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A sustainable performance measurement-based methodology for choosing food waste reduction and valorization options

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Abstract

Purpose – This paper addresses the need of practitioners in the food industry to choose among different food waste reduction and valorization options. To this aim, it proposes a methodology for benchmarking these options, considering economic, environmental and social performance.

Design/methodology/approach – The methodology guides the decision-makers into context understanding and business process options definition, performance assessment, until the final choice. The methodology is applied to the case of a canned food producer faced with surplus vegetables, by comparing two alternatives: (1) redistribution and (2) recovery.

Findings – Under certain conditions, i.e. high distance between the point of food surplus generation and food banks, refrigerated trucks and high redistribution network dispersion, from an economic and environmental perspective, recovery overperforms redistribution. Considering both the impact on employees' morale and on the people in need, redistribution prevails over recovery.

Practical implications – New competences in terms of life cycle assessment and social impact assessment are needed to support managers in taking informed decisions about food waste reduction and valorization.

Social implications – In the methodology, environmental and social sustainability are considered as important as economic sustainability. Considering social impact can guide decision-making towards food waste valorization options not economically or environmentally optimal.

Originality/value – Elements of strategic decision-making tools and science-based methods are integrated into an actionable benchmarking-like approach for practitioners. Results challenge the validity of the concept of "hierarchy" when comparing recovery and redistribution for human consumption.

Keywords Food waste hierarchy, Sustainability assessment, Food surplus, Benchmarking, Food waste reduction and valorization

Paper type Research article

1. Introduction

Food waste is defined as food that is no longer edible for humans (Bellemare *et al.*, 2017). It is generated at every stage of the food supply chain and can originate from misconduct in the management of the surplus food (Ciccullo *et al.*, 2021). Food surplus indeed is defined as edible food intended for human consumption that is not consumed due to factors, e.g. overproduction (Papargyropoulou *et al.*, 2014), owing therefore many recoverability potentials. Vlajic *et al.* (2018) claim that the food industry is facing the so-called "triple paradox of food waste, food scarcity and environmental pollution". While in developed countries, one-third of the available food is wasted, in developing countries, the 15% of the population deals with food shortages; furthermore, "one ton of food waste results in 1.9 tons of CO_2 and food waste generated in manufacturing sector is responsible for approximately 35% of annual greenhouse gas emissions" (Vlajic *et al.*, 2018).

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Organizations committed to reduce food waste, endorse Food Waste Hierarchy (FWH) as a reference framework to choose the most favourable business process option(s) for the preservation of sustainable value. The FWH includes business process improvements or technological innovations to prevent the generation of food surplus or different valorization approaches.

Currently, there is not a clear consensus in the literature on whether the FWH should be viewed as a ranking system reflecting environmental sustainability (Bergström *et al.*, 2020) or as an overly simplified framework that fails to effectively guide decision-makers (Wei *et al.*, 2024). The twofold interpretation arises from the fact that food waste valorization requires additional resources that may undermine environmental sustainability (Wei *et al.*, 2024), and in the recognition that desirability of food waste management options can differ significantly when assessed from environmental, social, or economic perspectives (Mourad, 2016). Therefore, decision makers evaluating different food waste reduction options need to perform a sustainability assessment (Chauhan *et al.*, 2018), which can represent an important part of a sustainable performance measurement system (SPMS) for agri-food companies (Ramos *et al.*, 2025; Voldrich *et al.*, 2020). Literature presents various approaches to assess the sustainability impacts of different process options to manage food waste, including life cycle assessment (LCA), food–energy–water nexus and cost and benefit analysis. However, as underlined by Do *et al.* (2021), there is a need for a balanced list of indicators to assess the different dimensions of sustainability to choose the optimal food waste prevention and management option. While several studies acknowledge this need and propose interesting approaches, there are still inconsistencies and inaccurate measurement practices (Do *et al.*, 2021; Valentini *et al.*, 2025), indicating that a comprehensive and reliable measurement is far from being fully implemented.

Therefore, the objective of this paper is *to develop and apply a methodology that can guide key decision makers (i.e. companies that generate surplus food) to benchmark different business process options for food waste reduction and valorization, part of an SPMS, which includes environmental, social and economic dimensions.*

The methodology developed integrates environmental, social and economic assessments, using real or actionable process steps, activities and actors as the main inputs of an LCA, direct and indirect social impact (i.e., considering impact on food security and indicators from the social LCA framework) as well as cost–benefit analysis. The methodology is then applied to one use case, a company that is confronted with the production of surplus food and in deciding among different food waste reduction and valorization options.

Different process steps as well as different actors characterize each option, which have been subject to a real decision on the surplus food generated from the case company: (1) Redistribution for human consumption (donation) and (2) Recovery for biogas production. In addition to providing an assessment methodology contextually applied to a real case, we directly respond to the call by Do *et al.* (2021) for research that incorporates redistribution – the second highest priority of the FWH. We do so by taking the perspective of a food processing company, thereby distinguishing this study from those that focus on companies in the food distribution (Sundin *et al.*, 2022) and in the food service stage (De Menna *et al.*, 2020).

The paper develops as follows: Section 2 introduces the theoretical background, i.e. the FWH framework and the sustainable performance measurement systems for food waste management. Section 3 proposes a comprehensive methodology to support decision-making among different options in the FWH, and in Section 4, the methodology is applied to a real case company. Section 5 discusses the key results, while Section 6 draws the conclusions.

2. Theoretical background

2.1 Business process options for food waste reduction and valorization

Food waste has economic, environmental and socio-ethical implications (de los Mozos *et al.*, 2020). One possible way for companies along the agri-food supply chain to tackle these interrelated issues is to rely on FWH frameworks.

Waste hierarchy frameworks have been developed and defined as tools to prioritize different waste management options. In the last decade, after the Waste Framework Directive 2008/98/EC, different waste hierarchy frameworks have been proposed with different levels and suggested initiatives from the most favourable to the least advisable (Ciccullo *et al.*, 2021). These initiatives reflect process-based innovations, which are mostly incremental innovations that harness existing business processes and technology, but which can also include more radical technological innovations (Martin- Rios *et al.*, 2018; Kusumowardani *et al.*, 2022).

The FWH proposes different options to reduce food waste, underlying preference for preventive actions that aim to avoid the generation of surplus food (Kusumowardani *et al.*, 2022). Hence, the different layers of the FWH include, as first priorities, strong technological innovation to prevent post-harvest losses, which consists of smart packaging or other technological innovation to extend the product shelf-life or in weak prevention practices (Mourad, 2016). Weak prevention actions focused on streamlining the existing linear supply chain (Ciccullo *et al.*, 2021), leveraging the waste reduction principle of lean manufacturing for food processing companies (Ema *et al.*, 2024). Moreover, the basic assumption behind weak prevention options consists of achieving optimized production quantities which rely on process improvement, monitoring and raising customer awareness for optimizing also their purchasing quantities (Mourad, 2016). These prevention options are followed by other process best practices, which include the redistribution of food surplus through Food Banks, and the reuse of food surplus to produce other edible alternatives or for feeding animals. Lower priorities are assigned to recycling to produce fertilizers or other products outside the food industry, followed by the recovery of the energy share contained in food products (Garrone *et al.*, 2014; Papargyropoulou *et al.*, 2014; Teigiserova *et al.*, 2020; Albizzati *et al.*, 2021; Parsa *et al.*, 2024) and incineration (Wei *et al.*, 2024). All the layers prior to the one at the bottom suggest alternatives to avoid the least efficient outcome (i.e. sending food to landfills) (Kusumowardani *et al.*, 2022).

