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Unlocking the potential of municipal solid waste: Emergy accounting applied in a novel biorefinery

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A B S T R A C T

The rampant municipal solid waste (MSW) generation caused mainly by people's lifestyle has required technological solutions to deal with this global issue. This paper assess an innovative and integrated biorefinery (2IB) to manage MSW. The 2IB is rooted in the circular economy concept, and it differs from any other currently existing technological route in managing MSW due to its integrated processes that receives both inorganic and organic fractions at the same time, besides unveiling an innovative aspect related to thermoplastic production. Due to its scientific-based advantages, the emergy accounting (withy 'm') is considered as method to quantify the 2IB environmental performance, comparing the results with alternatives MSW management facilities. Results show that 2IB has similar performance for the three traditional emergy indicators (m-EYR of 1.17, m-ELR of 5.73 and m-ESI of 0.20) compared to incineration and landfilling, indicating low yield, moderate load on the environment, and unsustainable. On the other hand, the emergy return indicator (ERI of 20.33) indicates higher performance for the 2IB, in which for each solar emjoule (sej) – the measure unit of emergy – invested it generates a return of about 20 sej that becomes available as benefits for societal development. From an emergy perspective, results support that 2IB should be considered as a powerful technological alternative to manage MSW. This study contributes from a theoretical perspective with discussions on the emergy accounting procedures applied on systems located at far right side of energy hierarchy, while contributing from a practical perspective by providing technical information about the 2IB that supports decision makers towards more sustainable MSW management systems.

1. Introduction

The unbridled increase in municipal solid waste (MSW) generation is driven mainly by population growth and changes in consumption patterns. To understand and mitigate future anthropogenic changes initiated by societal demands, MSW management is at the heart of the fundamental changes required (Iyamu et al., 2022), and the lack of awareness and suitable infrastructure to deal with the large amount of waste also triggers social and environmental issues. Currently, about 2 billion tons of MSW are generated each year worldwide (Khan et al., 2022) and this amount is estimated to increase to around 3.5 billion tons by 2050 (Ambaye et al., 2023). According to Vaverková (2019), the MSW is often sent to sanitary landfills and open dumps due to its relatively low cost and low-technical requirements. Specifically for the Brazilian case, the amount of MSW generated was 81.8 million tons in 2022, out of which 76.1 million tons were collected (93 %) and disposed-off in sanitary landfills (46.4 million tons; 61 %) and dumps (29.7 million tons; 39 %) (Abrelpe, 2022).

Recognizing that no single waste management approach suffices for handling all materials and waste flows, the United States Environmental Protection Agency (EPA, 2022) suggested a hierarchy of options to manage waste and non-hazardous materials. Aiming to mitigate greenhouse gas emissions and general energy balances, this hierarchy includes strategies that should be prioritized before sending waste to landfills, which is the last preferable option in the hierarchy. The initial focus should be on minimizing waste generation and promoting the reuse at source. Subsequently, the recycling of inorganic products and the composting of organic matter must be prioritized. In cases where recycling proves unfeasible, waste-to-energy technologies is advocated within the waste hierarchy. Treatment measures may be contemplated prior to the ultimate disposal of waste in a landfill, contributing to a reduction in both volume and toxicity. From this EPA's general concept,

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the biorefineries emerge as a promising alternative capable of managing the entire MSW composition while occupying a desirable position within alternatives. Biorefineries are able to recover energy from waste, transform waste into value-added products, promote composting and recycling, and provide incentives for waste to be separated at source as advocated in the circular economy concept.

Ambaye et al. (2023) revealed that the current existing management practices in high-income countries and other nations predominantly involve landfilling, however, it is well known that applying circular economy practices would lead to a reduction of waste generation at the same time lessens the continent's reliance on raw material imports, which is important for a sustainable development. Developing waste-based biorefineries would not only help to shift the linear economies toward circular economies but also contribute to improving the public health and environment (Nizami et al., 2017). Additionally, Sadeleer et al. (2020) outlined that adopting a circular economy reduces waste sent to landfills by promoting the continual circulation of waste-based products through redesign, reuse, recycling, and energy recovery. Fig. 1a shows a 'linear' production model, which involves resource extraction, production, use and disposal, generating an MSW stock that may cause stress on the natural capital (thicker arrow), draining useful energy that should be direct to societal development. This linear model must be replaced by the 'circular' one (Fig. 1b), which seeks to reduce, restore, and regenerate materials, energy and information, making them available in the production chain.

The Sustainable Development Goals (SDGs; UN, 2022) include goals related to MSW management activities, specifically SDG#11 (make cities and human settlements inclusive, safe, resilient, and sustainable), SDG#12 (guarantee sustainable patterns of consumption and production) and SDG#13 (take urgent measures to combat climate change and its impacts). From them, the #12 deserves special attention as it encompasses specific goals for MSW management, including: (a) target 12.4 that aims to achieve environmentally sound management of waste throughout its life cycle to minimize its adverse impacts on human health and the environment; (b) target 12.5 that seeks to substantially reduce waste generation through prevention, reduction, recycling, and reuse. These specific goals call attention to the need for adequate MSW management, which could be achieved by proposing innovative technological routes such as biorefineries to replace landfilling.

Biorefinery technological routes fed by diverse raw materials have been studied from different disciplines including economics, chemical, and environmental ones. Studies addressing biorefineries generally use feedstocks other than the entire composition of MSW, including sugarcane (Mafunga et al., 2023), microalgae and livestock manure (Rhee et al., 2021), corn fiber (Zhang et al., 2021), and the organic fraction of MSW (Ebrahimian et al., 2023). Scientifically validating a biorefinery is of paramount importance to avoid misleading results that would support non-effective decisions. It is imperative to ascertain the feasibility of implementing a waste-based biorefinery from an environmental standpoint through the utilization of robust tools endowed with a systemic perspective. In addition to conventional metrics used to quantify environmental impacts such as life cycle assessment and ecological footprint, the emergy accounting (with an 'm') is gaining prominence in scientific literature. This method distinguishes itself by considering the donor side perspective in quantifying real wealth, besides considering different degrees or qualities for energy resources, which setting it apart from alternative approaches. Emergy accounting has been applied in different fields such as engineering (Giannetti et al., 2018; Jing et al., 2023; Thomas and Praveen, 2020), agriculture (Agostinho et al., 2019; Enayat et al., 2023; Eyni-Nargeseh et al., 2023), logistic and cities (Agostinho et al., 2021; Blatt et al., 2020; Huang et al., 2018; Xie et al., 2022), sanitation (Ciobanu et al., 2022; Giannetti et al., 2016), DNA and genetic information (Abel, 2013; Jorgensen et al., 2004). Its characteristics and applicability make emergy accounting as a powerful tool for assessing the environmental performance of biorefineries fed by MSW – which lacks in the scientific literature –, providing complementary insights to those ones obtained when applying the traditional life cycle assessment method.

In the context of MSW management, emergy accounting was used by Wang et al. (2018) to assess three alternative scenarios for an incineration plant in China, incorporating economic aspects and emissions impact into traditional emergy-based indicators. The authors concluded that scenario containing incineration plus concrete paving brick production subsystem using bottom ash as raw material achieved the best performance due to its production efficiency. Yazdani et al. (2020) used emergy to compare a conventional natural gas steam power plant with another that incinerates MSW, concluding that renewability and sustainability indicators of the MSW power plant outperformed those of the natural gas power plant. A Sorting and Composting Waste Treatment Plant in Brazil was evaluated from an emergy perspective by Agostinho et al. (2013), who compared the obtained results with two traditional alternatives for managing MSW: sanitary landfill and sanitary landfill with methane recovery for electricity generation. Three modified emergy-based indicators were calculated, and the evaluated sorting and composting plant showed comparatively the highest emergy performance. According to the developed literature review, none of the identified related-studies has applied emergy accounting to an innovative and integrated MSW biorefinery, neither to another innovative facility that manage MSW, claiming efforts in this direction.

