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Emergy accounting of surplus food donation: Health Co-benefits and environmental implications using CEAGESP (Brazil) as a case study

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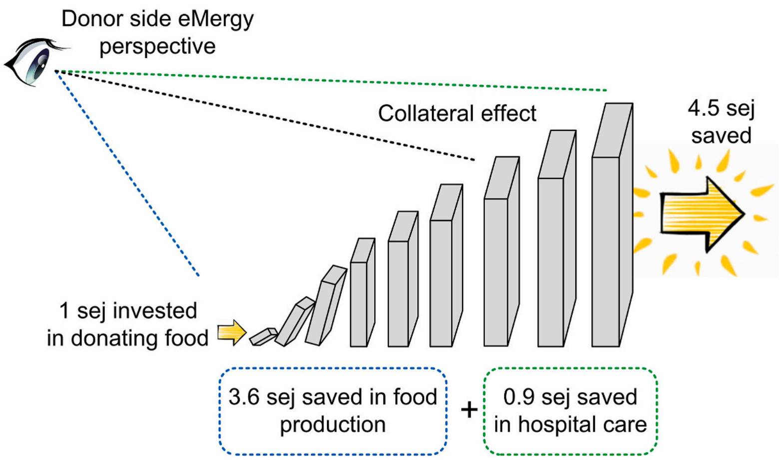
HIGHLIGHTS

- Food donation and landfilling are compared under an emergy synthesis approach.
- Food donation saves 33 sej for each sej invested, excluding collateral effects.
- The study expands system boundaries by adding health-related collateral benefits.
- Emergy savings from health gains match the emergy invested in food donation.
- Food donation outperforms landfill in emergy and should be supported by public policies.

GRAPHICAL ABSTRACT



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ABSTRACT

The wastage of surplus food poses significant environmental and social challenges, depleting valuable resources and exacerbating food insecurity, particularly among vulnerable populations. This study evaluates the environmental performance of surplus food donation compared to landfilling with energy recovery, using the emergy accounting method. Results show that for every 1 solar emjoule (sej) invested in the food donation system, 33 sej are saved through avoided food production, demonstrating a highly favorable emergy return. The donation scenario yields a net emergy gain of 5.73E+15 sej/ton of surplus food, while the landfill scenario presents a negative emergy result of −7.46E+14 sej/ton. These findings fully align with the principles of the Food Recovery Hierarchy. This study addresses a critical scientific gap by incorporating collateral consequences into the emergy framework -specifically, the avoided demand for hospitalization resulting from improved nutrition enabled by

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surplus food donation. The emergy savings associated with this health-related benefit (2.17E+16 sej/ton) are comparable to the total emergy invested in operating the donation system (2.19E+16 sej/ton). This study demonstrates the importance of expanding system boundaries to capture social co-benefits in emergy assessments. The findings support prioritizing food donation over landfill disposal and highlight the need for policy frameworks that incorporate emergy accounting to drive resource-efficient food waste management strategies.

1. Introduction

Food waste generation has significant social, economic, and environmental impacts, including crop losses during harvest and storage, increased hunger in low-income countries, and the depletion of natural resources without fulfilling their intended purpose (Vandermeersch et al., 2014). Food waste generates two major societal consequences. First, it exacerbates food insecurity, a condition consistently associated with adverse health outcomes and increased public health expenditures, as discussed by Ariya et al. (2021) and Gundersen and Ziliak (2015), among others. The second major societal consequence of food waste generation is that it intensifies the depletion of natural resources such as land, water, and energy, all of which are used throughout food production and distribution, resulting in considerable environmental loss (Munesue et al., 2015).

A growing body of literature has examined the adverse health effects linked to food insecurity. Among others, Men et al. (2020), in a Canadian study, found that the severity of food insecurity is positively associated with increased likelihood of intensive care admissions. The same population also exhibited higher odds of hospital readmission within one year, longer cumulative hospital stays, and a greater likelihood of undergoing same-day surgeries. Similarly, Correia et al. (2017), in a review of disease-related malnutrition in Latin America, reported that the average hospital stay for malnourished patients increases from 3.5 to 17.1 days compared to well-nourished patients. Gundersen and Ziliak (2015) observed that children living with food insecurity are at least twice as likely to be in poor health and significantly more prone to conditions such as asthma. In line with these findings, Laraia (2013) demonstrated a strong association between food insecurity and the development of chronic diseases, while Ariya et al. (2021) showed that malnutrition significantly increased hospitalization rates among patients with COVID-19. Collectively, these studies provide robust evidence linking food insecurity to a wide range of negative health outcomes, underscoring the importance of preventive interventions such as surplus food donation.

Given the clear links between food insecurity, health deterioration, and increased hospitalization rates, the recovery and redistribution of surplus edible food emerges as a promising strategy. This approach not only would mitigate nutrition-related health risks but also would reduce the environmental burdens associated with food waste management, offering a holistic solution to both social and ecological challenges.

From an environmental perspective, food waste is typically managed as part of municipal solid waste (MSW), with a significant proportion ending up in sanitary landfills - 23 % in Europe (Eurostat, 2020), 50 % in the United States (EPA, 2018), and 58 % in Brazil (Coelho and Lange, 2018). Salem et al. (2008) showed that leachate from landfills can contaminate groundwater with toxic substances. Methane emissions are also a major concern. In this regard, Nelson et al. (2022) tested passive methane oxidation systems as a promising low-maintenance solution. Complementarily, Themelis and Ulloa (2007) estimated that only a small fraction of global landfill methane is currently captured, highlighting the limitations of current practices. Regarding transport-related impacts, Buratti et al. (2015) linked non-differentiated waste collection to high greenhouse gas emissions, and Larsen et al. (2009) highlighted diesel use in collection routes as a persistent environmental burden. Moreover, food waste generation compounds the environmental impacts embedded across the entire food supply chain, as it leads to unnecessary consumption of raw materials, energy, and water (Papargyropoulou et al., 2014).

Food waste is generally classified into two categories: avoidable waste, consisting of discarded edible items, and unavoidable waste, such as inedible parts like peels and shells. Within this context, surplus food is a key component of avoidable waste. Rather than discarding it through landfill or composting, redirecting surplus food to feed people in need is a more sustainable and socially responsible solution (Salhofer et al., 2008). This is particularly relevant in developing countries, where food banks have proven to be effective in alleviating food insecurity (Schneider, 2013). Recent studies as that of Avrami et al. (2024) has also indicated that aligning consumer behavior with circular economy principles through targeted sustainability messaging can significantly enhance public support for food recovery systems such as food banks. While various technical alternatives exist for managing surplus food, including donation schemes, it remains essential that any proposed solution be assessed from diverse perspectives, including environmental performance.

Multiple environmental assessment methods have been developed and used to quantify the direct and indirect impacts of human activities on the environment, including ecological footprint, carbon footprint, energy analysis, emergy accounting, ecological pricing, and life cycle assessment (LCA) (Patterson et al., 2017). Among these, LCA has been widely applied to evaluate food donation, which generally provides greater environmental benefits than alternatives such as composting, anaerobic digestion, or incineration, especially in retail and distribution contexts. Donation can approach the environmental advantages of waste prevention (Albizzati et al., 2019) and results in lower greenhouse gas emissions across a range of food categories (Moult et al., 2018). Findings from different countries also report positive outcomes regarding climate impact (Brancoli et al., 2020), water use (Cakar, 2022), and contributions to circular economy goals (Sulis et al., 2021). However, Damiani et al. (2021) and Sundin et al. (2022) emphasized that logistical efficiency and potential rebound effects must be carefully considered to ensure net environmental gains. In general, the main conclusions of these assessments are that: (i) food donation outperforms other food recovery hierarchy (FRH) options in environmental terms; (ii) local conditions significantly affect LCA outcomes, requiring context-specific analyses; and (iii) the primary environmental advantage of donation lies in avoiding the need for additional food production.

Other studies, such as Sundin et al. (2023), have attempted to assess surplus food donation using multiple frameworks, including environmental, economic, and social ones. While these studies highlight that food donation reduces waste and delivers short-term socio-economic benefits, especially for vulnerable populations, they also point out the presence of positive environmental rebound effects. However, applying multiple assessment methods simultaneously often complicates result interpretation, hindering direct quantitative comparisons and obstructing the formulation of effective public policies. This is because each method tends to focus on different indicators (e.g., energy use, emissions, resource depletion) and employs different units and scales, making cross-method comparisons inherently difficult. Consequently, decision-makers face challenges in reconciling these diverse metrics when evaluating trade-offs or establishing priorities.

As discussed earlier, based on the contributions of Ariya et al. (2021), Gundersen and Ziliak (2015), Laraia (2013), Men et al. (2020), and Correia et al. (2017), the literature consistently demonstrates a strong link between food insecurity and adverse health outcomes, including higher hospitalization rates and increased chronic disease risk. These health burdens translate into substantial indirect economic and social costs, which food donation programs could help mitigate by improving nutrition and reducing hospitalization and medication use. Such cascading positive effects, or 'collateral consequences', remain underexplored in the literature and call for more systematic quantitative investigation.