Recently, Teigiserova *et al.* (2020), Albizzati *et al.* (2021) and Facchini *et al.* (2023) proposed updated versions of the FWH. Teigiserova *et al.* (2020) differentiate between re-use for animal feed and the valorization of food by-products into value-added products, while ranking nutrient recycling (e.g. fertilizer production) among the least preferred options. Albizzati *et al.* (2021) expand the FWH by identifying 21 specific post-processing pathways, offering alternatives within each hierarchical level. Facchini *et al.* (2023) expand the reuse layer of the FWH, by differentiating reuse of human consumption, animal feeding, recovery and integration into specific new business models (e.g. agro-park or functional food).

2.2 SPM for food waste reduction and valorisation

Within the agri-food industry, SPMS are fundamental tools (Ramos *et al.*, 2025) for operational, tactical and strategic decision-making. When it comes to relevant sustainability challenges, like food waste, SPMS acquire an even higher relevance, and specific sustainability assessment methods can represent the starting point to quantify the issue and to evaluate ad-hoc actions to tackle it.

A recent literature review by Redlingshöfer *et al.* (2020) collects and analyses a total of 64 contributions that are focused on assessing the effectiveness of the FWH by means of comparing the environmental performance of at least two alternatives of the FWH. The contributions are classified into (1) environmental science-based methods, including LCA and (2) decision support tools. While the former methods consider just the environmental dimension, and particularly GHG emissions, the latter also include the economic dimension, mostly through cost and benefit analysis or by developing models based on qualitative assessments (Redlingshöfer *et al.*, 2020).

Table 1 collects some significant contributions from the literature, published after the review by Redlingshöfer *et al.* (2020) and focused on different approaches for SPM to benchmark one or more options within the FWH, distinguishing between *assessment-based* studies, inspired by environmental-science methods and *decision support tools*.

Table 1. Main contributions focused on the assessment of FWH options after Redlingshöfer *et al*. (2020)

	Performance dimension	Methodology for performance assessment	WH options compared	Quantitative analysis?	Main elements of the model	Boundaries	Type of tool	Target decision maker
Bergström *et al.* (2020)	Environmental Economic Social	• LCA • S-LCA • LCC	• Different redistribution scenarios	Yes	Comparison of scenarios based environmental, economic, social performance treated separately	Supply chain	Decision support tool	Redistribution company
De Menna *et al.* (2020)	Environmental Economic Social	• LCA • E-LCC • S-LCC	• No specific differentiation made (methodological paper)	No	Comparison of generic scenarios, based on environmental, economic, social performance treated separately	Food service stage (canteens)	Decision support tool	Catering company, school (food waste provider) and biogas operator (food waste recipient)
Rivera *et al.* (2020)	Environmental	• LCA	• Production of biodiesel • Incineration • Landfilling • Anaerobic digestion • Composting	Yes	Comparison of different scenarios based on environmental performance	Food waste valorization stage	Assessment	Police makers at country level (UK)
Albizzati *et al.* (2021)	Environmental Economic Social	• LCA • S-LCC	• All WH options, focus on 21 pathways	Yes	Comparison of 21 pathways with environmental, economic and social performance treated separately	Europe	Assessment	Police makers at the EU level

(*continued*)

Table 1. Continued

	Performance dimension	Methodology for performance assessment	WH options compared	Quantitative analysis?	Main elements of the model	Boundaries	Type of tool	Target decision maker
Sundin *et al.* (2022)	Environmental	• Environmental footprint	• Redistribution (donation) • Recovery	Yes	Material flow analysis, environmental footprint and rebound effect	Supply chain (from retail gate to charity organization)	Assessment	Food retailers (food waste providers)
Teigiserova *et al.* (2022)	Environmental	• LCA	• Reuse for animal feed • Recycling • Disposal	Yes	Comparison of different scenarios based on environmental performance	Food Waste recovery stage (biorefinery)	Assessment	Biorefinery companies and policy makers at the EU level
Sundin *et al.* (2023)	Environmental Economic Social	• LCA • Net economic benefit • S-LCA	• Redistribution (donation) • Recovery	Yes	Comparison of generic scenarios, based on environmental (footprint, rebound effect and system expansion considered) economic, social performance treated separately	Supply chain (from the retail gate)	Hybrid	Policy makers at the local level and/or food retailers
Grossi *et al.* (2024)	Environmental	• Carbon footprint	• Composting • Landfill	Yes	Quantification of greenhouse gas emissions for two different organic waste options	Cradle-to-grave	Assessment	Not specified

(*continued*)

Table 1. Continued

	Performance dimension	Methodology for performance assessment	WH options compared	Quantitative analysis?	Main elements of the model	Boundaries	Type of tool	Target decision maker
Badeenezhad *et al.* (2024)	Environmental, economic	• Cost and benefit • Waste flow analysis	• Four scenarios involving recycling and recovery practices	Yes	Scenario analysis of different combinations of food waste management options	Waste recovery stage (containers, collection trucks, landfill site)	Decision support tool	Policy makers at the local level
Chen *et al.* (2025)	Environmental, Economic	• LCA • Cost-effectiveness analysis	• Composting • Anaerobic digestion • Pyrolysis • Hydrothermal carbonization + anaerobic digestion • Anaerobic digestion with biochar • Pyrolysis of the digestate after anaerobic Digestion • Gasification	Yes	Comparison of the cost effectiveness of alternative byproducts reutilization pathways that contribute to urban decarbonization, based on LCA and material and energy flow analysis	Food waste collection, pretreatment, processing and any post-treatment	Assessment	City councils, urban planners, policy makers at the local level
Muñoz-Torres *et al.* (2025)	Environnemental	• LCA	• Food valorization (two options) • Redistribution • Prevention	Yes	Comparison of scenarios based on environmental performance and multi-stakeholder perspectives	Supply chain	Assessment	Not specified

As Table 1 exhibits, the prevailing approach to assessing different alternatives included in the waste hierarchies consists of LCA. Given the importance of economic and financial considerations driving the adoption of food waste recovery practices (Dossa *et al.*, 2022), life-cycle thinking, as Life Cycle Costing (LCC), is adopted together with LCA (e.g., Iacovidou *et al.*, 2017) to identify the main hotspot from the purely environmental to the economic point of view (Hunkeler *et al.*, 2008).

LCA principles are also applied in the social life cycle assessment method (S-LCA) (Benoit *et al.*, 2010), while other connected approaches originating from the original LCC are the environmental life cycle costing (E-LCC) and the societal LCC (S-LCC) (Hunkeler *et al.*, 2008; De Menna *et al.*, 2020).

