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Research Paper

Assessing the food recovery hierarchy concept from an eMergy accounting perspective: Validation and theoretical insights

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ABSTRACT

The food recovery hierarchy (FRH) is an important concept widely used worldwide as a guideline for food waste management policies. It consists of different options for food waste management hierarchically organized, in which source reduction is the most preferable option, followed by food donation, feeding animals, industrial use, composting, energy recovery, and landfilling. The most common approaches used in the literature to validate the FRH concept consider both, a user-side and donor-side perspectives. While the former are typical of methods such as life cycle assessment and ecological footprint that are extensively explored in the literature, the latter is typical of methods such as eMergy accounting (EMA), a perspective that remains unexplored. This study aims to overcome that literature gap by discussing: (i) The validity of FRH concept under an EMA perspective; (ii) The differences on saving natural resources depending on the adopted FRH option; (iii) Obtaining a mathematical model representing the saved emergy as a function of invested emergy. Results show that the FRH is confirmed under the EMA lens as expressed by the proposed emergy return index (ERI). The most preferable options within FRH are by far more efficient in saving emergy than the least preferable options (about 250 times better). The obtained model $EMS = 2.44E+22/EMI^{0.51}$ describes the relation between the invested and saved emergy along the FRH hierarchy. Insights are presented to promote discussions on existing ERIs cluster within the FRH.

1. Introduction

The waste hierarchy management concept was a tool defined around half a century ago when the environmental movement began to criticize the practice of solid waste disposal. It is a conceptual framework used to prioritize waste management options based on their environmental impact, with the goal of reducing the amount of waste produced and promoting sustainable practices. In fact, according to Schall (1992), during the 1970 s, the old paradigm that considered waste as one homogeneous mass that should be collected, compacted, buried, or burned started to be replaced by a new paradigm that understands waste as composed of several different components. Depending on the characteristics of each component, the waste should be viewed from different perspectives and managed through different technological routes. For example, some parts simply should not be generated, while other parts are suitable for recycling; some parts could be composted, while others can produce energy, and some parts can only be landfilled. These different pathways correspond to the different levels in the waste hierarchy management concept, in which the highest or priority levels must be chosen for environmental impact reduction (Hultman and Corvellec, 2012; Van Ewijk et al., 2016).

Over the years, the waste hierarchy has been included in various national laws across the planet. For example, in the United States, the California Office of Appropriate Technology first defined a hierarchy for hazardous waste management in 1981 (OAT, 1981; Wolf, 1988). During the 1980s, the waste hierarchy concept also gained popularity for municipal solid waste (USC, 1989). The initial version of the waste hierarchy considered recycling and composting as the most preferable choices, followed by incineration and landfilling. In Europe, the concept of the waste hierarchy principle was first proposed in the Dutch Parliament in 1979 (Van Ewijk et al., 2016), and in 2008, it was included in the Waste Framework Directive 2008/98/EC (WFD) established by the European Commission (EC, 2008). This directive updated and refined the previous conceptual model for waste hierarchical management. In this new model, the priority order is waste prevention through management policies, which aim to reduce the demand for new products and/or the amount of generated waste. The alternative options proposed, from highest to lowest priorities, are waste prevention, preparing

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for reuse, recycling, energy recovery, and disposal.

Different kinds of waste management hierarchies exist according to different types of waste, with slight changes in denominations and characteristics. Focusing on food waste, the food recovery hierarchy (FRH) plays a key role in food waste management (Fig. 1). From the most to the least preferred options, source reduction is the most recommended one, followed by donation, feeding animals, industrial use, and composting. Incineration and landfilling are considered the worst options (EPA, 2018). The most recommended options suggest first valorizing "wasted food" as food by recovering its nutritional value for people in need, and then considering animal feed as the second option. This applies when food is wasted solely due to aesthetic or market reasons that do not affect its edibility and nutritional value. These types of food are often referred to as surplus food, unsold food, or non-marketable food (Albizzati et al., 2019; Brancoli et al., 2020; Cakar, 2022; Papargyropoulou et al., 2014). Only after the nutritional value is lost, food can be considered organic waste (Albizzati et al., 2019; Cakar, 2022) and managed according to the subsequent less recommended FRH options.

The environmental burdens related to FRH options have been assessed by different methods in search of possible validation of the FRH concept from a scientific perspective. The two most common approaches available in the literature focus on the "user side" and "donor side" perspectives. The first approach, typical of methods such as Life Cycle Assessment (ISO 14040, 2006; ISO 14044, 2006) and Ecological Footprint (Wackernagel and Rees, 1998), takes into account the flows of matter and energy under human control. The second approach, typical of methods such as Emergy Accounting (with 'm'; Odum, 1996), considers the anthropic processes incorporated into natural systems and includes all the inputs required to sustain them by extending the space–time scale to encompass such inputs.

From a user-side perspective, several studies have adopted Life Cycle Assessment (LCA) as method to assess various options of the FRH (Albizzati et al., 2019; Brancoli et al., 2020; Cakar, 2022; Damiani et al., 2021; Ebner et al., 2014; Eriksson et al., 2015; Eriksson and Spangberg, 2017; Guo et al., 2021; Kalogo et al., 2007; Moult et al., 2018; Papadaskalopoulou et al., 2019; Sundin et al., 2022). All these LCA studies tend to confirm the validity of the FRH concept, at least to some extent, since exceptions are identified depending on the kind of assessed waste products and on technological, social-economic, and environmental local factors. Still, from a user-side perspective, other methods have been applied to evaluate the environmental burdens of waste hierarchy options. For example, Cherubini et al. (2009) included the complementary perspectives of material flows and Ecological Footprint (EF) based on an LCA inventory, while Herva and Roca (2013) used the EF as a single composite indicator and applied multi-criteria analysis (MCA) by integrating the EF with other material flow indicators. Although their results confirm landfill as the worst option for waste management, the highest levels of the FRH were not assessed, and therefore, a general validation for FRH is still missing.

