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ENVIRONMENTAL ASSESSMENT OF FOOD LOSS AND WASTE PREVENTION AND REDUCTION SOLUTIONS: NAVIGATING THE COMPLEXITY OF INTEGRATING STAKEHOLDERS' DECISIONS

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Abstract

The objective of this research is to analyze the inherent complexity associated with decision-making concerning food losses and waste prevention or reduction, considering a multi-stakeholder approach and the possibility of contradictory environmental impact results derived from different solutions. This research defines six scenarios with the support of expert knowledge to assess the environmental impact of food loss and waste prevention and reduction (FLWPR) solutions that cover food valorization, redistribution and consumer behavioral change. After applying life cycle assessment consistent with the Environmental Footprint methodology, the results are fine-tuned with three groups of stakeholders' preferences: decision-makers, experts and business students. Although the perceptions of the three groups are different across several impact categories, the proposed aggregated environmental impact indicator reveals minimal changes in the prioritization of scenarios among the three group of stakeholders and shows that it is possible to choose the best option while minimizing environmental impacts from an aggregated perspective. Analyzing the detailed results, the values of the impact categories show contradictory outcomes, i.e. when a specific solution is implemented, some impact categories worsen while others improve.

This requires deciding to what extent and which aspects the decision-makers are willing to sacrifice, as these choices can influence the decision on the best option. This study includes two novelties, the dual perspective, which combines technical information and stakeholder preferences, and the proposal of an assessment method that assigns the environmental load to the quantities of product consumed, instead of assigning it to the total quantity produced through a balancing process.

Keywords

Food losses and waste; Food losses and waste prevention and reduction solution; environmental life cycle assessment; sustainable food system.

Highlights

- Assessing the impacts of FLWPR solutions is crucial for a sustainable food system
- FLWPR decisions require integrating technical data and stakeholder preferences
- Single scores show the best solution but hide fine-grained environmental data

1. Introduction

Countries around the world are promoting and implementing measures to prevent or reduce food waste (Council of the EU, 2020). Waste prevention and reduction interventions have implications for the social, economic and environmental sustainability that go beyond the boundaries of the promotor or the direct beneficiary of such interventions (Zhen et al., 2023). These implications make the decision-making process regarding waste reduction and prevention a complex and challenging task for all the stakeholders involved in the food system. From the environmental point of view, as Skaf et al. (2021) state, food loss and waste (FLW) generation also entail hidden environmental costs and effects. Moreover Osei-Owusu et al. (2023) emphasize that there is an intricate interplay between wealth, food waste, and environmental benefits from efforts to mitigate food loss and waste.

From the stakeholders' theory (Freeman, 1984) perspective, and according to Hörisch et al. (2014) an organization makes better decisions when considering the expectations and needs of its stakeholders to contribute to sustainable development. The identification of these stakeholders' expectations and needs involves implementing a process known as "stakeholder engagement", whose results enable the decision-makers to focus on the matters that are really critical for the achievement of their goals or for influencing stakeholders' decisions (Gerlak et al., 2023). In this sense, the variety of social, economic and environmental needs and expectations that stakeholders can have regarding food production and consumption (Roy et al., 2023), makes it difficult to arrive to the necessary consensus for identifying the best decisions along the food supply chain in terms of sustainability, and balance the political, societal or business answers to such expectations. In this context, what is the best decision for preventing or reducing food losses and waste?

Additionally better decisions are those that prevent and/or reduce FLW, while reinforcing other cross-cutting objectives, as the environmental ones, by promoting a more sustainable food system. From the European context, this implies to be aligned with the European Union environmental strategies (European Green Deal priorities, Farm to Fork Strategy, Bioeconomy strategy, Circular Economy) or at more global level contribute to the Sustainable development Goals. This involves: i) having detailed information about how much food loss and waste is produced, where it comes from, why it occurs, and the environmental burdens for crafting effective strategies to prevent and diminish food waste (Jeswani et al., 2021); and ii) acknowledging the social, environmental, and economic impacts associated with FLW, as well as considering the sustainability implications of the proposed solutions (Muñoz et al., 2024, Domínguez-Aldama et al., 2023).

Considering the complexity of food loss and waste prevention and reduction (FLWPR) decisions, one question arises.
RQ: *To what extent can preventing or reducing food loss and waste be aligned with minimizing the impacts of such decisions, thus contributing to the advancement of a more sustainable food system?*

The objective of this research is to address this question by analyzing the complexity of FLWPR decision-making process, paying special attention to the environmental impacts linked to different FLWPR solutions. This entails considering various environmental issues across the entire value chain and the stakeholder preferences, in addition to the essential requirement of preventing/reducing food waste. This analysis also allows to a deeper exploration of the decision-making process, particularly in pinpointing conflicting outcomes related to the potential increase or decrease of impacts associated with different solutions.

Previous research on FLW focuses on FLW management strategies, rather than on FLW mitigation strategies (Magalhães et al., 2022) and, consequently, on the reduction or prevention of FLW. Among others, Padeyanda et al. (2016), Salemdeeb et al. (2017) and Omolayo et al., (2021) have analyzed the environmental implications of various food loss and waste management strategies. To build on this gap this research focuses on FLW prevention and reduction, not in its management, and the complexity of the decision-making process when considering different stakeholders' preferences. This is critical when FLWPR decisions do not clearly imply improvements in all the environmental impacts categories resulting from such solution.

To address this objective, six simulated scenarios focused on the agri-food sector have been designed, supported by expert knowledge. The initial scenario serves as the baseline (ex-ante scenario), where no action regarding FLWPR is implemented. In contrast, the other five scenarios involve the introduction of five distinct potential solutions aimed at minimizing food waste, considering different strategies defined by the Joint Research Center (JRC) (2019). Environmental life cycle assessment have been used across various scenarios to evaluate changes in different environmental impact categories resulting from the reduction of food loss and waste. Stakeholder preferences have been determined through a series of multi-actor workshops, Delphi process and surveys conducted within the region where simulated scenarios are placed. Ultimately, these preferences have been used to prioritize the different solutions, simulated in a hypothetical decision-making process, where both science-based information regarding the environmental impacts of FLW solutions and multi-stakeholders' preferences have been considered.

The results are useful for all actors belonging to the fresh food value chain (FFVC), who must make some kind of decision to minimize FLW from food production, management, distribution to consumption. Stakeholders' decisions regarding the prevention or reduction of food waste can lead to contradictory outcomes (as per this research scope, in environmental terms) with a variety of roots (Roy et al., 2023). To address this challenge, this paper analyze the importance of integrating stakeholder preferences in a decision-making process based on science information, not only to identify the best solution from the different stakeholders' perspective, but also to provide a deeper knowledge on the environmental impact categories tradeoffs.