All in all, looking at Table 1, we can conclude that the existing studies, which focus on *assessment*, either perform a qualitative analysis (e.g. De Menna *et al.*, 2020) or a quantitative analysis based on lifecycle-based methods (Bergström *et al.*, 2020; Sundin *et al.*, 2023; Albizzati *et al.*, 2021; Muñoz-Torres *et al.*, 2025; Chen *et al.*, 2025), including carbon footprint computation (Grossi *et al.*, 2024). Interestingly, some studies (e.g. Badeenezhad *et al.* (2024) and Chen *et al.* (2025)) incorporate economic evaluations when comparing alternative scenarios, while Sundin *et al.* (2023) integrate the traditional LCA-based environmental assessment with a very detailed social sustainability assessment and with the net economic benefit method for comparing the sustainability impact of surplus food donation against anaerobic digestion, with a specific municipality as the main scope of the study. However, assessment-based studies rarely consider the three dimensions of sustainability, and they generally have researchers as the main users, thus being inherently complex.

Decision support tools help private or public players in understanding the impacts of specific interventions (De Menna *et al.*, 2020). For instance, Bergström *et al.* (2020) compare different options for redistributing surplus food, crafting a decision-making tool for organizations directly operating the redistribution, while Badeenezhad *et al.* (2024) develop a framework to be used decision-support tool for optimizing food waste management scenarios based on economic and flow analyses. Nevertheless, in these types of tools, companies are rarely considered the primary decision makers, with a predominant focus instead on policy makers. Moreover, these tools are designed to support the development of "business cases" related to the FWH, thereby considering environmental and social impact instrumental to the creation of economic value, not considering a shared value perspective in which economic, environmental and social dimensions are equally important (Kramer and Porter, 2011).

In both *assessment-based methods* and in *decision support tools*, when companies are the intended users of such frameworks, the studies typically consider food retailers (Sundin *et al.*, 2022) and food service companies (De Menna *et al.*, 2020). Alternatively, they consider food waste recipient companies as biorefinery (Teigiserova *et al.*, 2022), biogas operators (De Menna *et al.*, 2020) or redistribution organizations (Bergström *et al.*, 2020).

Moreover, only some recent studies include the social dimension, with a focus on the direct social impact of different surplus recovery options on end-users or recipients in terms of increased food security (Sundin *et al.*, 2023), or considering other impact categories like work opportunities (Bergström *et al.*, 2020) and poverty alleviation for the local community (Sundin *et al.*, 2023).

2.3 System-expansion as a specific SPM tool for food waste reduction and valorization

When applying *assessment-based* methods to FWH options, besides the impact of the activities that the waste undergoes during the life cycle, various studies (e.g. Bernstad Saraiva Schott *et al.*, 2016; Sundin *et al.*, 2022; Sundin *et al.*, 2023; Grossi *et al.*, 2024; Chen *et al.*, 2025) include in the overall estimation the value of the "avoided product". Each specific recovery scenario requires the use of resources to produce an output. This output has a value that can be assessed by quantifying the avoided resources, i.e., the resources that would have been needed to produce the output in a different way. Accordingly, to deal with this complexity, *assessment-based* methods take advantage of the *system expansion* logic. This approach consists of enlarging the boundaries of the system to include in the assessment the products that are obtained in the recovery process. The environmental impact of the products that they substitute and that are therefore not produced in the most conventional way is included as a credit to the system (Vandermeersch *et al.*, 2014).

3. Developed methodology for benchmarking food waste reduction and valorization options

In line with benchmarking literature (Wah Fong *et al.*, 1998; Bhutta and Huq, 1999), this methodology is structured following the logic of identifying, comparing and adopting best practices. It draws on the FWH to identify a set of alternative food waste management options, which are evaluated and compared to determine their sustainability performance. These alternatives represent, for the decision-maker, candidate business process options, which differ in terms of environmental, social and economic performance.

The methodology is structured as follows: Steps from 0 to 2 concern the identification of the internal baseline for the benchmarking, of the boundaries of the benchmarking process and of the potential business process options to be compared; Step 3 involves the sustainability performance measurement for each alternative; Step 4 aims to compare the alternatives based on the results of Step 3, in order select the best option to be adopted.

Step 0 – Establishing the internal baseline for benchmarking

In this step, the processes connected to the generation and management of the food waste are analysed and mapped, and the volumes of surplus food waste generated are calculated. The paper by Darlington *et al.* (2009) can be used as a reference for the mapping of the type of waste generated by the company. This step leads to the definition of the base case, i.e. the case against which the different business process options are evaluated in differential terms, serving as an internal benchmark against which alternative options will be compared. The setting described in the base case could be a fictional scenario used for the sake of comparison, that, for instance, reflects the features and the processes of the case company representing the key decision maker in a situation in which no food waste is prevented or managed. Alternatively, the base case can be the as is situation.

Step 1 – Definition of the benchmarking scope and system boundaries

The aim of the SPM consists of guiding a decision maker within a company in the food supply chain to choose a preferred option considering the three dimensions of sustainability.

While for the economic impact the scope of the analysis can be limited by the boundaries of the company generating surplus food, the environmental and social performance measurements need a larger scope that consider all the steps of the food supply chain to estimate the avoided environmental impact and a large set of stakeholders which includes, but is not limited to, the workers of the company of the decision maker.

Step 2 – Identification, characterization and validation of alternative business process options

The output of this step is the set of defined, described and validated alternative food waste reduction options that will be evaluated in the second part of the methodology. The guiding reference for defining the alternatives is the FWH, in that it provides the possible waste destinations (Batista *et al.*, 2021). At each layer of the FWH, more than one possible option can be defined. Then, they can be validated by the decision maker. This step includes the involvement, besides the company representatives, of possibly additional stakeholders, as industrial partners, technology providers, academic experts, not for profit organizations. In this step, the selected practices are defined by examining the technological constraints of the specific food product and context. This means, for example, to consider whether recycling technologies and infrastructures already exist or would require manageable innovations by the involved actors.

Step 3 – Sustainability performance measurement

In this phase, environmental, economic and social performance measurements are obtained. For each performance dimension, for each of the business process options previously identified, the impact is computed with respect to the internal benchmarking baseline with a differential logic (Arnaboldi *et al.*, 2014).

Step 3a – Environmental performance measurement: LCA

The environmental evaluation follows an LCA approach. In line with the "differential" logic used for, e.g. investment economic evaluation (Arnaboldi *et al.*, 2014), all the steps and processes common to all the alternatives are not taken into consideration.

The environmental evaluation follows four main steps, typical of the LCA methodology:

(1) Scope definition

In this first step, the functional unit must be defined in a way that allows comparison between the different options. System boundaries are set and the unit processes to be assessed are defined and shown in a graphical representation. A process map is created displaying all the activities performed for the food waste valorization, from the food waste generation to the final possible outputs obtained. These activities are described for all the alternative options, and the common ones are highlighted to be excluded from the assessment. Environmental impact categories are selected considering both the technology adopted for the different stages of the production process and some previous studies applying LCA methodology for the same scope (Vandermeersch *et al.*, 2014; Cristóbal *et al.*, 2018).