From a donor-side perspective, Emergy Accounting (EMA) is receiving increasing attention due to its scientific robustness (Giannetti et al., 2013) in quantifying real wealth (Odum, 1996). In fact, most definitions of 'value' are based on a utility approach for humans or what is received from an energy transformation process. Fossil fuels, for example, are evaluated based on the heat generated when they are burned, while economic evaluations are based on the willingness to pay for perceived utility. An alternative view of value in the Biosphere is based on what is invested rather than what is received, and this donor-side perspective forms the basis of EMA (Odum, 1996). Therefore, the FRH concept should also be validated by EMA to be fully recognized as a general concept. Several authors (Almeida et al., 2012; Agostinho et al., 2013; Marchettini et al., 2007; Patrizi et al., 2015; Santagata et al., 2019) have applied EMA in their studies focusing on systems located from intermediary to lower levels of the FRH. They calculated the total emergy demanded – or 'emergy invested' (EMI) – by the studied waste management processes and their capacity to generate gains in emergy terms – defined as 'emergy saved' (EMS). On the other hand, few studies (Patrizi et al., 2015; Santagata et al., 2019) have focused on systems located from intermediate to higher levels of the FRH, including Sulis et al., 2021 that compared the highest-level option (food donation) with the lowest one (food treated as organic waste and landfilled). Additionally, some studies have compared waste management options within the same FRH level. For example, while Agostinho et al. (2013) assessed the emergy of compost from municipal solid waste recycling compared to traditional farming compost production, Patrizi et al. (2015) assessed the bioethanol production from straw as a replacement for traditional gasoline production.

From a literature review, it was identified a scientific gap regarding information about the dynamic behavior of the FRH from an EMA perspective, indicating the need for further efforts in that direction. Thus, this study aims to provide additional quantitative information and insights to encourage further discussions on the concept of the FRH. Specifically, this work aims to (i) discuss the validity of the FRH from an emergy accounting perspective, (ii) to explore the capacity of the FRH in saving emergy per unit of emergy invested, and (iii) to propose a mathematical model to represent the relationship between emergy invested and saved along the FRH.

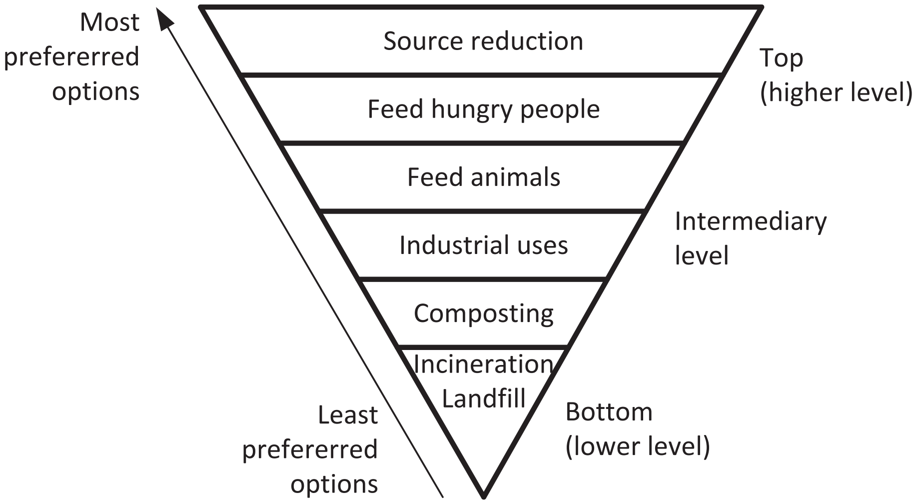

Fig. 1. Options for food recovery hierarchy (FRH).).
Source: Adapted from the US Environmental Protection Agency (www.epa.com

2. Methods

2.1. Food waste as organic by-product of the food supply chain

This section is presented to avoid any semantic confusion. The food supply chain refers to the movement of products and services along the value-added chain of food commodities, aiming to maximize value for customers while minimizing costs. It typically consists of five steps: (i) farm production, (ii) handling and storage, (iii) processing, (iv) distribution, and (v) consumption (Porter et al., 2016). Within each step, food losses occur, which can be defined as by-products of the production and distribution systems. According to Brown (2015, pg. 265), a by-product is “an incidental or secondary product produced in addition to the principal product, typically valued less than the product itself”. Although by-products are often considered as waste, they can be useful and sometimes even marketable. Given that the most preferable options within the FRH concept consider food as still edible, while the least preferable options consider it as organic waste, this study uses the term organic by-products (OBP) instead of organic waste.

2.2. Emergy accounting

Emergy accounting (EMA) aims to assess the long-term sustainability of a production system by considering the support from ecosystems. EMA quantifies the existing quality differences among different kinds of resources, based on the work performed by nature to generate them, considering anthropic systems as an integral part of the geobiosphere (Marchettini et al., 2007; Odum, 1996). The development of the emergy concept and its theoretical foundation cannot be separated from the development of the energy quality concept, which began in the 1950 s with H.T. Odum’s work on tracing energy flows in ecosystems. Different forms of energy possess varying abilities to perform work due to their different “energy quality”. Initially, the term ”embodied energy“ was used to refer to energy quality differences in terms of their generation costs, and a ratio called the quality factor was used to represent the amount of one kind of energy required to produce another (Odum and Odum, 1980). Later, the term ”embodied energy“ was replaced by ”emergy“ (with a ’m’), and the quality factor ratio was named ”transformity.“ Emergy is defined as ”the available energy of one kind of previously used up, directly or indirectly, to make a service or product“ (Odum, 1996; pg.7). The unit of emergy is the solar emjoule (abbreviated as sej), which measures the solar emergy required to accumulate and generate all inputs of natural or human-made production systems. For instance, sunlight, fuel, electricity, and human services can all be quantified on a common basis by expressing them in the same unit of measure: emjoules of solar energy required to make them available.

During the last decade, unit emergy values (UEVs) have been widely used as a general term to represent all kinds of energy quality factors. UEVs are calculated based on the emergy required to generate one unit of output. The emergy associated with a flow can be easily calculated if its UEV is known by multiplying the flow by its UEV. When comparing alternative processes, the UEV measures their global efficiency in delivering the same product. The total emergy use (U) measures the emergy that converges to produce the output yield (Y). Since it represents the emergy cost of the yield, U is the emergy assigned to the yield Y, which indicates the environmental work supporting the yield itself. Additional explanations of the meanings, concepts, and applications of EMA can be found in the scientific literature, including, among others, the works of Odum (1996), Brown and Ulgiati (2004), Giannetti et al. (2019), and Liu et al. (2021).

