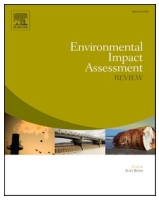
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A decision-making model for more sustainable municipal solid waste management

Arno P. Clasen *, Feni Agostinho, Cecília M.V.B. Almeida, Biagio F. Giannetti

Post-graduation Program in Production Engineering, Paulista University, Brazil

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ABSTRACT

The increasing volume of municipal solid waste (MSW) globally requires sustainable management strategies, especially in resource-constrained regions where landfilling remains predominant due to economic limitations. This study proposes a decision-support model focused on sustainability to guide the choice of technological routes for MSW management, comparing a conventional sanitary landfill with an integrated and innovative biorefinery (2IB), positioned at the top of the waste management hierarchy. The evaluation includes a diagnosis phase, which addressed only the treatment plants, and a simulation phase, which incorporated transportation distances and variations in MSW composition. Both phases were based on the five-sector sustainability model (5SEnSU), here applied for the first time to MSW management systems. Results focused on treatment showed that 2IB performs approximately 15 times better in terms of the sustainability synthetic indicator of the system (SSIS: 0.53) compared to sanitary landfill (SSIS: 8.12). Results from simulations revealed that 2IB remains the more sustainable option for additional transport distances up to 11,000 km/day and for any combination of organic and inorganic waste fraction. The study concludes that the adoption of 2IB should be prioritized in MSW public policies, particularly through intermunicipal consortia, which can facilitate implementation. This study contributes scientifically by assessing, for the first time using the 5SEnSU, the sustainability of an innovative biorefinery for MSW. Practically, it delivers a replicable and adaptable model to help local governments make informed, sustainability-based decisions. It further offers clear operational threshold, on transport distance and waste composition, that can be readily applied in real-world planning and policy.

1. Introduction

Population growth and changes in consumption patterns have led to increased waste generation, posing significant challenges for governments in establishing effective waste management systems. According to the United Nations Environment Programme (UNEP) and the International Solid Waste Association (ISWA), municipal solid waste (MSW) generation is predicted to grow from 2.1 billion tons in 2023 to 3.8 billion tons by 2050 worldwide (UNEP and ISWA, 2024). In Brazil, municipalities generated ~77 million tons of MSW in 2022 or ~ 211,000 tons of MSW daily, with 39 % still being inadequately disposed of (ABREMA, 2023). Effective management of such large volumes is essential to mitigate risks to human health and the environment degradation (Han et al., 2024; Zhang et al., 2025). Despite ongoing discussions regarding management systems, the issue of improper MSW management persists in numerous countries (Kaza et al., 2018).

The responsibility for collecting and managing MSW falls predominantly on municipal authorities, for whom waste services often represent a substantial share of municipal budgets, yet these services often end up disposing of MSW in unsuitable informal locations (USAID, 2023). Governance regulations, such as relevant laws, policies, taxes, and public awareness, play essential roles in shaping MSW governance (Zhou et al., 2022). Successful MSW management requires analyzing various factors to identify the most suitable technological route, considering both economic and sustainability aspects. In Brazil, Law No. 14,026 of 2020, known as the legal framework for basic sanitation (Brazil, 2020), facilitated the establishment of intermunicipal consortia to assist with environmentally appropriate solid waste disposal. Although such consortia are now common throughout the country, many initiatives continue to prioritize cost reduction over structural

* Corresponding author at: Universidade Paulista (UNIP), Programa de pós-graduação em Engenharia de Produção, Dr. Bacelar 1212, 4th floor, 04026-002 São Paulo, Brazil.

E-mail addresses: apclasen@gmail.com, arno.clasen@docente.unip.br (A.P. Clasen), feni@unip.br (F. Agostinho), cmvbag@unip.br (C.M.V.B. Almeida), biafgian@unip.br (B.F. Giannetti).

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innovation or the adoption of more sustainable technologies. This is evidenced by the projected MSW recovery rate of only 13.8 % in 2024, which includes recycling (5.7 %), thermal treatment (5.4 %), and biological treatment (2.7 %) (Brazil, 2022).

Among the MSW disposal practices in Brazil, sanitary landfilling remains the predominant, with many nearing full capacities. According to Vaverková (2019), landfilling is often preferred globally for its practicality and lower cost compared to alternative methods. However, before landfilling waste, the U.S. Environmental Protection Agency (EPA, 2022) recommended prioritizing waste reduction at the source, followed by recycling, composting, or energy recovery. In line with this hierarchy, a systemic strategy for MSW management that integrates technological solutions is crucial to reduce harm and reintegrate waste into production cycles (Ding et al., 2021). Within this context, waste biorefineries hold a position of priority as they use biomass as feedstock to generate bioenergy, chemicals and other products through integrated transformation processes (Yue et al., 2014). Thus, biorefineries are emerging as an alternative to traditional methods of MSW disposal such as sanitary landfills. Nonetheless, despite their potential, little is known about the sustainability performance of MSW-based biorefineries and potential technical and logistical constraints that may hinder their implementation.

Recently, a group of municipalities in the state of Santa Catarina, Brazil, established a consortium to implement an integrated and innovative biorefinery (2IB), designed to treat the entire waste stream through multiple technological processes. This technological route was previously detailed in Clasen et al. (2024a, 2024b), and includes both manual and mechanical separation system to recover value-added inorganic materials through recycling, along with a mechanical-biological treatment facility for the mixed organic and inorganic fractions. Anaerobic digestion is employed to process the segregated organic fraction, generating compost and energy. A notable innovation beyond technological integration is the incorporation of a thermoplastic transformation process, which produces materials for use in public infrastructure purposes. These characteristics render 2IB a suitable candidate for a case study.

Selecting an appropriate MSW technological route represents a complex problem for municipalities, involving numerous qualitative and quantitative criteria (Arıkan et al., 2017; Sondh et al., 2022). According to Ebrahimian et al. (2023), applying multi-criteria assessments is fundamental for evaluating the feasibility of implementing waste-based biorefineries. Although the concept of sustainability has gained prominence in recent years, there is still no standardized or widely accepted framework for assessing the sustainability of technological MSW routes. Assessment tools have attempted to address sustainability in MSW systems, particularly those based on life cycle assessment (LCA). However, LCA approaches are primarily designed to evaluate environmental impacts and therefore do not capture the full scope of sustainability, which requires the simultaneous and non-substitutable consideration of environmental, social, and economic dimensions. Existing sustainability-based tools include the DEWasT (Dimensional Evaluation of Waste Transition) model (Iyamu et al., 2022), the Metric of Sustainability – MOS (Chong et al., 2016), and mathematical programming models (Yi et al., 2023; Iqbal et al., 2025) or energy sustainability assessments (Gómez-Camacho et al., 2021). These studies reflect an important shift toward sustainability evaluation, yet diverge significantly in their methodological focus, data requirements, and treatment of sustainability dimensions. While some emphasize environmental impacts or energy recovery, others incorporate environmental, social or economic aspects in isolation. This lack of integration underscores the need for a model that is aligned with the principles of sustainability and enables comparative assessment of complex technological systems. Furthermore, few studies systematically incorporate the Sustainable Development Goals (SDGs) and their targets as part of their evaluation. As emphasized by Markard et al. (2020), inertia to structural change in current systems presents a significant barrier to achieving many of the SDGs.

Given these gaps, the Five-Sector Sustainability Model (5SEnSU; Giannetti et al., 2019) emerge as a viable alternative for multi-criteria sustainability assessment. It allows for an integrated and balanced evaluation of environmental, economic, and social dimensions. As noted by Łuczak and Just (2021) the 5SEnSU model elucidates the relationships between humans and the natural environment, establishes clear criteria for indicator selection, and leads to the construction of an easy-to-understand sustainability synthetic indicator of system (SSIS). Developed to address the absence of a robust assessment model for sustainability assessments, 5SEnSU has been utilized across various systems and scales, including the transportation sector (Agostinho et al., 2019), agriculture (García et al., 2021; Nacimento et al., 2022; Agostinho et al., 2023), basic sanitation (Giannetti et al., 2022), economic blocs (Dos Santos et al., 2022), cities (Pierucci et al., 2023), social inequality (Giannetti et al., 2023), manufacturing (Silva et al., 2024), and the automotive textile sector (Santos et al., 2024). Although 5SEnSU has been successfully applied in diverse sectors, it has not yet been explored as a supporting tool for municipal decision-making in MSW systems.