2. Theoretical background about decision-making process for sustainability assessment of FLWPR solutions

The identification and characterization of the problem of food loss and waste to be solved by the chosen solution is paramount to determine what is the best decision in terms of FLWPR. Operationalizing the dimensions that make up the problem influences the entire decision-making process (Winch and Maytorena, 2009), since the solution must have an impact on these dimensions. In a sustainable development context, the challenge is to prevent and reduce food loss and waste by making it compatible with a more sustainable food system.

To select the best alternative, is important to consider the potential consequences and impacts of the different solutions (Dong et al., 2018). It begins with the identification of the problem, the setting of the objective and the definition of alternatives; it would be followed by the assessment of the impacts of each alternative, considering the uncertainty of the process. It is not a linear process, but includes feedback and iterations (Dong et al., 2018). To address the FLWPR, various organizations, such as the EU's Joint Research Center (JRC) or the U.S. Environmental Protection Agency (EPA), propose actions structured around a waste hierarchy, which outlines a series of priorities aimed at optimizing the use of natural resources to alleviate the burden on natural ecosystems. Nevertheless, as Redlingshöfer et al., (2020) have pointed out, the existence of these hierarchies are not without controversy and criticism, considering that "*waste hierarchies applied to food remain a theoretical notion rather than a guideline applied in real-world situations*".

The complexity inherent in this process increases when considering the wide range of impacts that such a decision may have, in addition to the amount of food waste avoided or reduced. The estimation of these impacts increases the decision-makers' capacity of making more informed-based decisions but, in parallel, makes the analysis of this diverse (and sometimes contradictory) information more complex and time and resource consuming. These conditions enable the application of complexity theory to the analysis of FLWPR decisions. Complexity theory has been previously linked to food waste research, especially from the consumers perspective (Scarpi et al., 2021; Alsuwaidi et al., 2022).

This paper applies complexity theory to the decision-making process regarding FLWPR decisions following Najjar and Yasin (2023) approach. These authors adopt a social systems theory that highlights the complexity associated to the internal and intra (collective) complexity relationships among the actors (and variables) belonging to the system. In the context of this study, the internal complexity can be attributed to the analysis of the environmental impacts of the FLWPR solutions, under a life cycle thinking approach and the collective complexity should be associated with the process of comparing two (or more) potential FLWPR solutions, where stakeholders' preferences are also integrated.

According to Dyllick and Muff's (2016) 'input-process-output' model, the challenges around addressing the complexity of making multistakeholder decisions on FLWPR from an environmental sustainability perspective can be summarized as follows:

(i) 'Inputs': What is assessed?

There is not a commonly accepted frame of indicators for measuring environmental impacts; however, there are relevant international references (Domingo-Morcillo et al., 2024). From the environmental dimension, the Environmental Footprint defines sixteen specific categories of environmental impacts at the organizational and product level which includes resource use or emissions of environmentally damaging substances that may affect human health (European

Commission, 2013) —consistent with the SDGs and Planetary Boundaries, Muñoz et al., 2017). Previous studies focused on specific impacts as global warming potential of food waste (Amicarelli et al., 2021; Oldfield et al., 2016; Parsa et al., 2023); acidification (Oldfield et al., 2016); eutrophication (Oldfield et al., 2016) or energy (Parsa et al., 2023), among others. However, it should be noted that current research focuses on the environmental impacts of potential solutions for preventing or reducing FLW, going beyond the impacts of food waste itself. Moreover, prevention strategies are often under-represented in food waste research (Redlingshöfer et al. 2020), which primarily focuses on managing existing food waste.

(ii) 'Process': How the environmental sustainability indicators are quantified and hierarchized? There is no consensus about how the sustainability performance should be quantified along the supply chain (Garrido Acevedo et al., 2017, Rajesh, 2019). Nonetheless, Life Cycle Assessment and Footprints methodologies have been applied to face this challenge. In this regard, the above-mentioned Environmental Footprint is one of the most robust methodologies for assessing the environmental impacts (Testa et al., 2017, Muñoz-Torres et al., 2022) in terms of life cycle thinking. Consistent with this method, related databases and software have emerged to give support to the technical quantification of the impacts. For instance, SimaPro (https://pre-sustainability.com/) is a software tool to carry out LCA jointly with the data provided by Ecoinvent which can be used to assess the environmental impacts following different methods, like EF3.1.

In this context, Edwards et al. (2018) compare the environmental impact of seven food waste management systems using Life Cycle Assessment (LCA). Lin et al. (2002) comprehensively analyze the relative impacts of various environmental factors, such as climate change, acidification, and eutrophication, on different food waste valorization technologies, employing LCA as an analytical tool and optimization modeling within an integrated assessment model. Damiani et al. (2021) utilize LCA to evaluate strategies for managing food waste, focusing on their potential environmental effects. Their aim is to highlight the critical factors for developing locally impactful policies for food waste recovery, particularly through food donations. Liu et al. (2022) also apply a life cycle perspective in their assessment of the environmental impacts of food waste treatment, using the ReCiPe 2016 V1.1 Midpoint model (H) and considering 15 environmental impact categories related to energy and resource consumption, environmental burden, and human toxicity.

(iii) 'Output': What is the purpose of measuring environmental sustainability impacts?
Waste hierarchies as guidance for making decisions by different market actors are gaining momentum. At the top of the hierarchies, the prevention actions are positioned, presenting the greater environmental benefit. However, as Redlingshöfer et al. (2020) remarks, the mere existence of food waste hierarchies does not guarantee their effectiveness and high performance in environmental terms. The authors emphasize how waste hierarchies play a significant role in reducing greenhouse gas emissions effectively; however, in other impact categories such as human toxicity, acidification, ecotoxicity, or eutrophication, the food waste hierarchy seems not to be effectively supported.

Specific research remarks different limitations in current sustainability assessment within the food system. On the one hand, most current assessments are static without representing system feedback (Hadjikakou et al., 2019). Other limitation relates to the multi-dimensionality of the sustainability assessment of global food systems (Hoehn et al., 2021) and the necessity to include other contextual and sociocultural factors (Chaudhary et al., 2018). Finally, Life Cycle Assessment methodology alone can present some limitations to determine the best alternative in terms of sustainability, since it does not consider other relevant issues related to the preferences of the decision-makers or stakeholders when, for instance, LCA show contradictory results among the different environmental impact categories when comparing two or more FLWPR solutions.

At the same time, the relevance of introducing science-based information, despite its limitations, should be considered in the FLWPR solutions assessment. As Read and Muth (2021) point out, reducing food waste is often portrayed as beneficial for the environment, consumers, and businesses, but it's more complex. Some stakeholders, like producers and retailers, may resist waste reduction to maintain demand. Additionally, long-term benefits like food security and improved reputation for businesses are hard to measure. While reducing waste benefits society, it may harm some stakeholders. Government intervention is needed to promote waste reduction initiatives while considering potential negative impacts on certain collectives or individuals.