When applying EMA concepts to waste management systems, each option for managing organic by-products (OBP) proposed by the FRH triangle requires a certain amount of resources to reduce the environmental burden caused by the waste. For example, all the materials, energy, and processes needed to construct and maintain a sanitary landfill, to build an incineration plant, or to establish a recycling plant are accounted for through emergy accounting and referred to as “emergy invested” (EMI). Simultaneously, certain waste management options have the potential to provide direct beneficial outputs for society, such as electricity generated in landfills or incinerators, materials recovered in recycling plants, or donated food through food donation scenarios. These management options save resources that would otherwise be required to produce the same products elsewhere. This beneficial emergy is known as “emergy saved” (EMS) or recovered emergy. Recognizing that both EMI and EMS are important for assessing the emergy performance of OBP management options, it is also crucial to better understand how these two variables behave along the FRH triangle, as illustrated in Fig. 1.

According to emergy rules, any OBP management option can be represented as an interaction between the emergy carried with the OBP (EmOBP) and the emergy invested in managing or treating the OBP. The sum of these two represents the total emergy embodied in the generated output, while EMS corresponds to the emergy saved by the output. In this study, EmOBP refers to the emergy of 1 ton of OBP, EMI represents the emergy invested in managing or treating 1 ton of OBP, and EMS denotes the emergy saved by the generated output, which may include donated food, animal feed, biomaterials, biofuels, compost, or electricity. The amount of emergy saved depends on the chosen option among those ones proposed by the FRH (Fig. 2).

Recent discussions and advancements in emergy accounting for waste management, including concepts such as emergy algebra, co-products, and by-products (Agostinho et al., 2013; Brown, 2015; Gala et al., 2015; Santagata et al., 2019), have led to the computation of EmOBP as “lost.” In other words, the EmOBP that crosses the boundaries of the management system option is considered zero to avoid double counting. Therefore, EMS and EMI are the only two variables considered for analysis, and the approaches used to study their relationship are presented in the following subsections.

2.2.1. Emergy return index (ERI)

To provide information about the capacity of an FRH option to save emergy in relation to the emergy invested, a new indicator called the Emergy Return Index (ERI) is proposed in this study. The ERI represents the ratio of emergy saved (EMS) to emergy invested (EMI); $ERI = EMS/EMI$. The ERI indicates the amount of emergy saved per unit of emergy invested, with $ERI > 1$ indicating a gain in emergy terms. This new indicator is proposed to facilitate the comparison among the studied cases of OBP management options, which are characterized by different EMSs and EMIs based on their specific characteristics. A higher ERI signifies a greater ability of an OBP management option to save emergy for each sej of emergy invested. The relationship between ERIs and the levels of FRH options is quantitatively exemplified using available scientific data on invested and saved emergy as case studies.

2.2.2. Emergy saved as a function of emergy invested

As presented before, the EmOBP is independent of the adopted option for OBP management within the FRH and is assumed to be equal to zero. Therefore, it is possible to hypothesize that along the FRH triangle of Fig. 2, the emergy saved for different management options would depend exclusively on the EMI, leading to the following statement: The emergy invested (EMI) to manage the OBP behaves as an independent variable, and the emergy saved (EMS) acts as a dependent variable. Here, an $EMS = f(EMI)$ relation can be assumed, meaning that the emergy saved is a function of the emergy invested. This hypothesis is discussed in this study by considering data from the literature. The resultant $EMS = f(EMI)$ data is plotted in an x-y scatter plot graph using a Microsoft Excel® spreadsheet to identify possible relationships between both variables. Once a possible relationship is identified, a probable mathematical function able to describe it is hypothesized and verified. This step is performed by applying a curve fitting process, which according to Brown (2001; pg. 191), “describes the experimental data as a mathematical equation in the form $y = f(x)$, where x is the independent

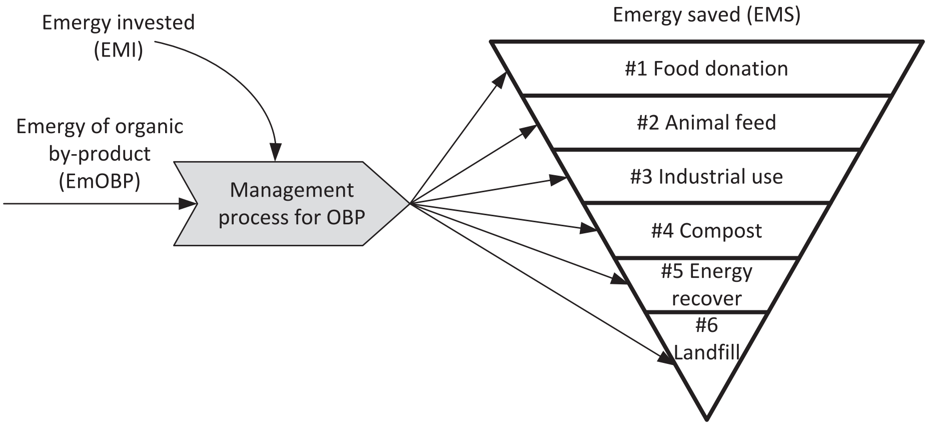

Fig. 2. Options for organic by-product (OBP) management and their dependence on emergy inputs. .
Source: Elaborated in this work

variable and is controlled by the experimenter; y is the dependent variable, which is measured; and f is the function that includes one or more parameters used to describe the data.” Since real scenarios are considered here as case studies, EMI is the variable controlled by the decision maker who chooses an option among others proposed by the FRH, while EMS is the result that depends on the chosen scenario. Once a probable function is obtained, the next step is to determine the goodness of fit, which shows how well the function describes the data. As suggested by Brown (2001; pg. 192), “the most commonly used measure of the goodness of fit is least squares. It is based on the principle that the magnitude of the difference between the data points and the curve is a good measure of how well the curve fits the data”.

The least squares method can be applied to both linear and nonlinear functions, with slight differences. The following example shows how it works for linear functions, in which the general mathematical process is described by Equation (1):

$$SS = \sum_{i=1}^{n} [y - yfit]^2 \tag{1}$$

where: y is the data point, y_{fit} is the value of the curve at point y, and SS is the sum of the squares.

For the purposes of this study, Equation (1) can be rewritten as shown in equation (2):

$$SS = \sum_{i=1}^{n} [EMS - EMSfit]^2 \tag{2}$$

where: SS is the sum of the square, EMS is the real emergy saved value found in a specific point and EMS_{fit} is the value of the theoretical model at the same point.

In the case of non-linear functions, the ultimate goal of minimizing the squared sum of the difference between data and the fit remains the same, but the approach differs from linear regression as it involves an iterative/cyclical operational process. After an initial estimation of the parameters based on prior user experience, the first iteration involves calculating the sum of squares (SS) based on these initial values. Subsequent iterations are then performed by carefully adjusting the parameters to calculate the subsequent SS values until the desired SS value is obtained (Brown, 2001).