Besides sustainability-oriented assessments of MSW, effective decision-making by municipal authorities is also important to avoid short-, medium-, and long-term negative consequences. Understanding the sustainability of different systems and technological routes for treating MSW is one matter, but effectively choosing, from a systemic and complex perspective, which technological route should be implemented in each specific region is another. According to Ravichandran and Venkatesan (2021), there is a need for a practical tool to help municipalities choose between biorefineries and traditional waste disposal. To support more sustainable choices in MSW management, this study aims to develop a decision-support framework for MSW management that integrates the 5SEnSU model and simulation procedures to guide municipalities in choosing between traditional landfilling and innovative biorefineries.

This study contributes to the ongoing debate on improving MSW decision-making by presenting a modeling framework that integrates sustainability criteria, captured through the SSIS index, into practical tools for municipal use. This is the first application of the Five-Sector Sustainability (5SEnSU) model to assess MSW treatment systems, integrating it with a novel simulation procedure that defines real threshold conditions to support public decision-making. By moving beyond the prevailing emphasis on economic costs, the model enables a deeper assessment that incorporates environmental, social, and economic dimensions, supporting the selection of optimized management strategies such as 2IB or traditional sanitary landfilling.

The structure of this article is outlined as follows: Section 2 describes the proposed alternative method, including both the diagnostic and simulation phases based on the 5SEnSU model. Section 3 presents and discusses the results, organized into two parts according the method: (i) the sustainability assessment comparing the 2IB and the sanitary landfill, and (ii) simulations of key decision-making variables, namely MSW transport distances and composition; as well as practical implications, limitations, and future research. Finally, Section 4 provides the main conclusions.

2. Methods

Fig. 1 shows the methodological steps necessary to achieve the objectives proposed in this study: (a) assess the sustainability of two municipal solid waste (MSW) treatment systems, a conventional sanitary landfill and an integrated and innovative biorefinery (2IB), by calculating the sustainability synthetic indicator of systems (SSIS); and (b) simulate the inventory data and indicators using a decision-support algorithm to assist municipalities in selecting the most appropriate technological route. The first step involves modeling the processes existing on both the 2IB and sanitary landfill, followed by compiling the

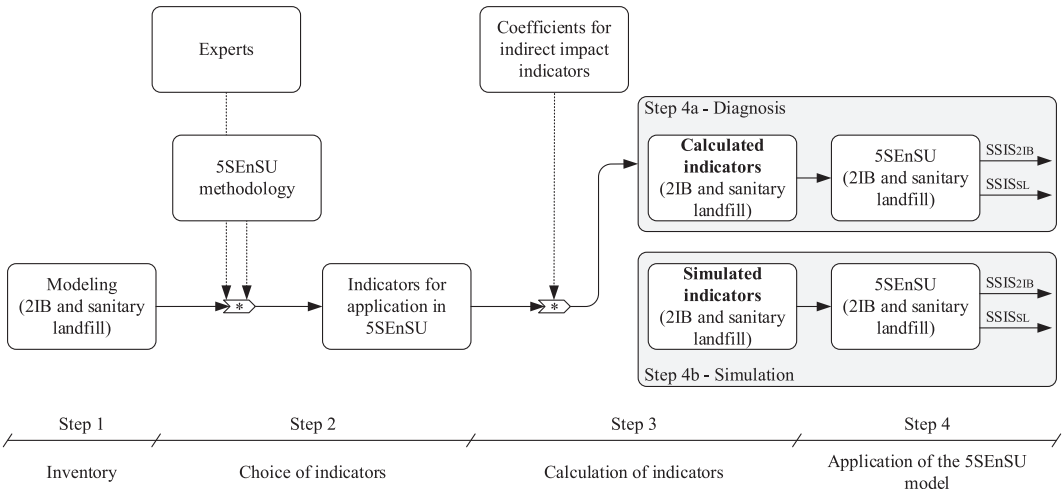


Fig. 1. Steps for applying the proposed alternative method to select more sustainable technological routes for MSW management.

data inventory. In Step 2, indicators are selected based on the five-sector sustainability model (5SEnSU), considering participatory meetings and the application of questionnaire to experts. Step 3 involves the collection of conversion factors for calculating indirect impact indicators, such as those derived from life cycle assessment (LCA) and eMergy synthesis (with 'M'; Odum, 1996), while direct indicators are also computed. In Step 4, all indicators are processed using the goal programming philosophy within the 5SEnSU model to derive the SSIS for each system. This stage constitutes the diagnostic phase (represented in the upper gray box of Fig. 1), enabling comparison between the 2IB and the sanitary landfill. Additionally, a simulation phase (lower gray box) is conducted, involving the simulation of key indicators that are essential for decision-making, which results in an updated SSIS value. Each step is outlined in the following subsections.

2.1. Step 1 - Inventory

The inventory phase involves the modeling of two MSW management systems under analysis: the *2IB* and the sanitary landfill. The *2IB* was modeled using primary data from a technical visit to an Intermunicipal Consortium in the state of Santa Catarina, Brazil. The information gathered during the visit accurately reflects the operational reality of the facility, as all potential technical challenges related to its implementation and use had already been addressed and overcome. The 2IB represents an innovative alternative for treating MSW, capable of managing its entire composition and transforming waste scraps into thermoplastic products, making it a notable case study (additional details regarding 2IB processes can be found in Clasen et al. (2024a, 2024b)).

Table 1 shows the aggregated inventory data for the 2IB on an annual basis. The detailed inventory is available in the Supplementary Material A. The data in units per year were later converted to the functional unit,

Table 1
Aggregated inventory data of the integrated and innovative biorefinery (2IB).

Item	Inventory in annual basis		Inventory in ton MSW			
			With collection and transportation		Without collection and transportation	
	Amount	Unit/year	Amount	Unit/ton MSW	Amount	Unit/ton MSW
			Inputs			
Steel	6.09E+04	kg	9.27E-01	kg	4.75E-01	kg
Concrete[a]	9.04E+03	kg	5.51E-05	m^3	5.51E-05	m^3
Diesel[b]	3.93E+05	L	5.10E+00	kg	1.10E-01	kg
Electricity[c]	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[d]	0.00E+00	kg	0.00E+00	kg	0.00E+00	kg
Labor	1.98E+02	person	3.01E-03	person	1.72E-03	Person
			Outputs			
Electricity (surplus)	2.51E+06	kWh	3.82E+01	kWh	3.82E+01	kWh
Compost[e]	8.80E+03	m^3	1.34E+02	kg	1.34E+02	kg
Paver (substitute concrete)[f]	4.80E+05	m^2	8.77E-02	m^3	8.77E-02	m^3
Paper and cardboard	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	1.23E+03	ton	1.87E+01	kg	1.87E+01	kg
Other (polystyrene, electronics, vegetable oil and tissue)	6.82E+02	ton	1.04E+01	kg	1.04E+01	kg

The detailed inventory of equipment and materials on an annual basis is available in the Supplementary Material A. Conversions of values for the functional unit:
[a] concrete from kg to m^3, density of 2500 kg/m^3;
[b] diesel from L to kg, density of 0.853 kg/L (diesel is considered to be that used in collection and transportation and internally);
[c] 2IB is self-sufficient in energy, therefore, electricity as an input is considered as 'zero';
[d] biowaste is used in the composting process, and this is considered as a byproduct like rice husk or wood residue, therefore, it has no environmental impact;
[e] compost from m^3 to kg, density of 1000 kg/m^3;
[f] paver from m^2 to m^3, first to kg (density of 30 kg/m^2) and then to m^3 (concrete density of 2500 kg/m^3).

defined as the management of 1 ton of MSW, with and without including collection and transportation phases. The inputs include materials used for infrastructure, operation, and labor. On the output side, the biorefinery generates several valuable co-products, including surplus electricity, compost, thermoplastic products (such as pavers), and a variety of recovered recyclables (paper, plastics, glass, metals). The sanitary landfill, modeled by Sulis et al. (2021) also with primary data, serves as a comparative reference due to its widespread use as a traditional MSW management method. It is important to highlight that although a biorefinery is being considered for comparisons to a sanitary landfill, the decision model proposed in this study can be applied to other technological routes including composting, waste-to-energy, among others.

2.2. Step 2 - Choice of indicators

A thorough literature review was conducted to identify indicators addressing social, economic, and environmental aspects, usually applied to assess MSW technological routes. From Cervantes et al. (2018), 377 indicators were initially identified. A preliminary selection carried out by the authors, reduced this set to 32 indicators based on three criteria: (i) frequency of indicator use in MSW assessments, (ii) diversity of waste management processes to ensure all stages of waste management are covered, and (iii) a balanced representation of social, economic, and environmental indicators. At this point, emergy indicator was recognized as a critical aspect missing from the original set and was subsequently added. To refine the selection, a participatory approach was employed involving 20 experts in sustainability. Using questionnaires applied via Microsoft Forms®, the experts were asked to allocate the indicators to the sectors of the 5SEnSU model and identify the most suitable ones for evaluating MSW management systems, such as 2IB and sanitary landfill.