Technological routes managing MSW often focus on the separate treatment of the organic and inorganic MSW fractions. Differently, the innovative and integrated biorefinery (2IB) presented and evaluated in this study endeavors to face this challenge by integrating various processes, enabling the comprehensive treatment of the entire waste

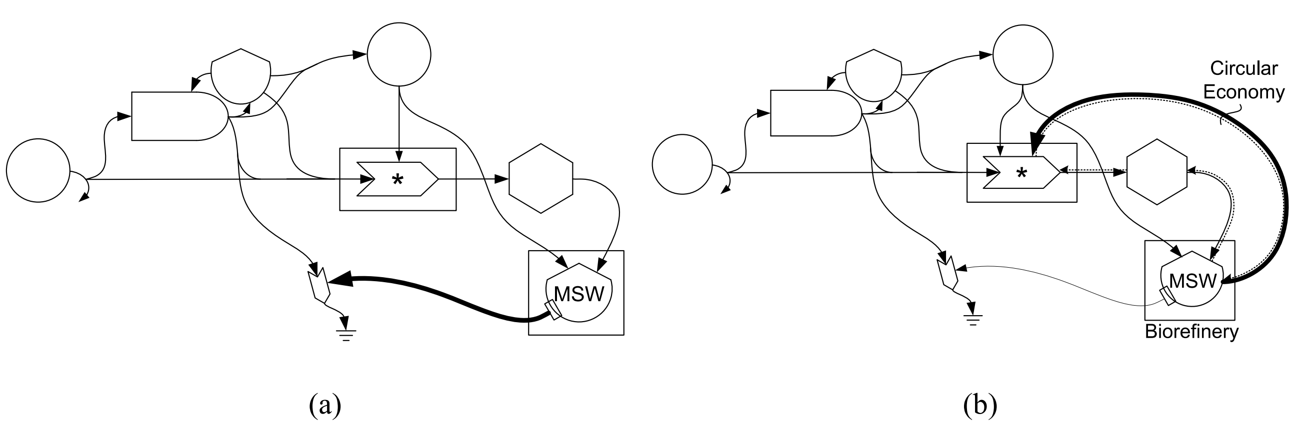

Fig. 1. Energy diagram showing (a) a linear economy gerating high amount of waste and stressing the natural capital, and (b) a circular enonomy through biorefineries feeding back usefull resources to society.

composition without pre-sorting and losses. This holistic approach encompasses a manual and mechanical internal separation facility designed to recover value-added inorganic products, and a mechanical-biological treatment plant dedicated to the mixed organic and inorganic fractions. Within the 2IB plant, anaerobic digestion is employed for the treatment of the separated organic/biodegradable fraction. Besides technological integration, another innovative aspect of 2IB is the introduction of a thermoplastic transformation process fed by the scraps from the previous steps (mixed plastics devoid of recycling potential after removing inert materials). This transformation process aims to generate a series of useful products for civil engineering as often demanded by municipalities in public work projects. Nonetheless, the 2IB exhibits characteristics typical of production systems situated at higher tiers within the energy hierarchy, in which they do not rely directly on natural and/or agricultural resources (both renewable and non-renewable), but solely on economic inputs. Consequently, adaptations in the emergy accounting are required to capture these characteristics. Thus, in addiction to providing technical information about the 2IB, considering emergy accounting as a method supports discussions regarding its applicability in such different systems, under a narrow spatial scale and situated far away from natural systems.

In light of the urgent need associated with addressing MSW management, none biorefinery possessing technology and processes similar to the ones existing within 2IB has already been evaluated or are available in the scientific literature. This stems from the capability of 2IB to handle the entire composition of the MSW in a single plant besides transforming the residual waste into thermoplastic by-products. Furthermore, it is noteworthy that 2IB aligns with the principles of the circular economy, meets the SDGs outlined in the 2030 Agenda, and has already overcome economic and technical aspects as it is being implemented in the South region of Brazil. For these reasons, it is important that 2IB be assessed under environmental lens using a method such emergy accounting that has different concepts and scopes, providing complementary thoughts to the traditional environmental and economic methods often applied.

This paper aims to apply the emergy accounting to assess the environmental performance of an innovative and integrated biorefinery (2IB) managing MSW, comparing the results with MSW management alternatives. This work contributes theoretically by using emergy accounting under modified indicators to better represent systems situated in the right side of an energy hierarchy, besides contributing practically by providing valuable insights for public policies towards more sustainable management for MSW.

2. Methods

2.1. Description of the system studied: An innovative and integrated biorefinery (2IB)

The concept of integrated biorefineries fed by municipal solid waste (MSW) is in its infancy and is starting to be discussed in the scientific literature, mainly for those biorefineries that process both the organic and inorganic fractions of MSW without pre-sorting stages. Although there are various definitions regarding biorefinery in the literature, the one established by Conteratto et al. (2021) is considered in this study: "[…] a physical, chemical or biological process that purifies, separates, refines or transforms constituent elements of biological assets from the kingdoms Monera, Protista, Plantae, Animalia or Fungi, originating from the terrestrial or oceanic environment, into bioproducts for final use or serve as raw material for other bioproducts." It is understood that this definition embeds all the characteristics of the innovative and integrated biorefinery (2IB).

It is well known that reusing or recycling MSW components through different technological routes would prevent the waste generation and its disposal to landfills, however, the integrated biorefineries are not widely explored in literature when compared to composting, incineration, and anaerobic digestion technological routes. The modeling approach of the studied 2IB is based exclusively on primary data obtained *in situ* through a technical visit to an intermunicipal consortium in the state of Santa Catarina, Southern Brazil, which has implemented a 2IB. The 2IB was implemented thanks to a partnership among municipalities as allowed by law 14,026 of 2020 (BRAZIL, 2020), which allows the formation of consortia among municipalities to support them with financial resources intended to implement essential measures on basic sanitation such as drinking water supply, sewage sanitation, urban cleaning, solid waste management, drainage, and rainwater management. It is understood that studying a technological route implemented and operating has already overcome potential barriers related to legislation, technical and financial aspects, missing exclusively its validity from an environmental perspective.

Fig. 2 shows in detail all processes for the MSW management within the 2IB. Municipalities participating in the consortium generates ~180 tons of MSW daily, separated into inorganic waste (20 %; 36 tons/day) and mixed organic and inorganic waste (80 %; 144 tons/day). The inorganic waste undergoes the recycling process that separates the value-added inorganic products (70 % of inorganic fraction; 25.2 tons/day). The residual waste (30 %; 10.8 tons/day) is taken to the ferromagnetic separation process in the thermoplastic transformation. The mixed organic and inorganic waste is diverted to a mechanical separation process that includes a manually pre-screening to remove bulky waste (5.76 tons/day), a hopper with bag ripper, screening conveyor and ferromagnetic separators (6.91 tons/day), a crusher, and at the end a separator/dehydrator that will remove the inorganics (19.70 tons/day) from organics (111.63 tons/day) of the remaining waste from screening process.