To address this scientific gap, emergy accounting (spelled with an 'm') offers a valuable framework for quantifying both environmental and social impacts of food donation within a single biophysical unit: solar emjoules (sej). Emergy accounting differs fundamentally from other methods such as LCA or energy analysis, as it adopts a donor-side perspective, accounting for the total energy embodied in the generation of goods and services (Odum, 1996). Unlike energy analysis, which focuses on direct energy content, emergy accounting incorporates both material and energy inputs, while also capturing the work done by nature to make resources available. This results in broader system boundaries and supports more holistic assessment of environmental costs (Odum, 1996). By emphasizing the quality and origin of energy and materials, emergy provides a comprehensive, biophysical view of sustainability, as argued by Lu et al. (2024), who analyzed regional ecological security using emergy ecological footprint models, and Wang et al. (2024), who developed an emergy-based sustainability index. One of the key strengths of emergy accounting is its ability to integrate environmental and socio-economic factors into a single, comparable metric, enabling a holistic evaluation of complex systems. For example, emergy can capture the intrinsic value of different food types using Unit Emergy Values (UEVs); foods with higher biological complexity or processing levels such as animal products typically exhibit higher UEVs, reflecting their greater environmental cost. This feature makes emergy particularly well-suited for assessing the value of various types of surplus food.

Several studies have applied the synthetic form of emergy accounting - hereafter referred to as emergy synthesis - to evaluate waste management systems, the research has focused on diverse materials. These include municipal solid waste, as examined by Almeida et al. (2012) in a waste-to-energy landfill in Brazil; Agostinho et al. (2013) in a sorting and composting waste treatment plant in São Paulo (Brazil); Clasen et al. (2024) in an innovative and integrated biorefinery in Santa Catarina (Brazil); and Marchettini et al. (2007), who compared landfill, composting, and incineration alternatives in the Italian context. Other applications include agricultural residues, analyzed by Patrizi et al. (2015) in second-generation bioethanol production in Siena (Italy), and animal fats, studied by Santagata et al. (2019) in a biorefinery located in the Campania Region (Italy). However, no previous research has employed emergy synthesis specifically to assess surplus food donation as a waste management strategy. Furthermore, while Cristiano et al. (2021) estimated the emergy cost of hospitalization in a developing country, no study to date has quantified the combined environmental and social benefits of surplus food donation, including direct, indirect, and collateral effects, particularly those associated with improved nutrition and reduced strain on healthcare systems. This clearly reveals a scientific gap: the absence of an integrated, systemic approach capable of capturing a wider spectrum of impacts (including environmental, economic, and health-related outcomes) linked to surplus food recovery.

Recognizing the need for broader assessments across spatial and temporal dimensions, this study applies emergy synthesis to address this gap. Specifically, it compares the environmental performance of surplus food donation to that of landfilling with energy recovery, based on a real-world case study of CEAGESP, the largest food supply center in Latin America. The key innovation of this research lies in incorporating health-related collateral benefits into the assessment, specifically the emergy savings associated with reduced hospitalization resulting from improved nutrition. This integrated perspective, which merges environmental and social dimensions within a unified metric, remains unexplored in the existing literature. The core hypothesis tested is that managing surplus food through donation, rather than through landfilling with energy recovery, results in a net emergy gain while generating positive 'collateral consequences' typically overlooked in conventional assessments. By explicitly capturing both the direct environmental benefits and the indirect social gains such as improved public health outcomes, this study shows that food donation is not only environmentally preferable but also offers broader systemic sustainability advantages that extend beyond the food system itself.

2. Methods

2.1. Case study description

This study explores the two current options used to manage the surplus food generated by CEAGESP, the largest Food Supply Center (FSC) in Latin America, located in São Paulo, Brazil. The two options are landfilling with energy recovery and food donation. Other options, such as composting or even a biorefinery, are potential alternatives that deserve attention but are outside the scope of this study. CEAGESP annually handles over 3 million tons of food products, with horticultural items playing a crucial role due to their perishable nature, economic importance, and impact on food security and sustainability. The main processes at CEAGESP include: preliminary weighing and quality checks upon product arrival, food trading operations, the output of marketable products, and waste management. Between 2007 and 2018, CEAGESP generated an average annual waste amount of 52,700 tons, approximately 1.61 % of the total traded food, with about 80 % of the waste being organic. Within this organic fraction, approximately 80 % consists of potential surplus food (Sulis et al., 2021).

The environmental performance of different surplus food management options is assessed under two scenarios, based on the triangular hierarchy of waste management (HWM):

a) Scenario I (Landfilling with energy recovery): Represents the current baseline, positioned at the bottom of the HWM.
b) Scenario II (Food donation): Represents an optimized recovery effort, aligned with the top of HWM.

In Scenario II, based on information from technical visits and corroborated by data from Fagundes et al. (2014) and Legaspe (2006), the recovery rate for surplus food is 80 %, with the remaining 20 % being directed to the landfill. The scenarios assessed in this study are based on CEAGESP's surplus food management figures of 2018, the most updated data available – although the primary data have remained largely consistent over the years according to CEAGESP staff. During that year, 47,065 tons of by-products (non-marketable food) treated as waste were sent to the landfill. About 80 % of this amount (37,652 tons/year) was the organic fraction, and 80 % of this organic fraction is potential surplus food (30,122 tons/year). The raw data used to model the scenarios consist of daily value estimates over 363 operating days, as the Food Distribution Center is closed on Christmas Day and New Year's Day. It includes: total waste generation of 47,065 tons/yr (130 tons/day), inorganic fraction of 9413 tons/yr (26 tons/day), organic fraction of 37,652 tons/yr (104 tons/day), and potential surplus food of 30,122 tons/yr (83 tons/day). The data collection and inventory modelling procedures used in this study are similar to those described in Sulis et al. (2021). The differences pertain to specific aspects of emergy synthesis and the modelling of the donation scenario, both of which are explained in the following subsection.

2.1.1. Scenario description and modeling procedures: landfilling with energy recovery (Scenario I)

Scenario I encompasses five main steps: internal collection and transport, transfer, transport to the landfill, disposal, and degradation. Internal collection is executed by eight diesel-fueled compactor trucks, each with a 15 m^3 capacity. These trucks operate for 1815 h per year, transporting waste to a designated area within CEAGESP for temporary storage. Transfer within CEAGESP involves an excavator that works 784 h annually to move waste to a 30-ton capacity truck. The waste is then transported to the ’Caieiras’ Landfill, located 24.2 km away, which also receives the urban solid waste from the São Paulo Metropolitan Region. Two trucks run 1569 trips per year, each one capable of carrying 30 tons.

Disposal in the landfill requires specialized vehicles, including an excavator, bulldozer, compactor, front loader, and truck. The natural degradation process produces biogas and leachate. Biogas is composed of 58 % methane, 40 % CO_2, and 0.6 % O_2, and it is partially captured (80 %) and incinerated. Leachate is collected, temporarily stored, and transported to the ‘SABESP’ wastewater treatment plant located in Barueri city 39.4 km away. This is achieved using a tank truck with a 30 m^3 capacity, making 550 trips annually. The wastewater treatment plant processes leachate similar to regular urban sewage. The treated water is released into the ‘Tietê’ river, while solid sludge residue is transported back to the ’Caieiras’ Landfill through nine yearly trips by a 30-ton truck. In 2018, the ’Caieiras’ landfill generated 142,350,000 Nm^3 of biogas, which follows three paths: 20 % is directly released into the atmosphere, 40 % is flared and released into the atmosphere, and 40 % is used in a power plant for electricity generation. This yields about 230,000 MWh of electricity annually, with 5750 MWh allocated to CEAGESP waste. This generated amount saves electricity from the Brazilian energy matrix.

In addition to the usual inputs considered for Life Cycle Assessment (LCA) (i.e. capital goods and fuel consumption), emergy synthesis for the Caieiras landfill included estimating the emergy contribution of the annual rainfall and the quantity of soil used to cover the waste. Rainfall calculation is based on climatological data available for the municipality of Caieiras (RIMA, 2016), while the calculation of soil input is based on information obtained during a technical visit (later compared with Buranakarn’s 1998 data for consistency). The quantity of used soil, initially removed during the landfill’s construction and later progressively reused to cover the waste, was estimated to be equal to 40 % of the total CEAGESP’s potential surplus food landfilled in 2018 and classified as a non-renewable local resource (N).

The Unit Emergy Values (UEVs) considered for the soil and other natural landfill materials such as gravel were calculated by accounting for the global sedimentary cycle work (Odum, 1996), focusing on the work done by nature to generate geological materials. Finally, regarding human labor, the following assumptions have been derived from on-site technical inspections and supplementary sources: for the task of waste collection and transportation, a workforce of three individuals is allocated per garbage truck. Concurrently, in the activities encompassing waste transfer, transportation, and landfilling, a ratio of one driver is designated per vehicle. Within the landfill setting, operational oversight is led by one engineer, along with one worker assigned per vehicle. For the wastewater treatment facility, the labor distribution includes two drivers, one dedicated to leachate transport and another for sludge transport. The staff at the wastewater treatment plant consists of three people: two operators and one engineer.