To evaluate the goodness of the proposed model, the coefficient of determination R-squared (R^2) is calculated. R^2 is defined as “the proportion of variance explained by the regression model, a useful measure of success of predicting the dependent variable from the independent variables (Nagelkerke, 1991; pg. 691). The SOLVER tool, provided as an add-in for Microsoft Excel®, is used to calculate the SS and R^2 for a potential function that can describe the EMS=f(EMI) relationship. This tool has been widely recognized in the literature for its high reliability and user-friendly interface (Brown, 2001; Brown, 2006; Briones and Escola, 2019; Delgado-Aguilar et al., 2018).

3. Results and discussion

Since the behavior of the relationship between invested and saved emergy along the FRH triangle has important implications for choosing the most appropriate FRH option, it is crucial to gain a better understanding and develop a potential mathematical model that represents this behavior. Each OBP management option along the FRH has its own characteristics, which depend on international standards, physical parameters, and constraints. The choice among the various options is in the hands of the decision maker. However, selecting one FRH option over another also involves certain physical factors that can be quantified as follows: (i) The potential gain in emergy terms per sej of emergy invested; (ii) The possible correlation between the emergy investment for system implementation and the emergy saved during the operational phase. These aspects have been superficially explored in the emergy literature, and additional information on them would provide further support for decision makers. In an attempt to shed light on these aspects, the results related to the proposed emergy return index and a potential EMS=f(EMI) relationship are separately presented in the following sections.

3.1. Emergy return index (ERI)

To calculate the ERI, the values of invested and saved emergy from different studies available in the literature are considered as presented in Table 1. In particular, the following studies are considered: landfilling with energy recovering, incineration and composting scenarios in Italy (Marchettini et al., 2007); organic compost and abiotic recycling process from a municipal solid waste recycling plant in São Paulo (Agostinho et al., 2013); electricity production from Biogas generated by a landfill in São Paulo (Almeida et al., 2012); EMS per ton of organic waste (animal fat) generated by a slaughterhouse to produce electricity and animal feed (Santagata et al., 2019); a biorefinery with ethanol production fed by straw from agriculture and residual geothermal heat (Patrizi et al., 2015) EMS per ton of theoretical biorefinery scenarios fed by cellulosic stillage (Baral et al., 2016); EMS and EMI of landfilling scenarios, compost + landfilling, and compost + incineration in Pakistan (Ali et al., 2018); incineration with and without bricks production in China (Wang et al., 2018); landfilling, landfilling with electricity generation, and food donation + landfilling with energy recovering from OBP generated by a Brazilian food distribution center (Sulis et al., 2021); scenarios for food donation from OBP generated by retail sectors (Sulis, 2023) based on data provided by Eriksson et al. (2015) and Eriksson and Spangberg, (2017); anaerobic digestion biorefinery with biomethane and fertilizers production, and a theoretical scenario considering 100 %

Table 1
Values of emergy invested (EMI), emergy saved (EMS), and the emergy return index (ERI) for different studies on organic by-products management as available in the literature.

Note[a]	Scenarios	Source	EMI	EMS	ERI
1	Donation (+electricity)	Sulis et al. (2021)	2.27E+14	6.57E+15	29.0
2	Donation (theoretical scenario)	Sulis (2023)	1.42E+13	8.20E+15	577.0
3	Donation	Sulis (2023) from Eriksson et al. (2015)	1.27E+14	9.69E+15	76.3
4	Donation	Sulis (2023) from Eriksson and Spangberg (2017)	2.01E+13	5.95E+15	296.5
5	Animal Feed (Electric Drying + Corn Substitution)	Estimated from San Martin et al. (2016)	2.25E+13	2.52E+14	11.2
6	Animal Feed (Electric Drying + Soybean Substitution)	Estimated from San Martin et al. (2016)	2.25E+13	3.93E+14	17.5
7	Animal Feed (Natural Gas Drying + Corn Substitution)	Estimated from San Martin et al. (2016)	2.60E+14	2.52E+14	0.97
8	Animal Feed (Natural Gas Drying + Soybean Substitution)	Estimated from (San Martin et al., 2016)	2.60E+14	3.93E+14	1.5
9	Electricity stillage combustion (biorefinery)	Baral et al. (2016)	3.27E+14	1.93E+13	<0.1
10	Bioethanol biorefinery	Patrizi et al. (2015)	2.57E+14	5.06E+14	2.0
11	Electricity + animal feed biorefinery	Santagata et al. (2019)	5.56E+14	4.02E+15	7.2
12	Biomethane biorefinery	Sulis (2023)	1.18E+14	1.80E+14	1.5
13	Compost	Agostinho et al. (2013)	3.04E+13	7.83E+13	2.6
14	Compost + incineration	Ali et al. (2018)	2.26E+15	9.91E+13	<0.1
15	Compost + landfilling	Ali et al. (2018)	1.61E+14	9.91E+13	0.6
16	Compost	Marchettini et al. (2007)	1.55E+14	6.12E+14	4.0
17	Incineration	Marchettini et al. (2007)	2.22E+14	7.10E+14	3.2
18	Incineration + paving brick production	Wang et al. (2018)	4.04E+14	2.27E+14	0.6
19	Incineration + non-burnt wall brick production	Wang et al. (2018)	2.59E+14	2.27E+14	0.9
20	Incineration + landfilling	Wang et al. (2018)	1.52E+14	2.27E+14	1.5
21	Landfill electricity	Almeida et al. (2012)	1.91E+14	1.64E+14	0.9
22	Landfill electricity	Marchettini et al. (2007)	6.63E+14	1.28E+14	0.2
23	Landfill electricity	Sulis et al. (2021)	1.06E+15	6.37E+13	<0.1
24	Landfilling	Ali et al. (2018)	6.11E+13	0.00E+00	<0.1
25	Landfilling	Sulis et al. (2021)	1.06E+15	0.00E+00	<0.1

[a] Calculation details presented as Supplementary Material, Sections A and B.

food donation in a Brazilian food distribution center (Sulis, 2023). Due to the lack of scientific studies utilizing emergy to assess animal feed production from organic by-products, an estimation of four potential scenarios was conducted by considering raw data from a LCA study by San Martin et al. (2016); details are available in Supplementary Material, Section B. The scenarios presented in Table 1 were grouped according to the FRH of Fig. 2.

