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Advancing towards circular economy: Environmental benefits of an innovative biorefinery for municipal solid waste management

Arno P. Clasen [a], Feni Agostinho [a,*], Cecília M.V.B. Almeida [a], Gengyuan Liu [b], Biagio F. Giannetti [a]

[a] Post-graduation Program on Production Engineering, Paulista University (UNIP), Brazil
[b] Beijing Normal University, School of Environment, China

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ABSTRACT

Inadequate municipal solid waste (MSW) disposal represents a current global challenge, contributing to environmental and societal issues. Instead of viewing waste as a problem, an alternative would be integrate it back into the production chain through a circular economic perspective. In response, an innovative and integrated biorefinery (2IB) has been implemented to effectively manage MSW, without the need for pre-treatment or source separation. This paper aims to evaluate the environmental performance of the 2IB using the life cycle assessment (LCA) method, comparing the results with a MSW landfilling alternative. The ReCiPe-LCA method is applied, and nine impact categories are calculated. Focusing on net emissions, the results show that 2IB yields higher environmental benefits than sanitary landfill in eight out of nine impact categories. For each 1 tonne of MSW treated, the 2IB causes from 2.6 to up to 8.9 times lower global warming, fossil depletion, photochemical oxidant formation, and freshwater eutrophication, 18.9 times lower metal depletion, 22.3 times lower human toxicity, 42.5 times lower terrestrial acidification, and 161 times lower particular matter formation. However, the sanitary landfill leads to two times lower water depletion compared to the 2IB. These findings advocate for prioritizing the 2IB over the sanitary landfill in propositions for public policies focused on MSW management. This work contributes by providing technical information on the 2IB that can be evaluated under methods other than LCA, besides showing its environmental advantages that would boost better decisions towards MSW disposal from a circular economy perspective.

1. Introduction

The concern over human-induced environmental impacts has been growing in recent decades, now being considered of equal importance when compared to economic issues. Excessive fossil fuel use adversely affects society by emitting greenhouse gases and degrading air quality. Similar to the unbridled consumption of non-renewable resources, the inadequate disposal of municipal solid waste (MSW) affects the environment and society (Malav et al., 2020). It is estimated that ~1.3 billion tonnes/year of MSW are generated in the world and it is expected to increase to 2.2 billion tonnes/year by 2025 (Chan, 2016; Silva et al., 2019) and 3.40 billion tonnes/year by 2050 (Kaza et al., 2018). As reported by Nizami et al. (2017a) and Vaverková (2019), MSW is often sent to landfills and dumps (reaching 90 % in developing countries), which pose environmental and public health concerns, leading to infections, respiratory problems, vector-borne diseases, lead exposure, heavy metal poisoning, and soil, air, and water pollution, including toxic gas and greenhouse gases emissions. Furthermore, Ziyang et al. (2015) and Shen et al. (2018) stated that if MSW is discarded in landfills without pre-treatment, it causes ongoing emissions even after landfilling end-of-life.

According to Shah et al. (2022), solid waste can be divided into MSW, commercial, industrial, electronic, medical, and agricultural, while Attard et al. (2020) define MSW as a type of solid waste that contains a variety of components including plastics, glass, metals, food, and textile. Specifically for the Brazilian case, law 12,305 of 2010 established the National Solid Waste Policy (NSWP) that defines solid waste as any material, substance, object, or good from human activities discarded by society (BRAZIL, 2010). MSW generation in Brazil was about 82 million tonnes in 2020 and 79 million tonnes in 2019; in 2019,

* Corresponding author at: Universidade Paulista (UNIP), Programa de pós-graduação em Engenharia de Produção, Dr. Bacelar 1212, 4th floor, 040026-002 São Paulo, Brazil.

E-mail address: feni@unip.br (F. Agostinho).

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the MSW in Brazil was disposed-off in sanitary landfills (57 %), controlled landfills (24 %), and dumps (19 %) (ABRELPE, 2020, 2021).

Landfills and dumps implemented and operated through long periods are considered as sources of environmental risks due to land occupation and air and water pollution, especially in developing countries (Singh and Chandel, 2022). Malinauskaite et al. (2017) stated that turning waste into energy can be a way to promote circular economy, allowing that value of products, materials, and resources be maintained in the market for longer periods by minimizing waste generation and raw resources demand. Similarly, Sadeleer et al. (2020) explained that applying circular economy would minimize waste landfilling, since waste-based products will keep circulating in the economy through redesign, reuse, recycling, and energy recovery. Kurniawan et al. (2021) revealed that introducing circular economy for waste management in cities requires political decisions in legislation and public participation, as well as the engagement of stakeholders in MSW management, as they obtain benefits from proper waste management for several reasons. It is important to recognize that an effective MSW management must be related to the circular economy approach, which avoids load on the environment as usually found in those linear consumption-production patterns.

Despite technological advances in MSW management options, Sondh et al. (2022) revealed that designing an efficient waste management system is a challenge faced by countries. Likewise, Ding et al. (2021) emphasized the importance of a systemic waste management strategy and technological utilization to reduce the harmfulness and enhance the effective use of MSW. Many nations are looking for technologies to convert biomass into biofuels, but decision-makers often lack information to choose from MSW management alternatives, which can prevent the implementation of biorefineries. Biorefineries are similar to oil-based refineries, but biorefineries use biomass as feedstock to generate bioenergy, chemicals and other products through transformation routes, integration of processes and equipment (Yue et al., 2014). According to Vaverková (2019), landfilling is usually chosen by decisions makers due to its practicality and cost-effectiveness compared to alternative disposal methods, but for a better world for all, it is important to include the environmental variable into decisions.

MSW management encompasses the active participation of multiple stakeholders, with decision-makers having a fundamental role in minimizing adverse effects on society since they should boost projects that effectively address related public concerns. Zhou et al. (2022) highlighted the importance of governance regulations, including pertinent legislations, policies, taxation frameworks, and public awareness initiatives to facilitate the operation of MSW management systems. Coban et al. (2018) emphasize that under such a complex scenario driven by fast population growth, higher living standards, and technological advances that consistently increase the quantity and diversity of solid waste generation, city authorities need to develop effective management for MSW. Although not an easy task, efforts are needed to overcome the current existing issues involving the MSW management. For the Brazilian case, law 11,445 of 2007 established national guidelines for basic sanitation (BRAZIL, 2007) under law 14,026 of 2020 updating provisions to improve basic sanitation conditions (BRAZIL, 2020).

