of the organic fraction of the municipal solid waste by anaerobic digestion in Sesto San Giovanni for fertiliser manufacturing (b) and the processing of the agri-food waste from industries with anaerobic digestion and incineration (c) and the *Biorefinery Scenario* (d). AD: Anaerobic Digestion; DM: Dry Matter; OFMSW: Organic Fraction of Municipal Solid Waste; PHA; Polyhydroxyalkanoate; VFA: Volatile Fatty Acid; WWTP: Wastewater Treatment Plant.

estimate the production of VFA, struvite and PHA are listed in Table 4. It is important to note that a conservative value was intentionally chosen for the VFA production yield.

2.3. *Life cycle assessment*

In this study, an attributional LCA was performed to benchmark the *Actual* and *Biorefinery Scenarios*. Additional processes (e.g. production of mineral fertilisers and plastic bags) were included in the *Actual Scenario*

Table 4
Key parameters adopted in the mass balance of the biorefinery scenario.

Biorefinery section	Parameter	Unit	Value	Reference
Fermentation	VFA production yield	gCOD (VFA)/gVS	0.15	Ros et al. [36]
Crystallisation	Struvite recovery efficiency	P (%)	70.0	SMART-Plant [18]
Biomass selection and nitritation	Biomass growth yields	gCOD (VSS)/ gCOD(VFA)	0.49	Valentino et al. [37]
PHA accumulation	VSS growth	gVSS/gVFA	0.23	Frison et al. [38]
PHA accumulation	PHA accumulation yield	gPHA/gVSS	0.30	Pei et al. [39]

Note: COD: Chemical Oxygen Demand; PHA: Polyhydroxyalkanoates; TP: Total Phosphorus; VFA: Volatile Fatty Acid; VS: Volatile Solids; VSS: Volatile Suspended Solids.

to ensure functional equivalence with the *Biorefinery Scenario*. This approach is consistent with attributional LCA practice when multi-functional systems require harmonisation of system outputs.

2.3.1. *Definition of scope and objectives*

Beyond the comparative evaluation of the environmental impacts of the *Actual* and *Biorefinery Scenarios*, the study identified key environmental hotspots through a contribution analysis and also incorporated a sensitivity analysis to assess the influence of specific technological choices, such as PHA extraction methods. The functional unit (FU) adopted was 1 t of input waste, comprising SS, agri-food waste, and OFMSW. This FU was selected to reflect the actual input basis of the waste treatment system and allows for a consistent and comparable assessment of the environmental performance of both scenarios, regardless the system multifunctionality. The technical system boundaries were defined as *Cradle-to-gate* since they include the transport of original waste materials to the facility gate, the impacts from the manufacturing of the consumed resources in the valorisation process