Fig. 2 shows the 5SEnSU model, which guided the selection of indicators used in both the diagnosis and simulation phases. In this model, both the environment and society serve dual roles as suppliers and receivers. For instance, the environment provides resources as raw materials (sector 1) for the production unit (sector 3; MSW management system), while also receiving (sector 2) waste and emissions generated by activities in sector 3. Similarly, the sector 4, which fulfills a socioeconomic function, provides resources such as labor, and receives financial compensation for it. Sector 3 provides products to society (sector 5) and is remunerated in return. It is interesting to note that the model allows the selection of indicators that, while representing and characterizing the sector to which they belong, can also reflect direct interactions between the environmental and social sectors, and vice versa. Sector 3, which represents the economic sector, is the central element of the model, but the nature of the selected indicators is the link that connects the functions of each sector of the model to the consequences for the system as a whole and for human life. Additional details on the 5SEnSU model are explained in the next sections.

Expert opinions were collected using a Likert scale, with the following values: extremely important = 1, very important = 0.75, moderately important = 0.5, slightly important = 0.25, and not important = 0. This method yielded a ranked set of indicators, which were assigned to the sectors of the 5SEnSU model. The final selection comprised 11 indicators with the highest importance scores, with two allocated to each of the first four sectors and three to the fifth sector. Indicators are denoted as k_{ij}, where 'j' represents the indicator number within sector 'i' (e.g., k_{32} refers to indicator 2 of sector 3). In Sector 1: k_{11}, Emergy Return Index (dimensionless); and k_{12}, Fuel and electricity consumption from the external grid (kWh/ton MSW). In Sector 2: k_{21}, Global warming potential ratio ($kgCO_{2eq}$ output/$kgCO_{2eq}$ input); and k_{22}, Human toxicity potential ratio ($kg1,4\text{-}DCB_{eq.}$ output/ $kg1,4\text{-}DCB_{eq.}$ input). In Sector 3: k_{31}, Amount of recycled waste (ton recycled/ton MSW); and k_{32}, Total revenues and earnings (BRL/ton MSW). In Sector 4: k_{41}, Employment (person/ton MSW); and k_{42}, Percentage of recyclable waste in collection (% recycled). In Sector 5: k_{51}, Average salary per capita (BRL); k_{52}, Electricity generation surplus (kWh/ton MSW); and k_{53}, Compost generation (m^3/ton MSW). Details on the indicator selection and participatory process are provided in Supplementary Material B. Notably, this decision-making approach is adaptable, allowing analysts to modify and apply different indicators depending on the context.

2.3. Step 3 - Calculation of indicators

The so-called direct impact indicators can be directly obtained from database or easily calculated and applied. However, for those so-called indirect impact indicators, the life cycle assessment (LCA) is recommended as the preferred approach (International Organization for Standardization - ISO, 2006a and ISO, 2006b). For the indirect impact indicators, the Ecoinvent® database (version 3.6, 2019, Allocation at the point of substitution) is used as data source for the conversion factors used in the LCA, employing the Recipe Midpoint (H) V1.13 method.

Additionally, emergy synthesis plays a key role in accounting for indirect impacts. Emergy is defined as all available energy (exergy) previously used, directly or indirectly, to produce a product or service (Odum, 1996), and is measured in solar emjoules (sej). The unit emergy values (UEVs; conversion factors for emergy application) are obtained from published articles in the scientific literature, besides those ones from the National Environmental Accounting Database V2.0 (http://www.emergy-nead.com/home). It is recommended to use UEVs that exclude labor and services (meaning both direct and indirect labor),

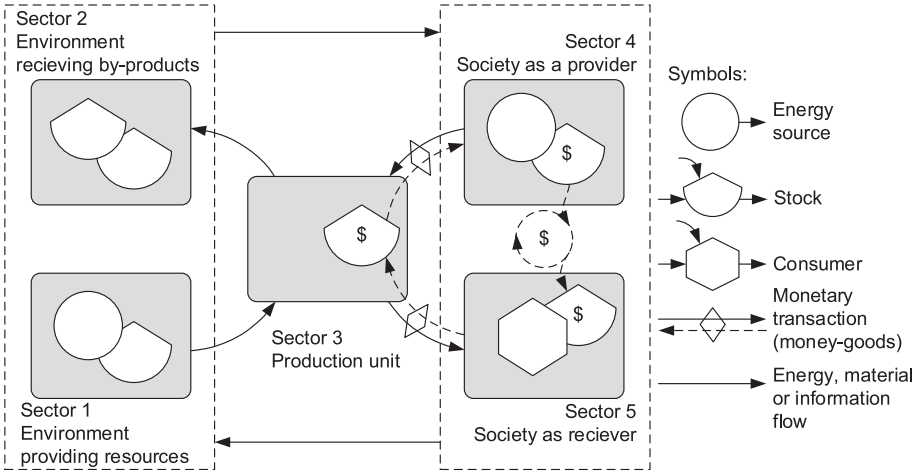


Fig. 2. Five sectors sustainability (5SEnSU) model. Adapted from Giannetti et al. (2019).

and standardizing them to the current emergy baseline of 12.00E+24 seJ/year (Brown et al., 2016).

Once the conversion coefficients are obtained, both direct and indirect indicators can be calculated. Collection and transportation phases were disregarded at this point, as they are assumed to be the same for any technological route, enabling a consistent comparison between 2IB and sanitary landfill. After calculating the indicators, they are feed into the 5SEnSU model, allowing for two distinct evaluation methods: diagnosis and simulation, as outlined in the following sections.

Table 2 shows the set of calculated indicators for 2IB and sanitary landfill, covering all five dimensions of the 5SEnSU model. Among them, indicators k_{11} (emergy return index), k_{21} (global warming potential ratio), and k_{22} (human toxicity potential ratio) are dimensionless and reflect the net relationship between system outputs and the resources or impacts required to produce them. The values can be interpreted as follows: values >1 indicate that the quantity obtained exceeds the investment of 1 unit suggesting positive performance, while values <1 indicate that the quantity obtained is less than the investment of 1 unit suggesting negative performance. The characterization factors and UEVs used to quantify the indirect impact indicators are provided in the Supplementary Material C. Indicators k_{42} (percentage of recyclable waste in collection) and k_{51} (average salary per capita) are not expressed in relation to the functional unit, as their values are independent of it.

2.4. Step 4a - 5SEnSU model

The 5SEnSU model enables the assessment of systems sustainability through a multidimensional approach, incorporating social, environmental, and economic dimensions. It employs the goal programming philosophy technique to quantify the SSIS, which requires the definition of objectives, goals, and punishments for each indicator listed in Table 2. Weights can be assigned to indicators and/or sectors when necessary; in this study, equal weights (1.0) were assumed for all indicators and sectors of 5SEnSU, but the framework enables the analyst to assign different weights whenever appropriate, according to the objectives and context of each case study. The result of applying the 5SEnSU model is the sustainability synthetic indicator of system (SSIS), a dimensionless metric that reflects the sustainability performance of a system. Lower SSIS values indicate comparatively better sustainability performance and higher values indicate poorer sustainability performance.

Table 2
Indicators for the integrated and innovative biorefinery (2IB) and the sanitary landfill.

Item	Indicator	Unit	Values	
			2IB	Sanitary landfill
#1	k_{11}, Emergy Return Index	Dimensionless	1.82E+00	6.01E-02
#2	k_{12}, Fuel consumption + Electricity consumption from external grid	kWh/ton MSW	1.37E+00	1.52E+01
#3	k_{21}, Global warming potential ratio	Dimensionless	9.44E+01	1.59E-01
#4	k_{22}, Human toxicity potential ratio	Dimensionless	6.33E+01	3.39E+00
#5	k_{31}, Amount of recycled waste	ton recycled/ ton MSW	2.10E-01	0.00E+00
#6	k_{32}, Total of revenues and earnings (income)	R$ (BRL)/ton MSW	3.92E+02	9.65E+01
#7	k_{41}, Labor/employment (total human resources)	person/ton MSW	1.72E-03	3.98E-04
#8	k_{42}, Percentage of recyclable waste in collection (source separation level)	% recycled	2.00E+01	2.00E+01
#9	k_{51}, Average salary per capita	R$ (BRL)	6.00E+03	6.00E+03
#10	k_{52}, Electricity generation (surplus)	kWh/ton MSW	3.82E+01	1.22E+02
#11	k_{53}, Compost generation	m^3/ton MSW	1.34E-01	0.00E+00

The calculation procedure for all the 2IB's indicators is detailed in the Supplementary Material C.