Considering the current low recycling rates for abiotic materials, most Brazilian municipalities have been looking for technical opportunities to improve their recycling systems (Penteado and De Castro, 2021) as supported by the concept of circular economy. At this point, the biorefineries emerge as an alternative, however, there are financial, technical, political, and social challenges that need to be overcome before putting this idea into practice (Shah et al., 2022). Since the stakeholders' action is a key factor for changes in MSW management (Kurniawan et al., 2021; Zhou et al., 2022; Coban et al., 2018), the current laws in Brazil allow the formation of inter-municipal consortia comprising exclusively municipalities to establish financial initiatives to implement essential measures such as drinking water, sewage sanitation, urban cleaning, solid waste management, drainage, and rainwater management. Technical alternatives for solid waste management are recommended to minimize environmental impacts by implementing new technological routes for MSW, while avoiding the landfilling practice. This initiative supports municipalities with financial and technical restrictions, as well as those that generate insufficient amounts of waste to enable for the application of other technological routes such as energy generation and/or biorefineries. Recently, fifteen municipalities in the state of Santa Catarina, Brazil, established a consortium to implement an integrated biorefinery, an innovation compared to all other similar technological routes in managing MSW. In this innovative and integrated biorefinery (2IB), the applied technological route has the advantage of managing the entire and usually mixed MSW collected (including biotic and abiotic materials) and provides specific outputs as products for the market, besides treating the waste according to legal parameters. The 2IB is already implemented and operating, and if validated from an environmental perspective, the 2IB could avoid the implementation of new projects for landfills and its resulting environmental impacts, as well as overcoming the issues related to the existing biorefineries that exclusively consider the organic MSW fraction as raw materials.

From other available scientific methods to quantify environmental burdens of production systems, the life cycle assessment (LCA) is, perhaps, the most widely used, mainly due to its standardized and clear procedures, besides considering a larger scale (life cycle) for its spatial boundaries. Although this study concentrates on MSW biorefineries, it is noteworthy that research in Latin America has predominantly centered around the LCA applied to conventional waste management techniques. Without delving deeply into the topic, three significant studies can be mentioned. Liikanen et al. (2018) assessed potential future alternatives to replace landfills in São Paulo city, Brazil, which include composting, anaerobic digestion, and mechanical-biological treatment (MBT). The findings demonstrated a decrease in environmental impacts linked to anaerobic digestion of source-separated organic waste and mechanical-biological treatment of MSW, provided that the resulting refuse-derived fuel is utilized in cement production as a substitute for coal. Similarly, Lima et al. (2018) assessed scenarios for MSW management in Brazil using LCA, concluding that higher environmental costs are associated with improper disposal systems such as open dumps and traditional landfills, and that benefits can be obtained when adopting recycling with biological treatment and MBT with materials recovery. Focusing on the Bolivian context, Ferronato et al. (2021) simulated scenarios related to the recycling rate, concluding that the increase of recycling fraction on MSW positively affects human toxicity and freshwater aquatic ecotoxicity impact categories.

A considerable body of scientific literature is dedicated to LCA studies focused on biorefineries. These studies consider various feedstocks, with a particular focus on agriculture, such as sugarcane (Agostinho and Ortega, 2013; Gnansounou et al., 2015; Katakojwala and Mohan, 2022) and cattle manure (Awasthi et al., 2022; Giwa, 2017), forest residues (Brassard et al., 2021; Zupko, 2021), and other biomaterials. LCA has also been conducted on biorefineries operating with MSW as a feedstock, usually failing to include the entire composition (organic and inorganic) of MSW, often considering exclusively the organic fraction. Specifically, Khoshnevisan et al. (2020) carried out an environmental assessment using LCA for different MSW-based biorefinery platforms, however, only the organic fraction was used in the evaluated scenarios. Sadhukhan and Martinez-Hernandez (2017) recommended the integration of recycling abiotic materials within the biorefinery, highlighting the importance of this process integration to achieve all the estimated benefits from MSW management while considering all its components. In addition, a study proposed by Papadaskalopoulou et al. (2019) focused on an LCA study of a biorefinery system producing ethanol from biowaste against four conventional waste management methods (landfilling, composting, anaerobic digestion, incineration), but the biowaste includes exclusively food and garden waste. In another study, Moreno et al. (2021) evaluated bioethanol and biogas production from the MSW organic fraction using an integrated biorefinery strategy; authors have suggested that source-separated waste is a superior substrate for integrated biorefineries that would lead to a bioethanol production increase. The literature shows that an integrated biorefinery study considering both the organic and inorganic materials of MSW is still missing.

Recognizing the importance in studying such an innovative technological route for managing MSW, this paper aims to evaluate the environmental performance of the 2IB under an LCA approach. The results are compared with a traditional MSW disposal method, the sanitary landfill. The 2IB stands out among MSW management alternatives by dealing with both inorganic and organic fractions mixed, and introducing a novel feature known as thermoplastic production. This study contributes by providing decision-makers with scientifically grounded data on the environmental advantages and/or disadvantages of implementing the 2IB compared to the sanitary landfill for MSW management. Additionally, this study provides a complete inventory regarding technological aspects related to the 2IB that has not yet been found in the literature.

2. Methods

2.1. Description of the innovative and integrated biorefinery for municipal solid waste management

From the diverse concepts of biorefinery available in the scientific literature (Bugge et al., 2016; Shah et al., 2022; Yue et al., 2014), the following definition of biorefinery provided by Conteratto et al. (2021) is here considered: "[…] 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." According to those authors, this definition resulted from a review of concepts based on inputs, processes, and products, providing an update to the existing definitions of biorefinery in the literature.

Fig. 1 shows the general processes within the innovative and integrated biorefinery (2IB). The modeling approach was based exclusively on primary data obtained in situ at an inter-municipal consortium in the state of Santa Catarina, Brazil, which implemented the 2IB to meet the regional needs and comply with the environmental legislation. Assessing an operating biorefinery instead of elaborating hypothetical scenarios is a better alternative since it has already overcome potential barriers related to legislation, technical and financial aspects. Therefore, it provides more accurate and reliable results to sustain its implementation in other regions.

The main processes in Fig. 1 starts with the municipal solid waste (MSW) generation, followed by collection and transportation, going through processing, and producing resources as outputs that can be used within the plant itself and/or to make available for society, such as electricity, agricultural compost, and thermoplastic products. The studied 2IB receives 180 tonnes/day of MSW composed by inorganic (20 %; 36 tonnes/day) and mixed organic with inorganic waste (80 %; 144 tonnes/day). The processing of the inorganic fraction entails the recycling of a larger fraction of the value-added materials (paper, plastic aluminum, metal, and glass), while the residual fraction that contains tinny parts with organics is diverted to the thermoplastic process that produces thermoplastic polymers by melting and molding inorganics into pavers, slabs, and tiles. In parallel, the processing of mixed organic waste involves, firstly, a sorting phase for iron, steel, and other materials with substantial volumes such as wood and tires. Then there is a waste separation process between inorganic and organic. While the inorganic fraction undergoes thermoplastic processing, the organic fraction undergoes anaerobic digestion. The anaerobic digestion system operates