Consequently, the information provided by the assessment should give support to the decision-making process of the different stakeholders, considering not only their individually analyzed preferences, but also the global sustainability challenges that are technically relevant (Barbosa-Póvoa et al., 2018; Muñoz et al., 2021; Domingo-Morcillo et al., 2024).

4. Materials and methods

This section describes the methodological part of the study to define the five simulated FLWPR solutions, to assess the environmental impacts of them, to aggregate the information and knowledge and to compare the main findings. Given the complexity of the problem analyzed and the broad scope from which it has been addressed, this study has followed a group model building (GMB) approach which holds great potential for problem conceptualization, model development, model testing and for extracting information and knowledge among experts and community decision makers (Parsa et al., 2023). This approach has been applied in conjunction with a Life Cycle Assessment, to assess the environmental impacts of the proposed FLWPR solutions, and the results of the environmental impacts have been adjusted by the stakeholder preferences to know to what extent the aggregated results obtained from different stakeholder groups are consistent. Figure 1 summarizes the methodological framework applied in the empirical part.

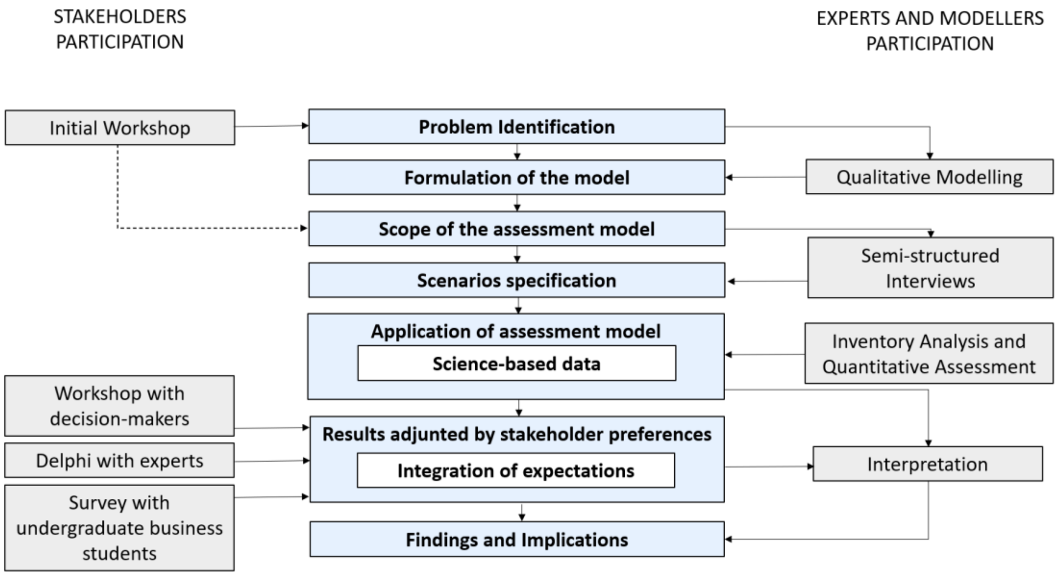


Figure 1. Methodological framework

4.1 Group Model Building Approach

This study adopts a GMB approach with the aim of integrating stakeholders' and experts' opinions in different phases of methodology. This subsection summarizes the GMB stages (for a detailed description see Appendix 1 in Supplementary Materials).

4.1.1. Problem Identification

Regarding the first stage 'Problem identification', a workshop was held on November 2022 with 31 stakeholders belonging to three groups of decision-makers: policymakers, consumers and food supply chain actors, as well as academics and sectoral experts and technicians. Regarding the methods applied to gather the opinions of the stakeholders, a brainstorming session was conducted initially, followed by a voting process to prioritize the causes and problems initially identified. The workshop outcomes led to identifying different gaps in the decision-making process (for a detailed description of the development and results of the workshops, see Appendix 1 in Supplementary Materials). The results of the workshop highlighted the insufficient information about the environmental impacts resulting from FLWPR solutions. Additionally, the workshop also prompted discussion of potential strategies to mitigate food loss and waste which were considered in the development of the underlying model for the empirical analysis.

4.1.2. Formulation of the model

In the next phase, this study defined a model to assess the environmental impacts associated with a FLWPR solution adoption that is displayed in Figure 2. When a FLWPR solution is put into practice, two opposite effects emerge: (i) implementing FLWPR requires resources, which can increase environmental impacts, and (ii) the reduction in food loss and waste leads to decreased environmental impacts. To make informed decisions, it is crucial to assess whether the net impact of implementing FLWPR is greater or less than the ex-ante situation. This causal diagram can still be more complex if other complementary FLWPR solutions are jointly implemented. In addition, the environmental impacts are measured using the Environmental Footprint (EF) 3.1 method (Commission Recommendation (EU) 2021/2279) which considers the impacts of 16 science-based categories. Accordingly, the intensity of the impact of the FLWPR solution implementation could be different in each impact category.

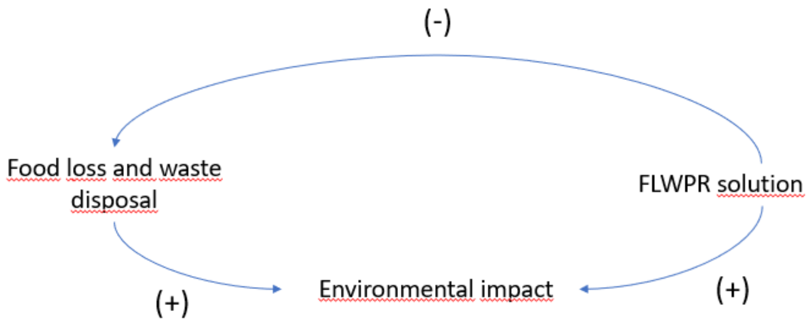


Figure 2. Causal diagram of environmental impacts of FLWPR solution

4.1.3. Scope of the assessment model and scenarios specification

This study defines 6 fictitious scenarios based on the result of the first workshop with decision-makers complemented with expert knowledge during the first workshop, decision-makers presented and discussed FLWPR solutions they were implementing, or planned to implement, that were closely related to the Joint Research Center (JRC) strategies on food valorization, redistribution or consumer behavior change. The results of the workshop helped to define the scope and objective of the simulated FLWPR solutions. The assumptions of the simulated scenarios were stablished based on semi-structured interviews with four experts: an expert on citrus fruit warehouse production management, a project manager for innovation with experience in providing FLWPR solutions in the citrus fruit sector; a head manager of R&D&I in the distribution sector; and a communication expert with experience in the field of training and raising awareness on sustainability (see Appendix 1 in Supplementary Materials).