2.1.2. *Scenario description and modeling procedures: food donation (Scenario II)*

The food donation scenario is modelled by considering the amount of by-products landfilled in 2018 as a baseline: 130 tons daily discarded by CEAGESP, composed of 104 tons of potentially edible organic fractions (surplus food) and 26 tons of non-edible organic and inorganic fractions derived from baskets and packaging. Materials, equipment, and machines with the lowest environmental impacts are chosen based on the available literature (including wood pallets and the ‘Misusumashi’ concepts, as explained below). The proposed collection scenario for surplus food considers a recovery rate of 80 % (best-case scenario), reaching 83 tons of surplus food (SF) per day. The remaining 20 % includes a 10 % loss due to mechanical injuries during transportation from producers to CEAGESP, while the remaining 10 % arises from quality checks at the food bank, as reported by Fagundes et al. (2014). This 20 % is sent to the landfill following current waste management practices as described in Scenario I.

The operations behind the food donation scenario consist of four steps, as previously studied by Sulis et al. (2021): the collection of SF, quality checking, storage and distribution, and consumption. For the first step, a network of 180 food collection points is modelled, with a maximum distance of 50 m between each wholesaler and the nearest collection point. In these collection points, wholesalers can deposit the surplus food after their daily trading operations. Each food collection point consists of a 1-ton capacity wooden euro pallet (1200 × 800 mm) placed on a steel trolley. Wooden pallets are preferred due to their lower global warming potential, as demonstrated by Deviatkin et al. (2019). To enhance surplus food transportation efficiency, an electric logistic train inspired by the ‘Mizusumashi’ concept has been considered. The Misusumashi concept enhances product collection efficiency in large wholesale markets by reducing the number of vehicles needed, thereby cutting energy consumption and direct emissions. By optimizing routes and schedules, it not only reduces operational costs but also minimizes traffic disruptions. This approach reduces the need for manual handling and provides a scalable, cost-effective, and potentially eco-friendly alternative to traditional methods such as manual labor and diesel-powered forklifts. This view is supported by prior research: Coimbra (2009) integrates *mizusumashi* into lean supply chain design; Oliveira et al. (2018) highlight how lean practices enhance both operational efficiency and worker ergonomics; and Vujanac et al. (2017) assess the benefits of tugger train systems in reducing energy consumption and workplace risks.

For the second and third steps, an infrastructure covering an area of 900 m^2 (30 m in length x 30 m in width x 6 m in height) is modelled to handle quality checking and store the surplus food in refrigerated rooms. When the logistics train arrives at the quality checking area, the staff unloads the pallets and transfers the crates to 108 stainless steel tables (1.6 m × 0.7 m) with a capacity of 300 kg each. After quality checking, approximately 10 % is discarded and sent to the landfill as described in Scenario I, while selected edible food is stored in refrigerated cold rooms. Edible food is temporarily placed on 72 plastic pallets inside six cold rooms, each with a 20-ton capacity. These cold rooms are constructed with steel panels and a polystyrene insulation system, resulting in a storage capacity of 120 tons.

Finally, the charity institutions can collect the edible food and either prepare it or donated it to people in need. The composition of the donated food is presented in Table 1. The top 18 food types donated by CEAGESP in 2018 were considered, representing approximately 88 % of the total mass converted to a 100 % basis. The recovery of food allows charitable institutions to avoid purchasing these products elsewhere, resulting in emergy savings. These savings are quantified based on the emergy costs associated with fruit and vegetable production. Due to data availability, the calculation considered the first seven donated products, which accounted for approximately 81 % of the total mass, but adjusted to a 100 % basis. The Unit Emergy Values (UEVs) used for calculating the emergy of donated food were sourced from various studies: Brandt-Williams (2002) for tomato, orange, and potato; Psota (2010) for

Table 1
The top 18 food types donated by CEAGESP in 2018.

Product	% (in mass)	Product	% (in mass)
Tomato	35.58	Onion	2.39
Orange	13.72	Banana	2.13
Potato	8.12	Eggplant	1.45
Apple	7.50	Peach	1.45
Papaya	6.12	Cucumber	1.32
Garlic	5.50	Manioc	1.21
Zucchini	4.37	Carrot	1.16
Chayote	3.49	Pear	0.88
Lettuce	2.74	Mango	0.87

apple; Lu et al. (2009) for papaya; and Cristiano (2021) for zucchini and garlic. Calculation details for the emergy in the donated food is available as Supplementary Material A (Saved Emergy tab).

Because the surplus food from CEAGESP consists of exclusively fruits and vegetables, it cannot provide 100 % of the calories needed for a healthy and balanced diet. Therefore, following information from Travassos et al. (2020), a daily intake of 990.1 g/day for a typical Brazilian individual aged 10 years or older is used as reference, and the typical products in the Brazilian diet are also included as additional input in the calculation procedures The different products considered and the related quantities consumed daily per individual are shown in Table 2. For each individual, 149.3 g of products, corresponding to the fruit and vegetable intake, are provided by CEAGESP surplus food, while the remaining 840.8 g are purchased food. By considering a daily surplus food recovery equal to 82,526,027 g/day, 552,753 individuals per day could receive their portion of fruit and vegetables through CEAGESP surplus food. Regarding the UEVs used for the emergy calculation, when the exact food correspondence was not found due to a lack of data, the known UEVs of the main ingredients were used. Calculation details provided in Supplementary Material A (Sc.#II Total + Collateral and Saved Emergy tabs).

According to Andrade et al. (2023), approximately 6.6 % of the Brazilian population was hospitalized for one day or more during 2019. Applying this statistic, 6.6 % of the 552,753 food beneficiaries from the charity results in 36,482 individuals that potentially require hospitalization. Considering that people in need are more likely to require medical care and hospitalization, it is assumed that these individuals rely on food from charities and suffer from malnutrition. Consequently, the full emergy benefits associated with avoided hospitalization days were incorporated, considering a variability from a minimum of 3.5 to a maximum of 17.1 days, according to the study of Correia et al. (2017). To allow the manifestation of the ‘collateral consequences’, it was also assumed that the beneficiaries are the same individuals throughout the entire year. Calculation details and raw data are available as Supplementary Material A (Sc.#II Total + Collateral tab). We acknowledge the uncertainties inherent in our modeling; however, instead of providing a precise value, this study aims to highlight the issue’s importance and foster discussions on the ‘collateral consequences’ of food donation.

Table 2
Average Brazilian diet and corresponding unit emergy values (UEVs).

Product	Product for UEV	Unit	Amount
Average individual daily intake	–	g/person day	990.1
Rice	Rice	g/person day	181.8
Legumes	Beans	g/person day	197.2
Greenhouse vegetables	Fruits & Vegetables (avg.)	g/person day	7.1
Other vegetables	Fruits & Vegetables (avg.)	g/person day	42.6
Fruit	Fruits & Vegetables (avg.)	g/person day	99.6
Pasta	Wheat	g/person day	46.7
Bread	Wheat	g/person day	64.6
Sweet/biscuits	Wheat	g/person day	74.8
Beef	Beef	g/person day	77
Pork	Pork	g/person day	20
Poultry	Poultry	g/person day	44.7
Food from fishing	Fish	g/person day	49.5
Eggs	Eggs	g/person day	12.3
Diary	Milk	g/person day	65.2
Other food	–	g/person day	7
Total purchased products	–	g/person day	840.8
Surplus food from CEAGESP	–	g/person day	149.3
Surplus food from CEAGESP	–	g/day	82,526,027.4
Number of daily beneficiaries	–	Individuals	552,753

Calculation details available as Supplementary Material A (Sc.#II Total + Collateral tab).

2.2. *Emergy synthesis*

Emergy synthesis (ES) aims to assess the long-term sustainability of a production system by considering the support from the natural environment. In particular, ES can quantify energy quality differences among various resources by considering the natural processes responsible for their generation, and it includes anthropic systems as an integral part of the geo-biosphere (Marchettini et al., 2007). As defined by Odum (1996), emergy is the available solar energy used up directly and indirectly to make a service or a product, with its unit denoted as solar emjoules (sej).

After defining the boundaries of the evaluated system and identifying all inputs and outputs of energy, material, information, and money, as well as internal processes, it becomes possible to elaborate the emergy diagram based on systemic principles, quantify all flows, and complete the emergy table. Each input is accounted based on its material quantity or energy content and is further weighted by its respective unit emergy value (UEV; emergy baseline of 12E+24 seJ/yr from Brown et al., 2016) to account for all of Nature’s effort to obtain a given product. After being converted into solar emjoules (sej), the sum of all inputs converging into a system is defined as the total emergy demanded (U) by the system. Emergy synthesis categorizes inputs into local renewable (R) and local non-renewable (N) natural inputs, and those originating from the larger economy (F) where money circulates. This classification enables the definition of several emergy-based indicators to support decision-making.