For each indicator evaluated within the 5SEnSU, the model computes the deviation between the actual system value and the predefined goal (Appendix A). If the system exceeds the target in a negative way such as emitting more CO_2 than the established goal, a higher penalty ($W_{above\text{-}goal}$) is applied compared to cases where the system performs better than the goal ($W_{below\text{-}goal}$). Even when the deviation is numerically the same, exceeding the goal incurs a greater penalty to reflect its undesirability. The final value is computed by dividing the distance from the goal (deviation) by the product of the punishment and the goal. Taking as example the minimization of the indicator, a system with emissions below the goal would be penalized less than one exceeding it. This logic also applies to maximization indicators, such as profit, where falling short of the target results in higher penalties. The closer a system is to its goal, the better its sustainability score. Please see Giannetti et al. (2019) and Agostinho et al. (2019) for more details on the algebra used within the goal programming philosophy.

This study employs two distinct approaches to analyze the results, as depicted in Fig. 1. The first approach, named 'diagnosis', enables the comparison of two MSW management systems through indicator calculations and application of the 5SEnSU model to determine the SSIS. The analysis includes evaluating each system's sustainability, identifying the 5SEnSU sector with the highest or lowest performance, and determining the indicator with the greatest influence on results. The second approach, designated as 'simulation', involves the simulation of essential indicators and/or variables within indicators calculation (when applicable), allowing decision-makers to identify the most suitable technological route for their municipality. This practical simulation approach facilitates the generation of varying SSIS values and the examination of scenarios, as explained in the next section.

2.5. Step 4b - Simulation tool

Based on Fig. 1, the diagnostic assessment is followed by indicator simulations. In this stage, assumptions and parameters were established to develop the decision-support algorithm, which can be considered one of the main contributions of this study. A key concern is whether the low amount of MSW generation makes 2IB technically or economically unfeasible. For the analyzed case study, the facility managers and engineers established a minimum operational input of 50 tons/day, adopted here as the technical constraint. This constraint represents the minimum amount of waste required to ensure the efficient and continuous operation of the 2IB. It is the only technical constraint explicitly included in the algorithm shown in Fig. 3, as it directly affects the feasibility of simulating 2IB operation. However, this limitation can be addressed through intermunicipal consortia, as permitted by Brazilian Law No. 14,026/2020.

Beyond the existing technical constraint of a minimum MSW amount of 50 tons/day, the literature revealed that transportation affects MSW treatment sustainability (Das and Bhattacharyya, 2015; Van Fan et al., 2018; De Campos et al., 2021). Transportation basically involves two stages: door-to-door collection, and the transportation of the collected MSW to the final destination (landfill or 2IB). Similarly to the transport distance, the MSW organic fraction may affect the 2IB performance, since some conversion processes rely exclusively on either organic or inorganic waste streams. This variable is important not only for assessing sustainability performance but also for evaluating the feasibility of implementing the system in different regions. For example, less developed regions tend to generate MSW with a higher organic and lower inorganic content, whereas more developed regions usually produce waste with a lower organic fraction and higher amounts of packaging materials, reflecting their lifestyle and socioeconomic conditions.

While intermunicipal partnerships can mitigate the limitation imposed by the technical constraint (>50 tons MSW per day), they may

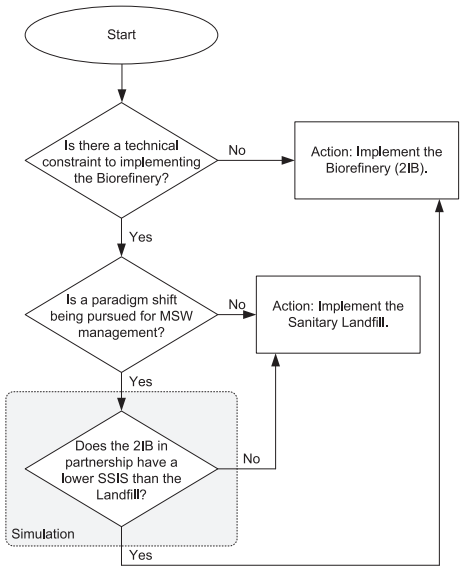


Fig. 3. Algorithm to assist in decision making about implementing a 2IB or sanitary landfill.

increase transportation demand, which in turn affect the indicators of the 5SEnSU model and the resulting SSIS. Thus, partner selection must balance MSW composition and transport distance to ensure 2IB's SSIS remains lower than that of landfills while maintaining operational efficiency; otherwise, the sanitary landfill would become the preferred technological option. It is acknowledged that technical constraints also exist in the development of sanitary landfills, where issues such as site availability, soil permeability, leachate control, and environmental licensing often limit their feasibility. However, since the aim of this study is to propose a decision model supporting the transition from traditional landfilling toward more sustainable technological alternatives these constraints were not detailed further, as they fall outside the analytical scope focused on the biorefinery option.

The financial constraint, specifically the implementation cost of the 2IB, in turn, was not included in the algorithm because it depends on subjective and context-specific variables such as funding sources (public, private, or mixed). While financial feasibility is recognized as an external factor that can influence the implementation of MSW treatment plants, it is treated conceptually as a boundary condition rather than a variable in the simulation process. For instance, smaller municipalities may have fewer residents but greater financial capacity, or vice versa. As shown in Fig. 3, this exclusion does not affect the model's applicability, since the economic factor is treated as an external constraint in the broader decision-making process. This constraint must be overcome through the establishment of a consortium; otherwise, a sanitary landfill must be implemented.

Fig. 3 presents the decision-making algorithm used to determine the optimal technological route: sanitary landfill or 2IB. By default, the preference is initially for 2IB due to its potentially superior sustainability performance. However, if technical constraints such as insufficient waste volume are not met, or financial feasibility cannot be assured, the sanitary landfill becomes the viable alternative, reflecting a business-as-usual model. Nevertheless, given the urgency for a paradigm shift toward sustainability, decision-makers should consider broader strategies aligned with the UN Sustainable Development Goals (SDGs) and Environmental, Social, and Governance (ESG) principles. This expanded perspective encourages partnerships and circular economy initiatives, as exemplified by the 2IB.

In this study, simulations were performed to estimate the SSIS of 2IB under partnership conditions by varying two key variables: (a) the distance required to transport MSW to the 2IB, and (b) the percentage of organic matter mixed into the MSW. These variables are expected to directly or indirectly affect the indicators utilized in the 5SEnSU model, resulting in different SSISs for 2IB and landfill. The objective is to answer: What is the maximum additional distance for transporting MSW that allows the SSIS of the partnership's 2IB to remain equal to or lower than that of a sanitary landfill? What is the maximum MSW organic matter percentage that enables the SSIS of the partnership's 2IB to remain equal to or lower than that of the sanitary landfill? The goal is to seek conditions ensuring a lower SSIS for 2IB than landfills. Simulations were automated using Excel® spreadsheets provided in Supplementary Material G, which generate updated indicator values showing how SSIS varies according to additional distance and MSW composition.

3. Results and discussions

This section is structured according to the two phases of the results evaluation outlined in the proposed method, as illustrated in Fig. 1: (i) a diagnostic evaluation of the two technological alternatives (landfill & 2IB) based on real performance data, focusing exclusively on the sustainability of treatment facilities without considering waste collection and transportation; and (ii) simulation of key decision-making variables, including transportation distances and waste composition, thereby encompassing the full MSW management chain from collection to final treatment.

3.1. Sustainability diagnosis

The application of the five-sector sustainability model (5SEnSU) involves six steps: data collection, indicator selection, goal and objective setting, punishment assignment, weight allocation, and sector indicator calculation; finally, the sustainability synthetic indicator of the system (SSIS) is obtained. Within the goal programming philosophy, goals can be established based on benchmarks. As noted by Agostinho et al. (2019) and Dos Santos et al. (2022), establishing goals and indicator weights for the 5SEnSU model may be a limitation of the method when such values are lacking. The sustainability assessment of technological routes in this study involves specific indicators without well-established benchmarks. Thus, benchmark-based goals were not set for the emergy return index (k_{11}), fuel and electricity consumption from external grid (k_{12}), and total revenues and earnings (k_{32}). Although benchmarks are unavailable for all indicators, references were identified in the literature for many, which supports the 5SEnSU model's application. Detailed objectives, justifications, and goals used in 5SEnSU-based goal programming philosophy to obtain the SSIS are provided in Appendix A and Supplementary Material D.