Table 1 shows that FRH options located from intermediate to bottom levels depict ERI values between < 0.1 to 7.2, without any particular distinction among incineration, composting, and biorefinery alternatives. Animal feed demonstrates better performance, showing values up to 17.5. Nevertheless, the most important difference is among the option located in the top region of the FRH (food donation) compared to all other options. Moving from the bottom to the top of the FRH triangle, some peculiarities can be observed: (1st) electricity generation at landfill always shows an ERI<1, indicating that electricity production at landfill is not convenient from an emergy accounting perspective; (2nd) options from the intermediate to bottom levels of FRH (including incineration, composting and biorefining) depict ERI values between < 0.1 to 7.2, in which the lowest value corresponds to compost + incineration of household solid waste management in Pakistan (Ali et al., 2018), while the highest value is shown by Santagata et al. (2019) who evaluated a biorefinery with electricity and animal feed & cosmetics production from animal fat. Among the options with 0.1 < ERI<7.2, their performance does not show any particular highlight, moving from ERI values close to zero to values that allows an emergy saving more than seven times the emergy invested; (3rd) animal feed shows the second-best performance, with minimum ERI values close to 1, similar to the lower FRH options, but with maximum values up to 17.5. (4th) donation scenarios show ERI values between 29 and 577, indicating that for each sej invested it is possible to save up to 577 sej, a much higher and better performance than all other OBP management options evaluated.

Considering the sample of emergy studies as show in Table 1, the distribution of ERIs values along the different FRH levels supports the validity of the FRH concept. In particular, the results clearly shows the difference between ERIs for those most preferable and least preferable OBP management options. Specifically, the emergy saving for the FRH top option (food donation) are much higher than emergy savings for the FRH bottom options (landfilling and composting). This suggests that saving the nutritional value of the OBP by considering it still edible for humans (when possible) is by far more convenient under emergy lens than all the other FRH options.

3.2. Exploring the correlation between invested and saved emergy

Fig. 3 illustrates the relationship between emergy invested (EMI) and emergy saved (EMS) for the studies presented in Table 1. Consistent with the emergy return index (ERI), it can be observed that OBP management options located in the lower level of the FRH (such as landfilling, energy recovery from landfill, and incineration) have a low or negligible ability to recover emergy. On the other hand, the four options at the top levels of donation show a high ability to save emergy per ton of OBP with a relatively low emergy investment. It is interesting to note that among the less preferable FRH options (including landfilling, energy recovery, composting, and biorefinery), there is not a significant variation in EMS since they are grouped. However, there is an exception for the electricity and animal feed generated by a biorefinery scenario fed by slaughterhouse waste (Santagata et al., 2019). This discrepancy could be attributed to the different type of OBP evaluated (animal fat) compared to the predominantly vegetable-based studies in all other cases.

The distribution of OBP management options in Fig. 3, based on their EMS as a function of EMI, aligns with the FRH concept. It indicates a non-linear decreasing trend in emergy saved (EMS) along the FRH triangle, moving from the most to the least preferable OBP management options. Specifically, the donation option stands out by saving

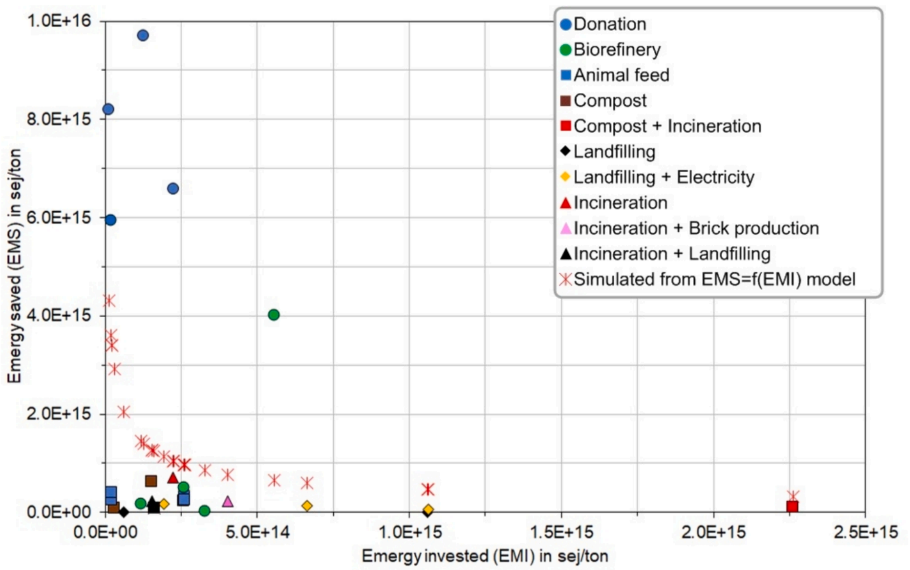

Fig. 3. Emergy saved as a function of emergy invested to manage 1 ton of OBP from different management options. Note: Data from Table 1. Details available in Table C1 of Supplementary Material.

significantly more emergy compared to the least preferable options, demonstrating a non-linear relationship as described by Equation (3):

$$EMS = \frac{a}{EMI^{b}} \tag{3}$$

where: EMS is the emergy saved, EMI the emergy invested, *a* and *b* are two parameters to be determined.

Using the Solver tool in Microsoft Excel® and following the calculation procedures recommended by Brown (2001) for the least square method, the parameters *a* and *b* are determined to obtain a mathematical model (Equation (4). The obtained model has an error sum of 1.71E+32 sej and an R-squared (R^2) value of 0.1302. The R^2 value is used to evaluate the model's goodness of fit, indicating how well it captures the distribution of the data. Among various simulations, including linear, logarithmic, and polynomial models (Table 2), Equation (4) showed the highest statistical quality in representing the data in Fig. 3. It is worth noting that a linear mathematical model is highly unlikely to represent the data, as evidenced by its very low R^2 value of 0.0499.

$$EMS = \frac{2.44E + 22}{EMI^{0.51}} \tag{4}$$

where: EMS is the emergy saved and EMI the emergy invested.

While some authors, such as Spiess and Neumeyer (2010), argue that R-squared (R^2) may not be the most suitable index for evaluating the quality of non-linear mathematical models, it was used in this study due to its simplicity and easy interpretation. Despite Equation (4) being the best option among the simulated models presented in Table 2, its R^2 value of 0.1302 indicates a relatively weak capacity (around 13 %) of the model to represent the relationship between EMS and EMI. However, considering the available data used in this study for the modeling approach, Equation (4) can be considered to have an acceptable level of reliability.

Table 2
Variables from alternative mathematical models simulated to represent data of Fig. 3 [a].