A commonly used indicator in waste management studies is net-emergy, defined as the difference between emergy benefits and emergy investment (Odum, 1996). Marchettini et al. (2007), for example, used it to compare the efficiency of landfill, composting, and incineration systems. Similarly, Agostinho et al. (2013) applied the indicator to evaluate the performance of a sorting and composting waste treatment plant in São Paulo, demonstrating that it provided a net emergy benefit when compared to landfilling, especially in scenarios with higher recovery rates for recyclable materials. For the Scenario I of this study, all the materials, energy and processes needed to implement waste collection, transport, construction, and management of the sanitary landfill are considered as emergy invested (EMI), while the avoided production of electricity from the Brazilian matrix replaced by landfill electricity is considered as emergy saved (EMS). For the Scenario II, the resources needed to implement the donation scenario are considered as invested emergy, while the avoided production derived from donated food that avoids the production of the same product elsewhere is considered as saved emergy.

In addition to net emergy, another useful indicator for evaluating the emergy performance of a waste management system is the Emergy Return Index (ERI). This indicator represents the ratio between the saved emergy and invested emergy (EMS/EMI), where ERI values greater than 1 indicate a net gain in emergy terms (Sulis et al., 2024).

In relation to the ‘collateral consequences’ of food donation, the literature review developed has revealed that individuals experiencing food insecurity have a higher likelihood of hospitalization as well a longer duration of hospital stays. Therefore, in a donation scenario where recipients are no longer experiencing food insecurity, it can be inferred that they might exhibit similar probabilities of hospitalization and length of stay as well-nourished individuals. Consequently, reducing the number of days of hospitalization can be seen as a positive collateral consequence of food donation. Correia et al. (2017) concluded that in Latin America malnutrition leads to an increase in the length of hospital stays ranging from 3.5 to 17.1 days (with an intermediate value of 10.3 days). Therefore, the 'collateral consequence' linked to the effect of avoiding hospitalization days are calculated by multiplying the number of avoided days of hospitalization by the daily cost per patient in emergy terms of 1.85 E+15 sej/patient-day as provided by Cristiano et al. (2021).

Additionally, the reduced days of hospitalization results in reduced healthcare waste generation, consequently reducing the amount of emergy demanded by waste management. The amount of waste saved per avoided patient per day considers the average healthcare waste generation value in Brazil of 2.97 kg per patient per day, as reported by Ribeiro et al. (2020). This figure comprises 1.98 kg of regular municipal solid waste (MSW) per patient per day added to 0.99 kg of infected waste per patient per day. The MSW fraction is considered to be managed similarly to processes applied in Scenario I. The infected waste, which needs a process of sterilization, is sterilized by an autoclaving process that is the typical infected waste treatment of São Paulo city. In our modelling, it is considered an autoclave with 800 kg capacity with an electricity consumption of 56 kWh/cycle, equal to 0.07 kWh per kg of treated waste. After sterilized, the waste is diverted as MSW as for in Scenario I. Calculation details are available in Supplementary Material A (Sc.#II Total + Collateral tab). It is important to emphasize that, due to the uncertainties in the modeling of Scenario II regarding the variables 'number of potential hospital patients', 'days of hospitalization' and 'infectious waste generation', they were included in the uncertainty analysis as described in the following sections.

From a general perspective, the collateral consequences could be positive (+) when they result in emergy savings and negative (−) when they result in additional emergy cost. They are calculated by considering the algebraic sum of the individual components. The collateral consequences associated with avoided hospitalization days are calculated using Eq. (1).

$$CC = (AHD * DEC) + (AHD * ADW * EC_{IFW}) + (AHD * ADW * EC_{MSW}) \quad \text{Eq. (1)}$$

Where:

CC = Collateral consequence in sej/yr;
AHD = Avoided Hospitalization (day/yr);
DEC = Daily emergy cost per patient in sej/day;
ADW = Avoided daily waste generation (per patient) in kg/day;
EC_{IFW} = emergy cost to treat 1 kg infectious waste in sej/kg;
EC_{MSW} emergy cost to treat 1 kg of Municipal Solid Waste (MSW) in sej/kg.

To facilitate the comparison among the different scenarios, two other indicators are proposed in this study, the collateral emergy index (CEI), and the collateral performance emergy index (CPEI). The CEI is defined as the ratio between the collateral consequence and the sum of invested emergy (EMI) and saved emergy (EMS) as shown in Eq. (2). The CEI shows the emergy amplitude of the collateral consequence compared with the emergy invested and saved in the system under analysis on a minor scale. Values $0 < CEI < 1$ indicate that the collateral consequences result in emergy savings lower than the emergy involved in the system under analysis. Values > 1 indicate that the collateral emergy savings are higher than the emergy involved in the system under analysis. Values $-1 < CEI < 0$ indicate that the collateral consequences result in collateral emergy cost lower than the emergy involved in the system under analysis. For $CEI < -1$, it indicates that the collateral consequences result in collateral emergy cost higher than the emergy involved in the system under analysis.

$$CEI = (CC)/(EMI + EMS) \quad \text{Eq. (2)}$$

Where:

CEI = collateral emergy index in sej/yr;
CC = collateral consequence in sej/yr;
EMI = invested emergy in sej/yr;
EMS = saved emergy in sej/yr.

The collateral performance emergy index (CPEI) is defined as the ratio between the collateral consequences divided by the invested emergy, as shown in Eq. (3). CPEI shows the emergy amplitude of the collateral consequence compared with the emergy invested in the system under analysis. Values $0 < CPEI < 1$ indicate that the collateral consequences result in lower emergy savings than the emergy invested in the system under analysis. Values > 1 indicate that the collateral emergy savings are higher than the emergy invested in the system under analysis. Values $-1 < CPEI < 0$ indicate that the collateral consequences result in lower collateral emergy cost than the emergy invested in the system under analysis. For $CPEI < -1$, it indicates that the collateral consequences result in collateral emergy cost higher than the emergy invested in the system under analysis.

$$CPEI = CC/EMI \quad \text{Eq. (3)}$$

Where:

CPEI = collateral performance emergy index in sej/yr;
CC = collateral consequence in sej/yr;
EMI = invested emergy in sej/yr.

2.3. Visualizing the modelled case scenarios

The energy diagrams of Figs. 1–3 provide a view of the studied systems from a systemic perspective, highlighting its relationships with the surrounding environment and internal processes. Fig. 1 displays the general diagram of Scenario I based on the current surplus food management. Renewable (R) inputs include rain (chemical energy), the natural local non-renewable input (N) is accounted for by the soil, and all other inputs are classified as purchased from the larger economy (F). The food arrives at CEAGESP to be traded and sold, and the surplus food considered as food waste is diverted to the Caieiras landfill; only a negligible amount is diverted to donation. External energy sources encompass food, diesel, materials for vehicle production (metal, rubber, plastic), human labor, and services, while the outputs include the food sold to market, food diverted to charity, and food waste.

According to Fig. 1, the food waste is transported by trucks to the Caieiras landfill. Resources considered at this stage include diesel, vehicle materials, and human labor. At the Caieiras landfill, organic waste is discarded, and subsequent processes involve the input of gravel and other materials to build the landfill, metals and diesel used by vehicles, rain (involved in the process of organic fraction degradation), soil to cover the various waste layers, human labor, and sludge (originated by the leachate generated in Caieiras) returning from the wastewater plant. As output, there is methane, which can be directly released into the atmosphere, burned with electricity generation, and burned without electricity generation converting CH_4 into CO_2. Another output is leachate sent to the wastewater plant by tank trucks, demanding diesel, vehicle materials, and labor inputs. The leachate arrives at wastewater plants, which demand concrete, chemicals, electricity, and labor. Outputs include the liquid effluent released into the Tietê River, CH_4 derived from anaerobic sludge digestion released into the atmosphere, and the dried sludge generated is sent back to Caieiras Landfill.