The scenarios have been configured based on potential FLWPR solutions that have been applied in the citrus fruit industry. The citrus fruit industry has been selected for two main reasons. First, the citrus fruit industry has a high contribution to the agri-food sector which produced 144 million tons worldwide in 2019 (FAO, 2020), which represents one of the most consumable fresh fruits (Yadav et al., 2022). Second, there is a lack of studies in the citrus fruit industry that assess and address different food waste solutions from cradle to grave perspective to contribute to more sustainable food systems (Muñoz et al., 2022).

Figure 3 shows the configuration of the six scenarios. The first scenario is the base scenario, in which no FLWPR solution takes place. In the other five scenarios, we introduce potential solutions to reduce food loss and waste addressing three JRC different strategies: Food valorization, redistribution of food for human consumption and consumers' behavioral change.

Scenario 0 (Ex-ante scenario): No FLWPR solution *taking place*

In Europe, Spain is the main producer, which provides more than 50% of the European production (FAO, 2020), and in Spain, the Valencia Region is the main producing area (Santiago et al., 2020). In this respect, this study simulates that 1 kg of fresh orange has been produced in Castellón (Spain) where has been carried out all the typical activities of the orchard such as soil cultivation, irrigation, fertilizer and pesticide application and harvesting. Note that during this phase, this study assumes that no losses have been produced since, according to the FAO (2019), the food loss is understood as "any food that is discarded, incinerated or otherwise disposed of along the food supply chain which starts with harvest (…)". Usually, the post-harvest center is located close to the citrus production since the transport between these two points has not been considered. In the post-harvest center, the oranges pass a set of processes to be sure that the fruit is in the right condition, and they reorganize the oranges according to the different client's requirements. In this case, this study, as one of the most common ways to deliver fruit, we assume that the orange is put on the market with a mesh. At this point, it is estimated that the processes generate 5% of losses due to discards for not complying with the market standards. After this phase, the oranges are distributed to Madrid, which is one of the main national markets. As point of sale, we have used a hypermarket with high presence in Spain. In the retail phase, based on the average values of the EU Commission information (Di Leo et al., 2020) adjusted by sectorial experts, this study has estimated that the food waste generated corresponds to 3% of the total production. Finally, the consumption phase has been in Madrid. According to the figures of waste from the household, food services and institutions (*Ministerio de Agricultura, Pesca y Alimentación*, 2022a, 2022b, 2022c; FEPEX, n.d.), the percentage of waste is about 12%.

Scenario 1: Food Valorization – Value added processing - orange juice and jam

This scenario introduces two food valorization strategies based on the evidence provided by an agri-food cooperative and by a hypermarket chain. In particular, in the post-harvest phase, 3% of the production (classified as losses in the scenario 0), which is not marketed due to aesthetic reasons such as size or imperfect fruit, is sent for juicing to a factory located 85 km away from the storage facility. For juice production, a cardboard packaging option is considered. In the distribution phase, it is estimated that around 10% of fresh oranges are ripe oranges that maintain their quality, which are sent to a jam factory located 75 km from the distribution point. For jam production, glass jars are considered.

Scenario 2: Food Valorization – Value added processing - orange juice

This scenario is based on scenario 1. The only difference is the production of orange juice with the ripe orange of the hypermarket, instead of producing jam.

*Scenario 3: Redistribution of food for human consump*tion - Surplus food redistribution

In scenario 3, a surplus of 3%, which is accounted for during the post-harvest phase, and 10%, generated during distribution, are donated to a food bank located in Madrid.

Scenario 4: Consumers behavior change - Awareness/educational campaign

In scenario 4, a communication campaign is launched aimed at raising awareness among consumers about food waste, particularly focusing on imperfect citrus fruit that may be rejected during the commercialization for aesthetic and size reasons. The campaign uses social media platforms and waste bins as dissemination channels. Analyzing the food waste reduction rates from various real-world awareness campaigns shared during the Meeting of Consumer Food Waste Prevention Food Group promoted by the EU DG SANTE on 24th October 2024, the result of reductions reveals significant variability. In fact, in a specific campaign, users reduced their food waste by up to 28%[1]. However, this result differs from the one reported by Read and Muth (2021) who applied a ratio of 2.2%. These discrepancies could be due to the success of awareness and educational campaigns are highly context-dependent and may vary depending on the type of campaign, target audience, product type, among others. Moreover, the estimation will be different depending on the time period considered.

This study focuses on the food waste of the "orange" product produced in the surrounding area of the city targeted by the awareness campaign, with a population familiar with the product and an economy dependent on it. Given these contextual factors, this study has estimated an intermediate reduction rate, assuming that the campaign achieves the target of reducing 3% of losses and 10% of waste. The resources estimated to develop and implement the communication campaign are the following: 2 hours of video conferencing, 6 hours of computer operation and 0,7 kg of photographic paper per waste bins (estimating a scope of 100 waste

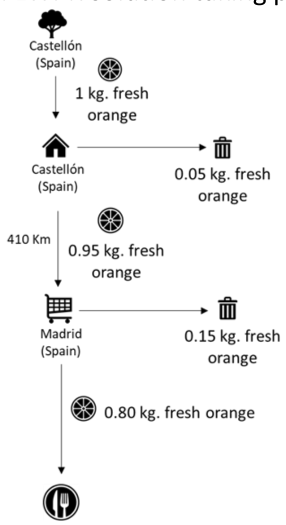
[1] For more information see: https://food.ec.europa.eu/food-safety/food-waste/eu-actions-against-food-waste/eu-platform-food-losses-and-food-waste/thematic-sub-groups/consumer-food-waste-prevention_en

bins given the target population according to National Urban Waste Plan, 2000). In this case, it is estimated a target population of 50.000 inhabitants, with a success rate of 30% which is validated by a communication expert (see Appendix 1 in Supplementary Materials). Based on the kg of oranges consumed per inhabitant (15,44 kg), we have estimated the production of oranges associated to the consumption of 15.000 inhabitants and the losses and waste saved in kg (37635kg) due to the awareness campaign.

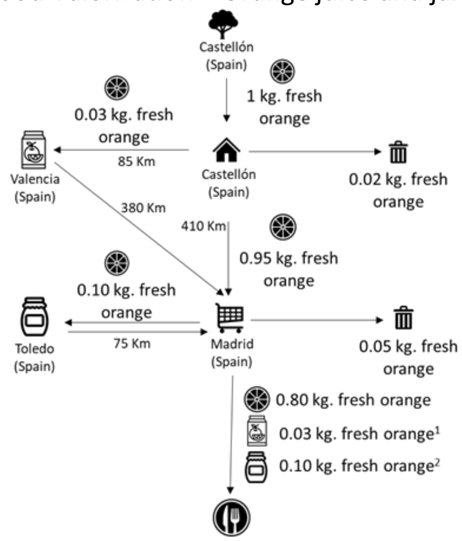
Scenario 5: Mix of FLWPR solutions – Food valorization, redistribution and consumers behavior change.