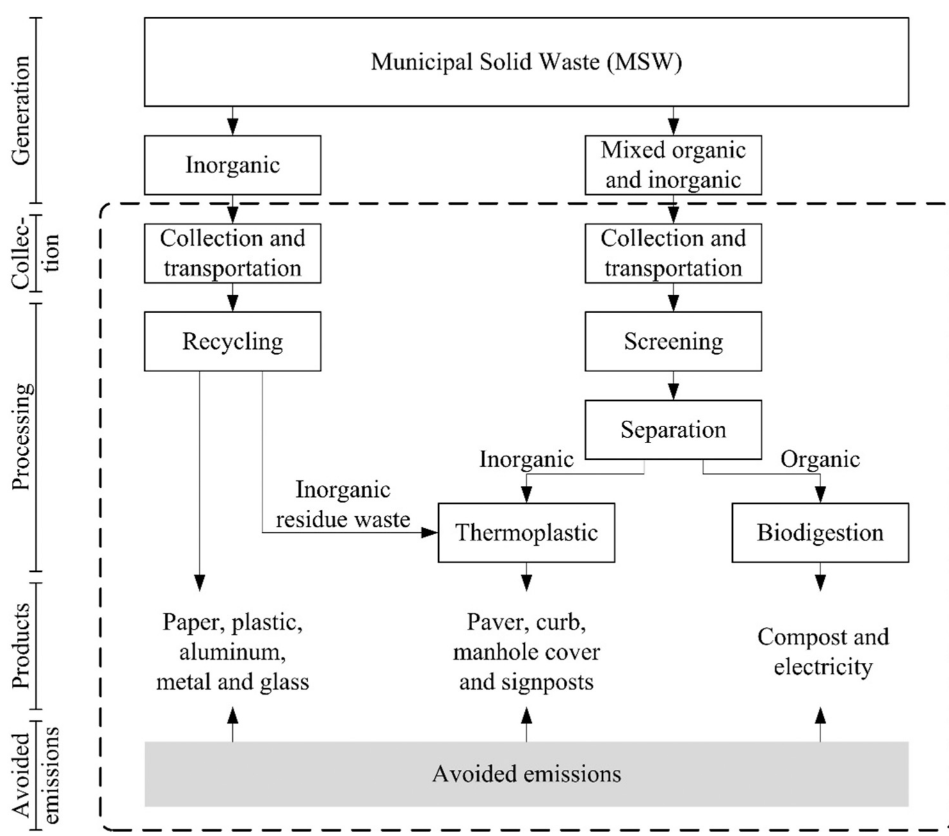

Fig. 1. Main steps involved in the operation phase of the innovative and integrated biorefinery. Dashed lines refer to the evaluated system boundaries. Details in Appendix A.

with 22 % of volatile solids (dry system), without a digestate separator as a centrifuge for compost production; this dry anaerobic process is similar to the well-known DRANCO system (De Baere, 2010). The generated biogas is converted into heat and electricity, but while heat is totally used for internal processes within the 2IB, the electricity is partially internally used, and the remaining fraction is sent to the national grid. It is worth noting that 2IB is self-sufficient in electricity, and it provides the electricity surplus to the grid. For this reason, there is no electricity input to the system. Deeper details about the processes within the 2IB are available in Appendix A.

2.2. Life cycle assessment

The life cycle assessment (LCA) is employed as a method for determining the direct and indirect emissions from the evaluated system. This assessment is carried out in accordance with the standards set by the International Organization for Standardization (ISO, 2006; ISO, 2006) to obtain environmental impact categories. LCA quantitatively measures the environmental impacts of a product or process over its entire life cycle, including four essential stages: goal and scope definition, inventory analysis, impact assessment, and interpretation of the results; all four stages are presented in detail in the next items. According to Papadaskalopoulou et al. (2019), the LCA is the most globally used method to examine the environmental performance of alternative products or systems as it considers the environmental impacts incurred throughout its entire life cycle.

2.2.1. Goal and scope definition

This study aims (a) to evaluate the environmental impacts by applying the LCA method on the 2IB for MSW management, and (b) to compare the results with those of a sanitary landfill option, the most traditional globally used waste management system. It is intended to validate the 2IB from an environmental perspective, since it is an innovative system with no similar technological route dealing with MSW available in the literature. In this study, the functional unit was established as the treatment of 1 tonne of MSW (1 metric ton or 1000 kg). The temporal scope reflects one year of plant operation, including operation and implementation phases. The products generated by the 2IB also include the so-called avoided emissions (Fig. 1), since their utilization replace the use of raw materials. This substitution encompasses various aspects including the replacement of energy derived from the national power grid, as well the reduction in the water consumption, cement, and other materials employed in the production of paver-oriented products. Furthermore, the 2IB is aligned with the principles of circular economy, as it ensures that products, components, and materials retain their maximum level of usefulness and value throughout their lifecycle.

2.2.2. Life cycle inventory

The 2IB inventory is based exclusively on primary data obtained from technical visit in situ during 2022. Data about the amount, kind and processes related to all equipment were obtained, as well as the consumption of energy (electricity and diesel), and the amount and kind of products resulting from the transformation of MSW into biogas, heat, electricity, thermoplastics, and recyclables. Raw data are presented in Appendix A and as Supplementary Material file (Tables S1 to S7), which resulted in the aggregated inventory of Table 1.

Table 1 is important to support the calculation of indirect emissions, while the direct ones must be modelled. Regarding indirect emissions, efforts were directed towards selecting characterization factors from Ecoinvent that closely align with the Brazilian context. However, due to the absence of characterization factors to Brazilian cases for all inputs in the inventory, the selection of representative factors relies on the analyst's expertise and knowledge of the system under study, as suggested by ISO 14040 and 14,044. Values may originate from different countries or the "rest of the world" (RoW) option, but before choosing a characterization factor, its alignment with the case study is verified. Detailed information about the chosen characterization factors is provided in the Supplementary Material (Table S9). Table 2 shows the inventory obtained from scientific literature (biodigestion and biogas burning processes) and from governmental reports (diesel combustion in engines). Surra et al. (2021) provide technical details about the biogas production, which is similar to the ones applied in the 2IB studied. The same authors provide information on the types and quantities of gases emitted during biodigestion and electricity production processes by burning the biogas. Emissions resulting from diesel burning in engines were derived from the Environmental Company of the State of São Paulo (CETESB, 2021) and then converted to the same functional unit for the sake of comparison.

Table 1
Inventory summary for the innovative and integrated biorefinery.

Item	Quantity	Unit/tonne$_{MSW}$
Inputs		
Steel	0.93	kg
Concrete	0.0001	m^3
Diesel	5.10	kg
Wood	0.012	kg
Biowaste[a]	0.00	kg
Outputs		
Electricity (surplus)	38.23	kWh
Organic compost	133.94	kg
Paver (concrete)[b]	0.088	m^3
Paper and cardboard	83.00	kg
Plastic	62.25	kg
Glass	33.20	kg
Metal/Iron	18.68	kg
Others (polystyrene, electronics, vegetal oil and tissues)	10.38	kg

The detailed inventory of equipment, materials and energy flows are available as Supplementary Material (Tables S1 to S7). [a] Biowaste is not included since it is considered as a by-product and thus has no environmental impact. [b] Paver was considered as substitute for concrete (they have similar functions) due to a lack of specific characterization factors in the Ecoinvent® life cycle assessment (LCA) database.