Model	General equation[b]	Specific Equation[b]	R-squared (R^2)
Proposed	$y = a / x^{b}$	$EMS = 2.44E22 / EMI^{0.51}$	0.1302
Linear	$y = a x + b$	EMS=-1.3082EMI+2E+15	0.0499
Logarithmic	$y = a \ln(x) + b$	EMS = − 7E+14In(EMI) + 2E+16	0.1079
Polynomial	$y = a x^2 + b x + c$	$EMS = 1E\text{-}15(EMI)^2 - 3.7926 (EMI) + 2E+15$	0.073

[a] Source: Elaborated in this work.
[b] EMS is the emergy saved, EMI is the emergy invested, a and b are parameters to be determined.

3.2.1. *Influence of food donation on the results*

From Fig. 3, the influence of food donation on the results is evident. The data related to the biorefinery based on animal fat also shows some influence. Due to this significant impact, a simulation was conducted by removing both the food donation and the biorefinery data. Under these conditions, none of the four proposed models in Table 2 were able to achieve an R-squared of at least 10 %, indicating a poor fit to the data. In fact, the models performed worse than the full model, which included the donation and biorefinery data and achieved an R-squared of 13 %.

Although the statistical models excluding the donation and biorefinery data proved to be weak, they offer interesting insights. Specifically for the linear model, it suggests that all by-product management options located in the intermediate-to-low region of the FRH have a low capacity for saving emergy, despite the minimal differences among the various management options. On the other hand, the emergy invested in the management options showed larger differences. This implies a clear message: avoiding the options located at the bottom of the FRH is recommended to reduce emergy investment. In fact, although the saved emergy values are of the same order of magnitude across all management options, it is the reduction in EMI itself that would generate resource savings and allow for a better emergy return, as previously demonstrated by the ERI.

It is important to emphasize that the aim of this study is not to provide a definitive conclusion on the subject, but rather to offer scientific evidence that the FRH concept is supported by emergy accounting. One limitation of this study is the limited dataset used for modeling. However, as more primary data on EMI and EMS become available in the future, Fig. 3 can be revisited and updated, allowing for the development of more accurate mathematical models.

3.3. *Insights on the relation between EMS and EMI*

The obtained results from the emergy return index (ERI) and from the equation representing the emergy saved as a function of emergy invested (EMS=f(EMI)) seem to support – recognizing all the limitations of this work – the food recovery hierarchy (FRH) concept. It was identified a considerable difference in emergy savings between the OBP management options located in the top of FRH compared to those options located in the bottom. Even these findings accomplished the goals of this study, there is an opportunity to discuss and try to find evidences about whether each option within the FRH has specific ranges for ERI, identifying clusters of ERI that would characterize them. Additionally, it could be interesting to align the findings of this work with general emergy theories and concepts, including whether the non-linear EMS=f(EMI) trend reflects any aspect related to the hierarchy of energy transformations in the Biosphere, similar to the studies of Giannetti et al. (2019) and Liu et al. (2021). Insights on both issues are presented separately in the next sections, reminding that the idea is not to end up the subject, but to support further discussions.

3.3.1. *Seeking for ERIs' clusters*

The highest, lowest, and average ERI values for OBP management options according to the FRH triangle are shown in Table 3. Again, it can be observed that the average values for ERI seem to follow the FRH triangle, ranging from 0.39 for electricity production at landfills to 245 for food donation scenarios. This pattern is also recognizable for the maximum ERI values, which range from 0.9 for electricity production at landfills (Almeida et al., 2012) to 577 for food donation scenarios (Sulis, 2023). However, the minimum ERI values present a random pattern, especially for the four lowest options in the FRH, with the exception of food donation (Sulis et al., 2021), and animal feed which showed as expected higher ERI value. The identified and unexpected pattern for the minimum ERI values can be explained, to some extent, by the different emergy inputs considered in each study. For example, the stillage used as biorefining input in Baral et al. (2016) has a low-quality energy input, requiring external energy to transform the low-grade energy available within the stillage into higher or more concentrated energy. This peculiarity affects its ERI. In fact, more traditional inputs for OBP biorefineries, such as straw (Patrizi et al., 2015) or fruits and vegetables (Sulis, 2023), result in an ERI that is more consistent with the other ERI values obtained for those FRH options located at the intermediate-low levels.

According to Van Ewijk et al., (2016), a common understanding about the OBP hierarchy is that, from an operational and practical perspective, it is sufficient to support an improvement by sustaining a planned and gradual movement from the bottom to the top levels of FRH rather than quickly achieve the highest top levels. According to authors, that statement is true since the hierarchy provides information on a direction rather than a target to be achieved. From that perspective, the ERI cluster results of Table 3 provide important information by showing the 'power' or the 'capacity' of each FRH cluster option in achieving higher emergy savings, supporting subsidies for decision makers towards better options in investing emergy and reduce the environmental load of OBP management processes.

From a general analysis, the obtained ERI values for cluster options align with the FRH concept, with the least preferable OBP management options having lower ERI values compared to the most preferable options. Key observations from this study include: (1st) Options located at the top level of FRH show significantly higher capacity for emergy savings compared to those at the bottom level, from an average value of 8 times the invested emergy in the case of animal feed to 245 times in the case of food donation; (2nd) Energy recovery at landfills should be avoided as all studied cases yielded ERI values less than 1. This indicates that the emergy invested in the collection, transport, and disposal of OBP outweighs the emergy obtained from biogas combustion for electricity and/or heat generation, which replaces the local/regional energy matrix; (3rd) Options at intermediary to low FRH levels (industrial use, composting, and incineration) show consistent ERI values with the FRH hierarchy. However, additional studies with larger samples are required to confirm this observation, as their ERI values are quite similar.

Table 3
Minimum, maximum and average values of ERI for the assessed studies [a].

FRH cluster options	Minimum	Maximum	Average
Food donation	29.00	577.00	244.70
Animal feed	0.97	17.5	7.79
Industrial use	0.06	7.20	2.70
Composting	0.04	4.00	1.83
Incineration with energy recover	0.60	3.20	1.55
Landfilling with energy recover	0.06	0.90	0.39

[a] Data from Table 1.

3.3.2. *Food recovery hierarchy and the energy hierarchy organization in the Biosphere*

According to Odum (1996), the universe is hierarchically organized and represents a manifestation of energy. This energy hierarchy is measured by the unit emergy values (UEVs), applicable to all quantity of matter, energy, and information. UEVs have numerous levels of magnitude that correspond to the energy levels in the universe (Fig. 4a). Since it is a general rule, the energy hierarchy could be also applied to the FRH concept, and more specifically to the OBP management hierarchy that presents a sequential list of management options hierarchically organized according to their ERIs.