Inorganic waste undergoes a thermoplastic transformation system that processes ~17 % (including the residual waste from recycling) of the total generated waste daily. The thermoplastic injection system contains a rotary table that produce thermoplastics using different molds that are changed according to the municipalities demand on a specific product. For example, when traffic signs are required, they are molded/produced. In the quality verification process, defective products are removed and submitted for material grinding and then returning to the mixing process. Within the 2IB, there is an anaerobic digestion that is employed to treat the separated organic/biodegradable fraction. A filter precedes the biodigester with hydrolysis tanks and fermenters in addition to other equipment, producing biogas that are burned to generate heat and electricity, which makes the 2IB self-sufficient in electricity and the surplus is diverted to the national grid. This system works with a volatile solids content of 22 %, which characterizes the system as 'dry', in which none digestate separator or centrifuge is required for compost production. Furthermore, even if this percentage varies, it is unlikely to be necessary to add water; hence, it was disregarded as an input. The spatial boundaries consider the entire 2IB (a gate-to-gate approach), including the processing stage and its products. The stages of waste generation, collection and transportation until plant are not considered for the purposes of this study, which is consistent for a fair comparison between the 2IB with alternatives.

2.2. Emergy accounting

Conventional energy and economic studies mostly account for quantifiable elements in terms of energy or currency, respectively, neglecting all those resources and sources fundamental to support the flow of energy and/or currency. To overcome this narrow perspective about system functioning, the emergy accounting was proposed to systematically examine the economic and environmental facets of a system. From a donor side perspective, emergy accounting includes the transformation of inputs (material, energy, monetary and information flows) since their origin, expressing the effort of nature in generating and

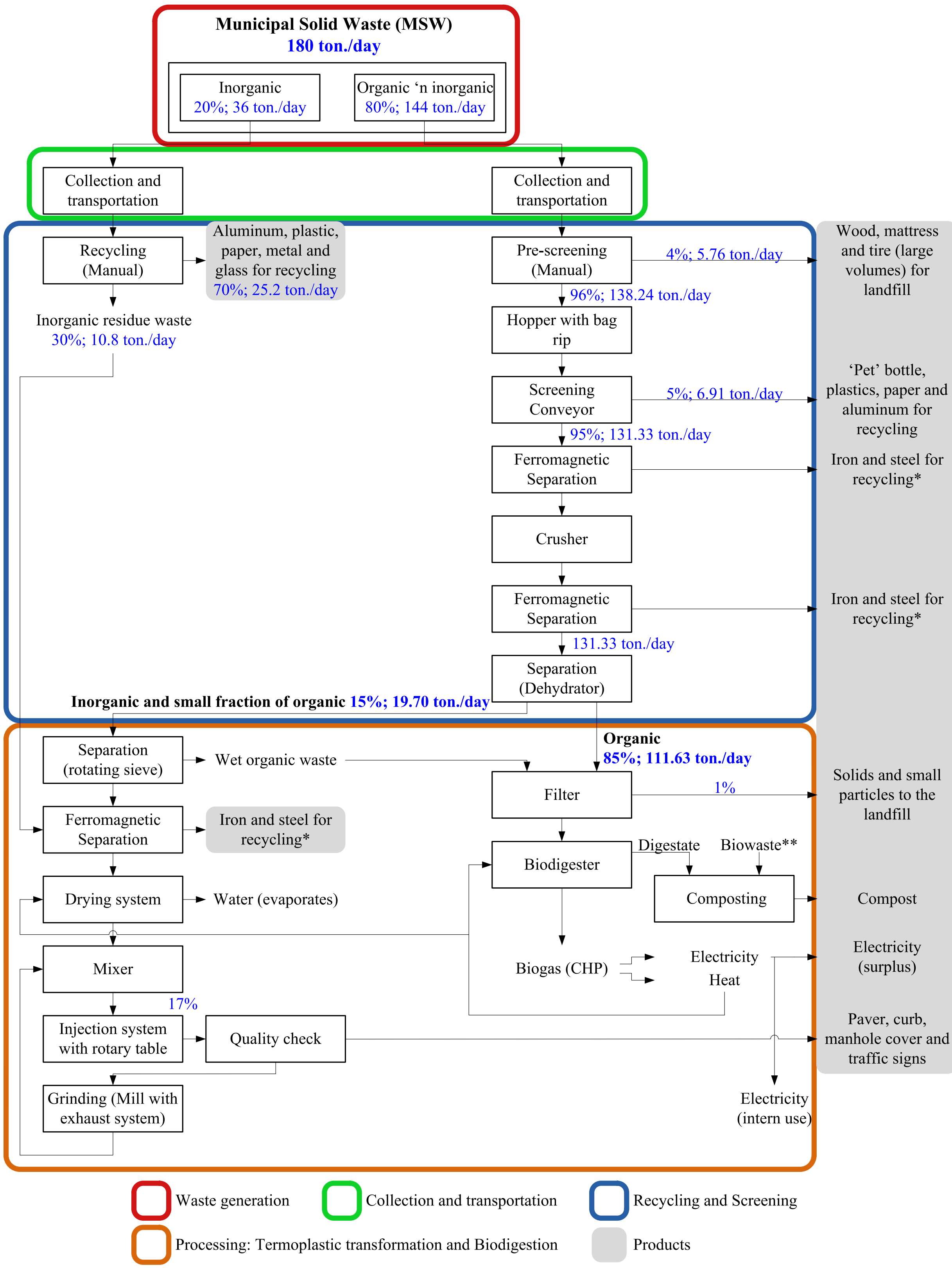

Fig. 2. Detailed flowchart of the studied integrated and innovative biorefinery (2IB) including processes and mass balance. Legend: * Included in 5 % of 'pet' bottle, plastics, paper, and aluminum for recycling. ** The composting process requires the use of biowaste due to the characteristics of the digestate (5 % of solid and 95 % of liquid); the biowaste used is that widely available in the region, such as rice husks. In this case, it would be a rice by-product and the emissions are embodied into the rice production (not the husks), so it has no environmental impact.

sustaining them within the Biosphere. According to Odum (1996, p.7), "Emergy is the available energy used up directly and indirectly to make a service or product".

Emergy accounting employs a top-down methodology, wherein the initial step involves the representation of the studied system through an energy diagram, utilizing symbols outlined by Odum (1996). Drawing energy diagram makes easier to understand how the system works, internally and with the surround environment from a systemic approach. Next, a complete inventory with data on the mass and energy flows for all involved processes must be prepared, which are then multiplied by intensity factors named as Unit Emergy Values (UEVs) to convert different kinds of units (J, kg, $, hours, etc.) into a single unit of solar emjoule (sej), the measure unit of emergy accounting. The UEVs are the core of the emergy method, since they embodies all previous energy used directly and indirectly to make available an item. All flows quantified in sej are classified into renewables (R), non-renewables (N) and feedback from the larger economy (F); their sum express the total emergy (Y) demanded by the system. After aggregation, the emergy-based indicators can be calculated. For a more in-depth comprehension of emergy accounting rules, definitions, and calculation procedures, the work of Odum (1996) is suggested as main reference. All the UEVs used in this study are collected from scientific literature, they do not include labor & services (direct and indirect labor, respectively), and they are standardized to the emergy baseline of 12.00E+24 sej/yr (Brown et al., 2016).

Literature contains examples of studies in which authors have differently interpreted the emergy accounting method from a practical perspective. Focusing on those studying MSW, Wang et al. (2018) and Yazdani et al. (2020) accounted for the MSW as an renewable (R) resource in their emergy accounting, as well as Ayub et al. (2023) assessing poultry manure by-product. According to Odum's (1996) method, by-products feeding back to the same or another production chain do not carry emergy, so its UEV is zero to avoid double accounting mistakes. Thus, the amount of MSW crossing the 2IB boundaries of this present study is not included in the emergy calculations. For comparison purposes, those all referenced studies are updated to exclude the by-product waste as an emergy input.