(1) Inventory analysis (life cycle inventory, LCI)

This phase of the LCA consists of the collection of all the primary and secondary data necessary for the assessment. Energy and material flows are mapped to show the links among units in the system, and the related data are provided by the companies or organizations involved in the study (primary data) or retrieved from databases or literature (secondary data).

(2) Impact assessment (life cycle impact assessment, LCIA)

In this phase, inventory data are converted into impacts using software that translates inputs and output flows into impacts by means of impact factors. The choice of the impact assessment method is required. Once the impact assessment has been performed, environmental KPIs are selected from the LCA impact categories.

(3) Life cycle interpretation

Discussion of the steps and the flows that are the most remarkable causes of the environmental impact identifying the "environmental hotspot" of the supply chain under investigation in light of the methodological assumptions of the study.

Step 3b – Economic performance measurement: cost and benefit analysis

The internal activities performed in the baseline for benchmarking and in the other defined business process options need to be identified. Then the *costs and benefits* (i.e. savings) connected to these activities required are computed. Most of the data useful for the economic performance measurement (i.e. direct and indirect costs) can be computed using company accounting and control data (e.g., cost of labour).

Step 3c – Social performance measurement: impact on stakeholders and on Food Security

The social impact is evaluated through direct and indirect measures. Direct measures include the ability of the analysed business process options to directly address food insecurity through the impact on consumers, including the recipients of donations. Indirect measures instead include the impact on other relevant stakeholders, both internal (e.g., employees) and external (e.g. suppliers). Impact categories can be retrieved and inspired by Social-LCA methodologies (UNEP, 2020), considering a differential logic.

While direct social impact can be measured through primary data, indirect social impact requires the design of ad hoc qualitative data collection tool (e.g. survey or focus group) with relevant stakeholders.

Step 4 – Multi-dimensional performance measurement and selection of the best business process option

This last step could be implemented with two distinct approaches. The first approach involves (1) data normalization and (2) data aggregation (Talukder *et al.*, 2017) to derive a composite indicator or a sustainability score. This allows a fast comparison of the different business process options but hinders the detailed evaluation of root causes of the most important impacts as well as trade-offs in place. The second approach includes separate performance measurement for each of the three dimensions of sustainability, alongside qualitative analyses of trade-offs and synergies between them (Sundin *et al.*, 2023).

3.1 Application of the benchmarking sustainability performance methodology to a use case

The proposed methodology integrates well-established tools from the SPM and sustainability assessment literature. While the methodology is here applied to a single case study, it builds on validated methods that are frequently used in single-case applications in the agrifood sector (Mu *et al.*, 2017; Zingale *et al.*, 2022).

In addition, the empirical application involved a collaborative and iterative process with the case company, which actively contributed to the definition and validation of both the business process options and the impact dimensions considered. Company representatives, who had initially performed a narrower evaluation with an economic approach, provided primary data and confirmed the relevance of also the other sustainability dimensions. This engagement ensured an internal validation of the methodology and its applicability for decision-making across different contexts.

4. Results from the use case: canned tuna company

The proposed methodology is applied to a real case study of a manufacturing company specialized in the production of canned tuna salads. The focus of this case study is on the food surplus of secondary raw materials, specifically frozen vegetables, supplied by various vendors.

4.1 Production process

Most of the secondary raw materials' ingredients (i.e. peas, carrots, pepper and corns) are received frozen in large sacks and stored in silos at -18°C. According to the production recipe, the vegetables fall from the silos directly to a conveyor belt that transports them through the defrosting oven to a quality control and finally to the mixing machine, where they are mixed with the not-frozen vegetables, sauces and oils. Once mixed, vegetables are added to the tuna, which has already been placed into the cans. At this point, cans are ready to be sterilized and sealed.

Step 0 – Definition of the internal baseline for benchmarking for the case

In the canned tuna salad manufacturing process, there is a small percentage of vegetables that unavoidably become surplus. The main cause of surplus food is related to a production scheduling issue. Production is programmed according to the available quantity of tuna.

However, since the vegetables are packed in fixed batches, the quantity of vegetables defrosted normally exceeds the needed amount that should be filled in the different cans. Therefore, since the priority is to minimize the waste of tuna fish, it happens that vegetables are defrosted, prepared and mixed but not used, thus leading to the generation of surplus food. This surplus is still edible, but it can no longer be used to produce canned tuna salads.

The internal baseline considered is represented by food surplus disposal through landfilling. This is a fictional scenario that doesn't lead to any form of valorization and is taken as the basis to confront the different alternative valorization options. Landfilling does imply a potential environmental, economic and social impact but since the alternative scenarios are then compared with each other, this impact is not differential and therefore not relevant for decision making.

Step 1 – Definition of the benchmarking scope and system boundaries for the case

Criteria that guide the focus on specific environmental, social and economic aspects have been discussed during two interviews, each one lasting around 90 min with two representatives of the case company, who are the proponents and key decision-makers regarding the different alternatives evaluated by the company. Moreover, as secondary sources of information, the company shared a presentation corroborating the problem setting as well as additional cost data for the economic impact assessment.

As reported in Table 2, the scope of the assessment changes depending on the considered dimension. For the environmental and social dimensions, it is necessary to consider the impacts generated outside the boundary of the company generating food surplus, extending the scope to the other stages of the supply chain dealing with food surplus valorization. The economic implications are considered relevant when impacting the decision-maker, as any possible cost or benefit for other players of the system are not relevant in the decision-making process.

Step 2 – Identification, characterization and validation of candidate food waste management options for case

The production manager of the company defined two feasible and interesting business process options to adopt for the evaluation, namely biogas production through anaerobic digestion (Case A) and donation through food banks (Case B). The first one is a solution highly used by companies in the sector, while the second has a social element that was considered important by the company. This step has been done with the support of informal interactions with other stakeholders that could be involved in the circular system (i.e., Food Banks), as well as with periodic meetings with the managers of other functions.

4.2 Biogas production (Case A)

This alternative is connected to energy recovery. The surplus food is conveyed to an external company that, through anaerobic digestion, produce biofuels, which can then be transformed

Table 2. Different scopes for sustainability assessment

Sustainability assessment type	Environmental	Economic	Social
Scope	End-to-end supply chain for food surplus valorization (from the generation of food surplus until the valorized surplus food reaches the recipient)	Company generating surplus food	End-to-end supply chain for food surplus valorization (from the generation of food surplus until the valorized surplus food reaches the recipient)

into electricity and heat and, eventually, fertilizers. Vegetable surplus produced at the facility is stored into industrial collection bins managed by the external biogas company. This company, situated about 200 km from the production plant, collects the surplus food weekly.

4.3 Food donation (Case B)

The second alternative is food donation, a food redistribution strategy that channels surplus food to a food bank that provides meals to people in need. This option involves additional handling and quality assurance steps to comply with food safety standards. At the end of each shift, production line workers sort vegetable surplus into 10 kg PET bags, label them, and store them in refrigeration units to preserve quality; the associated energy consumption is negligible, as the fridges are not exclusively used for surplus storage. A local food bank then collects the surplus and manages its distribution, delivering it to a charitable organization.

A system expansion logic is considered in the environmental performance measurement. Figure 1 shows the two options, the products obtained, and the substituted products accounted for in the modelling.