This scenario represents a mix of the previous ones, assuming that 3% of the losses generated in the post-harvest phase is sent for juicing, 5% of the distribution phase is donated to a food bank and 5% is prevented due to the awareness campaign.

Scenario 0
No FLWPR solution taking place

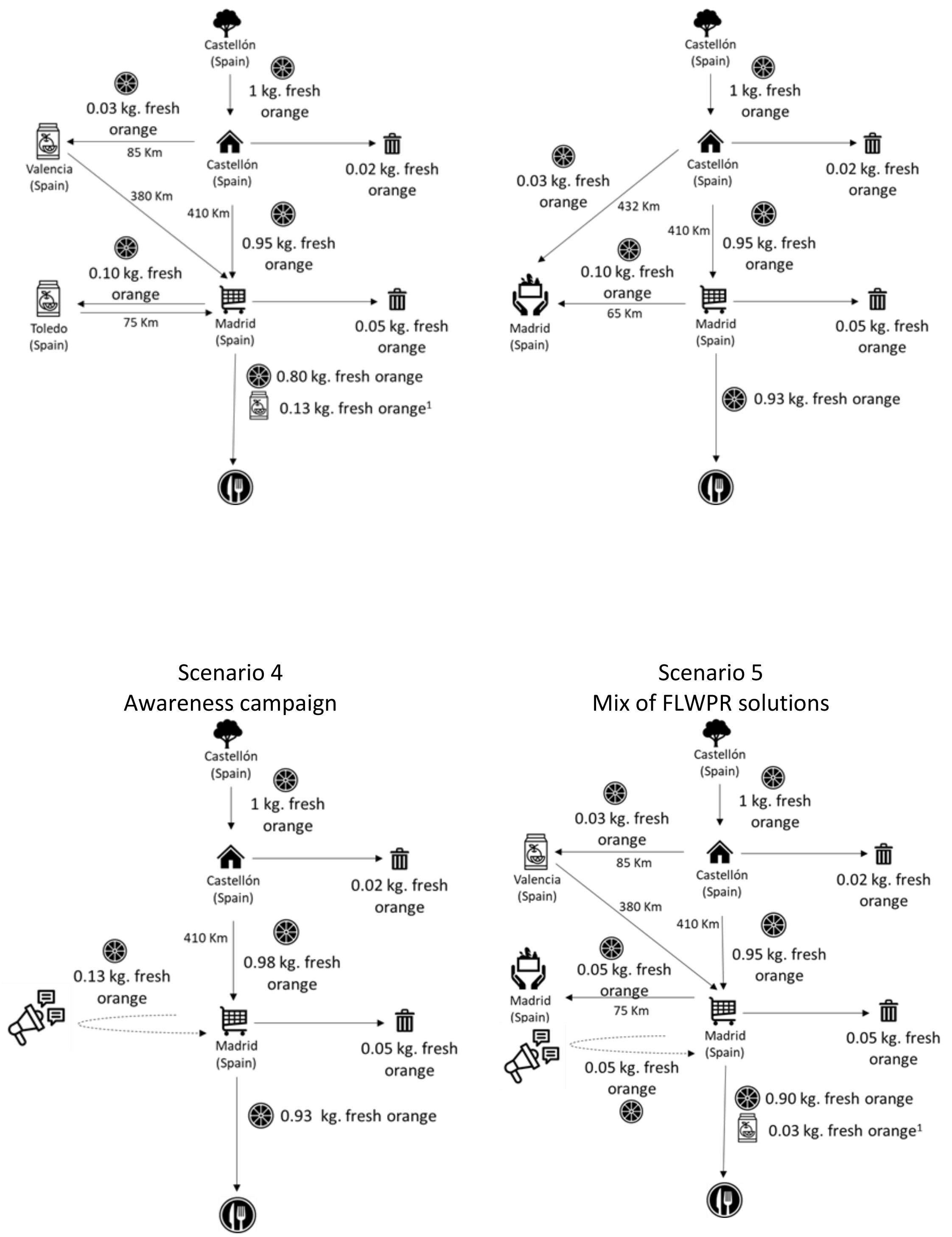


Scenario 1
Food Valorization – Orange juice and jam



Scenario 2
Food Valorization – Orange juice

Scenario 3
Surplus food redistribution



Note: [1] From 1 kg of fresh orange the average yield is to get 0.43 l. of orange juice; [2] from 1 kg of fresh orange the average yield is to make 3.4 kg of orange jam.

Legend:

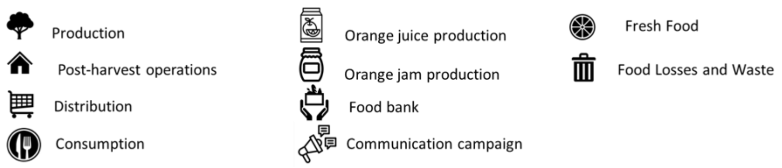


Figure 3. Characterization of Scenarios

4.1.4. Assessment of Environmental Impacts according to Life Cycle Analysis

To apply a life-cycle approach in the environmental impact assessment, this study adopts the phases of the standard ISO 14040/44. The goal of this life cycle analysis (LCA) is to conduct a comparative assessment of FLWPR solutions according to the different scenarios previously defined (Figure 3 illustrates the system boundaries of the assessment) and to provide comparable scientific data on which we can integrate stakeholder preferences. In all scenarios, the declared unit is 1 kg of fresh orange. In the citrus fruit industry, orange represents around 50-60% of total citrus production (Yadav et al., 2022), which is the most consumed citrus fruit. To consider FLW generated in the impact assessment, this study considers that the impacts generated correspond to the net production of 1 kg, therefore, the impacts are divided by 1 minus the waste or loss rate.

Regarding the life cycle inventory, the related datasets have been extracted from the Ecoinvent v3.8 database through the SimaPro license. The life cycle impact assessment is carried out with the EF 3.1 Method, which is consistent with the Commission Recommendation (EU) 2021/2279 on the use of methods to measure the life cycle environmental performance of products. In this respect, Domingo-Morcillo et al., (2024) concluded that the method promoted by the EU is the most suitable one, since it enables the calculation of a single score for environmental impacts and estimate these impacts by 16 science-based categories. This level of detail is adequate for identifying critical points and proposing corrective actions.