Instead of using the traditional emergy accounting, this work considers the partial renewability of each input to accurately reflect system's emergy performance as argued by Agostinho et al. (2019). This approach is been used in several studies, including Fonseca et al. (2022) and Correoso et al. (2022) that applied emergy accounting to assess fish production and to highlight the importance of homeopathy in small family-managed farms, respectively. Since many of the materials and energy flows that come from the larger economy have a certain degree of renewability, considering the partial renewability can be considered a step towards higher precision in studying those systems that largely depends on economic resources. This is especially true for those countries that have diversified energy matrix and are not fully dependent on fossil energy. Additionally, it is important to highlight that the inclusion of partial renewabilities overcomes an operational problem when applying emergy accounting for those systems located in the far right of energy hierarchy (far from natural or agricultural systems) and that strongly depends on resources from the larger economy. Once the traditional emergy indicators are considered for those systems without including partial renewabilities, most of them cannot be even calculated since there are no R and N resources being directly used by the system. Other option as usually applied in life cycle assessments would be enlarge the system boundaries to include natural or agricultural systems, but applying this criterion is in the hands of analyst and it must respect the goals of the study. Table 1 shows and describes the emergy-based indicators used in this study, all of them including the partial renewability of materials and energy that cross system boundaries.

Table 1
Emergy-based indicators used in this work.

Indicator		Meaning	Equation
m-EYR	Modified emergy yield ratio	Net emergy contribution that system makes available to societal development.	$m-\mathrm{EYR} = \frac{R+N+\mathrm{Mn}+\mathrm{Sn}+\mathrm{Mr}+\mathrm{Sr}}{\mathrm{Mn}+\mathrm{Sn}}$
m-ELR	Modified environmental loading ratio	The pressure on the environment caused by the production process. Values <2 indicate low pressure, between 2 and 10 moderate, and >10 high pressure (Brown and Ulgiati, 2004).	$m-\mathrm{ELR} = \frac{N+\mathrm{Mn}+\mathrm{Sn}}{R+\mathrm{Mr}+\mathrm{Sr}}$
m-ESI	Modified emergy sustainability indicator	Contribution of a resource/process to the economy per unit of environmental loading: higher values indicate higher sustainability. Values <1 indicates unsustainability, between 1 and 5 short-term sustainability, and >5 above high sustainability (Brown and Ulgiati, 2004).	$m-\mathrm{ESI} = \frac{m-\mathrm{EYR}}{m-\mathrm{ELR}}$
ERI	Emergy return indicator	Indicates how much emergy is being made available to society per unit of emergy invested: value <1 implies environmental load, while value >1 indicates a benefit.	$\mathrm{ERI} = \frac{\text{Emergy Saved}}{R+N+\mathrm{Mn}+\mathrm{Sn}+\mathrm{Mr}+\mathrm{Sr}}$

Y, yield (R + N+Mn+Sn+Mr+Sr); R, renewable resources from nature; r, renewable fraction of a source; N, non-renewable resources from nature; n, non-renewable fraction of a source; F, resources from the larger economy; M, materials from economy; S, services from economy; m, modified.

3. Results

3.1. Modelling the innovative and integrated biorefinery (2IB)

The energy diagram of Fig. 3 is a representative model of the innovative and integrated biorefinery (2IB), showing from a systemic perspective its main external energy sources and the material flows, energy and labor that supports its implementation and operation. A technical visit was carried out to obtain data *in situ*. The larger outer box represents the boundaries of a large system for MSW management (including collection and transportation), while the 2IB-evaluated boundaries encompasses the MSW processing (gray boxes) and products. The smaller gray box shows the 'recycling' process of inorganic waste, while the larger gray box reveals the 'thermoplastic transformation and biodigestion' processes that treat the mixed waste. Important to emphasize that while the previous Fig. 2 aims to show internal processes in detail (including values of mass and energy balances), the energy diagram of Fig. 3 aims to highlight the external driver sources sustaining the 2IB. External drivers include the MSW (inorganic fraction separated at source, and mixed organic and inorganic waste), diesel, materials, services, and labor. Internal processes represents the interaction of these materials and energy sources, resulting in product outputs such as recyclables, compost, electricity and thermoplastics.

In the recycling process, the inorganic waste is first classified by hand-working to separated recyclable materials such as plastics, paper, wood, glass, among others. Due to contamination with organics or small pieces of waste, a small fraction of inorganics cannot be separated, and it is named residual waste. This percentage is diverted to the thermoplastic transformation cycle, a novelty that has not yet been studied in scientific literature. Regarding the mixed organic and inorganic waste, the screening process aims to reduce the load on the system by removing iron and steel, and other large-sized waste such as tires. Next, a separator classifies the organic and inorganic waste, which go to subsequent processes. The thermoplastic transformation cycle produce pavers, curbs, manhole covers, and traffic signs by using the inorganic fraction. All these products are substitutes of concrete, wood, and steel, that are no longer needed due to thermoplastics usage. In the other production line, there are heat, electricity, and compost production by using the organic fraction that goes through the anaerobic digestion process. Heat is totally used in the plant, while the electricity is partially used internally (covering 100 % of plant's needs) and the surplus is sent to national grid. Important to note that the amount of all these output products may range according to local demand or stakeholders decisions, in other words, the 2IB is flexible in some extend and can produce greater or lesser amount of compost, electricity, heat, and kinds of thermoplastic products.

3.2. The inventory of the innovative and integrated biorefinery (2IB)

Table 2 shows the inventory data for the 2IB, which is based exclusively on primary data obtained from a technical visit *in situ* during 2022. The identification of energy and material flows supporting the 2IB is facilitated by the energy diagram of Fig. 3. Raw data was obtained about type, quantity, and processes associated with all internal equipment, data about energy demand (electricity and diesel), labor demand, and data about the type and quantity of output products (biogas, heat, electricity, compost, thermoplastics, and recyclables). Details are presented as Supplementary Material, which resulted in the aggregated inventory of Table 2.