In Scenario II represented by Fig. 2, the potential surplus food (90 %)

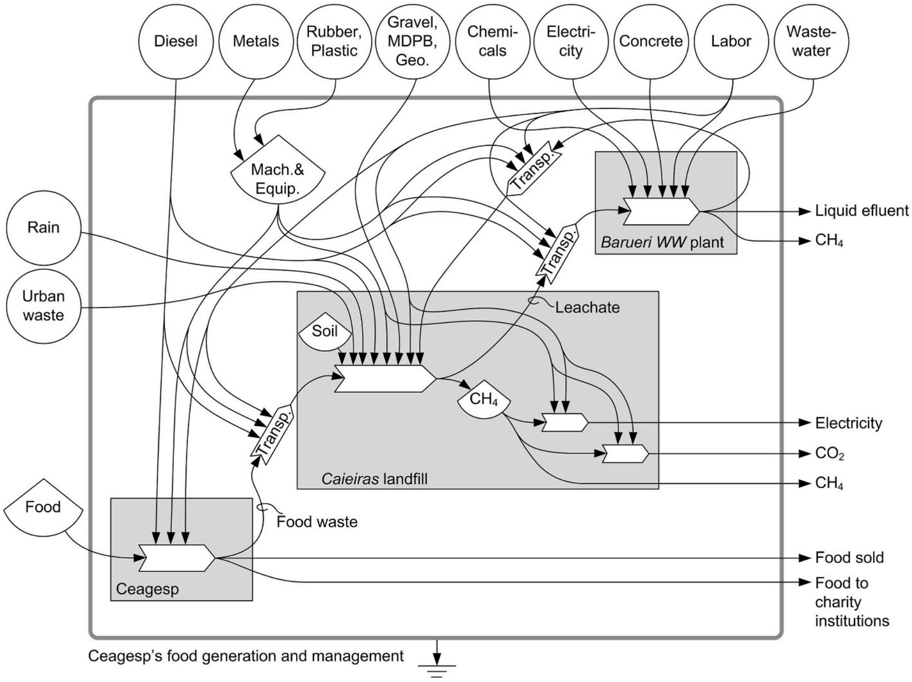

Fig. 1. Energy diagram of Scenario I: landfilling the surplus food with electricity generation. Symbols from Odum (1996). Legend: External circles, external sources of material, energy or labor; Tank symbol, storage of material or energy; Large arrow, interaction of materials, energy and/or labor; Larger rectangle, boundaries of studied system; Internal rectangles, processes.

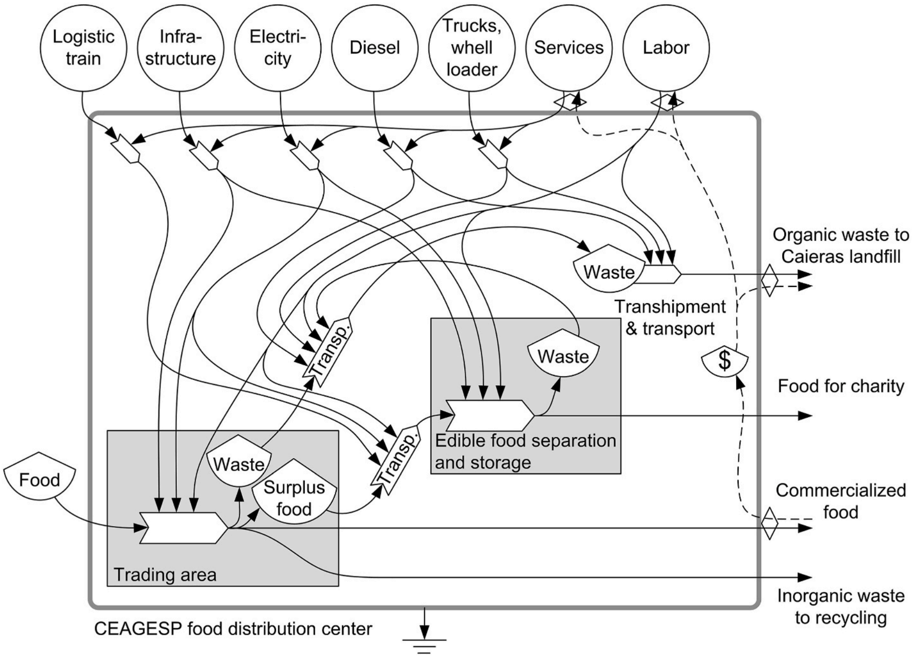

Fig. 2. Energy diagram of Scenario II: donating the surplus food. Symbols from Odum (1996). Legend: External circles, external sources of material, energy or labor; Tank symbol, storage of material or energy; Large arrow, interaction of materials, energy and/or labor; Larger rectangle, boundaries of studied system; Internal rectangles, processes.

is collected by a logistic train and transported to the food bank, where its quality is checked, products separated, and temporarily stocked inside cold rooms until withdrawal by charity institutions. This scenario requires material for the infrastructure (mainly steel) and vehicles (steel for the chassis and lead for the batteries), as well as electricity that has replaced the role of fossil fuel. External human labor is also needed. The food waste of Scenario II, including both the 10 % derived from mechanical injuries and the 10 % generated after quality-checking operations at the food bank, follows the path of Scenario I. The surplus food is sent to charity institutions (Fig. 3) where it is prepared or simply donated to people in need. The process needs infrastructure, labor, electricity, and the purchase of additional food. The people in need who receive the food would improve their health, demanding lower frequency of hospitalization and acting as a switch that reduces the need for resources necessary to implement and maintain the hospital.

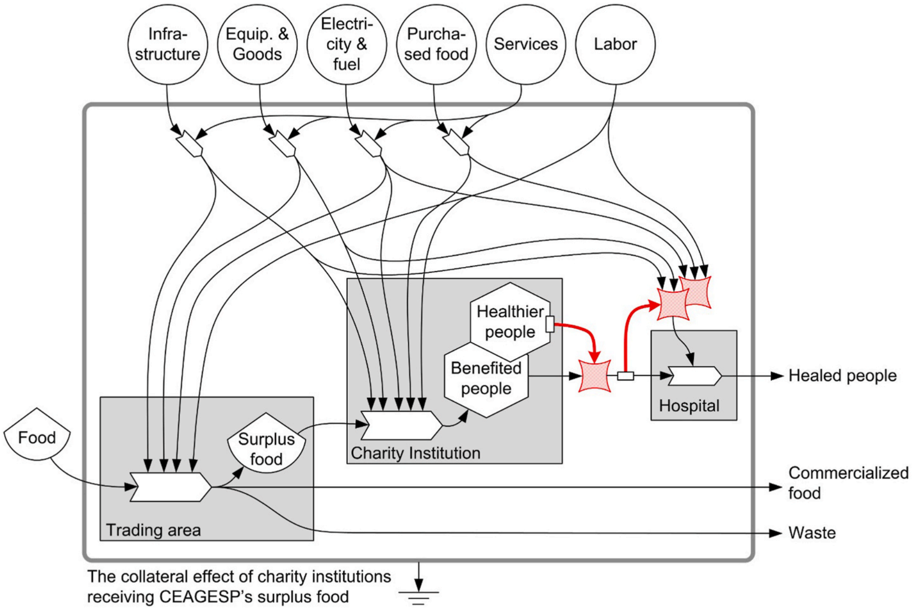

Fig. 3. Energy diagram of Scenario II (donating the surplus food) including the collateral consequence on the healthcare system. The achieved benefits of donating surplus food are represented by red lines and symbols. Symbols from Odum (1996). Legend: External circles, external sources of material, energy or labor; Tank symbol, storage of material or energy; Large arrow, interaction of materials, energy and/or labor; Larger rectangle, boundaries of studied system; Internal rectangles, processes; Flows in red, sensors controlling the flow of other resources.

2.4. Addressing uncertainties through Monte Carlo simulation

Due to some uncertainties related to the data and assumptions considered in the modeling of systems evaluated in this study, the Monte Carlo method was applied. The Monte Carlo Method is a statistical technique used to model the probability of different outcomes in processes that involve uncertainty. By running simulations based on random sampling, it helps estimate the impact of variability in input variables. This method is particularly valuable when precise data is unavailable or when input variables exhibit significant uncertainty or fluctuation (Metropolis and Ulam, 1949). Its use in emergy studies is supported by several authors, for example: Ingwersen (2010) highlighted the importance of including uncertainty in emergy assessments and proposed methods to estimate it. Li et al. (2011) compared different approaches and pointed out that the Monte Carlo method is especially useful when dealing with table-form calculations. Agostinho et al. (2015) used Monte Carlo simulations to evaluate the uncertainty in enzyme production for ethanol.

In practice, the Monte Carlo Method involves generating a large number of possible outcomes based on probability distributions assigned to uncertain variables (Kroese et al., 2011). These distributions could be normal, uniform, or other types, depending on the nature of the uncertainty. The results of these simulations provide a range of possible outcomes, allowing for a better understanding of the risks and uncertainties inherent in the system being modelled (Rubinstein and Kroese, 2016). Specifically, in this study the variables 'additional days of hospitalization,' 'number of potential hospital patients', 'emergy to treat 1 kg of infectious waste,' 'soil amount, and 'gravel amount' were included in the Monte Carlo simulation. A triangular distribution with 10,000 repetitions were considered. The simulation was performed by using a free Microsoft Excel® add-in developed by Barreto and Howland (2006), as suggested and used by Agostinho et al. (2015). Details regarding the types of variables, reasons for their inclusion, and the chosen ranges of variation are presented as Appendix A.