According to this method, this study has calculated the 16 weighted impact categories software since the results between categories are comparable and they have been added together to obtain the EF 3.1 single overall score. Note that the weighted impact categories results are based on the data of characterized impact categories, each one with its own unit, then they are normalized by dividing the results by the overall inventory of a reference unit and weighted by multiplying each category by a factor provided by JRC (Sala et al., 2018) that reflects its relative importance (Andreasi Bassi et al., 2023). The assessment has been carried out using the SimaPro 9.4.0.3 The last phase of the analysis, the life cycle interpretation, is presented in the section of results and discussion.

4.1.5. Results Adjusted by Stakeholders Preferences

This phase starts with the weighted results from EF3.1, which are then adjusted by multiplying them with stakeholder preferences and summing the result of each impact category to obtain an aggregated score. These preferences reflect the relative importance given to each impact category within the context of decision-making for FLWPR. The stakeholders' preferences were collected through a parallel process to the EF3.1 results, ensuring it remains independent of the specific issue and scenario evaluated. figure displays the results of the preferences of each group of stakeholders.

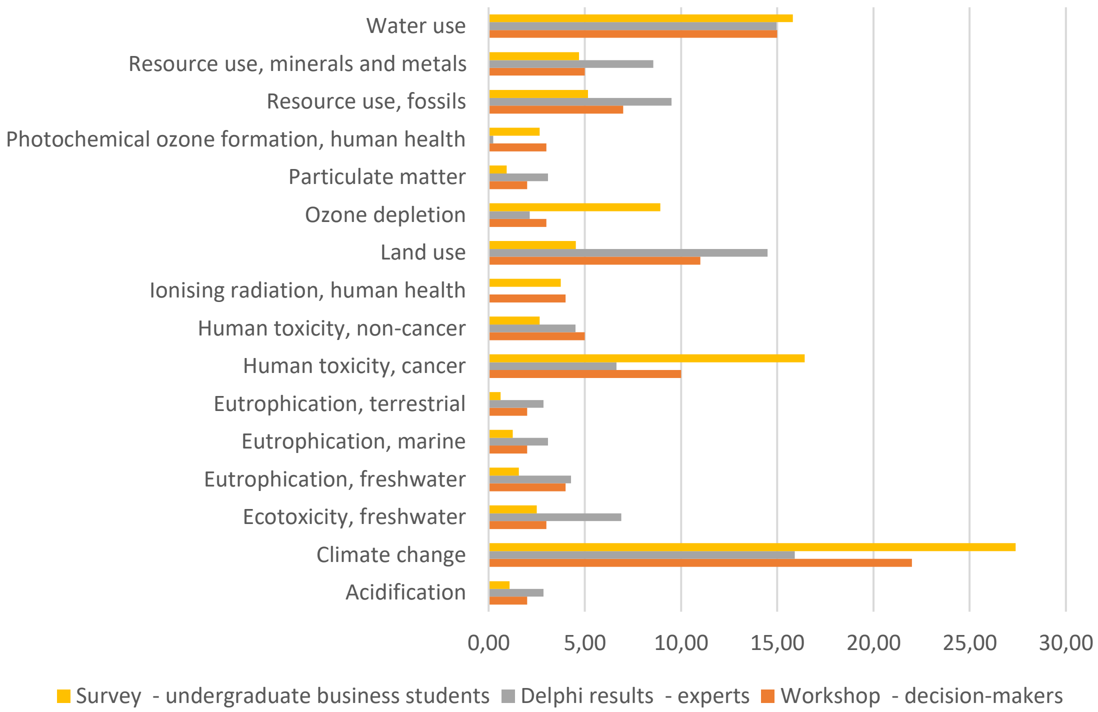


Figure 4. Relevance of environmental impact categories for the three groups of stakeholders

The decision-makers' preferences were extracted during a workshop attended by 30 participants, representing different market actors: supply chain actors, consumers and policymakers at local and regional level. During this workshop, discussions centered on how the sustainability of solutions could be measured to make good decisions in the FLWPR context. Focusing on the environmental dimension, the participants had to allocate 100 points to the 16 impact categories of the EF according to the relevance to make good decisions on FLWPR solutions.

The preferences of the experts were obtained through a Delphi process using a questionnaire with the aim of identifying potential assessment criteria for FLWPR solutions. A set of questions were developed and agreed upon during November and December of 2022. Questions were tested in an internal process and during a technical workshop in February 2023. A multilingual questionnaire was provided in German, English, Spanish, Greek, and Swedish to reach a broad number of experts. In total 77 experts sent the questionnaire (for more information about the profile of the experts see Appendix 1 in Supplementary Materials). Regarding the environmental question, the experts had to choose the most important environmental impact categories for evaluating FLWPR solutions.

Additionally, the preferences of undergraduate business students, as future members of corporate management teams, were also considered. Data collection took place during the welcome event for the 2024/2025 academic year, targeting first-year business administration related students at a Spanish higher education institution. The event focused on food waste and sustainability. At the conclusion of the event, students were asked to select the most important environmental impact categories for decision-making in a food waste prevention and reduction context via an online questionnaire. A total of 222 responses were received.

5. Results and discussion

The results of this study focus on environmental impact assessment of FLWPR solutions as a relevant input for decision-making processes to select the best alternative covering lack of information currently detected by decision-makers. This section shows the results of the environmental impact assessment of the different scenarios (see Table 1 and 2), jointly with the complexity and the different challenges a decision-maker may encounter when choosing the best alternative.

Exploring the results of environmental impacts at aggregate level, the single overall score, which represents the sum of the weighted EF 3.1 results of all environmental impact categories, shows that the scenarios that minimize the environmental impact correspond to the surplus food redistribution (Scenario 3) and the awareness campaign (Scenario 4) respectively by a slight difference. The least desirable scenario refers to the FWLPR solutions where loss and waste are reduced through the technological solution of producing juice and jam. Note that this situation, in environmental terms, is even worse than taking no action (Scenario 0). This finding is explained by the energy-intensive production process required for jam production which is not sufficiently offset by the environmental impact associated to loss and waste reduction. Note that in Scenario 2, i.e. when the jam production is not considered, the environmental impact is reduced substantially, improving the ex-ante situation. This finding is consistent with the result obtained by Domingo-Morcillo et al. (2024) in the evaluation of two solutions, dehydrated tomato soup and tomato juice, to reduce the potential fresh tomato waste. This insight does not support using food waste hierarchy as a tool for prioritizing reduction strategies from an environmental perspective, which is consistent with Redlingshöfer et al. (2020). On the other hand, the result of the mix of FLWPR solutions (Scenario 5) falls outside the range of results of the constituent FLWPR solutions. In fact, Scenario 5, which integrates the FLWPR solutions of Scenario 2, 3 and 4, generates higher impact than Scenario 2, which is the worst case of the three scenarios. The explanation of this insight is due to the combination of FLWPR solutions could have effects that may be either synergistic or antagonistic. Therefore, in this context, it is crucial for decision-makers to understand the mixed scenario considering the potential interactions between the integrated FLWPR solutions.