In the application of the goal programming philosophy-based tool, punishments must be established for indicators that are above or below the established goals, in line with the analyst's cultural profile - whether egalitarian, hierarchical, or individualistic. Here, punishments were set according to an egalitarian profile, which prioritizes the preservation of natural capital and emphasizes biophysical constraints for sustainable development. Punishments were set at 4.5 for environmental sectors (S1 and S2), 1.8 for the economic sector (S3), and 2.7 for social sectors (S4 and S5). These values were initially proposed in Eco-indicator 99 (Goedkoop and Spriensma, 2001), and further modified by Oliveira et al. (2016) and Agostinho et al. (2019).

After defining the objectives, goals, punishments, and weights (with equal weights assigned to each indicator), the automated goal programming approach in a Microsoft Excel® spreadsheet available in Agostinho et al. (2019) was applied to calculate the sustainability goal of indicators (ISG), sector sustainability indicators (SSI), and sustainability synthetic indicator of each system (SSIS). The goal programming philosophy application is available in the Supplementary Material E.

Fig. 4 shows the ISG results, representing the sustainability of each indicator after running the goal programming philosophy supported by the 5SEnSU. Among the indicators, the fuel and electricity consumption

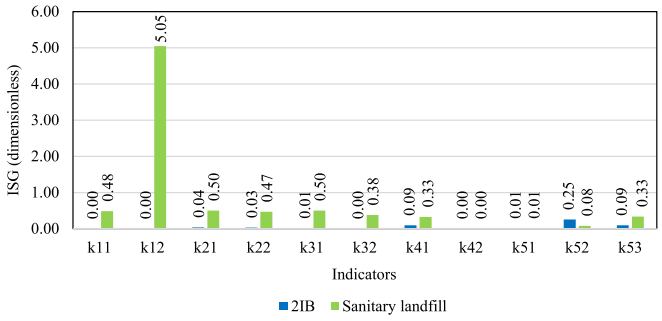


Fig. 4. Index of sustainability goal (ISG) after applying weights, goals and punishments. Indicators refers to Table 2: k_{11}, Emergy Return Index; k_{12}, Fuel and electricity consumption from external grid; k_{21}, Global Warming Potential ratio; k_{22}, Human Toxicity Potential ratio; k_{31}, Amount of recycled waste; k_{32}, Total of revenues and earnings (income); k_{41}, labor/employment (total human resources); k_{42}, Percentage of recyclable waste in collection (source separation level); k_{51}, Average salary per capita; k_{52}, Electricity generation (surplus); and k_{53}, Compost generation.

from the external grid (k_{12}) stands out. This indicator considers only diesel consumption, since both systems are self-sufficient in electricity and do not depend on external power sources. The disparity between the k_{12} values (0.00 for the 2IB and 5.05 for the sanitary landfill) results from the different energy demands of their operations. The 2IB primarily uses electrically driven equipment, minimizing fuel requirements, whereas the sanitary landfill depends on diesel-powered machinery and heavy vehicles for internal operations. In the sustainability assessment, this higher diesel consumption causes the landfill's k_{12} value to deviate further from the established target, leading to a greater penalty and consequently a lower performance score for this indicator.

Still regarding Fig. 4, the only indicator in which the sanitary landfill outperformed the 2IB was energy generation surplus (k_{52}), or net energy. This difference arises from the distinct energy balances of both systems. Although the 2IB is energy self-sufficient, a large portion of the electricity it generates is consumed internally to feed the processes involved in the treatment of MSW. As a result, the energy surplus sent to the external grid is relatively limited. In contrast, the opposite occurs with the sanitary landfill. Its biogas-to-energy system produces electricity with very low on-site consumption, which means that most of the generated power can be exported to the national grid, resulting in a higher value for the k_{52} indicator. This does not imply superior overall performance, but rather reflects a specific operational characteristic of the landfill energy recovery process compared to the more energy-intensive 2IB system.

Fig. 5 shows the results for the SSI and the overall performance (SSIS) of each technological route evaluated. In the 5SEnSU model, the goal programming philosophy approach typically sums indicators within each sector to compute the SSI (e.g., adding k_{11} and k_{12} to obtain the SSI for sector 1). However, this method assumes all sectors have an equal

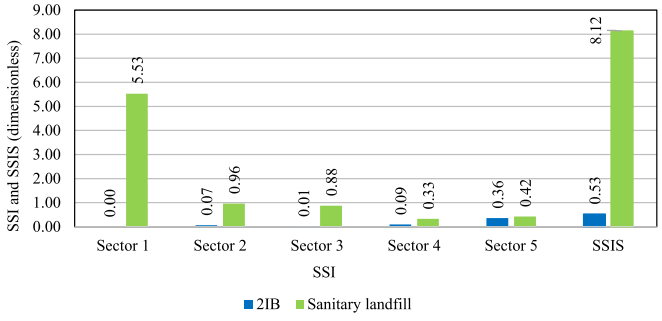


Fig. 5. Sector Sustainability Indicator (SSI) and Sustainability Synthetic Indicator of System (SSIS).

number of indicators, which is not the case here, as sector 5 has an additional indicator, potentially causing imbalance. Thus, the average of the indicators within each sector was considered to calculate the SSI, ensuring consistency. Finally, the SSIS is obtained by summing the SSI of all five sectors.

Fig. 5 confirms that 2IB outperforms the sanitary landfill in sustainability, reflected in a lower SSIS value. The SSIS of the sanitary landfill is ~15 times higher than that of 2IB, reflecting a markedly weaker sustainability performance under the perspective of 5SenSu model. This disparity is largely attributed to the environmental impact of sector 1 (resource provider to the production system), as a reflection of the ISG in Fig. 4. Sector 1's value of 5.53 accounts for ~68 % of the sanitary landfill's SSIS, followed by sectors 2 and 3, contributing with 0.96 (~12 %) and 0.88 (~11 %), respectively.

Once the overall system performance is understood, more specific decisions may be required by revisiting the analysis of each sector or the indicator that contributed most to the negative SSIS outcome. For instance, Fig. 5 shows that sanitary landfill exhibits the poorest sustainability performance, with sector 1 being the main contributor. In this sector, the k_{12} indicator has the most significant negative impact, accounting for 62 % of the SSIS score. Thus, priority should be placed on reducing the high diesel consumption of the sanitary landfill's internal machinery. Since truck usage is inherent to the system, transitioning to non-fossil fuels such as biofuels could enhance sustainability. As these actions are implemented, focus can shift to improving other indicators, following a prioritized approach.

Although 2IB exhibits superior sustainability, there is still room for improvements. In sector 5 (society receiving resources), indicator k_{52} (electricity generation; 0.25) is the most impactful, accounting for ~70 % of sector's score (0.36) and ~ 48 % of 2IB's SSIS (0.53). As previously stated, 2IB consumes part of the electricity generated in the anaerobic digestion process, reducing the surplus available to the national grid. The plant's processes and equipment demand high amount of electricity, which is a common challenge in technological systems. Thus, improving equipment efficiency could enhance overall performance. Sector 4 (society as a provider) of 2IB was solely influenced by indicator k_{41} (labor; 0.09). Indicator k_{42} (waste recycled at the generation site) met the established goal, resulting in an ISG of 'zero'. In sector 2 (environment receiving waste), even when an indicator exceeds the goal incurs a punishment - even if the objective is to maximize it -, albeit less severe than that for falling below the goal. This is seen in indicators k_{21} (Global Warming Potential Ratio) and k_{22} (Human Toxicity Potential Ratio), where 2IB reduces carbon emissions and human toxicity beyond the set goals.

Based on the SSIS values calculated through the 5SEnSU model, 2IB clearly emerges as the more sustainable technological route for MSW treatment when compared to sanitary landfill. Although this is the first known application of the 5SEnSU model in waste treatment systems – limiting comparative references - the study successfully fulfilled its primary objective of comparing the two routes under a consistent sustainability framework.

These findings support the recommendations of Ravichandran and Venkatesan (2021), who emphasized the need for integrated solid waste management strategies that consider technical, environmental, socio-economic, cultural, and institutional conditions. Moreover, 2IB (SSIS of 0.53) aligns with the waste management hierarchy proposed by the Environmental Protection Agency (EPA, 2022), reinforcing its prioritization in Brazilian municipalities. In contrast, the sanitary landfill presented lower sustainability performance with SSIS of 8.12. It is important to emphasize that these results only reflect treatment plants, without considering the collection and transportation stages. Furthermore, technical and financial aspects may arise as possible barriers for municipalities in their MSW management. Thus, to aid decision-makers in selecting the appropriate technological route, it is necessary to evaluate partnerships among municipalities that can mitigate these potential technical and financial constraints, in addition to determine optimal

locations for plant installation, considering the distances traveled by the trucks during MSW collection and transportation stages. As also recognized by Ravichandran and Venkatesan (2021), there is a need of a practical simulation tool that could support municipal authorities in deciding whether to implement 2IB or persist with traditional waste disposal methods, such as sanitary landfills. This topic is addressed in the next section.