2.2.3. Life cycle impact assessment

Ecoinvent® database (v.3.62019) is used as data source for the characterization factors employed in the LCA analysis; they are all available in Table S9 of Supplementary Material. The ReCiPe Midpoint (H) V1.13 method (allocation at the point of substitution) is applied to quantify the environmental impacts associated with the evaluated systems, since this method has been chosen by other authors studying MSW

Table 2
Inventory for direct emissions.

Emissions	Quantity	Unit/tonne$_{MSW}$
Electricity production (biogas burning[a]		
CH_4	0.0006	kg
NO_x	0.028	kg
N_2O	0.0006	kg
NMVOC	0.0008	kg
PM10	0.002	kg
Diesel burned in engines[b]		
CH_4	0.001	kg
CO_2	15.55	kg
NO_x	0.02	kg
N_2O	0.0006	kg
NMVOC	0.0004	kg
PM10	0.0002	kg

[a] From Surra et al. (2021), details are available in Supplementary Material (Table S8).
[b] From CETESB (2021).

management options (Paes et al., 2020; Pujara et al., 2023; Shekoohiyan et al., 2023). Although the ReCiPe 2016 is available, employing its 2008 version as executed in this study would have minimal effect on the results. According to Dekker et al. (2020), for most studies that used ReCiPe 2008, the interpretation of results is not likely to change when applying ReCiPe 2016 under the same inventory numbers, since similarities were verified when the hierarchical perspective is being applied or when performing studies at midpoint levels.

According to ISO 14044 (ISO, 2006) and the ILCD (2011) Handbook, the selection of impact categories should be aligned with the scope and goals of the LCA. Since the purpose of this study is to conduct a comparative assessment of the environmental performance between 2IB and sanitary landfill to support decision-makers in short and medium-term actions, the following impact categories are used: fossil depletion potential (FDP), freshwater eutrophication potential (FEP), global warming potential (GWP), human toxicity potential (HTP), metal depletion potential (MDP), particular matter formation potential (PMFP), photochemical oxidant formation potential (POFP), terrestrial acidification potential (TAP), and water depletion potential (WDP). Their selection is justified as these impact categories from the ReCiPe method are the most indicative of the impacts caused by MSW management systems (Paes et al., 2020; Sharma and Chandel, 2017; Cheela et al., 2021), and align with our expertise on the studied cases. It is worth noting that the sanitary landfill and 2IB systems under study are designed to prevent leaks, such as those involving leachate or other potentially harmful materials, as they are engineered to be leak-proof for both soil and aquifers. This explains, for example, why other impact categories such as those concerning ecotoxicity are of lesser importance in this study. Moreover, the use of limited number of impact categories contributes to reducing result complexity and improves their interpretation and utility for stakeholders' decision-making, a factor highlighted as crucial by Esnouf et al. (2019), Feng et al. (2023), and Lasvaux et al. (2016), among others. All these employed criteria ensure that the applied LCA delivers a more effective quantitative assessment of the environmental performance of the compared systems, offering transparent, impartial, and compelling evidence to inform policy decisions.

Table 3 shows the modeling approach in calculating the LCA impact categories considering indirect and direct impacts, as well the avoided emissions. The (a) indirect impacts represented by the inputs and the (c) avoided impacts represented by the outputs are both quantified by using data from Table 1. For (b) direct impacts, they are evaluated by considering data from Table 2, specifically those involving diesel combustion in engines and emissions resulting from electricity production (biogas burning).

2.2.4. *Interpretation of results*

Results discussion takes two distinct paths: (a) focusing exclusively on the environmental impacts caused by the studied 2IB, and (b) comparing the 2IB results with the sanitary landfill option. While (a) is important to identify weaknesses and strengths of 2IB and propose improvements, (b) is important to validate the studied 2IB by comparing it with the most largely practicable MSW management system that is the sanitary landfill. The study of Sulis et al. (2021), which assessed the environmental impacts of food donation scenarios at a large food distribution center located in São Paulo, Brazil, is considered as comparative reference for sanitary landfills' LCA impact categories. Specifically, the baseline scenario studied by Sulis et al. (2021) is considered, which includes collection, transportation, processing, and the sanitary landfill implementation and operation phases. This study was selected as a reference due to its representativeness for Brazilian conditions and data reliability. It is noteworthy that the data presented by Sulis et al. (2021) are exclusively primary, acquired in situ, eliminating dependence on secondary data or assumptions. As presented before by Fig. 1, the spatial boundary of this study includes MSW collection, transportation, and the 2IB itself, however, for comparison purposes, collection and transportation steps are excluded to allow for a fair comparison between the proposed 2IB with the sanitary landfill option. This exclusion is consistent because collection and transportation of MSW would feature the same LCA impact categories for both 2IB and sanitary landfill.

Table 3
Modeling procedures for life cycle impact assessment applied in this work.

(a) Indirect impacts	
The characterization factors from ReCiPe 2008 (hierarchist; Ecoinvent version 3.6, 2019) method for each impact category are applied on the inputs data of Table 1. All raw data are available as Supplementary Material (Tables S9).	
(b) Direct impacts[a]	
Diesel burned in engines (in kg), data from Table 2	
GWP ($kgCO_{2eq.}$/$tonne_{MSW}$)	(15.55 $kgCO_2$/$tonne_{MSW}$ * 1 $kgCO_2$/$kgCO_2$) + (0.001 $kgCH_4$/$tonne_{MSW}$ * 22.25 $kgCO_2$/$kgCH_4$) + (0.0005 kgN_2O/$tonne_{MSW}$ * 298 $kgCO_2$/kgN_2O)
PMFP (kgPM10/$tonne_{MSW}$)	(0.0002 kgPM10/$tonne_{MSW}$ * 1 kgPM10/kgPM10) + (0.02 $kgNO_X$/$tonne_{MSW}$ * 0.22 kgPM10/$kgNO_X$)
POFP ($kgNMVOC_{eq.}$/$tonne_{MSW}$)	(0.001 $kgCH_4$/$tonne_{MSW}$ * 0.01 kgNMVOC/$kgCH_4$) + (0.02 $kgNO_X$/$tonne_{MSW}$ * 1 kgNMVOC/$kgNO_X$) + (0.0004 kgPM10/$tonne_{MSW}$ * 1 kgNMVOC/kgPM10)
TAP ($kgSO_{2\ eq.}$/$tonne_{MSW}$)	(0.0005 $kgNO_X$/$tonne_{MSW}$ * 0.56 $kgSO_2$/$kgNO_X$)
Emissions from electricity production (biogas burning), data from Table 2	
GWP ($kgCO_{2eq.}$/$tonne_{MSW}$)	(0.0006 $kgCH_4$/$tonne_{MSW}$ * 22.25 $kgCO_2$/$kgCH_4$) + (0.0006 kgN_2O/$tonne_{MSW}$ * 298 $kgCO_2$/kgN_2O)
PMFP ($kgPM10_{eq.}$/$tonne_{MSW}$)	(0.03 $kgNO_x$/$tonne_{MSW}$ * 0.22 kgPM10/$kgNO_X$) + (0.002 kgPM10/$tonne_{MSW}$ * 1 kgPM10/kgPM10)
POFP ($kgNMVOC_{eq.}$/$tonne_{MSW}$)	(0.001 $kgCH_4$/$tonne_{MSW}$ * 0,01 kgNMVOC/$kgCH_4$) + (0.03 kgNOx/$tonne_{MSW}$ * 1 kgNMVOC/$kgNO_X$) + (0.0008 kgNMVOC/$tonne_{MSW}$ * 1 kgNMVOC/kgNMVOC)
TAP ($kgSO_{2eq.}$/$tonne_{MSW}$)	(0.03 $kgNO_X$/$tonne_{MSW}$ * 0.56 $kgSO_2$/$kgNO_X$)
(c) Avoided emissions	
The characterization factors from ReCiPe 2008 (hierarchist; Ecoinvent version 3.6, 2019) method for each impact category are applied on the outputs data of Table 1. All raw data are available as Supplementary Material (Tables S9).	