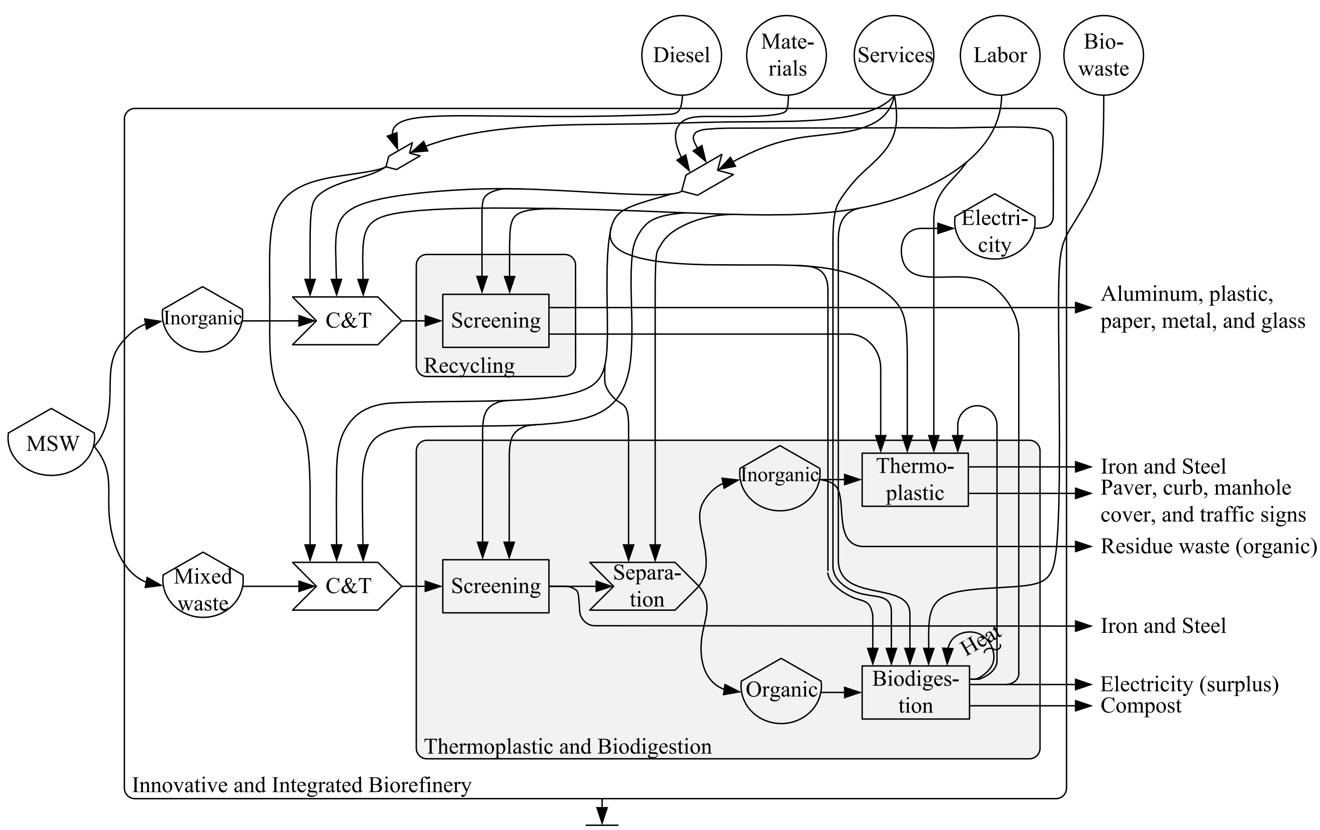

Fig. 3. Energy diagram of the integrated and innovated biorefinery (2IB). Symbols from Odum (1996). Legend: C&T, collection and transportation; External circles, external sources of material, energy or labor; Tank symbol, storage of material or energy; Large arrow, interaction of materials, energy and/or labor; Larger rectangle, boundaries of studied system; Internal rectangles, processes.

Table 2
Inventory summary table for the integrated and innovative biorefinery (2IB). Data for 2022.

Item	Data in annual basis	Data in tons of MSW				
		With C&T			Without C&T	
	Quantity	Unit/yr	Quantity	Unit/ton.MSW	Quantity	Unit/ton.MSW
Inputs						
Steel	6.09E+04	kg	9.27E-01	kg	4.75E-01	kg
Concrete	9.04E+03	kg	1.38E-01	kg	1.38E-01	kg
Diesel [a]	3.84E+05	L	4.99E+00	kg	0.00E+00	kg
Electricity	0.00E+00	kWh	0.00E+00	kWh	0.00E+00	kWh
Wood	7.80E+02	kg	1.19E-02	kg	1.19E-02	kg
Biowaste [b]	0.00E+00	kg	0.00E+00	kg	0.00E+00	kg
Labor	1.98E+02	people	3.01E-03	people	1.72E-03	people
Outputs						
Electricity (Surplus)	2.51E+06	kWh	3.82E+01	kWh	3.82E+01	kWh
Compost [c]	8.80E+03	m^3	1.34E+02	kg	1.34E+02	kg
Paver (substitute concrete) [d]	4.80E+05	m^2	2.19E+02	kg	2.19E+02	kg
Paper and paperboard	5.45E+03	ton	8.30E+01	kg	8.30E+01	kg
Plastic	4.09E+03	ton	6.23E+01	kg	6.23E+01	kg
Glass	2.18E+03	ton	3.32E+01	kg	3.32E+01	kg
Metal/Iron	1.23E+03	ton	1.87E+01	kg	1.87E+01	kg
Others (polystyrene, electronics, vegetal oil and tissue) [e]	6.82E+02	ton	1.04E+01	kg	1.04E+01	kg

The detailed inventory of equipment and materials is available in the Supplementary Material, 'Inventory (complete)' sheet.
C&T, Collection and Transportation.
[a] Diesel from L to kg, density of 0.853 kg/L;.
[b] Biowaste is a by-product from other system, thus its impact is allocated to the other system as explained in the main text;.
[c] Compost m^3 to kg, density 1000 kg/m^3;.
[d] Paver from m^2 to kg, density 30 kg/m^2;.
[e] Not considered because it represents a small fraction (<2 %) of the total recycled materials.

Despite the inventory featuring annual data including collection and transportation phases, the last two columns (gray colored) of Table 2 contains numbers per ton of MSW and without including collection and transportation, which is considered to meet the purposes of this work. As previously explained, it is consistent removing collection and transportation phases because the same approach is considered when comparing the performance of 2IB with alternatives; in fact, collection and transportation impacts are the same independently of the MSW management technical route being assessed. Consequently, any comparison is equitable as the assessment focuses solely on the MSW processing plant.

As previously delineated, the electricity generated by 2IB serves a dual purpose: a portion is allocated to support the plant's operational processes, and the surplus is designated as a substitute for the national energy matrix. The quantity of electricity utilized internally was subtract from the overall electricity output, thereby rendering the electricity input figure as zero in Table 2. In the case of diesel, a zero value is assigned due to the exclusion of collection and transportation phases, and no diesel is used within the 2IB. For the biowaste used in the composting process, its value is assumed as zero since it is a local by-product, including rice husks or wood residues.

3.3. *Emergy performance indicators of the innovative and integrated biorefinery (2IB)*

Table 3 shows the calculation of the invested (inputs) and recovered (outputs) emergy through the management of MSW by the 2IB. The second column outlines the type of flows involved in the waste biorefinery, in which it is interesting to note that 2IB do not directly demands natural resources R and N. External resources come exclusively from the larger economy, claiming an adaptation in the emergy accounting algebra for indicators calculation. The feedback resources from economy (F) is divided into Mr, Mn, Sr and Sn as a way to include the partial renewability of each input; suffixes 'r' and 'n' indicates renewable and non-renewable, respectively. All flows of the same type are summed to allow emergy indicators calculation as previously described in Table 1. The last column of Table 3 shows the emergy flows for each input, all under a functional unit of sej/ton of MSW. Initially, it is interesting to note that 2IB requires very simple inputs, basically steel for infrastructure and machines, energy to move the machines, and direct labor. Services are notably the input that contributes most to the total emergy (~98 %), followed by steel and concrete that combined achieved ~2 %. Similarly, a high emergy value of 85 % for services and labor was reported by Yazdani et al. (2020) studying an incineration plant. Differently, the three incineration scenarios assessed by Wang et al. (2018) presented a range from 18 % to 38 % for services, while Pan et al. (2018) obtained 44 % for services and labor assessing a landfill with electricity production. The high emergy dependence of 2IB from services may be a result of the high operational costs required a large number of engineering processes, perhaps, a characteristics of systems located in the far right of energy hierarchy; assessing this aspect claims for future efforts when more data becomes available.