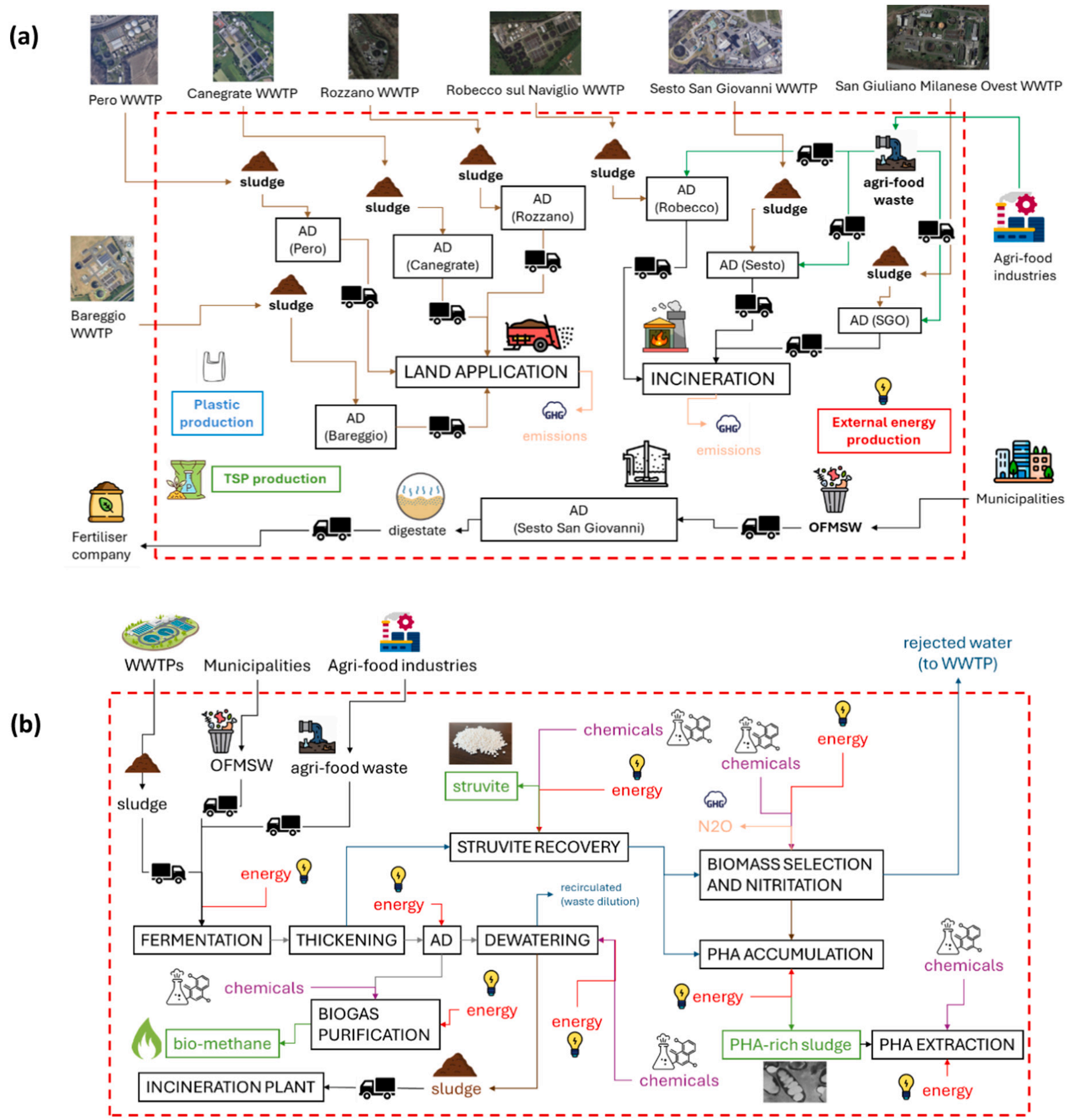

Fig. 2. Life cycle system boundaries of the *Actual* (a) and *Biorefinery* (b) scenarios.

and the direct emissions at the facility but exclude transport, use phase, and end-of-life stages related to the final products. The geographic system boundaries were chosen to represent as much as possible the Lombardian region. Accordingly, Italian data was used to determine the environmental impacts of the electricity demand, and a European level was considered for the remaining processes. There were exceptions where European-specific data were unavailable and thus, global background data were used for chemicals such as for the polyelectrolyte and magnesium chloride (more detailed information in Tables S2 and S3). Finally, a hierarchical perspective (H) was adopted for the temporary system boundaries. Also, this study adopted the cut-off by the classification system model from Ecoinvent v3.11 ("cut-off"). Consequently, the environmental burdens associated with the previous life cycle of secondary waste materials were not accounted for, nor are the potential benefits from their future reuse, recycling, or energy recovery beyond the system boundary. The system boundaries of the *Actual* and *Biorefinery* scenarios are shown in Fig. 2.

In addition to waste management and associated emissions, the production of fertilisers, plastic bags, and external energy was included in the *Actual Scenario*. This approach ensures a fair and meaningful comparison with the *Biorefinery Scenario*, where there is system multifunctionality (waste treatment and valorisation to valuable products, such as struvite, PHA and energy). Struvite can be used directly as a fertiliser, whereas PHA must first be extracted from the biomass through chemical digestion, mechanical disruption, or solvent extraction. The comparison between conventional fossil-based plastic bags and biobased alternatives was conducted in accordance with the study of Askham et al. [40]. The external energy considered in the *Actual Scenario* corresponds to the difference in biogas-derived energy production between the *Biorefinery* and the *Actual Scenarios*. The *Biorefinery Scenario* notably features the recent installation of a biogas purification system at the Sesto San Giovanni plant, enabling the production of biomethane with 99 % CH_4 purity.

2.3.2. *Life cycle inventory*

The LCI data used to model both the *Actual* and the *Biorefinery Scenarios*, expressed per FU, are presented in Tables S2 and S3. In both scenarios, the data of the waste and chemical input process flows were primary as well as the distances of transportation. In the absence of specific data, a default distance of 40 km was assumed as a conservative and regionally relevant estimate for intra-provincial waste transport. Beyond the shared assumptions, the scenarios differ in their estimations of waste transport, energy demand, chemical use and direct emissions.

In the *Actual Scenario*, the environmental impacts associated with transportation of the in-process generated waste and incinerated sludge were modelled using Ecoinvent background processes. The energy consumption associated with anaerobic digestion was estimated through mass balance calculations following the methodology described in Metcalf & Eddy [31]. The external energy production obtained from biogas combustion was estimated following the approach proposed by Omer [35]. This item in the LCI represents the net difference in energy production between the two scenarios, with higher energy generation observed in the *Biorefinery Scenario*. The emissions from biogas combustion were estimated using EPA [41] guidelines. Electricity and polyelectrolyte consumption for sludge dewatering were derived from technical literature sources, including IWA [42] and Metcalf & Eddy [31]. Emissions of N_2O from the treatment of the anaerobic digestion supernatant were estimated according to the study by Longo et al. [43]. Airborne and soil emissions resulting from land application of sludge (e.g., N_2O, NH_3, CH_4 and N_2O) were modelled following IPCC [44] and Yoshida et al. [45]. The presence and transfer of heavy metals to soil were based on the actual chemical characterisation of the sewage sludge applied. The study by Yoshida et al. [45] was also used to estimate energy and diesel consumption for sludge spreading activities. The production of phosphorus-based fertilisers was modelled using data from Alengebawy et al. [46]. The energy consumption and emissions associated with plastic bag production were based on the study by Askham et al. [40]. All the aforementioned processes were implemented again using datasets from Ecoinvent, as detailed in Table S2.