[a] Characterization factors of direct emissions are available in the Supplementary Material (Tables S10 and S11). Legend: GWP, Global Warming Potential; PMFP, Particulate Matter Formation Potential; POFP, Photochemical Oxidant Formation Potential; TAP, Terrestrial Acidification Potential.

At this point, it is important to emphasize the extant disparities among open dumps, conventional landfills, and sanitary landfills. While widely acknowledged as an unsuitable option for MSW disposal due to its socio-environmental issues, open dumps persist and account for the predominant share of waste disposal in underdeveloped nations (Ferronato and Torretta, 2019). Conversely, conventional landfills present a superior alternative for waste management, wherein waste is enveloped by soil to mitigate direct socio-related issues such as vector-borne diseases disseminated by insects and other fauna. Lastly, the sanitary landfill emerges as the optimal choice among the aforementioned options. Beyond mere soil coverage, it features an impermeable stratum designed to sequester leachate, along with pipework for biogas capture and subsequent conversion into electrical energy. In our study, the sanitary landfill is the system compared with the biorefinery.

Although uncertainty and sensitivity analyses are frequently employed to evaluate the reliability and robustness of LCA results, their utilization is not mandatory and depends on the scope, methodology, and data quality utilized in the study (ISO, 2006; ISO, 2006; Clavreul et al., 2012). Given that the data utilized in this study originates from primary and reliable sources obtained in situ, that scenario-based approaches are not being considered, and that the same life cycle inventory method and characterization factors are applied in both MSW management systems, uncertainty and sensitivity analyses are omitted from this investigation.

3. Results and discussions

3.1. Life cycle assessment results for the innovative and integrated biorefinery study case

Given the agricultural nature of the region in which the innovative and integrated biorefinery (2IB) is operating, one of its outputs is the agricultural composting product, however, the 2IB is flexible and it can be managed to maximize other outputs such as biofuels (after biogas upgrading), depending on the regional demand. Another important output is thermoplastic products such as pavers to be used in the urban infrastructure of municipalities that belong to the consortium (currently fifteen municipalities generating about 65,700 $tonnes_{MSW}$/year). Again, the geometric characteristics and functions of thermoplastic products depend on the regional needs, being flexible within the 2IB. Anyhow, the cost of these products is expected to be lower compared to similar products available in the market, and all these products, including composting and thermoplastics, are accounted for as avoided emissions in this study. A tiny residual fraction <1 % (~1.1 $tonnes_{MSW}$/day) of all municipal solid waste (MSW) treated is sent to the sanitary landfill after undergoing all processes within 2IB. This residual fraction was not considered in this study because it was assumed that it has no influence on the final life cycle assessment (LCA) results.

Table 4 shows the nine LCA impact categories resulting from the 2IB. Direct and indirect impacts are separately presented to provide a better understanding of the environmental burdens associated with each one. Net emissions are obtained by the subtraction of avoided emissions from indirect plus direct ones, representing an advantage or disadvantage for each LCA impact category.

Direct emissions are included in four impact categories related to diesel burning in engines and to electricity production (biogas burning) processes. Due to its current and worldwide importance, special attention is given to discussing the global warming potential (GWP) category, but a similar discussion can be applied to all other LCA categories of Table 4. The GWP presents a value of 6.61 and 15.96 $kgCO_{2eq.}/tonne_{MSW}$ for indirect and direct emissions, respectively, indicating that direct impacts are ~2.4 times higher than indirect ones. Conversely, the avoided emissions for the GWP (262 $kgCO_{2eq.}/tonne_{MSW}$) are ~11.6 times higher than the environmental burdens, resulting in a net emission of −239 $kgCO_{2eq.}/tonne_{MSW}$ that indicates an environmental benefit for GWP. Besides being a zero $CO_{2\text{-eq.}}$ emitter, the 2IB is able to indirectly absorb GWP gases. It is important to highlight that this environmental benefit is verified for all evaluated LCA impact categories, in which the highest gains or negative net emissions occur in the GWP and HTP, while the lowest gains occur in FEP, PMFP, TAP and POFP. These results emphasize that, from an LCA perspective, the 2IB should be implemented. Besides considering the lowest net emission performance among all LCA categories, the 2IB is able to reduce freshwater eutrophication (FEP) by 0.013 $kgP_{eq.}/tonne_{MSW}$, which means that 2.34 $kgP_{eq.}$/day is no longer being released on the natural environment.

The last column of Table 4 shows the ratio between avoided and total emissions for each assessed impact category, which indicates how many times higher the avoided emissions are (when >1) or lower (when <1) than the total emissions. The highest difference occurs for WDP, in which the avoided emissions are 41.2 times higher than total emissions, resulting in an environmental benefit of 1.55 $m^3H_2O_{eq.}/tonne_{MSW}$. Likewise, the HTP presented an environmental gain among the LCA categories, where the avoided emissions (75.6 $kg1.4\text{-}DCB_{eq.}/tonne_{MSW}$) for the HTP were 27.6 times higher than the total emissions. It is noteworthy that recycling inorganics played an important role in achieving this substantial emission reduction, since it contributes to ~90 % of total avoided emissions; on the other hand, steel accounted for approximately 80 % of the total indirect emissions. Other impact categories in the spotlight are GWP and POFP, achieving respectively 11.6 and 9.7 better performance in avoiding emissions than their total emissions. Although all other LCA impact categories have avoided more than emitted gases, their performance is different, in which the FDP, MDP, and TAP are the ones with the lowest performance with 2.1, 3.4, and 4.9, respectively.