3.2. Supporting decision-making: A simulation tool proposal

To support practical decision-making, the collection and transportation stages must be accounted for, since as they may differ between 2IB and landfill. These differences arise particularly in the context of intermunicipal consortia and agreements signed between the municipalities. This is especially relevant when a single 2IB plant is proposed to receive waste from multiple municipalities, potentially altering transportation distances and logistics, as well the MSW composition. Given the diagnostic results indicating that 2IB is more sustainable than the sanitary landfill, only 2IB is considered in the simulation. Consequently, any changes in MSW collection and transportation distances or composition generate a new SSIS indicator. The sanitary landfill's SSIS serves as a benchmark, identifying conditions under which 2IB can be implemented without exceeding the sanitary landfill's sustainability performance.

3.2.1. Additional transportation distance

The collection and transportation of waste constitute critical barriers in MSW management. According to Van Fan et al. (2018), transportation distances adversely affect the sustainability of anaerobic digestion systems. Similarly, Das and Bhattacharyya (2015) noted that waste collection accounts for 50 to 90 % of MSW management budgets. A key limitation of waste-to-energy technological routes in Brazil is the complexity of waste transportation (De Campos et al., 2021), which involves multiple trips by collection vehicles influenced by geographic conditions, MSW volume, truck types, and the sanitary landfill location. Since this complexity varies case by case, it was generalized in this study through the variable 'additional distance', which refers to the extra kilometers required for MSW collection and transportation if the existing sanitary landfills in the municipalities were replaced by a unique 2IB system treating all the MSW from a consortium of municipalities.

The central question addressed by the simulation is: What is the maximum 'additional distance' for collecting and transporting the MSW required to implement a 2IB in a consortium of municipalities, such that the SSIS of the 2IB does not exceed that of a sanitary landfill? To answer this, several scenarios were developed, starting from a reference scenario in which the additional distance was set at 0 km/day, representing the ongoing operation. From there, scenarios were constructed by incrementally adding 3000 km/day. This value was defined for the case study of the existing consortium in Santa Catarina state, Brazil; however, other distances could have been standardized, since the same results would be obtained. The simulation focused solely on 2IB, while for the sanitary landfill, the additional transportation distance remained 0 km/day across all scenarios, as current MSW collection and transportation practices would persist without the implementation of 2IB. A limitation of this practical simulation approach is the uncertainty regarding the specific location of 2IB implementation, which will be determined only after discussions on consortium formation; it is worth to note that the location of 2IB does not impact on the results of simulation approach developed.

While the reference scenario does not include additional variables, each subsequent scenario assumes a proportional increase in diesel consumption and operating costs associated with collection and transportation. Specifically, Scenario 1 (3000 km/day) assumes a doubling of diesel and operating costs, Scenario 2 (6000 km/day) a tripling of diesel and operating costs, Scenario 3 (9000 km/day) a quadrupling of diesel and operating costs, and so forth, up to Scenario 7 (21,000 km/day), which assumes an eightfold increase of diesel and operating costs. In the simulation, all scenarios affect the same set of indicators of Table 2: the Emergy Return Index (k_{11}), Fuel Consumption (k_{12}), Global Warming Potential Ratio (k_{21}), and Human Toxicity Potential Ratio (k_{22}).

As more municipalities are integrated into the hypothetical consortium, the amount of MSW processed by the biorefinery increases. However, since the calculations are based on a functional unit of 1 ton of MSW, this increase does not influence the results. Therefore, only the additional distance is considered in the analysis. Despite this, by increasing the transportation distance the system may experience an increase in vehicle use, personnel, diesel consumption and operating costs, all of which are accounted for in the simulation stage (reference scenario). Based on prior experience, diesel consumption is anticipated to have the greatest impact on the results, a characteristic primarily of transportation systems based on internal combustion engines. Although an increase in vehicle fleet and workforce could occur, this was not explicitly simulated, as route optimization and transfer stations may mitigate such effects. Thus, only the variable diesel and the operating costs are simulated in the alternative scenarios.

Fig. 6 shows the SSIS values for the simulated scenarios involving additional transportation distance. The results indicate that for every 3000 km/day increase in MSW transportation, the SSIS for 2IB rises, whereas that for the sanitary landfill slightly decreases; though not simulated, the variation on SSIS of landfill results from changes in the goal programming philosophy objectives, which depends on the indicators affected by the simulation. Up to an additional 15,000 km/day, 2IB revealed superior sustainability performance (i.e., a lower SSIS) compared to the sanitary landfill, achieving parity at 18,000 km/day with an SSIS of 2.78. These results emphasize that partnerships for MSW management through 2IB could be formed among municipalities, allowing for a maximum additional transportation distance of 18,000 km/day. In summary, all vehicles collecting and transporting MSW within the consortium municipalities can travel 18,000 km/day more than their current distance as the 2IB would still maintain equal or higher sustainability performance compared to the sanitary landfill. Beyond this threshold, the sanitary landfill begins to show superior sustainability performance relative to 2IB. In other words, the sustainability advantages of the 2IB represented by the SSIS are expressed by a buffer of 18,000 km/day, a number that is straightforward to interpret and serves as a clear threshold for planning and selecting municipalities to join the consortium for implementing a 2IB.

It is nothing worth mentioning that SSIS in the simulation stage (Fig. 6; 8.12 and 0.53 for landfill and 2IB respectively) differs from the diagnostic stage (Fig. 5; 0.47 and 3.03 for landfill and 2IB), as it now includes collection and transportation. With the expansion of the system's boundaries, there is an increase in materials and equipment in the assessment, as well as in the established goals, thus a change in the SSIS was expected. Anyhow, the most important outcome is the relative comparison among the evaluated systems; however, caution should be exercised when making comparisons using the 5SEnSU model.

To analyze the uncertainties of the SSIS calculated for the Sanitary Landfill and the 2IB, a Monte Carlo analysis was performed (available in the Supplementary Material E), considering a variation of ±30 % for all indicators presented in Table 2. A linear distribution was assumed for the random data sampling, with 10,000 iterations. The results show that the SSIS for the Sanitary Landfill was 8.3 ± 1.95, while the SSIS for the 2IB biorefinery was 0.6 ± 0.1, both with a 95 % confidence interval. Since the variation in SSIS for the Sanitary Landfill was approximately ±23 %, and for the 2IB biorefinery approximately ±17 %, these percentages were applied in the sensitivity analysis of SSIS shown in Fig. 6 to assess the variation in additional transport distance. Thus, it can be stated that when considering the 95 % confidence interval, the results from simulations revealed that 2IB remains the more sustainable option for additional transport distances up to 11,000 km/day.

According to the National Sanitation Information System (SNIS, 2023), Brazil generates 0.98 kg of MSW per capita per day. Given the

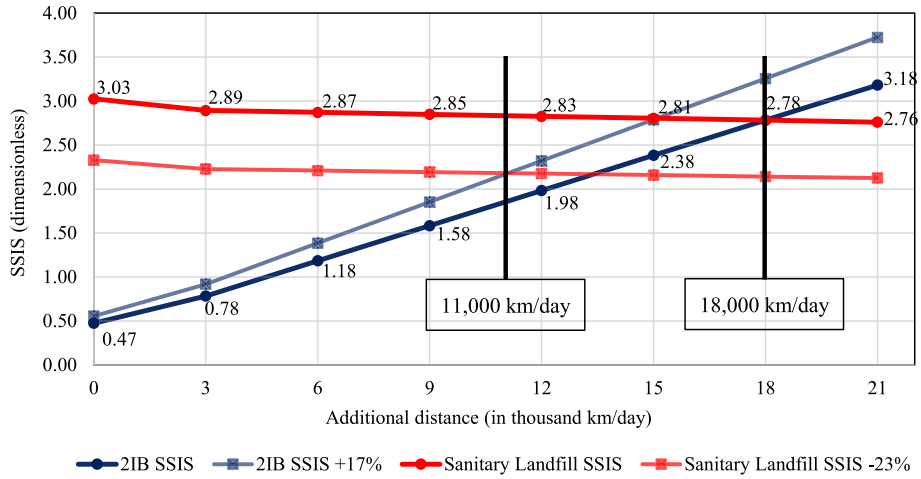


Fig. 6. Simulation results of additional transport distance. The simulated SSIS values resulted from the application of the 5SEnSU model using the data from Table G1 and Table G3 of Supplementary Material G.