Step 3a – Environmental performance measurement

4.3.1 Goal and scope definition for LCA. Firstly, the functional unit was set as the *daily vegetable surplus generated* from the production process, and it is set at the maximum value of 100 kg/day. The reason for this choice was that we focused on the valorization of the food surplus generated, rather than on the prevention of it. In the latter case, we might have opted for the total input of vegetables entering the process.

Secondly, the system boundaries of the LCAs of the two alternatives were defined (see Figure 2). Six generic unit processes (UP) have been defined to describe any possible waste

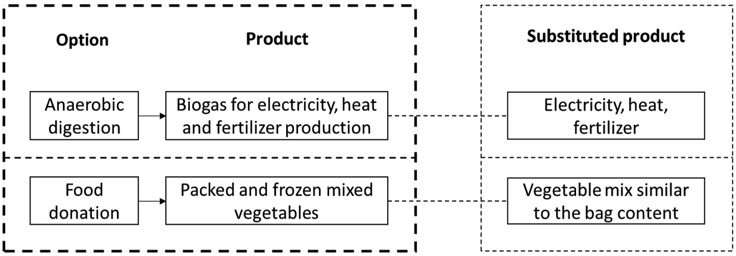

Figure 1. Alternative options considered

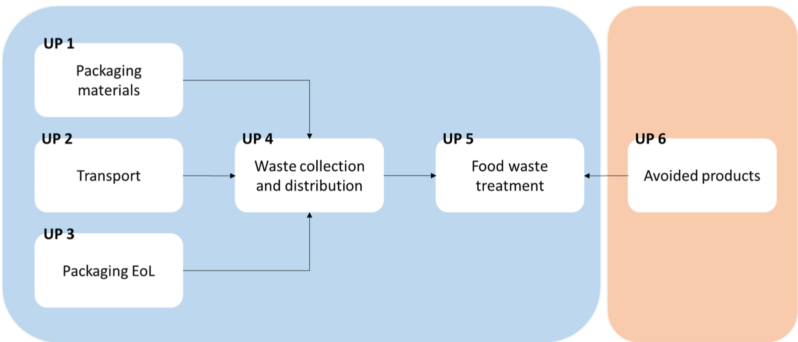

Figure 2. System modelling

recovery option: “packaging materials”, “transport”, “packaging End-of-Life (EoL)”, “waste collection and distribution” and “food waste treatment” are the activities which, performed either by the company or the waste treatment facility, generate an environmental impact; the last unit process, “avoided products”, is the one which allows to consider in the assessment the recovered products which, according to the system expansion logic, are associated with an “environmental credit”, and are therefore assumed to generate a negative impact.

4.3.2 Life cycle inventory. Primary data have been collected by means of two interviews: one with the Head of Quality and one with the Quality Assurance Specialist. The main source of secondary data was the database Agribalyse, except for data referred to biogas production and outputs, which have been retrieved from the literature.

As exhibited in Table 3, only the differential information between the two options have been included in the inventory data, therefore excluding all the activities and flows that are equally present in the different cases and the internal baseline.

4.3.2.1 UP 1 – packaging materials. Primary data for Case B include the material of the envelopes (PET) and the proportion between plastic bags and the mass of food waste recovered (10 kg of food waste per bag). The containers used for biogas production (Case A) are not single-use packaging. Therefore, their contribution to environmental impact has been neglected.

4.3.2.2 UP 2 – transport. The company gave information about the locations of both the destinations of the food waste: the biogas producer is located 200 km from the plant, while the donation structure is only 50 km. The lorries used for transportation in Case B must be refrigerated, while there is no need for specific storage conditions in Case A.

4.3.2.3 UP 3 – packaging end-of-life (EoL). For what concerns the EoL treatment of the packaging materials, in the case of donation, the same data of the UP 1 has been used, and landfill has been hypothesized as the worst-case scenario.

4.3.2.4 UP 4 – waste collection and distribution. This unit process has been used to group all the ones listed before. No additional flows have been included, since for both cases, no additional machinery is required, given that all the activities performed to collect the waste are done by humans.

Table 3. Data type for unit processes

Unit process	Technological flows	Data type and source	Case A (recovery)	Case B (donation)
UP 1	PE envelopes	Primary (type and quantity) + secondary (database)		X
UP 2	Regular transport	Primary (type and distance) + secondary (database)	X	
	Refrigerated transport	Primary (type and distance) + secondary (database)		X
UP 3	Waste treatment of PE	Secondary, database		X
UP 4	Collection of waste	Primary	X	X
UP 5	Production of biogas	Secondary (Literature, Zhou *et al.*, 2021)	X	
UP 6 (avoided products)	Vegetables	Secondary (Agribalyse)		X
	Electricity	Secondary (Literature, Zhou *et al.*, 2021)	X	
	Heat	Secondary (Literature, Zhou *et al.*, 2021)	X	
	Fertilizers	Secondary (Literature, Zhou *et al.*, 2021)	X	

4.3.2.5 UP 5 – waste treatment. In the case of donation, no treatment is required, as the food waste can be re-used as it is. For biogas, this process encompasses all the materials and energy flows needed to produce the biogas from the food waste. Data from literature (Zhou *et al.*, 2021) have been used for this section.

4.3.2.6 UP 6 – avoided products. As explained in Section 4.3, a system expansion approach has been adopted. The products avoided by the recovery case are electricity, heat and fertilizers, which are all products usually obtained from biogas. For this case, data have been retrieved by the literature (Zhou *et al.*, 2021). Donation allows to avoid the production of new vegetables, whose impact has been calculated using data retrieved on Agribalyse.

4.3.3 Life cycle impact assessment. The selected impact categories for the impact assessment are global warming, eutrophication, photochemical oxidation and acidification, in line with previous studies on food waste (Zhou *et al.*, 2021).

The results of the life cycle impact assessment are presented in Table A1 and A2 in the Appendix. Results of the impact assessment relate to the waste treatment, and the avoided products are separated from the impacts related to the activities for which the company is responsible. In Case A, the only UP contributing to the first portion of the impact assessment is the transportation phase, since no additional packaging is required; a significant impact is instead related to the waste treatment phase, that is, the production of biogas. In Case B, the impact is due to transportation, packaging and packaging disposal; no impact is attributed to the transformation phase, since no additional activities are needed to prepare the vegetables for consumption. A comparison between the two options in terms of environmental impact of the activities before waste treatment is shown in Figure 3(a).

As shown in Figure 3(a), even if in the recovery alternative there is no need for packaging (nor consequently of its disposal), this is the most impacting option, due to the long distance to be covered to transport the waste to the biogas production facility. In fact, as can be seen in Figure 4, to parity of mileage, the refrigerated lorry is more demanding in terms of resources and therefore more impactful.

However, since the redistribution for donation option requires the food to be delivered and consumed in a short time, to guarantee its safety, the total impact results in less for this alternative. Data used and results for the impact of transportation alone are presented in Table 4.