Generally speaking, waste is generated as by-product from the main human transformation processes, thus it is located at downstream of a human process (Fig. 4b). The FRH presents possibilities to potentially recovering a fraction of the previous lost energy at each step in the production chain, at different rates according to the different FRH hierarchical levels. When well applied, the FRH option will increase the amount of available energy at upstream along the main energy flows through the Biosphere and Technosphere, which will reduce the demand for primary energy. As shown in Fig. 4b, there is a feedback of energy and materials moving back to the main processes (red lines), regulating and reducing the input of energy from the economy and natural environment. The previous by-product is now considered as a useful energy source, closing the cycle and increasing the system energy efficiency. Besides recovering and redirecting resources that would otherwise be lost, FRH options also effectively reduce generated waste (Fig. 4b, black storage of waste) and subsequently lower the resources required for waste management. From a societal standpoint, waste management, including healthcare implications, is significantly impacted by FRH applications that decrease unrecovered waste. This reduction mitigates issues such as sanitary concerns associated with incineration, landfilling, or open dumping. While emergy synthesis doesn't directly measure these impacts – at least directly –, the societal benefits justify reconsidering the prioritization of food recovery in sustainable public policies. The previously mentioned differences among ERIs for OBP management options depicts their importance on the overall system efficiency. In fact, food donation with low EMI is able to save a high amount of available energy, since the emergy demand in producing similar food elsewhere is avoided or saved. Comparatively, animal feed, biorefinery, composting, incineration and electricity/heat generation from landfill biogas show, by far, lower net capacity to recover available energy. This means that these OBP management options have, directly or indirectly, lower capacity to send back available energy to the main energy flows in the Biosphere.

From Equation (4), it is possible to hypothesize a potential connection between the FRH concept and the more general laws of the Biosphere. For example, an interesting aspect is related to the 0.51 value for the parameter b in Equation (4). In the work of Giannetti et al. (2019), a similar value (under all uncertainties involved in our model) of 0.60 was obtained as a constant mean value representing the marginal relation between energy quality and energy quantity in the Geobiosphere. Rewriting Equation (4) by isolating the variable a, Equation (5) is obtained:

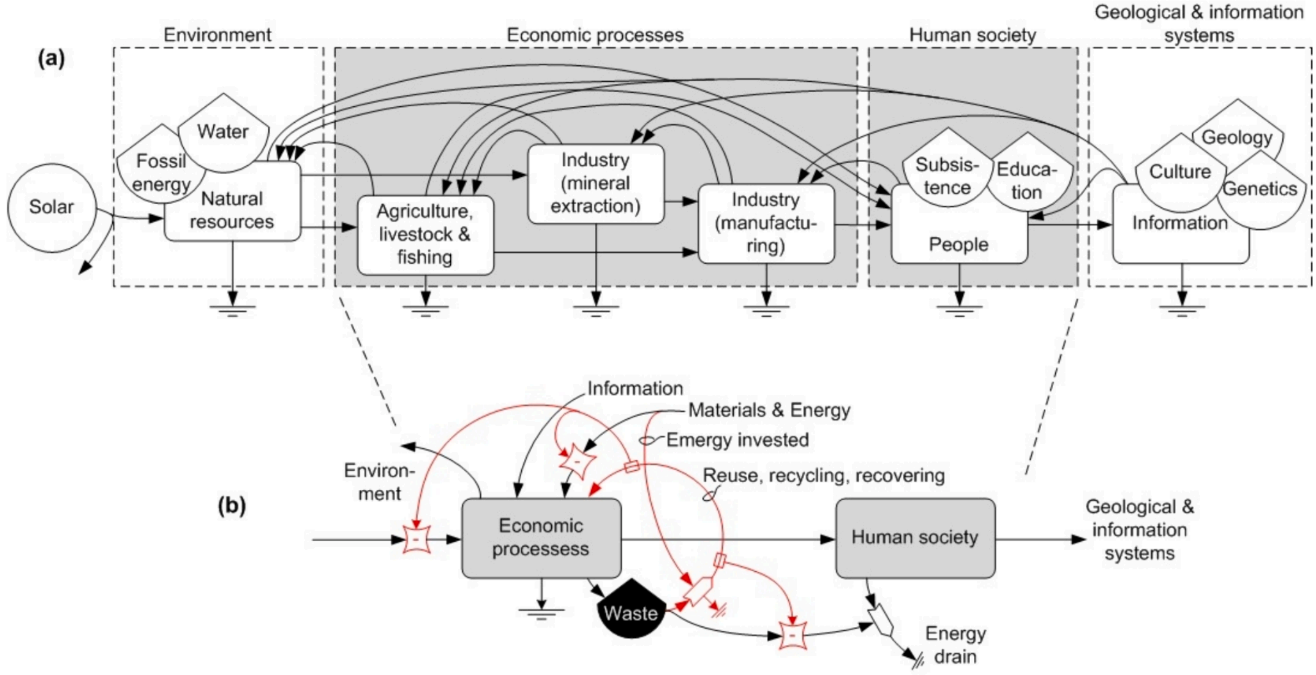

Fig. 4. The hierarchical organization of the energy quality in the Geobiosphere. – (fig. a). Macro-perspective of economic processes showing (in red color) by-products generation, the main energy flows involved to convert them into primary inputs, and its influence on reducing the amount of virgin primary inputs. Source: Elaborated in this work (fig. b).
Source: Giannetti et al. (2019)

$$EMS\,EMI^{b} = 2.44E22 \tag{5}$$

where: EMS is the emergy saved, EMI the emergy invested, b is a parameters to be determined.

Equation (5) shows that the product between the emergy saved and the 'corrected' (due to b parameter) emergy invested is equal to a constant. The equation written in this form allows further insights. This type of relation corresponds to the general form $A\ X^{b} = C$. Among possible others, this type of general equation is a characteristic of polytropic states, specifically represented by $P\ V^{n} = C$. From a theoretical exercise by assuming an existing similarity between the polytropic states model with the Equation (5), some insights can be provided. When b is equal to 0, Equation (5) becomes $EMS = a$, theoretically representing the maximum value of emergy that can be recovered from OBPs management. This supports that humans living within the Earth's biological time is a key concept for a more sustainable world. Reducing OBPs generation by changing lifestyle and/or other individual habits are mandatory for a more sustained world. This issue is deeply discussed by Giannetti et al. (2020), in which authors emphasize that circular economy is an important action but that hardly will overcome the current human-nature dichotomy. Furthermore, when b is > 1 ($b \rightarrow +\infty$), Equation (5) becomes $EMI = a$, once again indicating limits for investing emergy, and consequently saving emergy. Of course, this theoretical exercise must be updated and double checked when larger amount of data feeding the $EMS = f(EMI)$ model becomes available, but it is a starting point for discussion on the theme.