specific conditions of the studied 2IB, processing 50 tons of MSW per day renders the plant both technically and economically viable. Thus, municipalities with over 50,000 inhabitants could implement 2IB independently of consortia. However, many municipalities lack the financial capacity for such initiatives and rely on intermunicipal collaborations. Potential partnerships can be identified by evaluating additional transportation distances. Sanitary landfills, widely used for MSW disposal, should only be replaced by 2IB if all performance criteria confirm its feasibility. Fig. 7 presents a decision-making framework for municipal authorities, based on transportation distance and supporting the selection of appropriate partners for the implementation of a 2IB within an intermunicipal consortium: First, address technical barriers by ensuring a minimum daily generation of 50 tons of MSW (>50 tons/day); Second, overcome financial barriers, which can be achieved through consortia ($); Third, ensure that the additional transportation distance does not exceed 11,000 km/day (<11,000 km/day); and, lastly, if any of the previous stages are not met, seek new partners, adjusting the composition of the consortium by adding or removing municipalities until a combination capable of meeting the first three criteria is found. If no viable partnership is achieved, sanitary landfills should remain in use. An example of a practical application is presented in detail in Supplementary Material F.

Concerns may also arise regarding the maximum MSW volume or the number of municipalities in the consortium. Although 2IB can process large MSW volumes by adding new processing lines, this expansion may be constrained by the availability of physical space for additional infrastructure. Furthermore, incorporating numerous municipalities into the consortium, while feasible in theory, may be impractical due to regional policy conflicts and challenges in aligning with municipal

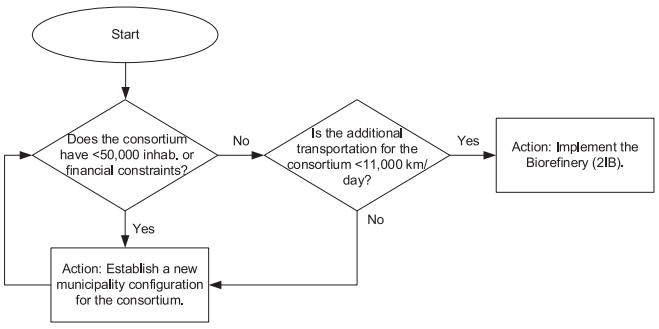


Fig. 7. Algorithm to assist in choosing municipalities and formalizing consortia for implementing the integrated and innovative biorefinery (2IB).

legislation regarding the usage of urban spaces. In this case, a solution would involve implementing multiple 2IB plants in adjacent areas.

The formalization of intermunicipal consortia depends on factors beyond those discussed in this study. For instance, municipal authorities may prioritize partnerships based on party loyalty, referred to here as 'partisan collegiality'. Moreover, urban planning through the municipal master plans establishes short-, medium-, and long-term development guidelines that municipalities are required to follow. This may reveal divergences in the municipal' goals, as one city might focus on local tourism, another economy growth, and yet another on sustainability issues. Hence, a careful analysis of municipal interests and the pursuit of synergies for integrated and sustainable regional development is recommended.

MSW management systems must adapt to meet future demands. New systems aim to produce goods aligned with circular economy principals and sustainable development goals. Ambaye et al. (2023) asserted that circular economy practices reduce waste and reliance on imported raw materials, supporting sustainable development. The 2IB technology can meet societal needs, whereas traditional methods such as sanitary landfills, require adaptation. Esfandabadi et al. (2022) emphasized the urgency of circular economy-driven MSW treatments to address geopolitical challenges and support local economies. It becomes increasingly evident that municipal authorities must prioritize sustainability-focused solutions, guided by legislation and technical-economic assessments.

3.2.2. *MSW composition*

The MSW composition represents a critical barrier to the adoption of new technological routes, as plant technical specifications depend directly on the proportion of organic and inorganic fractions. According to Nizami et al. (2017), the selection of suitable MSW treatment technologies relies on the regional characterization of waste. Specifically, a facility deemed sustainable in Europe may not exhibit the same viability in South America due to variations in MSW characteristics, such as moisture content, gravimetric properties, and overall composition. The objective of simulating waste composition is to determine the minimum and maximum quantities of organic waste required for a 2IB system to maintain superior sustainability performance compared to conventional sanitary landfills. For this simulation, the sanitary landfill once again serves as a reference point, as it remains the predominant MSW disposal method in Brazil.

To conduct the simulation, typical MSW composition values from Brazilian states are utilized. Scenarios featuring above 80 % of inorganic waste are excluded, as such compositions are uncommon both in Brazil and even globally. Given that 2IB processes both organic and inorganic

waste, variations in waste composition (currently represented by a scenario with 20 % inorganic and 80 % mixed organic and inorganic waste) may affect key parameters. It includes the equipment requirements, labor, transportation logistics (trucks and diesel), implementation and operational costs, electricity consumption, and the production of compost, recyclables, and thermoplastics. These variables collectively influence the sustainability performance of the 2IB system, highlighting the importance of MSW composition in guiding technology selection tailored to regional characteristics.

Four scenarios were developed to assess the influence of MSW composition on the sustainability performance of the 2IB system. The baseline scenario reflects a composition of 80 % mixed organic waste and 20 % inorganic waste. Three alternative scenarios simulate increasing proportions of inorganic content: Scenario 1 assumes 100 % mixed organic waste and 0 % inorganic waste; Scenario 2, 60 % mixed organic and 40 % inorganic; and Scenario 3, 40 % mixed organic and 60 % inorganic. Intermediate compositions between the defined scenarios would simply result in intermediate SSIS values, and were therefore not explicitly simulated. Although Scenario 1 represents a fully organic composition, in practical terms such waste could be more efficiently managed through conventional composting, which is a simpler and less costly treatment option. Nevertheless, including this scenario in the simulation allows assessing the full operational range of the 2IB system and verifying its performance under extreme but conceivable conditions. Variations in waste composition were found to affect 10 of the 11 indicators evaluated of Table 2, with the exception of k_{51} (average wage per capita), which remained constant. Detailed results for each scenario are available in Supplementary Material G.

Since ten from eleven indicators are influenced by the simulation on MSW composition, it was expected that SSIS value may vary significantly. This would be mostly prominent in the scenario 3, where emissions increased, the electricity generated proved insufficient to power the plant, and the number of trucks and consequently diesel consumption increased (Table G2 of Supplementary Material G). However, as shown in Fig. 8, the sanitary landfill's SSIS of none scenario was able to achieve better performance than 2IB's SSIS. This is an important finding that highlighted that 2IB can be effectively implemented in various Brazilian regions, as it accommodates the diverse MSW compositions as a result of different climatic, cultural and other socioeconomic characteristics.

Fig. 8 indicates that even in the least favorable 2IB scenario (40 % mixed organic and inorganic, and 60 % inorganic), its SSIS remained significantly lower than that of the sanitary landfill. Notably, the scenario with the lowest sustainability performance (i.e. highest SSIS) for 2IB presents an increasingly desired composition in waste management practices, where the majority (60 %) of MSW is source-separated.

The comparative analysis revealed that the simulation phase of MSW management using the 2IB system outperformed the sanitary landfill alternative in both transportation distance and composition variation.

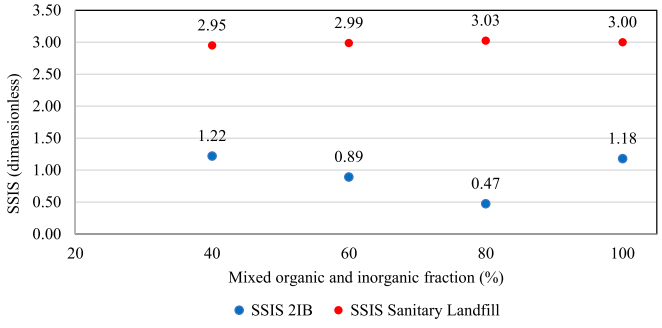


Fig. 8. Composition simulation results. The simulated SSIS values resulted from the application of the 5SEnSU model using the data from Table G2 and Table G3 of Supplementary Material G.

Integrated processes, including material recovery for recycling, mechanical separation, and mechanical-biological treatment that generates electricity and compost, as well as generating thermoplastics to replace concrete, wood, and metal-based materials, indicate that these practices are significantly more advantageous from a sustainability perspective than disposing of MSW in a sanitary landfill.