For what concerns the contribution to the environmental impact of the subsequent phases, namely waste treatment and avoided products, in the donation case, the food doesn't require any additional treatment to be consumed, and the only contribution is the positive one due to the avoided vegetables produced. In this case, around 70–80% of the impact is due to their production, i.e. the agricultural stage, and the rest is mainly due to transportation, while processing plays a minor role. Figure 3(b) reports the total environmental impact, considering before waste treatment activities, waste treatment and avoided environmental impact.

Step 3b – Economic performance measurement for case

Under a comparative lens, costs and benefits can be assessed. Donations are associated with the differential labour costs due to surplus food collection and packaging into PET bags, as well as internal transportation in the storage area. Indirect labour costs are instead associated with the additional time spent by the quality control and administrative departments to handle donations. The data reported in Table 5 refer to a worst-case scenario identified by the case company, according to which the company would need to hire additional employees to perform the activities connected to the management of surplus food. Additionally, extra materials (i.e. PET bags) are adopted for the redistribution alternative. This is the only material cost for the specific case study, since the recovery alternative utilizes containers that also serve other applications within the company, thus not representing a differential cost for the company.

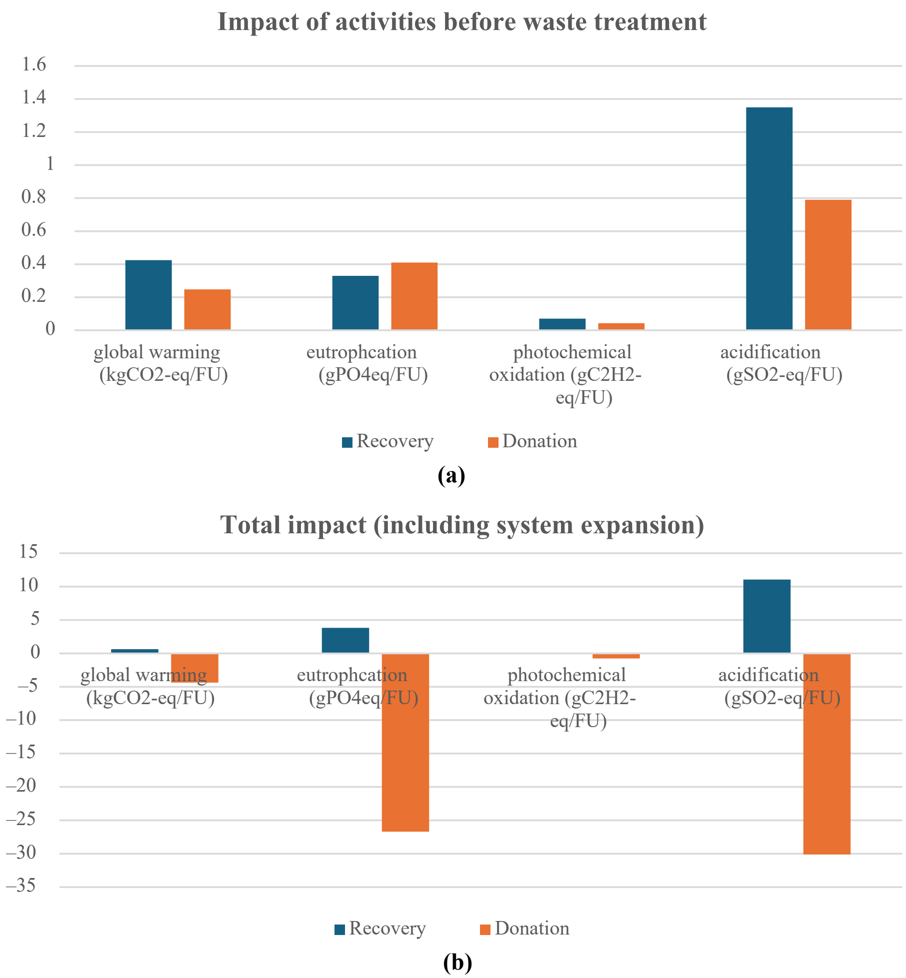

Figure 3. Environmental impact before waste treatment (a) and total environmental impact for the two options (b)

In the recovery, there are no differential cost compared to landfilling, while differential monetary benefits are associated to the extra revenues obtained from the sale of surplus food to the biogas converter and tax savings in the donation option, due to specific incentives scheme available in Italy (where the company generating surplus food is located), which allow companies donating surplus food to save 20% of the value of the donated food in the form of tax discount (Italian Parliament, 2016).

Step 3c – Social performance measurement for the case

Direct social impact is assessed by computing the number of meals offered. Considering the FU of 100 kg of vegetables, the average nutritional value is equal to 53000 kcal, which allows to cover a total of 46.7 meals (see Table A3 and Eq. (1) in Annexes).

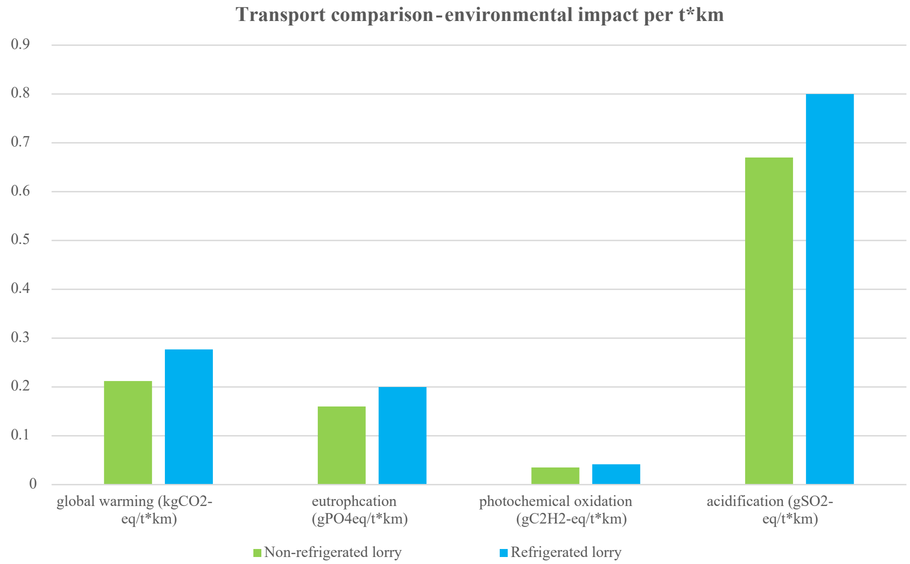

Figure 4. Comparison between transport modes to parity of mileage

Table 4. Transportation impact for the two scenarios

		Resulting environmental impacts for transportation			
	Mileage	Global warming ($kgCO_2e/FU$)	Eutrophication ($kgPO_4e$)	Photochemical oxidation (kgC_2H_2e/FU)	Acidification ($kgSO_2e/FU$)
Recovery	200 km	0.424	0.00033	0.00007	0.00135
Donation	50 km	0.139	0.0000983	0.00047	0.00044

$$Meals\ Offered_{per\ FU} = \frac{Nutritional\ Value\left[\frac{Kcal}{FU}\right]}{MDER\left[\frac{Kcal}{day}\right] \div Meals_{In\ one\ day}\left[\frac{Meal}{day}\right]} \quad (1)$$

The MDER (Minimum dietary energy requirements) depends on age, sex, location, body and lifestyle of a person. For an average male between 30 to 60, with a weight of 65 kg and a height of 176 cm, we can consider it equal to 2,850 kcal. Dividing it by 2,5 meals per day – breakfast assumed as half of lunch and dinner in terms of energy requirements – the result of the MDER per meal is 1,140 kcal.