In the *Biorefinery Scenario*, the environmental impacts associated with transportation were modelled as in the *Actual Scenario*, detailed in Table S3. Likewise, the energy consumption of fermentation and anaerobic digestion processes, along with biogas combustion emissions, was calculated using the same references cited above. Electricity and chemical consumption related to biogas purification were derived from measured data at the sludge treatment line of the Sesto San Giovanni WWTP. Energy and magnesium chloride demand for the struvite crystallisation process were based on data from the SMART-Plant project [18] and Mayor et al. [24]. Comparably, electricity and sodium hydroxide consumption, as well as N_2O emissions in the biomass selection and nitritation stage, were calculated using the results from SMART-Plant [18] and Longo et al. [43]. Electricity and polyelectrolyte consumption for sludge dewatering were taken from technical literature sources [31,42]. Regarding the PHA extraction, the specific technology was selected based on a critical review of available alternatives (to be further discussed in Section 2.3.4). The associated water, chemicals, and energy demand were derived from a combination of scientific and technical literature and patents, including PHARIO [17], Werker et al. [47], BIO ON [48], and Saavedra del Oso et al. [49]. The incineration of residual sludge, as well as all the aforementioned processes, were modelled using specific datasets from Ecoinvent (Table S3).

2.3.3. *Life cycle impact assessment*

The LCIA phase was conducted through the support of the LCA software SimaPro® version 10.2.0.1, which enabled a systematic transformation of the LCI inventory data into environmental impacts. The Product Environmental Footprint (PEF) 3.0 was the impact assessment method applied, a harmonised framework with European characterisation factors developed to facilitate a robust multi-criteria environmental evaluation across diverse impact and damage categories. In this regard, impact calculations are regionally relevant and reflect the specific environmental conditions and policy contexts of Europe. Thus, the selection of PEF 3.0 aligns with current European standards and regulatory expectations as it is recommended by the Commission Recommendation (EU) 2021/2279 [50].

The LCA midpoint impact results for both the scenarios are presented with respect to seven key environmental impact categories of the PEF method, including climate change (CC – kg $CO_{2eq.}$), terrestrial acidification (TA – mol $H^+_{eq.}$), particulate matter formation (PMF – disease inc.), freshwater eutrophication (FE – kg $P_{eq.}$), land use (LU – Pt), water consumption (WC – m^3 depriv.), and fossil resource depletion (FRS - MJ). These categories were selected to align with the key sustainability performance indicators established within the BioReCer project [21], which were subsequently chosen from a through legislation and certification schemes revision for bio-based products manufacturing and biomasses processing.

2.3.4. *Sensitivity analysis*

Given that downstream processing of PHA represents one of the main environmental hotspots of biorefinery systems [17,49], a sensitivity analysis was performed to assess how different extraction routes influence the overall environmental performance. Four alternative extraction methods documented in technical and scientific literature (mechanical disruption, 2-butanol extraction, dimethyl-carbonate extraction and sodium hydroxide extraction) were modelled as alternative configurations of the *Biorefinery Scenario*. This approach allows testing the sensitivity of the system to a key technological parameter whose variability can significantly alter the environmental performance of the process.

Among the four previously cited PHA extraction methods, mechanical disruption was chosen for the baseline *Biorefinery Scenario* (and thus to be compared with the *Actual Scenario* in Section 3.1), as it offers a full-scale implemented alternative (as reported for example in the BIO ON project) with a reduced consumption of chemicals. The procedure applied in this study was based on a patented method in which PHA-rich biomass is processed through a high-pressure homogenisation system with surfactants. This step disrupts the non-cellular PHA matrix, thereby facilitating digestion [51]. Subsequently, the PHA is separated from the dissolved biomass by liquid–solid separation, purified through bleaching, and finally dried.

As an alternative to mechanical extraction, solvent extraction with 2-butanol was also considered, since it remains the only solvent-based process with well-documented data available on a pilot scale [17]. This method follows the patent developed by Werker et al. [47]. However, laboratory-scale studies have indicated that the use of alternative extraction agents, such as dimethyl carbonate or sodium hydroxide, may lead to lower environmental impacts [52,53]. While these alternatives have not yet been applied on an industrial scale, they demonstrate promising potential for greener and more sustainable performance.

3. Results

3.1. Material flow analysis results

Table 5 summarises the annual average quantities of waste (as wet mass) managed between 2016 and 2022 across the WWTPs operated by CAP Holding SpA. The total mass of input waste is consistent across both scenarios, allowing the MFA to be analysed jointly. However, it is important to note that the *Actual Scenario* involves distributed feedstock treatment across multiple WWTPs, whereas the *Biorefinery Scenario* assumes the centralisation of all waste streams at a single integrated biorefinery located at the Sesto San Giovanni WWTP.

The sewage sludge originates exclusively from these facilities, with annual inputs between 1570 and 9490 t for Bareggio and Pero plants, respectively. TS concentration of this sludge exhibited significant variability (22–90 %) among them, which is a consequence of the use of different sludge stabilisation and dewatering techniques at each site and that has an influence on the downstream processing and resource recovery potential. The agri-food waste stream is treated at selected WWTPs, primarily those located in San Giuliano Milanese Ovest, Sesto San Giovanni, and Robecco sul Naviglio. Among these, the first one records the highest annual input, processing approximately 1280 t/y of waste classified under the EWC code 02 07 01. This category typically represents waste with a low TS content (3.4 %) and is sourced from a diverse range of food processing industries (Table S1). In contrast with sludges and agri-food wastes, the contributions from OFMSW are relatively less relevant in mass, with a maximum of 52.7 t/y coming from the municipality of Cinisello Balsamo.

Table 5
List of the managed wastes in the selected WWTPs of Lombardian region of Italy between 2016 and 2022.