Focusing on the aggregate results adjusted for stakeholder preferences, there is a consensus in the ranking regardless of the group considered (decision-makers, experts or undergraduate business students). The results are consistent with the previous discussion since the best FLWPR solutions are those presented in Scenario 4 and Scenario 3. However, considering the preferences of stakeholders, the minimum score is obtained in the awareness campaign instead of the surplus food redistribution by a narrow margin. This is due to the decision-makers have given greater importance to categories that had a lesser impact than Scenario 3, like Climate Change.

This finding indicates that when stakeholders weigh different impact categories, they tend to account for a broad range of them, leading to a final ranking that shows minimal variation despite the assigned weightings. However, this ranking shifts significantly when the analysis focuses on a single impact category, such as water. In this case, prioritizing water as a critical impact category makes the food valorization with jam (scenario 1) preferable to taking no action (scenario 0). These differences highlight how the ranking can vary depending on whether the assessment aggregates multiple impact categories or simplifies the analysis to focus on just one.

This study goes in-depth in the analysis of results, disaggregating the results by impact category. Table 1 shows the relevance of the environmental categories according to a life cycle impact assessment. On the one hand, it is noteworthy the significant importance of the “water use” category across all scenarios, as it is the category that generates the greatest environmental impact. This result can be explained by the importance of water in the Spanish agrifood sector, Muñoz et al. (2022), which also analyzed the life cycle of oranges produced in Spain, also reached this conclusion. On the other hand, other notable impacts include climate change, acidification, and particulate matter, although their order of relevance varies depending on the scenario. The differences in relevance are higher in the categories of “Resource use, fossils” and “Ecotoxicity, fresh water”, with their importance fluctuating between the 3rd or 4th and 8th positions depending on the scenario. These discrepancies are explained by the different nature of resources required for the implementation of each FLWPR solution.

Despite this discrepancy, in general terms, the relevance of these impacts contrast with the preferences of the stakeholders. For them, the categories “Human Toxicity, Cancer” and “Land Use” have considerable influence in the decision-making process in this context. However, both categories have relatively minor impacts, accounting for less than 1% and 2% respectively, across all scenarios. Consequently, this result raises new research questions about how the stakeholders establish their preferences: do stakeholders place more importance on those categories that are familiar with due to their experiences? For instance, water usage in regions where water scarcity is a critical issue, or those with greater institutional prominence, such as climate change in the EU? Would their priorities shift if they were aware of the results based on a scientific approach, such as a detailed life cycle assessment? For example, if stakeholders were provided with the results of the environmental footprint impact categories prior to establishing their weightings, perhaps, their decision-making process would be influenced by the observed outcomes. Table 2 shows the reduction (in green) or increase (in red) in impact for each scenario compared to the baseline scenario. In this context, all the scenarios of this study that involve the implementation of FLWPR solutions result in conflicting outcomes between impact categories. Further exploration reveals that, expect for Scenario 2 (which performs worse results across all categories except “Water Use”), all scenarios contribute to mitigating climate change, Eutrophication- terrestrial, Human toxicity - non-cancer, Land use, Particulate matter, Photochemical ozone formation, Resource use – fossils, Resource use - minerals and metals and Water use, at the expense of worsening other categories, in particular: Acidification, Ecotoxicity-freshwater, Eutrophication-freshwater, Eutrophication-marine, Human toxicity – cancer, Ionizing radiation, and Ozone depletion. In this context, it is essential to consider both the stakeholders’ criteria and the scientific data to evaluate the significance of changes and tolerance levels between and within each impact category. This approach will ensure a rational decision-making process and will contribute to determine how much can be sacrificed in each impact category to achieve a better overall outcome.

Table 1. Environmental impact assessment and preference order of FLWPR solutions

	Scenario 0: (Ex-ante scenario) No FLWPR solution taking place	Scenario 1: Food Valorization – Orange juice and jam	Scenario 2: Food Valorization – Orange juice	Scenario 3: Surplus food redistribution	Scenario 4: Awareness campaign	Scenario 5: Mix of FLWPR solutions
Loss, Waste and Consumption Rate						
Loss (%)	0,05	0,02	0,02	0,02	0,02	0,02
Waste (%)	0,15	0,05	0,05	0,05	0,05	0,05
Total Consumption (%)	0,80	0,93	0,93	0,93	0,93	0,93
Environmental Impact Category (EF 3.1 Method)						
Acidification	4,67	10,92	7,06	6,92	6,91	7,06
Climate change	9,10	16,99	7,47	6,67	6,61	7,00
Ecotoxicity, freshwater	3,17	4,76	3,67	3,54	3,54	3,65
Eutrophication, freshwater	1,11	4,50	1,53	1,43	1,41	1,47
Eutrophication, marine	1,50	2,86	1,62	1,55	1,55	1,60
Eutrophication, terrestrial	3,54	5,26	3,29	3,19	3,19	3,31
Human toxicity, cancer	0,48	1,15	0,58	0,57	0,57	0,58
Human toxicity, non-cancer	3,61	3,80	3,15	3,12	3,12	3,22
Ionizing radiation	0,30	0,82	0,35	0,31	0,33	0,33
Land use	2,25	2,59	2,02	1,99	1,99	2,06
Ozone depletion	0,06	0,17	0,11	0,11	0,11	0,11
Particulate matter	4,81	8,70	3,41	3,22	3,22	3,36
Photochemical ozone formation	1,51	2,58	1,17	1,10	1,09	1,15
Resource use, fossils	4,97	8,77	2,67	2,34	2,33	2,50
Resource use, minerals and metals	2,69	5,14	1,85	1,77	1,82	1,86
Water use	72,98	68,56	62,81	62,77	62,79	64,68
Single overall score (preference order)	116,74 (5)	147,58 (6)	102,77 (3)	100,59 (1)	100,60 (2)	103,95 (4)
Note: the above values are expressed in μPt						
Environmental Impact Aggregated Scores adjusted by stakeholder preferences						
Aggregated score with decision-maker preferences (preference order)	1439,52 (5)	1647,57 (6)	1231,26 (3)	1207,62 (2)	1206,90 (1)	1248,16 (4)
Aggregated score with experts' preferences (preference order)	1429,09 (5)	1620,80 (6)	1224,65 (3)	1204,01 (2)	1203,73 (1)	1243,98 (4)
Aggregated score with undergraduate business students' preferences (preference order)	1497,70 (5)	1716,59 (6)	1278,84,26 (3)	1252,56 (2)	1251,57 (1)	1294,88 (4)