These results are consistent with the findings of Fiorentino et al. (2015) who applied LCA to assess four options in managing MSW, including direct landfilling with energy recovery, mechanical-biological treatment with waste-to-energy conversion, an innovative material advanced recovery sustainable systems (Mechanical-Biological Treatment/ Material Advanced Recovery Sustainable Systems - MBT/MARSS) process with landfill disposal, and the MBT/MARSS process with waste-to-energy conversion. Although not having a better performance in all LCA impact categories, the MBT/MARSS option showed the best environmental performance overall, indicating that splitting abiotic from biotic, applying recycling strategies, and generating energy with the organic route should be supported. This technical strategy is very similar to the 2IB studied, indicating consistency among obtained data in this present study with the Fiorentino et al. study (Fiorentino et al., 2015). Focusing on the organic fraction, Mancini et al. (2019) assessed the environmental impacts of two MSW organic fraction treatment options in southern Italy, concluding that integrating anaerobic digestion with composting improves environmental performance compared to traditional composting. Again, these findings support the results obtained by the 2IB studied, in which an anaerobic process is applied, followed by a composting step. Although the literature is plentiful with LCA studies applied to biorefineries, they usually consider raw materials other than MSW, including agriculture feedstocks such as sugarcane (Agostinho and Ortega, 2013; Gnansounou et al., 2015; Katakojwala and Mohan, 2022) and cattle manure (Awasthi et al., 2022; Giwa, 2017), forest residues (Brassard et al., 2021; Zupko, 2021), and other biomaterials. This difference on raw materials feeding the biorefinery makes direct comparisons among their results with the ones obtained in this present study difficult.

From a general view, the results showed that 2IB is able to avoid environmental impacts, even providing ‘credits’ or negative emissions for all LCA impact categories assessed. This is an important result of this

Table 4
Results (values in E-02) for the life cycle assessment impact categories of the evaluated innovative and integrated biorefinery.

Impact categories	$Unit/tonne_{MSW}$	Impacts				Avoided/total emissions ratio[b]
		Indirect	Direct	Avoided	Net[a]	
Fossil Depletion Potential (FDP)	$kgoil_{eq.}$	717.94	0.00	1480.87	−762.93	2.1
Freshwater Eutrophication Potential (FEP)	$kgP_{eq.}$	0.25	0.00	1.55	−1.30	6.3
Global Warming Potential (GWP)	$kgCO_{2eq.}$	660.90	1595.62	26,168.95	−23,912.43	11.6
Human Toxicity Potential (HTP)	$kg1.4\text{-}DCB_{eq.}$	273.86	0.00	7563.46	−7289.60	27.6
Metal Depletion Potential (MDP)	$kgFe_{eq.}$	260.87	0.00	893.45	−632.58	3.4
Particulate Matter Formation Potential (PMFP)	$kgPM10_{eq.}$	2.11	1.38	23.99	−20.50	6.9
Photochemical Oxidant Formation Pot. (POFP)	$kgNMVOC_{eq.}$	3.25	5.32	82.91	−74.33	9.7
Terrestrial Acidification Potential (TAP)	$kgSO_{2eq.}$	3.67	2.91	32.56	−25.98	4.9
Water Depletion Potential (WDP)	$m^3H_2O_{eq.}$	3.86	0.00	158.94	−155.08	41.2

[a] Net emissions = Indirect + Direct − Avoided. Negative values mean environmental benefit.
[b] Total emissions = Indirect + Direct.

work, supporting the implementation of 2IB. However, from a continuous improvement cycle, it is important to identify those input items that negatively influence the results the most. As usual in LCA analysis, indirect emissions are mostly influenced by few types of materials and/or energy inputs. For the 2IB, the indirect demand for steel and diesel are the ones with the highest influence on impact categories (please see all numbers in Supplementary Material, Tables S12 to S15). Precisely, steel impacts 91 % in FEP, 64 % GWP, 84 % HTP, 97 % MDP, 68 % PMFP, and 78 % WDP impact categories, while diesel consumption is responsible for 86 % in FDP, 54 % POFP, and 59 % TAP. These numbers are important to support decision makers towards a 2IB with even lower total emissions, by applying technological improvements or better management practices on internal processes, when possible.

3.2. *Life cycle assessment comparative study between sanitary landfill and the innovative and integrated biorefinery*

Table 5 shows the LCA impact categories comparison between the 2IB and sanitary landfill, calculated without collection and transportation stages. The same consideration was made by Gadaleta et al. (2023) assuming that technological routes do not depend on waste collection and transportation stages. Both systems have a gate-to-gate spatial boundary, and they are compared since sanitary landfill is the largest global technological practice for MSW management. Results of Table 5 are colored green to represent the lowest environmental impacts or highest savings, while orange-colored numbers indicate the highest impacts when comparing the 2IB with sanitary landfill numbers. Negative values for net emissions indicate environmental gains, while positive values represent environmental burdens. Analyzing the numbers in Table 5, the 2IB achieved the lowest indirect impacts for eight out of nine LCA categories, excluding the MDP. The observed indirect impact for the MDP category in the 2IB was that, despite being ~22 % higher than sanitary landfill option, it is predominantly composed of ~99 % of the steel input. Thus, reducing the amount of steel used in the 2IB in infrastructure and machineries would greatly decrease its MDP. The best overall LCA performance on indirect impacts by the 2IB was a surprise, since implementing and operating a sanitary landfill would require lower amount of materials and energy, compared to implementing and operating the 2IB. A possible justification lies in the fact that 2IB is self-sufficient in electricity, therefore, it does not use energy from the national electricity grid.

When analyzing direct impacts and avoided emissions, the scenario is quite similar as for the indirect impacts, because the 2IB shows the lowest direct emissions for all LCA impact categories, at the same time showing the best performance for avoided emissions in almost all categories, with the exception of WDP. This LCA category is influenced by the electricity produced from hydropower plants in Brazil, which demands a large amount of water. The 2IB is self-sufficient in electricity usage, so high energy demand for internal use affects the amount of surplus electricity and, consequently, reduces the embodied avoided emissions. In the case of the sanitary landfill, the largest amount of electricity generated is diverted to the national grid, as there is insignificant internal demand for electricity.

Focusing on total (indirect + direct) emissions, Table 5 shows that sanitary landfill has higher environmental burdens than 2IB in eight out of the nine impact categories, again excluding the MDP. Notably, GWP stood out with ~68 times higher for sanitary landfill (188 $kgCO_{2eq.}$/$tonne_{MSW}$) than 2IB (2.76 $kgCO_{2eq.}$/$tonne_{MSW}$). For comparison, Nizami et al. (2017b) evaluated a waste-based biorefinery and recycling plant in Makkah city considering a waste-to-energy technology including anaerobic digestion, transesterification, pyrolysis and refuse derived fuel. Authors concluded that this technology is able to manage organic (~88 % of MSW) and inorganic (~12 % of MSW) fractions while reducing by 1.15 million Mt.CO2eq. the city's current GWP based on landfilling MSW. This reinforces the importance of 2IB in reducing GWP. The second largest difference occurred for POFP, which reached a 7.7 times worse performance for sanitary landfill (Table 5). Other expressive differences were found for TAP and FDP, which were respectively 7.3 and 5.5 times higher for sanitary landfill, compared to 2IB. This suggests that the sanitary landfill system has a significantly higher potential for depleting fossil resources and causing terrestrial acidification, compared to the 2IB. For the FEP, PMFP and WDP impact categories, the obtained values were respectively 5.4, 4.4, and 4.1 times higher for sanitary landfill, compared to 2IB. The only category in which 2IB showed a higher total impact than sanitary landfill was for MDP (1.3 times higher). Finally, the difference between 2IB and sanitary landfill for HTP was comparatively insignificant, compared to the most impacting LCA categories; the sanitary landfill showed a 1.2 times worse performance than 2IB. It was expected that 2IB would show a worse performance for a greater number of LCA categories due to the existing high energy demanded by industrial processes in converting MSW into recyclables, electricity, composting, and thermoplastics. However, the sanitary landfill considered for comparisons in this study (Sulis et al., 2021) has characteristics that are different from those of traditional landfills, including sewage treatment, biogas and electricity production plant, which demand a higher amount of materials and energy than a

Table 5
Life cycle assessment impact categories result (values in E-02) for the innovative and integrated biorefinery (2IB) and sanitary landfill, without including collection and transportation stages (details are available in the Supplementary Material, Tables S16 to S19). Data for sanitary landfill were obtained from Sulis et al. (2021).