Type of waste	Value (t/y)
Sludge treated in Bareggio WWTP (TS = 24 %)	$1.57 \cdot 10^3$
Sludge treated in Canegrate WWTP (TS = 23 %)	$3.26 \cdot 10^3$
Sludge treated in Pero WWTP (TS = 25 %)	$9.49 \cdot 10^3$
Sludge treated in Robecco sul Naviglio WWTP (TS = 26 %)	$7.29 \cdot 10^3$
Sludge treated in Rozzano WWTP (TS = 22 %)	$3.44 \cdot 10^3$
Sludge treated in San Giuliano Milanese Ovest WWTP (TS = 90 %)	$2.96 \cdot 10^3$
Sludge treated in Sesto San Giovanni WWTP (TS = 24 %)	$3.44 \cdot 10^3$
Agri-food waste 02 02 01 (to San Giuliano Milanese Ovest WWTP)	660
Agri-food waste 02 02 04 (to San Giuliano Milanese Ovest WWTP)	720
Agri-food waste 02 03 01 (to San Giuliano Milanese Ovest WWTP)	430
Agri-food waste 02 03 04 (to Robecco sul Naviglio WWTP)	47.2
Agri-food waste 02 03 04 (to Sesto San Giovanni WWTP)	31.7
Agri-food waste 02 03 05 (to San Giuliano Milanese Ovest WWTP)	26.5
Agri-food waste 02 05 01 (to Sesto San Giovanni WWTP)	188
Agri-food waste 02 06 01 (to San Giuliano Milanese Ovest WWTP)	540
Agri-food waste 02 07 01 (to San Giuliano Milanese Ovest WWTP)	$1.28 \cdot 10^3$
Agri-food waste 02 07 01 (to Robecco sul Naviglio WWTP)	6.82
Organic fraction of municipal solid waste from Cinisello Balsamo	52.7
Organic fraction of municipal solid waste from Sesto San Giovanni	46.5
Organic fraction of municipal solid waste from Segrate	22.1

Note: TS: Total Solids; WWTP: Wastewater Treatment Plant.

3.2. Analysis of the inventory

The life cycle inventories of the *Actual* and *Biorefinery Scenarios* (Tables S2 and S3) can be compared in terms of total energy consumption, chemical and resource inputs, transport activities, and emission profiles. In the *Actual Scenario*, the total electricity and thermal energy used in the treatment processes accounts to approximately 46.9 kWh/t, being the most impactful elements the anaerobic digestion (66.1 %), land application activities (15.0 %) and sludge dewatering (1.4 %). In addition to this, credits from external energy production to make the scenario comparable to that of the biorefinery counterpart has been considered and has been quantified as 51.8 kWh/t for thermal and 146.0 kWh/t for electrical energy. Thus, the total energy of this scenario achieves 244.5 kWh/t. Regarding chemicals, the key input is the polyelectrolyte for dewatering (0.81 kg/t). Transport distances range between $2.35 \cdot 10^{-2}$-26.4 t·km, depending on the type and destination of the waste. Direct emissions to air (CO_2, N_2O, NH_3, CH_4) and soil (As, Cr, Mg, Ni and Pb) are dominated by land application and biogas combustion. The highest impact per mass corresponds to air emissions during land application, mainly ammonia gases (58.3 %). For heavy metals, lead from soil deposition is the most significant (30.2 % of all elements considered).

In the *Biorefinery Scenario*, the total energy demand reaches 162.6 kWh/t, with the main contributors being biogas purification (66.4 %), anaerobic digestion (18.7 %), fermentation (11.5 %), crystallisation (1.5 %), biomass selection and nitritation and PHA accumulation (0.7 %), PHA extraction (0.7 %), and sludge dewatering (0.4 %). This implies that the *Biorefinery Scenario* has 1.5 times lower energy demand than the *Actual Scenario*. The chemical inventory includes a broader set of substances which is indicative that the *Biorefinery Scenario* might not be energy intensive but has been penalised by a larger demand for chemicals (a total of 8.17 kg/t) than the *Actual Scenario*. They can arrange from most to less impactful as: ferric chloride (50.6 %), magnesium chloride (41.4 %), sulphuric acid (5.4 %), sodium hydroxide (2.1 %), and sodium dodecyl sulphate (0.6 %). The transport activities cover a similar range to that of the business-as-usual scenario, including the delivery of feedstocks and chemicals, and disposal of residual sludge. Emissions include 59.4 kg CO_2, 3.65 g CH_4, and 0.72 g N_2O from biogas combustion, and 5.26 g N_2O from the biomass selection and nitritation unit. Overall, the *Biorefinery Scenario* exhibits higher chemical demand but also greater integration of recovery processes, including the annual production of approximately 32.5 t of PHA and 8.3 t of struvite. PHA can serve as a bio-based and biodegradable alternative to conventional plastics, supporting the transition toward more sustainable materials. In contrast, the *Actual Scenario* is limited to the recovery of biogas (also recovered in the *Biorefinery Scenario*) and the land application of digested sludge, which, although beneficial, do not provide the same level of added-value product generation or nutrient circularity.