Indirect measures concerning the impact on other internal and external stakeholders, in addition to direct food recipients, would require a qualitative yet extensive data collection from employees as well as the top management. As reported in Table 6, for the sake of the specific case under evaluation, the social impact has been explained by the two informants within the company. They underlined the positive impact of the donation alternative on employee motivation and morale and the fundamental role of the support received from the top management.

Table 5. Cost and benefit analysis for the two scenarios of the canned tuna company – Source of data: case company

Impact categories (yearly cost or benefit)	Inventory indicators	Source (companies or others)	Indicator metrics	Recovery	Donation
Differential costs **	Direct labour	Company	Additional hours* #workers* hourly cost	–	Estimated around 12.000 €/year (worst case)
	Indirect labour	Company	Administrative personnel: Additional hours * #workers* hourly cost	–	Estimated around 500 €/year (worst case)
	Raw materials – packaging	Company	#Additional Packaging * €/piece	–	Estimated around 200 €/year
Differential monetary benefit **	Tax incentives for surplus food donation	Company + National legislation (Italian Parliament, 2016)	Value of food donated [€] * Kg of waste *20%	–	Estimated around 7,000€/ year
	Partnership revenues	Company + secondary data	Kg of waste * €/Kg sold for recovery	Estimated around 0.15-0.2 €/kg	

Note(s): **: differential compared to the base case

Table 6. Social sustainability assessment with data for the food donation option

Stakeholder	Impact categories	Indicator	Source	Data type	Included	Value (for donation)
Employees	Job Satisfaction and Engagement	a. Motivation of workers for each scenario b. Motivation of managers for each scenario c. Impact on employees' working conditions	Primary (company)	Qualitative interviews	Only a) is included (through interviews)	High
	Employment	Job Creation	Primary (company)	Quantitative	No	NA
Consumers	Health and safety	Nutritional values	Secondary (Internet/ Database)	Quantitative	Yes	53250 Kcal/ FU
		#Meals offered perday	Secondary (Internet/ Database)	Quantitative	Yes	46.7

> (The redistribution alternative) is considered by workers as a noble project. Despite they were asked to perform extra activities, they were highly motivated (. . .).

Employee in the quality department for the Canned Tuna Case

Step 4 – Multi-dimensional performance measurement and selection of the best business process option

Following the second proposed approach, a qualitative evaluation of the two business process options reveals synergies and trade-offs across the three sustainability dimensions. For environmental sustainability, donation is the alternative with the lowest impact. Despite the impact of refrigerated transportation for defrosted vegetables, if there are short distances travelled, the avoided impact outweighs the impact associated with transportation. For economic sustainability, in the presence of specific incentives, and with the current price granted by biogas producers for food surplus, the redistribution alternative has economic benefits for the company that generates food surplus, which can outweigh the costs connected to the management of surplus food for donation purposes, and the benefits from the recovery. Finally, under the social sustainability perspectives, donation is the preferred alternative for both food insecurity and for employees' motivation (indirect impact).

5. Discussion

As analysed in the literature, effective and efficient surplus food management in food processing companies depends on a structured surplus food control system, of which measurement through specific indicators is the main component (Garrone *et al.*, 2014). Despite its importance, measuring surplus food sustainability impacts is far from consolidated in practice, as there is a lack of accurate and applicable measures (Valentini *et al.*, 2025) with mostly fragmented measures of volumes and types of surplus foods rather than encompassing comprehensive sustainability indicators (Garrone *et al.*, 2014). Our proposed methodology seeks to address this gap.

The methodology proposed is a multi-dimensional tool that can be used in practice, in line with a shared value logic (Kramer and Porter, 2011), to assess the simultaneous generation of economic, environmental and social value. In fact, compared to existing approaches in literature, our methodology does not solely focus on evaluating "business cases", which prioritize economic value. At the same time, our approach is innovative in that it shifts the perspective to consider the point of view of the company generating surplus food, which is the main decision maker in a circular system, responsible for determining how to handle surplus food. This perspective integrates the work by Bergström *et al.* (2020), which focuses on the point of view of the company managing food redistribution. Moreover, in the context of agri-food supply chains, the proposed methodology targets decision makers at the food transformation stage, thereby offering a novel perspective with respect to recent research that focuses on other stages (e.g. Sundin *et al.*, 2022; De Menna *et al.*, 2020). Additionally, we translate the work of Sundin *et al.* (2023) into a methodology for companies considering a narrower monetization scope for economic analysis. We consider costs and benefits for the company generating surplus food rather than looking at the distribution of costs and benefits among different stakeholders.

Our results highlight that FWH is a powerful tool to support the identification of business process options. However, when all three aspects are considered, their ranking might not be the one suggested by the FWH. This supports our initial statement about the need for practical methodologies applicable to companies generating surplus food, to assess food waste management scenarios.

5.1 Environmental impact

To assess the environmental impact of a business process option within the FWH, all the set of extra activities needed to adapt the existing processes are considered: e.g. for donation, the re-packaging and the transportation of the recovered food to the food bank. Moreover, the assessment, in line with the system expansion approach, considers the avoided impacts as well. In fact, if this is not the case, all the alternatives in which food waste is reused for human or animal consumption will, more likely, present worst environmental performance than landfill, since new polluting activities are added. However, these business process options allow for reducing the overall environmental impact of the food supply chain, by means of substitution of presumed food production. Overall, this suggests that when deciding on the circular option to implement, in line with what Abdelkafi *et al.* (2023) suggest, the impacts of the decision should be measured considering a system larger than the company. The use of the avoided impact approach requires defining a substitute for the energy and food production. This choice is strongly impacting the results of the environmental assessment. Therefore, in the assessment, it seems advisable to understand in the specific case of application which source of energy production would have been used.

Our results support the suggestion by Damiani *et al.* (2021) that when assessing whether to prefer the redistribution to recovery, from an environmental point of view, the specific characteristics of the production and distribution supply chain should be considered. In our case, we observed that the environmental impact of the options, thus the validity of the FWH, can be affected by two types of factors: (1) the characteristics of the network, i.e. distance among the point of production of the waste and the place of redistribution and (2) the characteristics of the means of transport required, i.e. trucks or refrigerated trucks. In fact, the higher the distance between the point of production and the point of use of the waste, the higher the environmental impact. Similarly, the refrigerated trucks have a higher environmental impact than normal trucks, due to higher energy consumption. In the analysed case, the environmental impact of donation is lower than that of biogas, but this is because, despite the transportation of refrigerated products using refrigerated trucks, the distance is short. Unlike other studies whose results support the FWH (Sundin *et al.*, 2022; Eriksson and Spångberg, 2017), our results suggest that, if the distance between the factory and the recipients of surplus food was higher, the impact of recovery could have been lower than that one of redistribution for human consumption. Similarly, if the food transported was canned, there was not the need to use refrigerated trucks. Moreover, our results support that local donation networks overperform dispersed networks, making them competitive in terms of environmental impact with recovery. While the FWH might not be valid for a dispersed donation network.