In terms of generated products, plastic reclaimed through recycling constitutes a substantial contribution to total emergy recovered (~43 %), followed by thermoplastic paver (~37 %). Important to emphasize that thermoplastic products and their inherent saved emergy represent a novel approach in MSW management, diverging from previous studies that addressed exclusively the organic fraction in biorefineries. The electricity and compost products are both usually obtained by traditional technologies routes managing MSW like incineration and composting, and their emergy saved achieved together 3.5 % of the total recovered emergy. These results highlights the potential application of 2IB, since it generates more products than the usual compost and electricity; in some technological routes, the only product obtained is usually electricity. Differently, two of the integrated incineration systems evaluated by Wang et al. (2018) produced, in addition to electricity, concrete paving brick and non-burnt wall brick. Anyhow, electricity assumed an important role for the second evaluated scenario, achieving 31 % of total emergy saved.

Table 4 shows the emergy indicators of 2IB calculated using numbers of Table 3. The value of 1.17 for m-EYR indicates a high dependence on non-renewable purchased resources (Mn+Sn) of total emergy. The 2IB is not able to explore large amount of emergy from renewable purchased resources and make them available to societal development. The referenced studies available in Table 4 reached m-EYR from 1.02 to 1.59, similar performance than for 2IB. These low performances for m-EYR

Table 3
Emergy table for the innovative and integrated biorefinery (2IB). Collection and transportation phases are not included.

Items and their partial renewabilities [a]	Type	Unit/ton MSW	Quantity	UEV [b](sej/Unit)	Emergy(sej/ton MSW)	Emergy (% of total)
Inputs						
Steel (0 %)	Mn	kg	4.75E-01	2.01E+12	9.54E+11	1.78
Concrete (0 %)	Mn	kg	1.38E-01	1.83E+12	2.52E+11	0.47
Diesel (0 %)	Mn	kg	0.00E+00	5.98E+12	0.00E+00	0.00
Electricity (68 %)	Mn	kWh	0.00E+00	4.18E+11	0.00E+00	0.00
Wood (82.4 %)	Mn	kg	2.09E-03	1.94E+11	4.05E+08	0.00
	Mr	kg	9.79E-03	1.94E+11	1.90E+09	0.00
Biowaste (100 %)	Mr	kg	0.00E+00	–	–	0.00
Services (15.2 %)	Sn	USD$	5.28E+00	8.41E+12	4.44E+13	82.89
	Sr	USD$	9.46E-01	8.41E+12	7.96E+12	14.86
Labor (15.2 %)	Sn	people	1.46E-03	1.54E+07	2.25E+04	0.00
	Sr	people	2.61E-04	1.54E+07	4.04E+03	0.00
Total emergy (Y = Mn + Mr + Sn + Sr) =					5.36E+13	100.00
Total renewables (Mr + Sr) =					7.96E+12	14.90
Total non-renewables (Mn + Sn) =					4.56E+13	85.10
Outputs						
Electricity (surplus)		kWh	3.82E+01	4.18E+11	1.60E+13	1.5
Compost		kg	1.34E+02	1.61E+11	2.16E+13	2.0
Paver (concrete substitute)		kg	2.19E+02	1.83E+12	4.01E+14	36.8
Paper and paperboard [c]		J	1.31E+09	5.60E+04	7.32E+13	6.7
Plastic		kg	6.23E+01	7.46E+12	4.65E+14	42.7
Glass		kg	3.32E+01	2.75E+12	9.14E+13	8.4
Metal/Iron		kg	1.87E+01	1.09E+12	2.03E+13	1.9
Others (polystyrene, vegetal oil, electronics and tissue) [d]		kg	1.04E+01	–	–	–
Total emergy saved with outputs =					1.09E+15	100.0

Calculation details is available as Supplementary Material. Legend: UEV, unit emergy value; sej, solar emjoules; r, renewable fraction of a source; n, non-renewable fraction of a source; M, materials from economy; S, services from economy.

[a] Partial renewabilities obtained from: Electricity (68 % from Brown and Ulgiati, 2002); Wood (82.4 % from De Oliveira et al., 2018); Labor & Services (15.2 % from Sweeney et al., 2007);.

[b] UEVs under the emergy baseline of 12.00E+24 sej/yr;.

[c] Paper calorific value: 15,740 kJ/kg. Therefore 83 kg of paper/ton.RSU = 1.31E+09 J;.

[d] Not considered because it represents a small fraction of the total recycled materials.

were expected since systems designed to manage MSW have different goals than production system that makes available goods and services. They are not designed to explore emergy from R or N resources, instead, they are highly dependent on F resources with the ultimate goal of treating MSW, a downstream issue generated by humankind. In fact, this characteristic is observed also for m-ELR and ESI emergy indicators. The m-ELR for 2IB of 5.73 indicates moderate load (Brown and Ulgiati, 2004) on the environment due to a 6 times higher consumption of non-renewable economic resources (Mn+Sn) than renewable economic ones (Mr+Sr). For comparison, the incineration alternatives studied by Yazdani et al. (2020) e Wang et al. (2018) have found m-ELR values between 11 and 63, which means an extremely high pressure on the environment. For the landfill with electricity generation of both Pan et al. (2018) and Sulis (2023), the results presented a wider range of values, ranging from 1.7 to 28, respectively causing low and extremely high pressure on the environment. Due to its low emergy yield and moderate load on the environment, the 2IB obtained an m-ESI of 0.20, which indicates an unsustainability scenario under emergy perspective. For comparison, none of the comparative studies in Table 4 was able to achieve a minimum value for m-ESI of 1, indicating that they are all unsustainable. As explained above, this would be a characteristic of this kind of system that deals with waste management, since from a narrow

Table 4
Emergy-based indicators obtained for the integrated and innovative biorefinery (2IB) and other references for technological routes dealing with the management of municipal solid waste. All indicators are dimensionless.

Source (facility)	Emergy-based indicators			
	m-EYR	m-ELR	m-ESI	ERI
This study (Biorefinery 2IB)	1.17	5.73	0.20	20.33
Yazdani et al. (2020) (Incineration)	1.09 [a]	11.69 [a]	0.09 [a]	2.84 [a]
Wang et al. (2018) (Incineration Scenario A)	1.03 [a]	30.51 [a]	0.03 [a]	0.90 [a]
(Incineration Scenario B)	1.02 [a]	63.52 [a]	0.02 [a]	7.44 [a]
(Incineration Scenario C)	1.03 [a]	37.90 [a]	0.03 [a]	2.22 [a]
Pan et al. (2018) (LFG)	1.48 [a]	2.09 [a]	0.71 [a]	–
(LFG with electricity generation)	1.59 [a]	1.70 [a]	0.93 [a]	0.73 [a]
Sulis (2023) (Landfill with electricity generation)	1.02 [a]	28.26 [a]	0.04	0.06 [a]

[a] These values are based on the original numbers provided by authors, but they were updated to allow comparisons since the algebra in calculating emergy indicators was modified in this study.

Legend: LFG, landfill gas.

perspective (gate-to-gate approach), their ultimate goal is to treat the waste rather than be sustainable.

Perhaps the most representative emergy-based indicator to assess the performance of MSW treatment systems is the ERI, since it shows a kind of efficiency performance comparing inputs with outputs. Table 4 shows the best score obtained by the 2IB with 20.33, which means that for each sej invested in the 2IB, about 20 sej returns back to society, a social gain since the 2IB is a positive net emergy system. The lowest performance for ERI was obtained by the landfill with electricity generation (Sulis, 2023), while the second-best performance was for incineration (scenario B; Wang et al., 2018). Due to its importance in showing the emergy performance for waste treatment systems, the ERI is deeper discussed in the next section. From a general view, Table 4 shows that 2BI achieved similar emergy performance for yield, environmental load and sustainability compared to other referenced studies, occupying an intermediary position within average values as expected for waste treatment systems. Exception can be observed for the ERI, in which the 2IB obtained by far the best performance.