3.3. Comparative analysis of scenarios

The *Biorefinery Scenario* shows consistently better environmental performance than current waste management practices, with reductions in nearly all assessed impact indicators, except for particulate matter formation. The comparison shown in Fig. 3 reveals that the improvement may be found between 2 and 22 % (for FE and CC, respectively). The reasoning behind the larger environmental impact of the *Biorefinery Scenario* in the particulate matter category (47 %) comes from the demand of chemicals (~52 % of the profile) and more specifically from the use of $MgCl_2$ in the stage of struvite crystallisation. In contrast with the outcomes indicated in Section 3.2 for the analysis of the inventories, the

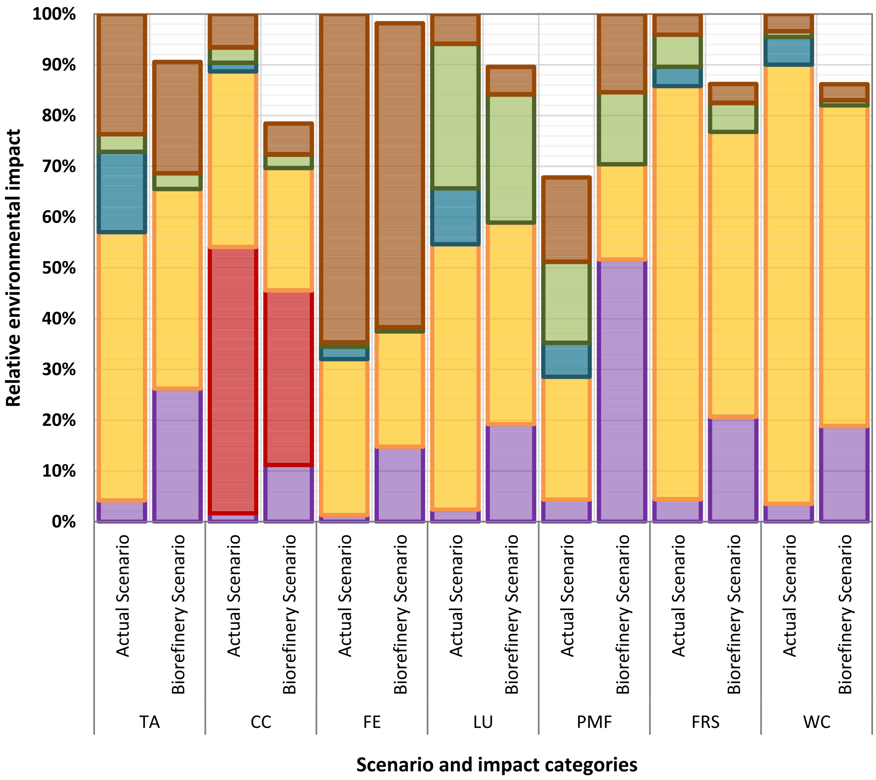

Fig. 3. Contribution and comparative environmental impact profile between the *Actual* and the *Biorefinery Scenario*. 🟧 Energy; 🟪 Chemicals; 🟥 Direct emissions; 🟦 Fossil-based products; 🟩 Transport; 🟫 Incineration. CC: Climate Change; FE: Eutrophication, freshwater; FRS: Fossil Resource use; LU: Land use; PMF: Particulate matter formation; TA: Terrestrial acidification; WC: Water use. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

impact profile is dominated by the demand of the $MgCl_2$ and not by the $FeCl_3$. This indicative of the larger characterisation factor of the former compound, which implies that smaller amounts of the chemical result into higher impacts to the environment. While Fig. 3 shows a relative profile for the two scenarios, more information about the absolute environmental impacts per FU can be found in Tables S4-S5. Furthermore, a direct comparison of the environmental footprints is provided in Table S6.

A comprehensive cross-category analysis identifies energy consumption as a key environmental driver across four of the categories. Specifically, it contributes substantially to TA (up to 53 %), LU (<52 %), WC (<87 %), and FRS (<81 %). Although energy demand it is also important for CC (31–35 % for the *Biorefinery* and *Actual Scenarios* respectively) and FE (23–31 % for each scenario, respectively), these two categories are mostly influenced by the direct process emissions (<52 %) and incineration (<65 %), respectively. In particular, direct emissions from biogas combustion (CO_2, CH_4 and N_2O) represent the most significant contributor, accounting for up to 33 % of the total emissions. Regarding the incineration, these emissions were modelled using the "*treatment of raw sewage sludge, municipal incineration FAE (CH)*" process from the Ecoinvent database, which includes average emission factors for flue gas cleaning systems and accounts for both airborne pollutants and residual ash disposal. In line with this, incineration plays a notable role in acidification, representing up to 24 % in both scenarios, as well as to particulate matter formation (<25 %).

3.4. Contribution analysis per process stage for the biorefinery scenario

After comparing both scenarios and identifying the LCI categories (e.g., energy, chemicals, transportation, emissions) with the highest potential impact, the next step in the LCIA outcome analysis is to determine the critical process sections and equipment for the proposed biorefinery. In this context, further monitoring of already well-established technologies is necessary to ensure long-term sustainability. Fig. 4a shows that the biogas purification and combustion (30 %–82 %, for PMF and WC respectively) is the hotspot section, caused on one hand by the direct emissions to the environment (i.e., 55 % in CC) and the electricity needed for purification (i.e., 37 % in CC). After the biogas treatment, the incineration of the wasted sludge and phosphorus recovery are the other two more concerning activities with a representativeness around 3.7 %–61 % (WC and FE) and 3.0 %–32 % (WC and PMF), respectively.

Although these results seem to contradict the initial hypothesis described in Section 2.3.4 indicating that the downstream processing of the PHA should be the critical environmental process bottleneck, the lower representativeness of this section is only valid for the mechanical disruption extraction technique and for a solvent extraction with sodium hydroxide (shown in Fig. 4b and d). In the latter case the PHA extraction section represents up to 39 % (FE) of the process overall impact. The 2-butanol and dimethyl carbonate extractions led, however, to a process with an enormous dependency of the operational management of the PHA extraction section (beyond the 54 % of the process impact as seen in Fig. 4c and e).