Impact categories	Unit /$tonne_{MSW}$	2IB				Sanitary Landfill				2IB/Landfill net emissions ratio [b]
		Indirect	Direct	Avoided	Net [a]	Indirect	Direct	Avoided	Net [a]	
Fossil Depletion Potential (FDP)	$kgoil_{eq.}$	63.41	0.00	1,480.87	-1,417.46	349.00	0.00	838.00	-489.00	2.9
Freshwater Eutrophication Potential (FEP)	$kgP_{eq.}$	0.12	0.00	1.55	-1.43	0.12	0.50	0.44	0.18	8.9
Global Warming Potential (GWP)	$kgCO_{2eq.}$	221.66	54.64	26,168.95	-25,892.65	438.00	18,400.00	2,990.00	15,848.00	2.6
Human Toxicity Potential (HTP)	$kg1.4\text{-}DCB_{eq.}$	118.96	0.00	7,563.46	-7,444.50	140.00	0.00	474.00	-334.00	22.3
Metal Depletion Potential (MDP)	$kgFe_{eq.}$	130.28	0.00	893.45	-763.17	101.00	0.00	58.30	42.70	18.9
Particulate Matter Formation Potential (PMFP)	$kgPM10_{eq.}$	0.74	0.83	23.99	-22.41	1.79	5.12	6.77	0.14	161.0
Photochemical Oxidant Formation Potential (POFP)	$kgNMVOC_{eq.}$	0.80	2.90	82.91	-79.21	5.04	23.30	9.81	18.53	5.3
Terrestrial Acidification Potential (TAP)	$kgSO_{2eq.}$	0.81	1.58	32.56	-30.17	4.49	13.00	18.20	-0.71	42.5
Water Depletion Potential (WDP)	$m^3H_2O_{eq.}$	1.57	0.00	158.94	-157.37	6.46	0.00	316.00	-309.54	0.5

[a] Net emissions = indirect + direct – avoided. Negative values mean environmental benefit.
[b] When both 2IB and Sanitary Landfill have negative values for net emissions, than 2IB/Landfill net emissions ratio = (2IB net emissions) / (Landfill net emissions). When net emission for 2IB is negative and for Sanitary Landfill is positive, than: 2IB/Landfill net emissions ratio = (|highest value for net emissions| + |lowest value for net emissions|) / highest value for net emissions.

traditional landfill does, and this could have influence of the sanitary landfill's LCA performance.

Focusing on the avoided emissions, the 2IB achieved better performance than sanitary landfill in eight out of nine impact categories, with exception for WDP. The sanitary landfill achieved ~2 times better performance for WDP category, with 3.16 $m^3H_2O_{eq.}/tonne_{MSW}$ against the 1.59 $m^3H_2O_{eq.}/tonne_{MSW}$ obtained by the 2IB. As explained before, this is a result of the electricity used internally by the 2IB, which reduces the electricity available as output. Among those eight LCA categories that showed better performance for the 2IB, the most expressive environmental gains are related to HTP (16 times higher), MDP (15.3), GWP (8.7) and POFP (8.4). Although presenting lower differences than other impact categories, the FDP and TAP (1.8) as well as FEP and PMFP (3.5) have shown a better performance for the 2IB than sanitary landfill.

Finally, it is also important to discuss the net emissions in relative terms, as presented in the last column of Table 5, in which numbers show how many times better (when >1) or lower (when <1) performance than the sanitary landfill the 2IB has. For FDP, although both studied systems have negative net emissions meaning positive performance, the 2IB achieved a 2.9 times better performance than sanitary landfill. This behavior also occurs for the HTP category, with the 2IB achieving a 22.3 times better performance than sanitary landfill, and for the TAP category achieving 42.5 times better performance for 2IB, the second highest observed difference among all nine assessed LCA categories. As for the FEP, a different behavior is observed, as while the 2IB (−0.0143 $kgP_{eq.}/tonne_{MSW}$) contributes to decreasing the freshwater eutrophication, the sanitary landfill contributes to FEP increase (0.0018 $kgP_{eq.}/tonne_{MSW}$). The observed relative difference in Table 5 indicates that 2IB has an 8.9 times better performance for FEP than sanitary landfill. This behavior also happens to other four LCA categories (GWP, MDP, POFP, and PMFP) in different ratios: the 2IB is able to cause 2.6 times lower global warming, 18.9 times lower metal depletion, 5.3 times lower photochemical oxidant formation, and finally, 161 times lower particulate matter formation, the highest difference among all nine LCA categories. Both evaluated systems showed good values for net emissions in WDP, but differently from all other eight LCA categories, the sanitary landfill has a 2 times better relative performance than 2IB for WDP. As shown by Table 5, the 2IB emitted 4.2 times lower WDP than sanitary landfill, but it has 2 times lower avoided emissions due to the lower amount of electricity made available as an output, resulting in a worse WDP net emissions performance.

The study of Papadaskalopoulou et al. (2019) showed that a biorefinery for ethanol production from biowaste has a higher LCA environmental performance than the landfill, composting, anaerobic digestion, and incineration options. Albeit considering biowaste rather than MSW as raw material feeding the biorefinery, the author's findings are consistent with the results obtained for the 2IB. Focusing on MSW management, Sadhukhan and Martinez-Hernandez (2017) applied LCA to analyze a novel system for complete waste valorization. The studied integrated material recovery facility and biorefinery includes pulping, chemical conversion, effluent treatment plant, anaerobic digestion, and combined heat and power systems to produce recyclables, metals, fiber, levulinic acid, water, fertilizer, and electricity. Results indicated that process integration was crucial for achieving the environmental benefits, including GWP savings of 2.4 and 1.3 $kgCO_{2eq.}$ per unit mass of levulinic acid used as a solvent and fertilizer, respectively, and 0.17 $kgCO_{2eq.}$ per MJ of grid electricity offset. Once again, the literature corroborates the notion that integrating processes within a biorefinery as in the 2IB studied herein results in environmental gains.