3. Results and discussion

3.1. Emergy performance of the studied case scenarios without considering collateral consequences

The emergy inventory and related results for both evaluated scenarios (Figs. 1 and 2) without considering collateral consequences are shown in Table 3, accounting for all the available inputs, annual emergy flows for each input, the total annual emergy flow (U), and the UEV's considered. For the charity institutions, the infrastructure and equipment were not accounted for due to a lack of data, and based on our own experience, they would have little influence on the results. Charity institutions are system that demand very low amount of materials and energy, which can be represented by a structure of tables and chairs for people to eat and a kitchen to prepare meals, or even just a warehouse where people come to pick up food and take it home. The activities of these institutions, which are primarily focused on packaging various products for beneficiaries to collect within 24 h, are similar to the packaging processes in the regular food supply chain. According to Yuan et al. (2023), packaging has a negligible impact compared to transportation or sales activities, suggesting that charity institutions contribute minimally to the overall emergy of the process. Additionally, the charity institutions are structures that already exist and operate, with or without the evaluated donation scenario, so allocating the emergy of charity institutions to the donation scenario would be attributing a responsibility that might not be appropriate.

Analyzing the total annual emergy required by each scenario, landfilling (Scenario I) exhibits higher emergy demand (U), with a value about 4.6 times the emergy necessary to donate the surplus food (Scenario II). These data indicate that the process strictly connected to food recovery at CEAGESP (collection and transport, quality check, stocking) requires a small amount of emergy. These outcomes exhibit consistency within the context of this particular system, given the absence of emergy in the potential surplus/wasted food (the embedded emergy is considered lost) and the minimal infrastructure and equipment requirements.

In Scenario I the main contribution for U derives from the soil used to cover the waste followed by the gravel used for the leachate drainage system. This high influence of the materials consumed by the landfill is

Table 3
Emergy accounting table for the two studied case scenarios (Figs. 1 and 2) without considering collateral consequences.

Input		Type	Unit	Input (unit/yr)		UEV [a] (sej/Unit)	Emergy flows (sej/yr)	
				Scen. I	Scen. II		Scen. I	Scen. II
1	Rain, chemical	R	Kg	4.61E+07	9.22E+06	4.68E+06	2.16E+14	4.31E+13
2	Labour	F	person	4.20E+01	1.90E+01	1.55E+07	6.51E+08	2.95E+08
3	Water (River)	R	Kg	2.28E+05	4.56E+04	2.58E+08	5.88E+13	1.18E+13
4	Wood	F	Kg	n.a.	4.50E+02	1.94E+11	n.a.	8.73E+13
5	Electricity	F	kWh	1.50E+04	6.25E+04	4.18E+11	6.28E+15	2.61E+16
6	Iron	F	Kg	2.30E+03	4.60E+02	1.09E+12	2.50E+15	5.00E+14
7	Gravel	F	Kg	MC	MC	1.27E+12	MC	MC
8	Geotextile (poliprop.)	F	Kg	4.45E+03	8.90E+02	1.64E+12	7.30E+15	1.46E+15
9	Soil	N	Kg	MC	MC	1.27E+12	MC	MC
10	Concrete	F	Kg	2.65E+03	5.29E+02	1.83E+12	4.84E+15	9.67E+14
11	Cement	F	Kg	6.63E+02	1.33E+02	2.50E+12	1.66E+15	3.32E+14
12	GCL (Clay)	F	Kg	1.95E+04	3.90E+03	2.54E+12	4.95E+16	9.90E+15
13	Steel	F	Kg	1.37E+04	6.42E+03	2.01E+12	2.74E+16	1.29E+16
14	Lubricant oil	F	Kg	2.53E+03	5.05E+02	4.72E+12	1.19E+16	2.38E+15
15	Rubber	F	Kg	1.26E+03	2.52E+02	5.46E+12	6.87E+15	1.37E+15
16	Diesel Fuel	F	Kg	1.95E+05	3.90E+04	5.99E+12	1.17E+18	2.33E+17
17	HDPE	F	Kg	1.52E+04	3.04E+03	6.69E+12	1.02E+17	2.03E+16
18	Polyacrylamide	F	Kg	1.27E+03	2.54E+02	6.78E+12	8.61E+15	1.72E+15
19	Plastic (PVC)	F	Kg	1.22E+03	3.29E+02	7.45E+12	9.06E+15	2.45E+15
20	Polystyrene	F	Kg	n.a.	6.59E+01	7.45E+12	n.a.	4.91E+14
21	Services	F	US$	6.62E+05	1.74E+05	8.41E+12	5.57E+18	1.46E+18
22	Ferric chloride	F	Kg	1.66E+04	3.31E+03	2.93E+13	4.86E+17	9.72E+16
23	Aluminum (Billet)	F	Kg	7.75E+02	1.55E+02	8.60E+13	6.66E+16	1.33E+16
24	Lead	F	Kg	n.a.	4.20E+02	3.59E+14	n.a.	1.51E+17
Total Emergy U in sej/yr							3.05E+19	6.64E+18
UEV, in sej/ton surplus food							8.09E+14	1.76E+14

Legend: MC = Monte Carlo, please refer to Appendix A and Supplementary Material B; n.a., non-applicable; R = renewable input; N = not renewable input; F = purchased input.
Calculation details are presented as Supplementary Material A (Sc.#I Inventory, Sc.#II Inventory No Purch. Fr.).
[a] All the UEVs were converted to the most recent emergy baseline of 12 E+24 seJ/year from Brown et al. (2016). All the UEVs are without labor and services. Details available as Supplementary Material A (UEVs tab).

consistent with Marchettini et al. (2007), while the different results obtained by Almeida et al. (2012) depend on the different assumptions regarding the UEV for soil.

Regarding the net-emergy indicator, Table 4 shows food donation yields a substantial net positive value of 5.73 E+15 sej/ton, while landfilling with electricity generation produces a negative value of −7.46 E+14 sej/ton. This contrast underscores the significant emergy advantage of donating surplus food over landfilling. Specifically, the emergy return index (ERI) calculation shows that the emergy savings from avoided food production are about 33 times greater than the emergy invested in the donation scenario. In contrast, the ERI of 0.08 for Scenario I indicates that the electricity generated at the landfill offsets only 8 % of the emergy invested in landfilling the surplus food, assuming this electricity displaces grid supply from the Brazilian energy mix – ultimately resulting in a net emergy loss. From an emergy perspective, this suggests that using surplus food for electricity generation in landfills should be discouraged whenever alternative options, such as donation, are available.

Table 4
Net-emergy value for different organic waste and management options.

Scenarios		Emergy investment (sej/ton)	Saved emergy (sej/ton)	Net-emergy [a] (sej/ton)
1	Scenario I (this work)	8.10E+14	6.37E+13	−7.46E+14
2	Scenario II (this work)	1.76E+14	5.91E+15	5.73E+15
3	Compost (Agostinho et al., 2013)	3.04E+13	7.83E+13	4.79E+13
4	Electricity (Almeida et al., 2012)	1.91E+14	1.64E+14	−2.73E+13
5	Electricity (Marchettini et al., 2007)	6.63E+14	1.28E+14	−5.35E+14
6	Incineration (Marchettini et al., 2007)	2.22E+14	7.10E+14	4.88E+14
7	Compost (Marchettini et al., 2007)	1.55E+14	6.12E+14	4.57E+14
8	Bioethanol (Patrizi et al., 2015)	2.57E+14	5.06E+14	2.49E+14
9	Electricity + Anim. Feed (Santagata et al., 2019)	5.56E+14	4.02E+15	3.47E+15
10	Stillage Combustion (Baral et al., 2016)	3.27E+14	1.93E+13	−3.07E+14

Calculation details are presented as Supplementary Material A (Table SM4 Details and Saved Emergy tabs).
[a] Net-emergy = saved emergy - emergy investment.

To broaden the discussion and provide an overview of net emergy behaviour across different waste management options, Scenarios I and II are compared with other organic waste management alternatives within the food recovery hierarchy. As shown in Table 4, several studies evaluating various organic waste management options have reported positive net emergy values in certain cases. Assessing compost production from the separated organic fraction of a municipal solid waste recycling plant in São Paulo city, Agostinho et al. (2013) reported a net emergy of 4.79E+13 sej/ton of waste. Marchettini et al. (2007), examining composting and incineration scenarios for municipal solid waste in Italy, net emergy values of 4.57E+14 and 4.88E+14 sej/ton of waste, respectively. Patrizi et al. (2015), assessing a biorefinery scenario for bioethanol production, demonstrated a net emergy value of 2.49E+14 sej/ton of waste, while Santagata et al. (2019), evaluating electricity and animal feed production from slaughterhouse waste materials, reported a net emergy value of 3.47E+15 sej/ton of waste. Conversely, electricity production from landfilled organic waste has yielded negative values for net emergy. The numbers obtained in this work are consistent with landfill electricity production scenarios assessed by Agostinho et al. (2013), based on the information provided by the study of Almeida et al. (2012) assessing a landfill in São Paulo, and with the results obtained by

Marchettini et al. (2007), who applied emergy analysis to evaluate different waste management options in Italy, showing that composting and incineration offer higher emergy recovery and net emergy benefits than landfilling. It is interesting to note that those options located at the bottom of the hierarchy of waste management (HWM) have a negative net emergy while scenarios with higher priority (top of the pyramid) presented positive values. Therefore, it seems that the validity of the food recovery hierarchy is consistent under a net-emergy perspective.