3.5. Sensitivity analysis

The sensitivity analysis described in Section 2.3.4 evaluates how the environmental performance of the *Biorefinery Scenario* changes depending on the selected PHA extraction route. Fig. 5 (absolute results in Table S9) compares the four extraction methods, revealing substantial differences (beyond 69 % depending on the impact category) in environmental performance across the impact categories evaluated. Among the four alternatives selected, 2-butanol extraction consistently exhibits the highest environmental burdens, emerging as the least sustainable option. It results, for example, in the highest global warming potential

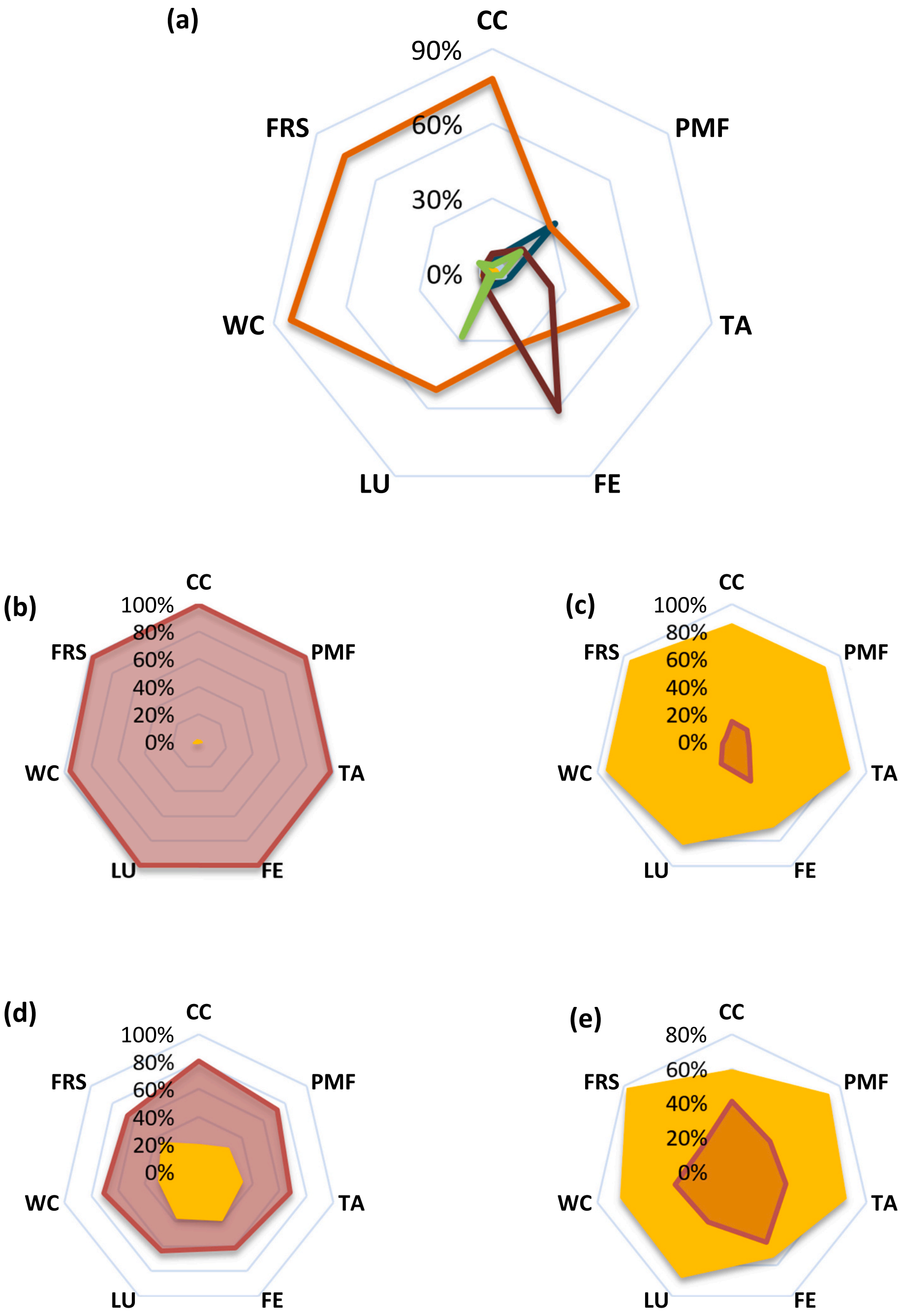

Fig. 4. Contribution impact profile per process stage of the *Biorefinery Scenario* (a) and contribution profiles highlighting the PHA extraction processes by mechanical disruption (b), 2-Butanol (c), Sodium hydroxide (d) and Dimethyl carbonate (e). 🟦 Fermentation; 🟦 Phosphorus recovery through crystallisation; 🟪 Anaerobic digestion; 🟧 Biogas purification and combustion; 🟦 Dewatering; 🟩 Biomass selection and nitritation; 🟨 PHA accumulation and extraction; 🟫 Incineration plant; 🟩 Transportation; 🟥 Other process sections. CC: Climate Change; FE: Eutrophication, freshwater; FRS: Fossil Resource use; LU: Land use; PMF: Particulate matter formation; TA: Terrestrial acidification; WC: Water use. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(809.2 kg $CO_{2eq.}$/t feedstock) which increases the overall CC impact of the biorefinery from the 139.5 kg $CO_{2eq.}$/t feedstock in the baseline scenario using mechanical disruption as PHA extraction up to 947.7 kg $CO_{2eq.}$/t feedstock. This implies a rise of the equivalent carbon emissions of around 6.8 times. According to what is previously mentioned, mechanical disruption is the most environmentally favourable method across all categories considered. It achieves the lowest impacts, with only 1.05 kg $CO_{2eq.}$/t feedstock. The use of sodium hydroxide ranks second, as it is the next more environmentally friendly solution and, lastly, dimethyl carbonate should be chosen as third option. Sodium hydroxide appears to be the most sustainable choice among the solvent extraction methods primarily due to its lower carbon intensity and lower required quantity. Specifically, the use of 36.6 kg of 50 % NaOH solution per functional unit results in approximately 33.5 kg $CO_{2eq.}$ (based on an emission factor of 0.915 kg $CO_{2eq.}$/kg). In contrast, the dimethyl carbonate-based method requires 65.4 kg per functional unit, leading to a significantly higher burden of approximately 198 kg $CO_{2eq.}$ (with an emission factor of 3.03 kg $CO_{2eq.}$/kg).

The *Actual Scenario* has a total impact of 177.8 kg $CO_{2eq.}$/t feedstock for climate change. This implies that the *Biorefinery Scenario* should have

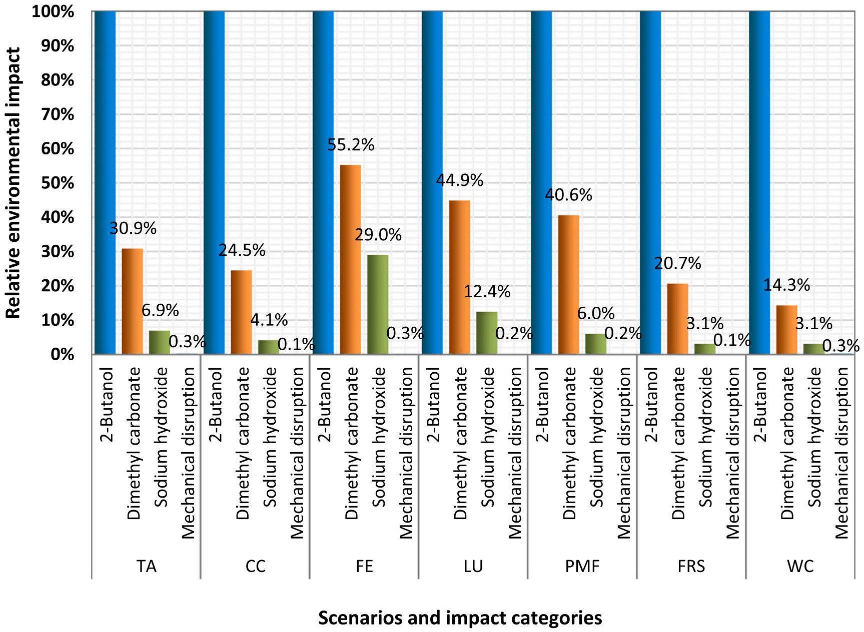