4. Discussions

Emergy accounting applied to technological routes fed by different raw materials than MSW has been studied and are available in the literature. For instance, Jalili et al. (2022) investigated an energy system utilizing a multi-stage flash desalination unit to recover waste heat from a gas turbine. The authors assessed three scenarios with different feedstocks: biomass/natural gas, natural gas, and biomass. Although most indicators yielded very similar results for the three scenarios, the scenario powered by biomass stood out by achieving a sustainability indicator ~6 times higher than the other two. Ali et al. (2018) used household solid waste as feedstock to be managed in sanitary landfilling with composting and recycling, and incineration with composting and recycling. Results showed no significant differences for emergy indicators between systems, indicating that other methods such as life cycle assessment could be applied as an attempt to highlight differences. Spagnolo et al. (2020) studied a biogas power plant under two scenarios, the reference scenario fed by agricultural crops such as wheat and maize, and an expanded scenario that also includes liquid cattle manure. Even though the first scenario incurred an environmental load (ELR) approximately 2.5 times higher than the second scenario, the emergy-based sustainability (ESI) indicator did not reveal substantial differences in the results, achieving 0.003 and 0.007 respectively. Moss et al. (2014) evaluated two types of digesters, one designed for treating human waste (sanitary waste from hospitals) and the other for treating dairy manure. It is noteworthy that digester working with dairy manure caused an environmental load (ELR) ~20 times higher than the one dealing with human waste, while the renewability ratio exhibited the opposite trend. Other examples include studies on diverse feedstocks such as cassava chips for fuel ethanol (Yang et al., 2010), palm oil and jatropha to produce biofuels (Nimmanterdwong et al., 2015), and agricultural and food industrial residues for biofuel and biomaterial production (Saladini et al., 2016). All these studies highlights that biomass plays important role as feedstock under different technological routes, however, none of them have considered municipal solid waste (MSW) as feedstock. The literature review indicates a dearth of studies focusing on emergy accounting applied to novel technologies for the integrated management of both organic and inorganic waste in the MSW. This raises the importance of assessing the innovative and integrated biorefinery (2IB), providing information and trying to cover a scientific gap.

Notwithstanding the lack of emergy studies on MSW technological routes, most of them have considered the traditional emergy indicators and ignored a net-emergy analysis such as the ERI indicator used in this study. Perhaps, focusing on net-emergy analysis would be most significant for decisions than indicators of sustainability and renewability, since the waste management projects have different goals (treat the waste) than traditional production systems that aims to produce a good or service and make them available for use. Anyhow, diverse emergy-based indicators for different MSW technological routes are presented in Table 4 for comparisons, including the ERI. Despite the limited availability of studies on MSW biorefineries, it is imperative to evaluate also traditional waste disposal strategies (*e.g.* landfilling and waste-to-energy) to ascertain their respective performances, which is the reason for comparative analysis among all potential technological routes, looking for advantages and disadvantages. The pursuit of facilities capable of treating all components of MSW remains a priority, and a potential project on this regard is the assessed 2IB, which aligns with the priority measures outlined in the waste management hierarchy as proposed by the EPA (2022).

For deeper discussions supporting insights, the results obtained in this study for the 2IB are compared with data obtained from others studies that applied emergy accounting in different MSW technological routes, even few studies are available in the scientific literature. It is important to emphasize that to make comparisons consistent, the studies from literature were standardized according to the calculation procedures and assumptions carried out for 2IB. Specifically, two aspects are focused and explained as follows. (1) Although recognizing that the analyst must decide what input should or should not be accounted for when applying emergy accounting, it appears peculiar that some studies accounted for MSW as a renewable input, since from emergy theory, the MSW is a co-product of another system, and it has no emergy. Thus, all referenced studies have been updated to exclude the MSW input from emergy tables. The same applies to renewable and non-renewable resources such as rainfall, solar radiation, oxygen, and soil, since none of them seems to pertain to an emergy accounting of MSW treatment plants. (2) The inclusion of partial renewability is recognized in this study as an advance and important step when applying emergy accounting on those systems located far to the right side of the energy hierarchy. Thus, all the referenced studies were updated to include the same value of partial renewabilities for the same inputs as considered by the 2IB. The spreadsheet containing all amendments on the emergy tables and indicators from the referenced studies are available upon request from the corresponding author.

It is crucial to highlight the importance of comprehensive assessment in waste management strategies, thus comparing the results of 2IB with other studies helps to discuss the validation of this system. In this regard, Yazdani et al. (2020) applied emergy accounting to study the treatment of MSW through an incineration process, obtaining m-EYR of 1.09, m-ELR 11.69, and m-ESI 0.09. Comparing these indicators with those ones obtained by the 2IB in Table 4, one can see that incineration has an m-EYR similar to that of the 2IB, while the m-ELR indicated a twice-as-high environmental load for incineration; anyhow, both systems are considered unsustainable with an m-ESI lower than 1. Wang et al. (2018) studied an existing incineration plant in China by expanding the system into three new scenarios for comparisons. The first modeling incorporates incineration together with the bottom ash landfill subsystem, the second incorporates incineration with the concrete paving brick production subsystem using bottom ash as raw material, while the third includes the incineration plant and the non-burnt wall brick production subsystem using bottom ash as raw material. The three systems obtained a m-EYR of 1.03, a value similar to the incineration plant studied by Yazdani et al. (2020) and to the 2IB. Notably, the second modeled scenario stood out with a value of 63 for the m-ELR, causing a load on the environment ~11 times higher than that of the 2IB. Due to low yield and high load on the environment, the systems studied by Wang et al. (2018) presented the lowest values for m-ESI among all the compared systems in Table 4. None of the three incineration systems was able to perform better than 2IB for any emergy indicator.

Pan et al. (2018) applied emergy accounting to assess two technological routes managing MSW, a landfill gas generation system and a landfill gas with electricity production system. The emergy yield indicator (m-EYR of ~1.5 for both systems) presented a value slightly better to the one found by Yazdani et al. (2020; m-EYR of 1.09) regarding incineration, as well slightly better to Wang et al. (2018) for incineration scenarios (m-EYR of 1.03). Anyhow, a 1.5 ratio is far from being considered a good general performance, since it is not difficult to find EYR values higher than two for those systems with characteristics of natural and/or agricultural environments. These results were anticipated, as all the compared systems are closely situated within the energy hierarchy chain. This proximity implies a high demand for resources from the economy, with minimal or no impact on the natural environment. The environmental load proved to be lower for both the first (2.09) and the second (1.70) systems examined by Pan et al. (2018) in comparison to 2IB (5.73), indicating lower load on the environment. However, that good performance for m-ELR was not enough to provide better sustainable performance (m-ESI) for the first (0.71) or second (0.93) systems. Even obtaining higher m-ESI than for the 2IB (0.20), the m-ESI resulted in values below 1 that indicates an unsustainable scenario for all. Finally, the emergy indicators for the landfill system with electricity production from Sulis (2023) showed performance similar to that of the incineration 'scenario A' of Wang et al. (2018), regarding the m-EYR, m-ELR and m-ESI indicators. It is important to keep in mind that in 'scenario A' studied by Wang et al. (2018) only the landfilling of the MSW was considered, that is, it was not incinerated, a very similar scenario to the one studied by Sulis (2023). From a general comparison, Table 4 indicates the system LFG (landfill gas) with electricity generation studied by Pan et al. (2018) as the best one, although emphasizing that its emergy performance is far from being considered sustainable; worst general performance was obtained for incineration 'scenario B' of Wang et al. (2018).