Waste management practices play a crucial role in shaping net emergy by affecting resource utilization, environmental quality, and economic efficiency. By embracing more sustainable waste management strategies that align with emergy principles and resource conservation, societies can move toward more sustainable and resilient resource management systems. Nevertheless, the scientific goal of modeling this relationship is to enhance our comprehension of the intricate interactions between waste management and net emergy. This deeper understanding can assist decision-makers in prioritizing strategies that optimize resource efficiency, reduce environmental impacts, and improve overall system sustainability.

3.2. Quantifying the intangible effects: the collateral consequences arising from the donation scenario (Fig. 3)

Small-scale systems often influence larger systems through material, energetic, and behavioural changes, creating ripple effects across interconnected scales, especially within the context of sustainability. These changes, while initially localized, can propagate outward, influencing broader market dynamics, policy decisions, and cultural attitudes toward resource use, waste management, and consumption patterns. Recognizing these interactions, which can be considered intangible or collateral externalities, is key to designing interventions that promote sustainable practices and leverage small-scale systems as catalysts for systemic transformation. By understanding how localized sustainability efforts can have far-reaching impacts, we can enhance the effectiveness of global sustainability strategies and encourage a more sustainable future.

Redirecting surplus food from landfills to donation exemplifies how small-scale initiatives can exert broader systemic impacts through intangible effects. As previously presented, this practice reduces environmental impacts by decreasing waste, lowering landfill emissions, and avoiding the production of the substituted products. At the same time, recipients benefit from improved nutrition and health, which can result in a reduction in hospitalization days associated with malnutrition, assuming other variables remain constant. This reduction represents an intangible externality - a collateral consequence - reflecting indirect societal benefits that extend beyond the immediate objective of food donation. It is classified as intangible not because it cannot be quantified, but because it falls outside the primary scope of food donation and the predefined system boundaries.

Understanding their importance while simultaneously recognizing the limitations of the modeling involved, the collateral consequences are calculated here with the ultimate goal of supporting discussions rather than providing a precise numerical value. For Scenario II, to account for the collateral consequences, all products required to provide a balanced diet (Appendix B) were included in the emergy synthesis, resulting in the performance indicators of Table 5.

Table 5
Collateral emergy-based indicators for the donation scenario evaluated.

Indicators	Unit	Average value
Collateral consequence (CC), Eq. 1	sej/yr	8.18E+20
Collateral consequence (CC) per ton of surplus food (SF), Eq. 1	sej/ton SF	2.17E+16
Collateral emergy Index (CEI), Eq. 2	–	0.8
Collateral performance emergy index (CPEI), Eq. 3	–	1.0

Indicators calculation using data from Table 3 and Equations (1)–(3). Details are presented as Supplementary Material A (Sc.#II Total + Collateral tab).

The additional saved emergy related to the avoided hospitalization days (AHD) is 8.18E+20 sej/yr (Table 5). The collateral emergy index (CEI) is 0.8, reflecting the emergy of the collateral consequence, a secondary effect that is concealed, delayed, and occurs on a larger scale compared to the reference system. Indeed, the reference system comprises CEAGESP surplus food management alternatives, namely landfill disposal with electricity production and food donation. Both alternatives demonstrate the ability to save emergy, associated with the avoidance of electricity production in the Brazilian matrix and the production of the same donated products elsewhere. In the donation scenario, by expanding the spatial scale under analysis from a larger perspective, the collateral consequence related to health improvement becomes recognizable and quantifiable as avoided hospitalization days. In short, the results indicate that for each sej accounted for in the reference system at a smaller scale, a positive externality of 0.8 sej is generated at a larger scale.

The Collateral Performance Emergy Index (CPEI) quantifies the potential collateral consequences per sej of invested emergy in the food donation scenario, yielding a value of 1.0 (Table 5). This value was obtained because the emergy saved through collateral consequences (2.17E+16 sej/yr) is approximately equivalent to the emergy of the purchased food required to complement the diet (2.18E+16 sej/yr). These findings serve as important input for decision-makers, as they highlight the potential of a donation scenario to provide benefits on larger scales, quantified in terms of real wealth expressed in emergy.

3.3. Perspectives and future research

This study contributes to the growing body of research on sustainable food waste management by comparing surplus food donation with landfilling coupled with electricity generation, using emergy synthesis. It not only confirms the environmental advantages of food donation through emergy synthesis but also lays the groundwork for expanding emergy applications into broader social domains.

A distinguishing feature of this study is its first attempt to include a 'collateral consequence', specifically the avoided hospitalization resulting from improved nutrition. To the authors' knowledge, no previous emergy-based assessments have incorporated such social co-benefits. While recent literature such as in Sundin et al. (2023) and Sulis et al. (2021) has analyzed food donation using Life Cycle Assessment (LCA) and included efforts to account for environmental rebound effects, these approaches have not translated long-term health outcomes into a unified emergy-based metric. The integration of such collateral benefits into emergy synthesis thus represents a novel and valuable methodological advancement.

Nonetheless, modeling these effects presents challenges. Food donation could lead to a wider range of long-term societal benefits for vulnerable populations, such as enhanced quality of life, reduced frequency of medical visits, improved mental health, increased productivity, and overall well-being. Emergy synthesis excels at quantifying environmental support through solar energy-based accounting, but it is limited in addressing qualitative, long-term societal benefits such as those mentioned above. These outcomes are often intangible and lack standardized units of measurement, making their inclusion in emergy synthesis complex.

Given these limitations, future research should explore integrated approaches that combine emergy synthesis with complementary methods such as LCA, Ecological Footprint, and Social LCA. Such hybrid frameworks can provide a more comprehensive understanding of both environmental and social impacts. Interdisciplinary work will be essential to fully capture the systemic benefits of food recovery strategies and to advance sustainable food systems.

3.4. Sensitivity and limitations

The model results are sensitive to variations in the dietary composition and caloric needs of the target population. Specifically, beef, beans, and rice together account for approximately 62 % of the total purchased emergy. As such, even minor changes in the proportion of these food items (particularly beef, which has a high Unit Emergy Value) can lead to significant shifts in the overall emergy outcome. This highlights the importance of carefully defining dietary assumptions when applying the model to different populations or contexts.

Moreover, results indicate high sensitivity to the following variables: soil quantity, gravel quantity, avoided hospitalization days, and number of potential patients. Due to the uncertainties associated with these variables, all of them were included in the Monte Carlo analysis. In particular, regarding the collateral consequence, the number of avoided hospitalization days is a key factor since it is a highly variable value that depends on local factors. In this study, the values suggested by Correia et al. (2017) related to Latin America (3.5–17.1 days for avoided hospitalization days) are used, since they are the most representative and up-to-date ones available. Anyhow, these values are similar to those in other developing countries. For example, in their study on the relationship between malnutrition and the length of hospital stay in Ethiopia, Nigatu et al. (2021) found that malnourished patients had significantly longer hospital stays (17.2 ± 6.8 days) than well-nourished patients (8.3 ± 4.9 days) during a 30-day observation period. In their study on hospital stay length and costs in Ethiopian children, Teka et al. (2022) found that malnourished children compared to well-nourished children were more likely to require mechanical ventilation (78.3 % versus 66.2 %, OR = 2, $p = 0.045$), experienced longer time on mechanical ventilation (10.3 ± 13.2 days versus 6.1 ± 7.9 days, $p = 0.012$), developed hospital-acquired infections (HAIs) more often (30.4 % versus 19.2 %, $p = 0.045$), and had a prolonged length of stay (10.7 ± 16.4 days versus 6.1 ± 8.4 days, $p = 0.005$). Conversely, in developed countries, while the effect of malnutrition on hospitalization length is still apparent, it is less pronounced. For instance, as shown by Men et al. (2020) for Canada, which can be considered a developed country with fewer issues related to food insecurity and a more efficient healthcare system, data indicate a lower increase in hospitalization days (up to 3.27). These data suggest that the results of our study could serve as a starting point for reflections in other developing countries, while their application to developed countries should be approached with caution. The collateral consequences are influenced by social, economic, and cultural factors, and results representing a region with specific socio-cultural and economic characteristics may not be directly applicable elsewhere.

The main limitation of the donation model presented in this study is its exclusive reliance on avoided hospitalization days, e.g. the causal relationship between malnutrition and the need for hospitalization. Even using the highest quality data (published and peer-reviewed), an uncertainty analysis was considered to obtain a more robust donation scenario. From a systemic perspective, health improvements for beneficiaries may include additional collateral benefits, such as reduced medication use at home, fewer medical visits, psychological improvements, and overall enhancements in quality of life. Incorporating these aspects into emergy synthesis poses significant challenges due to insufficient data and the lack of suitable methodologies for their inclusion. Other collateral consequences that should be addressed in future works include: the internal impact on charity institutions, specifically the monetary funds they save when receiving products from the Food Distribution Center, and the external impact on local markets, where these institutions previously purchased food. Although these limitations do not diminish the importance of our study, which achieved its initial objectives, it is recommended that future research address these aspects.