Other interesting observation regards the connection between the FRH triangle with the 'eMformation' concept along biosphere, including emergy form, function, and concentration. The eMformation is the regular information concept including creation, copy, storage, spreading and dispersing, but quantified from an eMergy perspective. According to Brown (2015), supply chains of unit processes could be considered as energy hierarchies that upgrade the form of materials and products by progressively adding information jointly with increase of their spatial concentration. This means that products and by-products have higher emergy at each step in an energy hierarchy pathway, but this process is interrupted when the material or product is downgraded and then considered as waste, losing its initial utility. In this specific case, the stored emergy begins to disperse, following a rate proportional to the decrease in form and concentration. In this context, confirming and complementing Brown's (2015) propositions, the FRH could be seen as a hierarchy for different degradation levels that follow a non-linear decreasing trend. For example, in the most preferable OBP management options (e.g., food donation), the form of OBP expressed by its main function (nutritional value for humans) is maintained. As a result, the emergy concentration is preserved instead of being lost. This conceptual perception would justify, from an emergy perspective, that the reusing approaches within the FRH triangle as represented by food donation could be considered as a waste prevention approach. Conversely, all other least preferable OBP management options within the FRH indicate that emergy form is progressively being dispersed, and thus they must be avoided as much as possible.

Further works are necessary to confirm all these preliminary findings, insights and statements presented in this section, by enlarging the sample of EMI and EMS values when they become available in the scientific literature. This would bring higher statistical accuracy for results and support conclusive statements.

3.4. Sensitivity and limitations

While this study contributes to the advancement of knowledge on the waste management topic, it is important to acknowledge its limitations. These limitations stem from various sources, including the sample size, the inclusion of mixed OBP options in some case studies, assumptions made during emergy accounting by experts, clustering of FRH options with different raw material sources for biorefineries, and regional variables that can have influence in the emergy flows.

The sample size comprises 25 case studies, which was the maximum available in the scientific literature and deemed appropriate for the goals of this study. However, the inclusion of mixed OBP options within the same case study introduces uncertainties in calculating EMI and

EMS. It would be more appropriate to analyze specific scenarios that exclusively represent a single FRH option. For example, the case study of Sulis et al., 2021 on donation + landfill electricity relies heavily on the residual fraction not donated and sent to landfill, comprising 94 % of EMI. Similarly, the compost + incineration case study by Ali et al. (2018) assesses two FRH options simultaneously. Another source of uncertainty arises from the different assumptions made by authors when applying emergy accounting. For instance, the inputs considered in landfilling processes vary among published references. Additionally, the estimation of geological materials such as rocks and soil, which are important emergy inputs according to Marchettini et al. (2007), can differ based on the criteria used by authors. Furthermore, the EMS=f (EMI) model does not incorporate the specific characteristics of OBP feeding biorefineries. For example, Patrizi et al. (2015) evaluated straw as a raw material, Marchettini et al. (2007) focused on municipal solid waste, and Santagata et al. (2019) considered waste from slaughterhouses. Different raw materials for biorefineries would result in different EMS and EMI relationships. Lastly, local and regional characteristics can influence EMI and EMS values.

These identified limitations need to be addressed in future studies to enhance the scientific robustness of the findings obtained here. As more studies on emergy accounting of OBP management systems become available, additional data can be utilized to replicate the procedures employed in this study.

4. Final remarks

Instead of ending the discussion on the subject, the main goal of this study is to provide evidences and support discussions about the relationship between organic by-products (OBP) management options and the food recovery hierarchy (FRH) concept, as well as to discuss a general mathematical rule expressing EMS with EMI along the FRH triangle. Despite recognizing the existing limitations and uncertainties that call for future efforts to advance this study, important insights were obtained on both main focused topics.

Firstly, from an emergy accounting perspective, this study supports the use of the general waste hierarchy concept as a reference for highlighting OBP management and resource policies. Calculated for each FRH option evaluated, the proposed emergy return index (ERI) indicates that FRH options at the highest levels are able to save significantly more emergy than those at the bottom level. This means that policy makers should promote FRH options located in the top level to accelerate the achievement of the highest possible emergy savings. Additionally, the FRH concept is validated from an emergy accounting perspective through the ERI, making it a rule of thumb to be followed by decision-makers. These results align with previous LCA-based research (Albizzati et al., 2019; Brancoli et al., 2020; Cakar, 2022; Damiani et al., 2021; Ebner et al., 2014; Eriksson et al., 2015; Eriksson and Spangberg, 2017; Guo et al., 2021; Kalogo et al., 2007; Moult et al., 2018; Papadaskalopoulou et al., 2019; Sundin et al., 2022), which, from a general perspective, supports the FRH concept.

Regarding the relationship between emergy saved (EMS) and emergy invested (EMI) along the FRH triangle, a non-linear mathematical model ($EMS=2.44E+22/EMI^{0.51}$) has been shown to be the most appropriate in describing the data currently available and concepts. The model depicts that, besides saving lower emergy, the OBP management options located at the bottom level of the FRH are also associated with a relatively higher amount of EMI. The donation scenarios have a significant influence on the model obtained, and from a simulation exercise excluding the donation data, the final message is simply that managing them through the options located at the bottom level of the FRH should be avoided due to their high EMI and consequently low ERI.

From the Biosphere energy hierarchy, other interesting insight is that the “eMformation” concept also applies to the FRH concept, as OBP downgrades and disperses along the hierarchy. The utility or emergy form progressively stocked in the OBP over the production chains is lost and dispersed according to a non-linear trend, in which the reuse approach (e.g., donation) represents the best alternative while landfilling the least preferable one.

The findings of this study are applied exclusively to OBP’s management, claiming efforts to study inorganic waste to verify potential similarities. Anyhow, the general hierarchy of reusing, recycling, and recovering approaches is expected to be similar for inorganic waste management, with differences among the EMI, EMS, and ERI indicators due to waste and processes characteristics.

CRediT authorship contribution statement

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

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 will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2024.09.015.

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