Besides calculating the traditional emergy performance indicators of m-EYR, m-ELR and m-ESI, the ERI is also calculated since it plays an important role in decision-making regarding the implementation - or not - of a specific MSW management system, because it reveals the return on investment in emergy terms. In other words, it focuses on a net-emergy approach by indicating how many solar emjoules (sej) can be obtained for each sej invested. The ERI is, perhaps, the most important emergy performance indicator for systems dealing with MSW treatment. Values higher than 1 indicate a net positive return on emergy invested, while values lower than 1 indicates the opposite. Table 4 shows values ranging from 0.06 to 20.33. The lowest performance was obtained by the landfill system (Sulis, 2023), while the 2IB showed the best performance of 20.33. Three systems indicate a negative emergy return – or an emergy disadvantage –, including landfill, LFG with electricity generation, and incineration scenario A. Differently, four systems indicate a positive emergy return, including the 2IB, incineration scenarios B and C, and incineration. Under the ERI lens, the 2IB should receive priority in public policies than all other six – excluding the LFG that has no ERI – MSW treatment systems evaluated.

From Table 4, it is interesting to note that obtained ERIs are consistent with the waste management hierarchy as proposed by EPA (2022). Landfills with electricity production deemed a low priority as MSW ultimately ends up in a landfill. These systems obtained the lowest ERIs (0.06 and 0.73) among all compared systems, indicating that they are the least preferable options in MSW management. The incineration alternatives showed medium ERIs comparative values, ranging from 0.90 to 7.44. Emphasis is placed on the performance of 2IB with the highest performance for ERI of 20.33, indicating that it is the most preferable option for MSW management and consistent with EPA's (2022) waste management hierarchy. Although it requires a higher amount of emergy for its implementation and operation phases, the 2IB's output products culminated in the highest ERI among the technological routes compared in Table 4, providing a high amount of emergy to society with low emergy investment.

Another way to evaluate the comparative performance of the 2IB supplementary to the emergy perspective would be through an economic approach as usually considered in decisions. As previously discussed, the ERI indicates how much emergy is being made available to society per unit of emergy invested. This indicator can also be represented from an economic point of view, known as Return on Investment (ROI). ROI is a performance-measuring tool used to evaluate the profit in investment, which can be calculated by dividing the net profit by the cost of investment (Ahmad et al., 2024); slightly different from ERI in concept. However, in this study it was opted to adapt ROI to mirror the ERI from a financial standpoint, thus establishing an output/input relationship (the correlation between money obtained from product sales per money invested in production) with the aim at verifying whether both indicators express similar performances, albeit from different approaches such as economic and emergy. The result obtained for the 2IB showed an ROI of 5.28, meaning that 5.28 monetary units are saved for each 1 monetary unit invested. This result is aligned with the ERI value of 20.33 for 2IB, showing both economic and emergy gains. For comparison purposes focusing on ROI, Rubio-Romero et al. (2013) reported a value of 1.73 for biogas recovery from landfills, Xin-Gang et al. (2016) obtained 1.37 for the incineration industry in China, and Chowdhury (2021) a value of 1.22 for anaerobic digestion considering only the organic fraction; although the latter study also included collection and transportation within its scope. These numbers highlight an average 3.6 times higher ROI performance for the 2IB compared with alternatives. It is noteworthy that literature data were adjusted to maintain the same output/input relationship as proposed in this study, ensuring consistent comparisons. Overall, these results suggest a win-win performance under environmental and economic perspectives for the MSW management techniques.

While providing interesting insights into the emergy performance of 2IB, this study still has limitations that should be considered in future efforts. Firstly, it is suggested to address the economic, environmental, and social feasibility of the 2IB by simulating the MSW composition, since the proportion of organic and inorganic waste within MSW varies across regions according to socio-economic status and could render the 2IB impractical from a technological perspective. Typically, affluent individuals generate higher amounts of inorganic waste, whereas less affluent individuals produce more organics. Secondly, the practical implications of public policies should encompass the collection and transportation stages. Both stages were not included in this study since the focus was a comparative analysis among technological routes, which is considered theoretically consistent. Nevertheless, the considerable distances involved in transportation may impact the viability of 2IB, both economically and environmentally, potentially influencing decisions regarding its implementation. A third recommendation involves calculating the Emergy Exchange Ratio (EER) to facilitate discussions on a 'fair' or 'balanced' market price for the 2IB's output products (paver, compost, electricity, etc.). This approach can offer insights into the scope of traditional economic disciplines compared to an emergy perspective in valuing goods or services. Important to emphasize that, although recognizing these limitations, the results obtained in this study are consistent with the methods applied and comparisons discussed, leading to scientifically solid conclusions. It is expected that this work contributes by supporting related public policies, enabling more informed and robust decision-making when exploring new technologies for effective MSW management. Additionally, the modified emergy indicators considered would allow discussions about the method and its applicability on systems that do not directly demand natural resources for its implementation and operation, whether classified as renewable or non-renewable.

5. Conclusions

This study applied emergy accounting to an innovative and integrated biorefinery (2IB) that manages municipal solid waste (MSW), discussing its emergy performance indicators with technological alternatives. One main contribution of this study is the detailed introduction of an innovative technological route dealing with MSW management.

The 2IB distinguishes itself from other technological routes by presenting an integrated processes approach, in which both inorganic and organic fractions are jointly managed to facilitate operational issues without the need of pre-sorting processes. Additionally, differently from traditional MSW plants, the 2IB produces thermoplastics from the scraps from inorganic waste fraction instead of exclusively recycling materials, at the same time it generates compost, biogas, and electricity from organics.

From an emergy accounting perspective, the 2IB obtained low performance for the emergy yield (m-EYR of 1.17), moderate load on the environment (m-ELR of 5.73) and it finds itself in an unsustainable scenario (m-ESI of 0.20). This performance was expected due to the inherent characteristics of systems dealing with MSW management, located in the far right of an energy hierarchical scale and depending exclusively on resources from the larger economy. On the other hand, the 2IB obtained good performance for the emergy return indicator (ERI of 20.33), showing that for each solar emjoule (sej) invested to implement and operate the 2IB, about 20 sej are obtained back as emergy saved embodied in the outputs products (thermoplastics, recyclables, compost, and electricity). This implies that the 2IB should receive priority when chosen MSW technological routes for municipalities.

From a theoretical perspective, this study emphasize the importance of modifying operational procedures of emergy accounting to make it more accurate when assessing systems located at a far right of the energy hierarchical scale. The consideration of partial renewabilities for each item in the emergy table has proven to be an alternative to overcome existing issues in the emergy method, allowing the calculation of emergy performance indicators and making scientifically grounded diagnoses to support effective public policies on the MSW management thematic.

CRediT authorship contribution statement

Arno P. Clasen: Writing – review & editing, Writing – original draft, Validation, Resources, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Feni Agostinho:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Federico Sulis:** Visualization, Methodology, Investigation, Data curation, Conceptualization. **Cecília M.V.B Almeida:** Writing – review & editing, Visualization, Methodology, Formal analysis, Conceptualization. **Biagio F. Giannetti:** Writing – review & editing, Visualization, Methodology, Formal analysis, 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.

Data availability

All primary data are available in the supplementary material.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ecolmodel.2024.110725.

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