Moreover, the 2IB aligns with Brazilian Law No. 12,305 of 2010, which establishes the National Solid Waste Policy, outlining principles, objectives, instruments, and guidelines for the integrated solid waste management (Brazil, 2010). The 2IB technology encompasses multiple processes for treating MSW, characterized by mixed inorganic and organic materials, in accordance with this law. It makes the 2IB technological route more feasible for implementation compared to alternative hypothetical scenarios that may pose challenges in the short and medium term. Overall, the simulation and diagnostic stages conducted in this study are crucial for informing decision-making processes related to strategic planning for more sustainable MSW management.

3.3. *Practical implications, limitations, and future research*

The findings of this study have direct practical implications for municipal MSW management and policymaking. The decision-support model developed here provides a replicable framework that enables municipalities to identify the most sustainable technological route based on sustainability principles and technical variables. By quantifying the SSIS through the 5SEnSU model, local authorities can objectively compare management alternatives, such as sanitary landfilling and the Integrated and Innovative Biorefinery (2IB), considering not only environmental but also social and economic dimensions. The model's outputs, such as the operational threshold of 11,000 km/day for transportation and its robustness across varying waste compositions, offer actionable guidance for forming intermunicipal consortia, optimizing logistics, and prioritizing investment in 2IB facilities. From a policy perspective, the model can support the inclusion of sustainability-based criteria in municipal and regional waste management plans, guide the establishment of financial and regulatory incentives for intermunicipal cooperation, and inform national strategies to promote circular economy. Its results can also serve as a technical reference for policymakers to evaluate the socioeconomic return of sustainable waste infrastructures, fostering evidence-based public decisions and long-term planning beyond cost-driven approaches. These results support the integration of sustainability-based decision tools into public planning processes and reinforce the feasibility of adopting circular economy strategies in MSW management.

Nonetheless, some limitations must be acknowledged. Political and institutional barriers to consortium formation in countries outside Brazil were not modeled, although they may influence the feasibility of implementation. Additionally, in rare contexts where municipal solid waste is stored for long periods before treatment, partial decomposition of the organic fraction may influence the performance of anaerobic digestion. While this may not compromise the overall feasibility of the 2IB route, it represents an aspect to be addressed in future analyses, potentially supported by policy measures to minimize storage times and ensure optimal system performance. Another limitation concerns the technological maturity of the 2IB system. While the present study relies on primary data from an operational biorefinery – therefore demonstrating technological feasibility at the plant scale - the large-scale deployment of such facilities may still face challenges related to supply chain readiness, equipment manufacturing capacity, and logistical integration. These aspects were not explicitly modeled. Additional practical constraints include the implementation costs. The average cost of implementing a biorefinery is about BRL 15,000,000.00 (details are available in Supplementary Material A, Table A9). Because this is a subjective aspect due to its dependence on context-specific funding availability, it was treated as an external constraint. Understanding these cost implications enables more robust economic assessments by

allowing direct comparison and analysis with sanitary landfilling.

Future research should expand the application of this decision-support model to different geographic and socioeconomic contexts, incorporating governance and policy dimensions that directly shape municipal decision-making. Comparative analyses including additional technological routes, such as composting or waste-to-energy, would enhance understanding of trade-offs among sustainability dimensions. Furthermore, testing the framework with alternative indicators, and validating results through empirical case studies in other regions would provide valuable insights for refining the model and improving its robustness for real-world applications.

4. Conclusions

This study proposed an alternative method to support decision-making in the selection of more sustainable technological routes for municipal solid waste (MSW) management, specifically between sanitary landfills and an integrated and innovative biorefinery (2IB). The alternative method is based on the sustainability synthetic indicator of the system (SSIS) and incorporates two key variables: the additional transport distance and the MSW composition.

Considering the methods applied and results obtained, it can be concluded that the 2IB outperforms sanitary landfill. The SSIS for 2IB was 0.53, while the sanitary landfill scored 15 times worse achieving 8.12. The k_{12} indicator (fuel and electricity consumption from the external grid) accounted for 62 % of the sanitary landfill's SSIS, while the k_{52} indicator (surplus energy generation) contributed 47 % to the SSIS of 2IB, showing that both are targets for future improvements. Scenario simulations showed that 2IB implemented through partnerships in the municipal consortia remains the more sustainable option up to an additional transport distance of 11,000 km/day, and across all tested MSW compositions. This suggests the feasibility of implementing 2IB in diverse territories, including those with limited infrastructure or variable waste characteristics.

Although this study was conducted in Brazil, the proposed decision-support methodology is based on variables such as waste composition and transport distance, which can be easily adapted to different contexts. These variables inherently allow for broad flexibility, making the model suitable for application in diverse geographic and socioeconomic conditions. Nonetheless, its transferability has not yet been empirically validated outside Brazil, and further testing in other countries is recommended to confirm its effectiveness and to refine the model under distinct regional scenarios.

The proposed alternative method for diagnosing and simulating scenarios in MSW management contributes by integrating the SSIS with a practical simulation approach tailored to real-world policy contexts. The results suggested that prioritizing 2IB over sanitary landfill should be advocated in public policy proposals, particularly in light of the circular economy and the United Nations Sustainable Development Goals. By applying this alternative method, the study offers a structured and replicable tool for identifying the most sustainable technological route for MSW management, whether or not through the establishment of municipal consortia.

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

Data are available in the supplementary material

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Appendix A. Objectives, justifications and goals used in goal programming philosophy based on 5SEnSU to obtain SSIS

Table A1
Objectives, justifications and goals used in goal programming philosophy based on 5SEnSU to obtain SSIS.

Indicator		Unit	Objective	Justification	Goal	Source
k_{11}	Emergy Return Index	Dimensionless	Maximize	The aim is to reduce the environmental impact caused by the exploitation of renewable and non-renewable resources	Maximum	Liu et al. (2014); Viglia et al. (2018)
k_{12}	Fuel consumption + Electricity consumption from external grid	kWh/ton MSW	Minimize	The aim is to reduce the environmental impact caused by the exploitation of renewable and non-renewable resources	Minimum	
k_{21}	Global warming potential ratio ($kgCO_{2eq.}$ output/$kgCO_{2eq.}$ input)	Dimensionless	Maximize	At COP26, the Brazilian Federal Government announced the goal of reducing carbon emissions by 50 % by 2030	x^{-} + 50 %	Brazil (2021)
k_{22}	Human toxicity potential ratio ($kg1,4\text{-}DCB_{eq.}$ output/$kg1,4\text{-}DCB_{eq.}$ input)	Dimensionless	Maximize	The same justification as the previous indicator was adopted, as it is understood that both refer to environmental impacts, even though they evaluate different aspects: climate & human health.	x^{-} + 50%	–
k_{31}	Amount of recycled waste	ton recycled/ton MSW	Maximize	The National Solid Waste Plan stated that it is possible to achieve 20 % recovery of dry recyclables, in relation to the total mass of MSW, within a 20-year horizon (2040)	0.2 ton/ton MSW	Brazil (2022)
k_{32}	Total of revenues and earnings (income)	R$ (BRL)/ton MSW	Maximize	Although it is the municipality's responsibility to manage MSW, even without taking into account whether or not it will make a profit, the 'maximum' value among the technological routes was adopted as the goal, that is, the one with the best economic performance.	Maximum	–
k_{41}	Labor/employment (Total human resources)	person/ton MSW	Maximize	Unemployment rate according to IBGE for the 2nd quarter of 2023 is 8.0% in Brazil	x^{-} + 8 %	IBGE (2023)

(*continued on next page*)

Table A1 (*continued*)

Indicator		Unit	Objective	Justification	Goal	Source
k_{42}	Percentage of recyclable waste in collection (source separation level)	% recycled	Maximize	The National Solid Waste Plan stated that it is possible to achieve 20 % recovery of dry recyclables, in relation to the total mass of MSW, within a 20-year horizon (2040)	20 %	Brazil (2022)
k_{51}	Average salary per capita	R$ (BRL)	Maximize	According to DIEESE (Inter-Union Department of Statistics and Socioeconomic Studies) in October 2023 the minimum amount to serve a family consisting of two adults and two children is R $6210.11	R$ 6.210,11	DIEESE (2023)
k_{52}	Electricity generation (surplus)	kWh/ton MSW	Maximize	SDG 7 (7.3): Double the global rate of improvement in energy efficiency by 2030	$\bar{x} * 2$	UN (2022)
k_{53}	Compost generation	m^3/ton MSW	Maximize	The recovery of the organic fraction was projected at 13.5 % by 2040, in technological routes such as composting and anaerobic digestion (National Solid Waste Plan)	$\bar{x} + 13.5$ %	Brazil (2022)

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eiar.2025.108258.

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