Regarding the donation scenario, it is crucial to emphasize that the final numbers obtained should not be used as a sole reference for all types of surplus food management. For instance, the logistics solution modelled (a logistic train based on the 'Mizusumashi' concept), while potentially suitable at the wholesale level due to product concentration, is likely impractical at the retail level due to the long distances between sellers. Another issue relates to the amount and types of donated food established. The products donated by CEAGESP are primarily horticultural. This significantly influences the modelling of our study, particularly concerning the additional food purchases required to complete a balanced diet. If the evaluated Food Distribution Centre were able to include other products such as meat, dairy, pasta, and rice among the donated food, the emergy invested (EMI) value would be considerably lower. Consequently, the values of the collateral consequences performance indicators would change, but the main contribution - the discussion of the collateral effects - would be maintained.

Finally, it is important to emphasize that the modeling developed in this study is based on the emergy synthesis method, which has certain advantages compared to other methods, since it includes the effort of nature in making a resource available and recognizing different types of energy. Nevertheless, emergy synthesis is not without limitations. It depends on extensive datasets and predefined UEVs, which can vary across regions or studies. The results are also sensitive to system boundary definitions and methodological assumptions. Moreover, the complexity of emergy calculations and their reliance on systems thinking can limit accessibility for policymakers or stakeholders unfamiliar with the method. It is suggested that future efforts include applying the Life Cycle Assessment method to account for both direct and indirect emissions that cause environmental impact. This would provide an additional perspective to the results obtained, further strengthening strategic decisions regarding the implementation of food donation policies.

4. Conclusions

Emergy synthesis was used in this study to evaluate the environmental performance of surplus food donation compared to landfilling with energy recovery. The main findings are summarized as follows:

a) High Net Emergy Performance of Food Donation: For every 1 solar emjoule (sej) invested in the food donation scenario, there is a saving of **33 sej** through avoided food production. This demonstrates a highly favorable emergy return for food donation compared to landfill with energy recovery.
b) Alignment with the Food Recovery Hierarchy (FRH): The food donation scenario, with a net-emergy of 5.73E+15 sej/ton, positioned at the top of the FRH, demonstrates substantially better environmental performance than landfilling, which shows a negative net emergy of −7.46E+14 sej/ton and sits at the bottom of FRH. These results confirm that the emergy-based analysis is consistent with the theoretical principles of the FRH.
c) Inclusion of Collateral Benefits (Rebound Effect): A key methodological contribution of this study is the incorporation of 'collateral consequences' into emergy synthesis. Specifically, the avoided demand for hospitalization due to improved nutrition from donated food was considered. The emergy savings associated with this collateral effect (2.17E+16 sej/ton of surplus food) are comparable to the total Emergy Investment (EMI) required to operate the food donation system (2.19E+16 sej/ton).

Beyond these core results, the study also highlights important policy implications. The findings strongly support the prioritization of surplus food donation over landfill disposal, demonstrating that food donation delivers substantial emergy-based environmental benefits. Policymakers are encouraged to incorporate these insights into strategies aimed at reducing food waste and strengthening donation programs.

The use of emergy synthesis in this study adds significant value beyond other established assessment methods for sustainability discussions. Unlike approaches that measure isolated indicators such as carbon emissions or water use, emergy integrates multiple environmental and social impacts into a single biophysical metric (solar emjoules) from a donor-side perspective, recognizing the quality of energy. This holistic approach provides deeper insights into resource use and collateral social benefits, such as reduced hospitalization from improved nutrition, which are often overlooked in conventional assessments. The research also identifies a relevant methodological gap in current sustainability tools and advocates for combining emergy synthesis with complementary methods, such as Life Cycle Assessment (LCA) and the Ecological Footprint, to capture a broader spectrum of environmental and social impacts.

Finally, the modeling approach developed here, although tailored to the Brazilian context (CEAGESP), is adaptable to other regions or systems through the incorporation of local data. Incorporating emergy accounting into policy frameworks can lead to more effective solutions oriented to sustainability, supporting resource efficiency and more responsible surplus food management.

CRediT authorship contribution statement

Federico Sulis: Writing – original draft, Methodology, Data curation, Conceptualization. **Feni Agostinho:** Writing – review & editing, Conceptualization. **Alexandre Souza:** Writing – review & editing. **Cecília M.V.B. Almeida:** Writing – review & editing. **Biagio F. Giannetti:** Writing – review & editing.

Declaration of competing interest

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Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.146519.

Appendix A. Variables considered in the Monte Carlo simulation

Type	Description	Original values	Uncertainties considered
Uncertainties on the 'collateral consequence' emergy calculation			
Additional days of hospitalization (day)	The original number of additional hospitalization days, as reported by Correia et al. (2017) based on 66 studies conducted in Latin America. An additional 10 % has been included as a safety buffer.	3.5–17.1	±10 % on the range of original values
Number of potential hospital patients (individuals)	The number of potential hospital patients among the beneficiaries of CEAGESP's recovered food program was estimated based on an initial value of 6.6 % of the 552,753 beneficiaries. This percentage, derived from Andrade et al. (2023), reflects the proportion of the Brazilian population hospitalized for 24 h or more in 2019. To account for variability, a range from −10 % to +30 % was applied using the following criteria: (1) A −10 % adjustment was made to include a safety margin; (2) A +30 % adjustment was applied due to evidence from Correia et al. (2017) and Men et al. (2020) indicating that individuals with malnutrition have higher odds of readmission within a year. This adjustment reflects the increased likelihood of hospitalization among malnourished individuals, leading to an increase of up to 30 % above the average value for the general Brazilian population.	36,482	From −10 % to +30 % of original value
Emergy to treat 1 kg infectious waste (sej)	The emergy required to treat 1 kg of infectious waste in São Paulo is based on combined data from Giannetti et al. (2015), Ribeiro et al. (2020) and Sulis (2023). This estimate includes the emergy costs of both autoclave sterilization and traditional landfilling. Given the lack of detailed information on the autoclave process at the landfill, an uncertainty of ±30 % has been applied.	1.09E+12	±30 % on the original value
Uncertainties on the 'emergy investment' calculation, for Scenarios I and II			
Soil amount (kg)	Geological materials represent the most significant emergy inputs in a landfill, accounting for 95 % of the total emergy (Marchettini et al., 2007). In particular, calculating the total amount of soil required for landfill operations involves inherent uncertainties, especially regarding the soil used in the bottom layers and for the final cover at the landfill's end of life. These aspects are often excluded from conventional assessments. In this analysis, a maximum reference value of 40 % (by mass) of the soil mixture was established for incorporation with the waste (Buranakarn, 1998). However, an uncertainty factor has been introduced, indicating that this maximum value could decrease by up to 80 % according to the authors' experience and the generally available literature on emergy and landfills.	18,826,000	From 0 % to −80 % of original value
Gravel Amount (kg)	Gravel is a crucial component in landfill operations, representing the second most significant input. Given its importance, a variation of ±30 % was calculated to account for potential fluctuations in its usage.	6,745,983	±30 % on the original value

Results of Monte Carlo simulation are available as Supplementary Material B.

Appendix B. Emergy of the food purchased to supplement that donated by CEAGESP in order to meet the diet established for Scenario II

Product		Amount (kg/year)	UEV (sej/kg)	Emergy (sej/year)	Emergy (sej/ton)	Emergy (%; sej/sej)
1	Rice	36,679,033	3.02E+12	1.11E+20	2.94E+15	13.52
2	Legumes	39,786,058	3.82E+12	1.52E+20	4.04E+15	18.56
3	Pasta	9,421,952	3.90E+12	3.67E+19	9.76E+14	4.49

(*continued on next page*)

(*continued*)

Product		Amount (kg/year)	UEV (sej/kg)	Emergy (sej/year)	Emergy (sej/ton)	Emergy (%; sej/sej)
4	Bread	13,033,364	3.90E+12	5.08E+19	1.35E+15	6.21
5	Sweet/biscuits	15,091,263	3.90E+12	5.89E+19	1.56E+15	7.19
6	Beef	15,535,124	1.58E+13	2.45E+20	6.52E+15	29.97
7	Pork	4,035,097	6.15E+12	2.48E+19	6.59E+14	3.03
8	Poultry	9,018,442	4.35E+12	3.92E+19	1.04E+15	4.79
9	Food from fishing	9,986,865	4.40E+12	4.39E+19	1.17E+15	5.36
10	Eggs	2,481,585	5.53E+12	1.37E+19	3.64E+14	1.68
11	Diary	13,154,417	3.25E+12	4.28E+19	1.14E+15	5.22
12	Other food	–	–	–	–	–
13	Total	198,345,199		8.19E+20	2.18E+16	100.00

Data availability

All the data used in this study are available in the main text or as supplementary material.

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