5.2 Economic impact

When assessing the economic impact of a circular process option, decision makers consider costs and benefits for the company, as in traditional approaches such as cost and benefits analysis (Iacovidou *et al.*, 2017). Food waste management implies new activities, e.g. quality check, logistics and administrative, that generate costs. If the volume of food waste can be managed with the personnel already hired, these costs do not include dedicated personnel, vice versa when the volume is higher than what can be managed. Existing literature discusses that, at the food transformations stage, companies often lack procedures, and they are not adequately organized to address all the causes of food waste generation (Garrone *et al.*, 2014).

When comparing the food transformation stage with the food retail stage, there are some differences in the economic impact generated by food waste valorization strategies, including, for instance, lower personnel costs for retailers (Mattsson *et al.*, 2018). This suggests that surplus food management, consisting primarily of the sorting and removal of bad produce, and surplus registration, is relatively straightforward (Mattsson *et al.*, 2018). Differently, in the food transformation stage, managing food surplus for redistribution imposes operational costs for manufacturers, such as repackaging and arranging transport for donations (Garrone *et al.*, 2014). Moreover, our findings highlight the presence of further costs connected to food quality and safety controls, making the food transformation stage a more complex context for implementing surplus food redistribution.

This suggests the important role of the policy maker in defining incentives to support companies in the food transformation stage that decide to redistribute the surplus food for human consumption, to cover the abovementioned costs. Italy, for instance, has already in place actions to financially support companies donating food waste (Italian Parliament, 2016). Hence, we agree with Albizzati *et al.* (2019), on the need to promote food redistribution, by addressing donors' liability for food safety aspects, food labelling and durability, as well as economic incentives. Parsa *et al.* (2024) calculate that food redistribution is an option with a positive impact on all the dimensions of the TBL, provided that the government supports the redistribution activities. Interestingly, they also observe that if the UK government directly purchased the food for insecure households, it would pay at least four times more than what is needed to support redistribution initiatives.

Moreover, in addition to the quantifiable need for incentives to obtain a sound business case for food redistribution, our study does not consider the possibility of further economic benefits as intangible reputational benefits (Read and Muth, 2021), which can make the redistribution alternative even more desirable in the medium-long term.

5.3 Social impact

Decision makers assess the social impact of a circular process option by identifying all the stakeholders, both internal and external to the company, impacted by the option, while defining metrics for assessing the impact. Other studies propose an assessment of the social impact of food donation by proposing the focus on both workers and food donation recipients (Sundin *et al.*, 2023). In our methodology, the proposed indicators are measured with the perspective of the industrial decision-maker, hence the workers we consider are from the company donating food and not from the Food Bank. This has led to the introduction and valorization of indicators related to the morale of the donating company's employees, a stakeholder category that is often neglected. In addition, we consider the direct social impact connected to meals offered to people in need, aligned with Cicatiello *et al.* (2016) as well as Sundin *et al.* (2023).

Therefore, we observe that redistribution through donation has a higher social impact than the other layers of the FWH inherently, given it has both an impact on the people who suffer food poverty, and an impact on the donating company employees' morale and motivation.

6. Conclusions

This paper proposes a methodology that assists decision makers in evaluating different options for food waste reduction and valorization. The methodology is composed of four steps, namely (1) identification of the internal baseline for benchmarking, (2) identification of the main decision maker and the scope of the sustainability performance measurement, (3) identification, description and validation of a specific business process options for each layer of the FWH and (4) business process options performance measurement in terms of economic, environmental and social impact. The proposed methodology has been applied to a manufacturing company.

From a theoretical perspective, our paper discusses the validity of the concept of "hierarchy" when it comes to compare recovery and redistribution for human consumption. Our results show that, under certain conditions, from an economic and environmental perspective, recovery can be better than redistribution. Social performance of donation, instead, are higher than that of the recovery alternative.

Our paper aims to propose a methodology to make decisions on surplus food management in a structured way, including in the decision-making the three pillars of the triple bottom line (TBL). We believe that having a structured, while reasonably easy-to-use, way to approach

TBL assessment of surplus food management solutions can improve the ability of managers to assess, and then implement, such solutions. Moreover, our results suggest to managers that local redistribution networks are preferable from an environmental perspective, especially when frozen food is at stake.

The results obtained through our methodology can be used by managers for reporting environmental and social impacts of food waste management actions, as well as for internal benchmarking among different business units or plants.

In the food industry, the reference framework is the FWH, but the waste hierarchy is a concept applicable to all industries (Gregson *et al.*, 2013; European Parliament and Council of the European Union, 2008). Therefore, the proposed approach can be applied in the contexts where a set of viable options for waste management is available. In particular, the approach can be applied by any company that produces waste and is in need of comparing different options for waste management, which are defined by existing frameworks, e.g. waste hierarchies or R-strategies.

This paper and the methodology present some limitations. Firstly, the final step devoted to the choice of the business process options, considering the results of the assessment, was performed only qualitatively, comparing the two alternatives to let synergies and trade-offs emerge. We suggest future research devoted to performing the test of this final step in the methodology by developing and using a decision support system for waste management options selection in a company. Secondly, we believe that the options compared are representative of the main differences among the layers of the FWH; however, since we miss, for example, the first layer, i.e. prevention, future research could be devoted to compare prevention with the following ones. Thirdly, we did not consider the rebound effect, which in other studies has been studied in association with donation (Sundin *et al.*, 2023). Future research can be devoted to enlarging the methodology to include this element. Finally, we proposed a methodology which includes the social impact, with a focus on multiple stakeholders. Nevertheless, the specific assessment we were able to perform in the studied company is limited only to employee morale and motivation, which gives a novel but partial view on the social impact.

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Appendix

Table A1. Numerical results of the LCA for the recovery option

Recovery (biogas)	Global warming ($kgCO_2e/FU$)	Eutrophication ($kgPO_4e$)	Photochemical oxidation (kgC_2H_2e/FU)	Acidification (kgSO2e/FU)
Transport + waste distribution	0.42439	0.00033	7.03E–05	0.00135
Waste treatment + avoided products	0.2004	0.0035	2.01E–05	0.0097
Total	0.62479	0.00383	9.04E–05	0.01105

Table A2. Numerical results of the LCA for the donation option

Donation	Global warming ($kgCO_2e/FU$)	Eutrophication ($kgPO_4e$)	Photochemical oxidation (kgC_2H_2e/FU)	Acidification (kgSO2e/FU)
Packaging materials + transport + packaging EoL	0.2478	0.00041	4.27E-05	0.00079
Avoided products	−4.6256	−0.0271	−0.000808	−0.0309
Total	−4.3778	−0.02669	−0.00077	−0.03011

Table A3. Estimated average nutritional value per functional unit (100 kg of mixed vegetables)

Vegetables part of the surplus quantity	Nutritional value (kcal / FU)
Corn	74000
Peas	77000
Carrots	36000
Peppers	26000
Average (vegetables)	*53250*

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