Note: environmental impacts defined in

Legend: Color means the position	
	1
	2
	3
	4
	5

Table 2. Avoided impacts derived from the FLWPR solutions

	Scenario 1: Food Valorization – Orange juice and jam	Scenario 2: Food Valorization – Orange juice	Scenario 3: Surplus food redistribution	Scenario 4: Awareness campaign	Scenario 5: Mix of FLWPR solutions
Loss, Waste and Consumption Rate					
Loss (%)	0,02	0,02	0,02	0,02	0,02
Waste (%)	0,05	0,05	0,05	0,05	0,05
Total Consumption (%)	0,93	0,93	0,93	0,93	0,93
Environmental Impact Category (EF 3.1 Method)					
Acidification	-6,26	-2,40	-2,25	-2,25	-2,40
Climate change	-7,89	1,63	2,43	2,48	2,09
Ecotoxicity, freshwater	-1,59	-0,50	-0,37	-0,37	-0,48
Eutrophication, freshwater	-3,39	-0,42	-0,32	-0,30	-0,36
Eutrophication, marine	-1,36	-0,13	-0,05	-0,05	-0,11
Eutrophication, terrestrial	-1,72	0,25	0,35	0,35	0,24
Human toxicity, cancer	-0,67	-0,10	-0,09	-0,08	-0,10
Human toxicity, non-cancer	-0,19	0,46	0,49	0,49	0,39
Ionizing radiation	-0,52	-0,05	-0,01	-0,04	-0,04
Land use	-0,34	0,23	0,25	0,25	0,19
Ozone depletion	-0,11	-0,06	-0,05	-0,05	-0,06
Particulate matter	-3,89	1,40	1,59	1,59	1,45
Photochemical ozone formation	-1,08	0,33	0,41	0,41	0,36
Resource use, fossils	-3,80	2,30	2,63	2,64	2,47
Resource use, minerals and metals	-2,45	0,84	0,92	0,87	0,83
Water use	4,41	10,17	10,21	10,19	8,30
EF 3.1 Single overall score	-30,84	13,97	16,15	16,14	12,79
Environmental Impact Aggregated Scores adjusted by stakeholder preferences					
Aggregated score with decision-maker preferences	-208,06	208,26	231,89	232,61	191,36
Aggregated score with experts' preferences	-191,72	204,44	225,08	225,36	185,11

Aggregated score with undergraduate business students' preferences	-218,89	218,86	245,13	246,12	202,81

Data shows the differences between environmental impacts derived from scenario 0 and scenario 1/2/3/4/5

6. Conclusions

The decision-making process for food loss and waste reduction involves subjective and contextual factors, including individual expectations and awareness of global issues. Additionally, the repercussions of such decisions transcend individual spheres, thereby rendering decision-making processes not solely is a matter of private preferences but rather an issue of individual accountability with collective ramifications. In this context, an objective framework supported by science-based tools is necessary to make informed decisions which not only focused on the objective of reduction/prevention food loss and waste but also contribute to the sustainability of the entire food system.

Being aware of this complexity, this research has focused on the environmental dimension of this issue. The advanced level of empirical and technical knowledge generated around science-based tools for measuring environmental impacts allows for a robust approach to measuring and analyzing the previously mentioned decision-making complexity. The proposed research question asks to what extent the prevention or reduction of food loss and waste can be aligning with minimizing the impacts arising from such decisions, thereby contributing to the advancement of a more sustainable food system. What have been the results obtained in this regard? Based on the aggregated scores, the answer is that it is feasible, although it involves accepting some compensation of improved categories with worsen ones. However, by deepening in the results of the impact categories and comparing them with the ex-ante situation, it is possible to identify areas for improvement to continue moving towards minimizing the environmental impact of the FLWPR solution. Moreover, making decisions implies also ranking the potential alternatives and prioritizing the best one. But, as this research has evidenced, such prioritization among different alternatives (scenarios) for the prevention/reduction of FLW can vary depending on the decision parameters considered (for instance: aggregated score vs. individual impact category). Specifically, this paper delves into the reflection around the implications of considering only science-based information, or to consider this science-based information as input, jointly with other individual and contextual factors inherent to the stakeholders.

6.1 Implications

Based on the aggregated scores, the best options for minimizing environmental impact are the awareness campaign (Scenario 4) and the redistribution of surplus food (Scenario 3). The worst option involves FWLPR solutions where food loss and waste are reduced by making juice and jam using technological approaches. Interestingly, this approach has a greater environmental impact than doing nothing (Scenario 0). This highlights that the environmental sustainability of solutions depends more on the characteristics of those solutions than on their nature. Therefore, the hierarchy of food waste solutions provided by the EU does not necessarily align with the hierarchy resulting from applying methods to assess the environmental impacts of those solutions.

A sustainability assessment framework for the identification of the best FLWPR solution requires the integration of science-based evidence, expert knowledge and stakeholders' expectations and needs. These three perspectives are addressed in the practical methodology presented in this study, which attempts to introduce rationality into decision-making processes, identifying the food waste solution that generates the least environmental impact. Other novelties of the assessment method used in this study is that it assigns environmental burdens to the product quantities consumed instead of assigning it to the total amount produced. This provides a more realistic view of the impact by considering the inefficiencies caused by waste on sustainability.

The paper analyzes the impacts from a double perspective, the technical one and introducing the stakeholder perspective from three different groups: decision-makers, experts and business students. Despite that each group showed differences in environmental concerns, after adjusting the scientific assessments for their preferences, the results were consistent regardless of the group. This approach can aid decision-makers of various types, by helping to answer data-driven questions such as: What FLWPR solutions can I implement, support or promote? How can I measure the impact of my FLWPR interventions? How can I collaborate with other stakeholders to minimize the environmental impact? How can I improve the FLWPR solution in environmental terms?

6.2 Limitations and future studies

The primary limitation of this study is its focus on the environmental dimension. Future research can contribute to this discussion by incorporating economic and social dimensions into the complex decision-making process to determine the best FLWPR solution. Another limitation is the simplification of the proposed scenarios. Although these scenarios were designed in collaboration with experts and practitioners, they involve a considerable number of assumptions about the raw data. In this regard, this study highlights a limitation in establishing the food waste reduction rates for the awareness campaign, which have been estimated considering a short-term time horizon. This rate would likely be significantly lower if additional factors, such as the forgetting curve or the decline in motivation over time, were taken into consideration. Therefore, the results should be understood only as an exercise in applying the model and highlighting the complexity of the decision-making process. Future studies could propose solutions using real data, including other FLWPR strategies and addressing FLW across different food products and setting long-term time horizons. This paper aims to be a starting point for contributing to the complex process of deciding which FLWPR solution is the best to promote a more sustainable food system.

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Author agreement statement

We the undersigned declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us. All the authors have participated in the Conceptualization, Investigation, Methodology, Formal analysis, Writing, Reviewing and Editing of the research carried out. We understand that the Corresponding Author is the sole contact for the Editorial process. He/she is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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