Fig. 5. Relative comparative profile of the environmental impacts of polyhydroxybutyrate extraction methods. CC: Climate Change; FE: Eutrophication, freshwater; FRS: Fossil Resource use; LU: Land use; PMF: Particulate matter formation; TA: Terrestrial acidification; WC: Water use.

at least lower impacts than these to be a more competitive option. For this reason, PHA extraction using 2-butanol or dimethyl carbonate compromises the environmental sustainability of the process. Although dry mechanical extraction remains the preferred option, wet solvent extraction could still be viable if greener solvents such as sodium hydroxide are employed, or if significant improvements are made to existing methods (e.g., reduced solvent consumption, higher recovery rates, and greater extraction efficiency).

4. Discussion

The environmental impacts of the *Biorefinery Scenario* are consistent with findings reported in previous research (the respective systematic literature review undertaken for LCAs on struvite and PHA recovery is shown in Tables S7 and S8). Considering the multifunctionality of the biorefinery facility, which resulted into three *co*-products (polymer, fertiliser and energy) types, the discussion was subdivided in terms of highlighting the sustainability compared to struvite production processes and to PHA manufacturing. To ensure comparability with previous studies, the impacts originally calculated per functional unit (1 t of input waste) were subsequently expressed per kilogram of recovered struvite or PHA, by relating the total scenario impact to the corresponding co-product mass. This conversion step was performed exclusively to align the reference unit with literature values and does not affect the LCA modelling.

In terms of phosphorus recovery through struvite crystallisation, the studies of Zhang et al. [28] and Mayor et al. [24] should be cited as a reference of laboratory and pilot scales. The first assessment concentrated specifically on the environmental burdens associated with the production of the chemicals employed in the struvite recovery process when an inoculated with activated sludge and fed by synthetic wastewater reactor was involved. The achieved environmental impact was around 0.77 kg $CO_{2eq.}$/kg struvite recovered for CC and 0.33 g $P_{eq.}$/kg struvite for FE. By comparison with this research, the *Biorefinery Scenario* under study exhibited impacts of 0.60 kg $CO_{2eq.}$/kg struvite and 0.19 g $P_{eq.}$/kg struvite, demonstrating comparable or even slightly improved performance. When compared to the pilot-scale nutrient recovery technology of Mayor et al. [24], the proposed alternative of this study still outperforms. The reported impacts were 7.33 kg $CO_{2eq.}$/kg struvite and 1.93 g $P_{eq.}$/kg struvite. The outcomes are even better when excluding the impacts related to transportation and PHA extraction to ensure a fair comparison (0.57 kg $CO_{2eq.}$/kg struvite and 0.18 g $P_{eq.}$/kg struvite).