From a general comparative analysis, the obtained results presented in Table 5 clearly indicate that MSW management through the studied 2IB has better performance for most LCA impact categories than the sanitary landfill option. Considering integrated processes such as recycling of inorganic materials, anaerobic digestion of organic materials, heat and electricity generation, compost production for gardens and municipal plant beds (also for agricultural use, when meeting quality standards), as well producing thermoplastic materials to replace concrete, wood, and metal-based materials, has shown to be a better environmental initiative from an LCA perspective than just landfilling the MSW. Notwithstanding, it is important to highlight that 2IB is aligned with the Brazilian law 12,305 of 2010 about the national solid waste policy (BRAZIL, 2010), that outlines principles, objectives, instruments, and guidelines for an integrated management of solid waste. Complying with the law, the 2IB integrates several processes to treat the MSW in its usual characteristics of mixed inorganics and organics materials, making the technological route of 2IB more plausible to be implemented than alternative hypothetical scenarios that would hardly be implemented in short to medium terms.

4. Conclusions

This study applied the life cycle assessment (LCA) method on an innovative and integrated biorefinery (2IB) feeding by municipal solid waste (MSW). Comparing LCA results with a sanitary landfill option for MSW management, the main conclusion is that 2IB has, by far, a better environmental performance. The 2IB achieved better performance than sanitary landfill in eight of nine LCA categories analyzed, including: 161 times better for particulate matter formation potential (PMFP), 42.5 for terrestrial acidification potential (TAP), 22.3 for human toxicity potential (HTP), 18.9 for metal depletion potential (MDP), 8.9 for freshwater eutrophication potential (FEP), 5.3 for photochemical oxidant formation (POFP), 2.9 for fossil depletion potential (FDP), and 2.6 for global warming potential (GWP). The sanitary landfill showed a 2 times better performance than 2IB exclusively for the water depletion potential (WDP) category. These figures suggest that prioritizing 2IB over sanitary landfills should be advocated in public policy propositions as an alternative for environmental mitigation in MSW management under the circular economy lens.

While the net emissions indicate that 2IB is an 'absorber' rather than an 'emitter' across all nine LCA impact categories, attention should be directed towards improving performance in the FDP, GWP, and WDP categories. These three LCA categories showed the lowest comparative performances for the 2IB among all others. Strategies aimed at reducing the steel usage in machineries and equipment, coupled with higher efficiency for internal electricity consumption, are essential for enhancing performance in these LCA indicators.

It is expected that the methodological approach applied in this work, as well the 2IB studied case, can both be considered as a reference for future studies on innovative biorefineries for MSW management. Although uncertainty and sensitivity analysis has not been included in this study due to data reliability and standardization of the method applied, future research could explore scenarios aimed at optimizing the environmental performance of 2IB. LCA assessments, such as the one developed in this study for an innovative system, are imperative for informing decisions in strategic planning geared towards mitigating the environmental impacts associated with MSW management.

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. Tree-diagram processes of the studied innovative integrated biorefinery

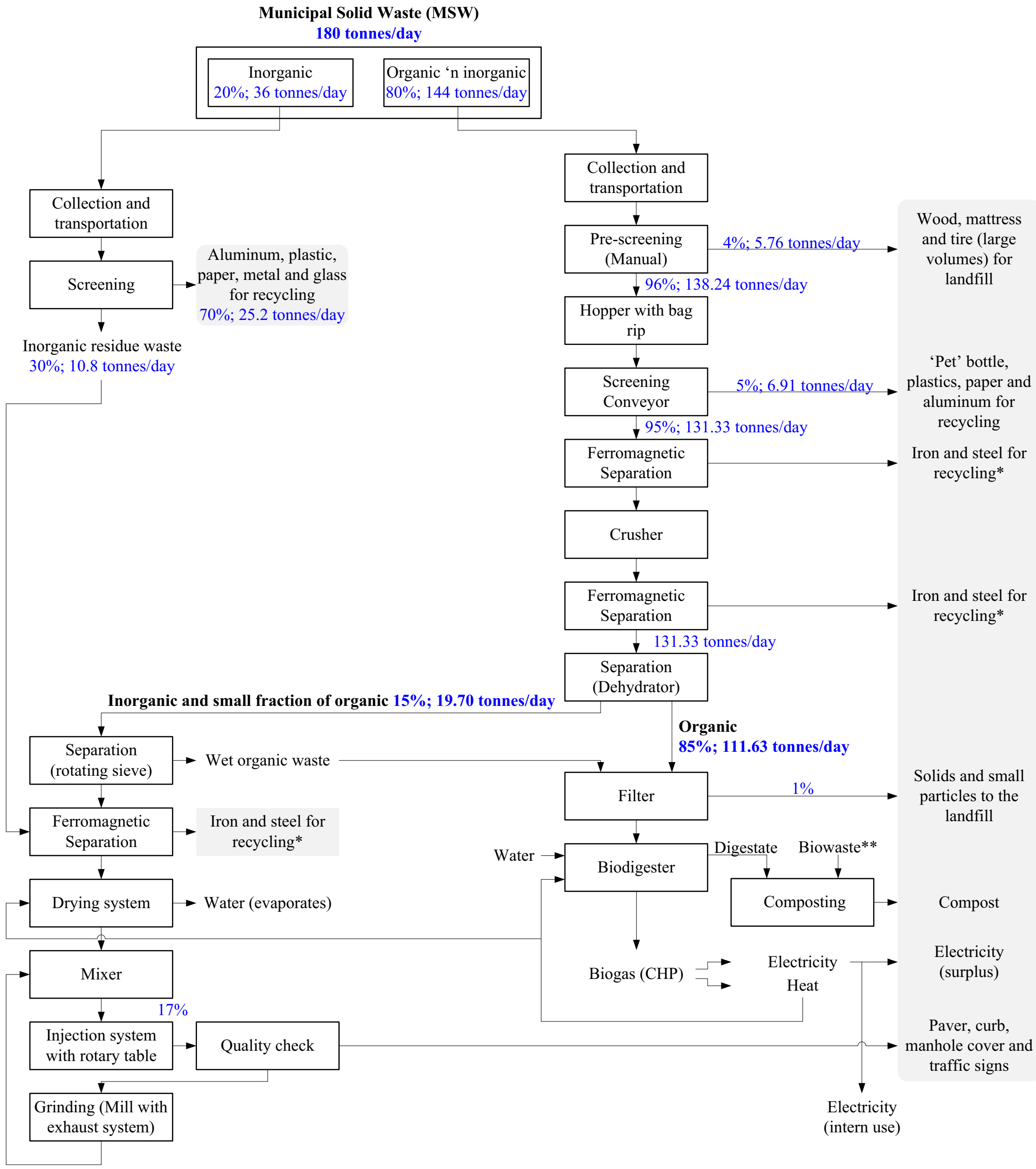

Fig. A.1. The 2IB-related processes (including mass balance).
* Included in 5 % of PET bottles, other plastics, paper, and aluminum for recycling.
** The composting process requires the use of a biowaste due to the characteristics of the digestate (5 % solid and 95 % liquid); the biowaste type is the one available in the region according to its availability, such as rice husks. In this case, rice husk is a by-product of rice, so it has zero-emissions embodied.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2024.03.015.

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