For PHA production, the results should be compared with the study of Vega et al. [26], who assessed two biorefinery pathways treating a mixture of cow manure and grape marc to produce either biogas alone or biogas together with PHA. Similar to our findings, which reported a 26 % reduction in CC relative to the baseline scenario (excluding struvite recovery impacts to ensure a fair comparison), their work showed that integrating PHA production resulted in a 25 % decrease in CC compared to the biogas-only pathway.

Beyond the comparison with single-resource recovery pathways, the results of this study can also be contextualised with respect to other integrated biorefinery configurations reported in the literature. Recent works have investigated multi-output biorefineries combining wastewater treatment with the recovery of polymers, nutrients, and energy streams. For instance, the SMART-Plant project [18] demonstrated that the integrated recovery of PHA and struvite or cellulose at WWTP scale can lead to climate change reductions compared with conventional sludge management. In particular, it is possible to achieve up to 12 % climate change reduction with the integrated recovery of PHA and struvite and up to 19 % when considering the recovery of cellulose only. These values are consistent with the 22 % reduction achieved in the present work under the optimal extraction pathway.

Similarly, the PHARIO project [17] showed that the introduction of PHA recovery into existing WWTPs can reduce the overall environmental burden, although solvent-based extraction significantly increases the impacts. This aligns with the sensitivity results of our study, in which 2-butanol extraction was identified as the least sustainable option, whereas mechanical disruption or sodium hydroxide extraction performed significantly better.

5. Conclusions

This study assessed the environmental performance of a centralised biorefinery designed to integrate the treatment of sewage sludge, agri-food residues and OFMSW in the Lombardy region (*Biorefinery Scenario*). The results demonstrate that the proposed configuration can deliver substantial environmental benefits, including a 22 % reduction in climate change impacts compared with the current decentralised system (*Actual Scenario*). These improvements are driven by higher resource-recovery efficiencies, notably the co-production of PHA, struvite, heat and electricity.

The analysis also shows that the environmental performance of the biorefinery is highly sensitive to the choice of PHA extraction pathway. Mechanical disruption and sodium hydroxide extraction yield the lowest impacts, while solvent-based techniques such as 2-butanol and dimethyl carbonate increase climate impacts by up to 6.8 times, undermining circularity benefits. Hotspots were identified in biogas purification, sludge incineration and struvite crystallisation, indicating priority areas for process optimisation and technological development.

This study provides a novel contribution by assessing, for the first time, a fully centralised biorefinery concept that integrates three heterogeneous organic waste streams (sewage sludge, agri-food residues and OFMSW) using real operational data from multiple WWTPs, while simultaneously recovering PHA, struvite and energy. The combined MFA–LCA framework and the comparative assessment of four PHA extraction pathways offer an unprecedented systems-level evaluation of how technological choices influence the sustainability of regional biorefineries.

Beyond these quantitative findings, the results have clear policy and planning implications. First, regional waste and wastewater strategies should explicitly support the consolidation of organic waste streams, as centralised facilities can achieve higher recovery efficiencies and improve economic feasibility, consistent with recent regional assessments of sludge and biorefinery hubs [7]. Second, the development of technical standards and quality criteria for recovered PHA and struvite is essential to ensure market acceptance and to harmonise product specifications across the region. Third, the establishment of industrial ecosystems and symbiosis networks (linking wastewater utilities, agri-food industries, fertiliser producers and bioplastics manufacturers) can strengthen supply chains for bio-based products and reduce implementation risks. Finally, accelerating the deployment of low-carbon energy sources across wastewater and biorefinery operations would significantly mitigate the impact of energy-intensive stages identified in this study.

These findings position integrated biorefineries as promising enablers of regional circular economy objectives. Despite these insights, the study presents some limitations that should be acknowledged. The MFA and LCA are based on average waste composition and flow data from 2016 to 2022, which may not fully capture the intrinsic variability of sewage sludge, agri-food residues and OFMSW over time. Some process parameters, particularly those related to VFA production, PHA accumulation and alternative extraction methods, derive from laboratory or pilot-scale studies and may not fully reflect full-scale performance. In addition, key processes such as sludge incineration and chemical production were modelled using generic datasets, which may differ from site-specific technologies and emission control systems. The analysis also assumes linear scalability of inputs and outputs and does not include an economic assessment, which may influence the practical feasibility of large-scale implementation. These limitations highlight the importance of further work integrating uncertainty analysis and techno-economic evaluation. Future research should also evaluate the scalability and replicability of this configuration across different territorial contexts and explore how emerging regulatory frameworks and pollutant standards may influence the viability of multi-output resource recovery systems.

CRediT authorship contribution statement

Elisa Blumenthal: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sofía Estévez:** Writing – review & editing, Visualization, Validation, Supervision, Methodology. **Francesco Fatone:** Supervision, Project administration, Funding acquisition, Conceptualization. **María Teresa Moreira:** Writing – review & editing, Validation, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jwpe.2025.109279.

Data availability

Data will be made available on request.

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