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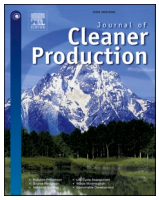

# Carbon and water footprint of food loss and waste prevention actions: Cradle-to-grave life cycle assessment of a prepared salad

M. Amador-Cervera [a,*], S. Scherhaufer [b], S. Gollnow [b,c], A. Alonso-Vicario [a]

[a] DeustoTech, Faculty of Engineering, University of Deusto, Av. Universidades, 24, 48007, Bilbao, Spain
[b] Institute of Waste Management, Department of Water-Atmosphere-Environment, University of Natural Resources and Life Sciences, Muthgasse 107, 1190, Vienna, Austria
[c] Mondi Group, Marxergasse 4a, 1030, Vienna, Austria

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ABSTRACT

Food loss and waste (FLW) represents a major challenge for sustainable development. FLW prevention actions are proliferating, but key gaps persist in assessing their actual net environmental benefits, particularly in prevention at the point of generation. Additionally, data transparency is still a key issue. This study aims to assess the environmental impacts avoided by 5 groups of FLW prevention actions implemented in a prepared salad case study in Spain. Additionally, 4 different salad recipes are analysed, so that the influence of ingredient composition on the effectiveness of FLW prevention actions is accounted for as well. A cradle-to-grave life cycle assessment (LCA) was conducted to have a holistic view of the real impacts across the entire system. The methodology involves an identification and characterisation of the points of FLW generation, enabling a more precise estimation of the FLW that can be reduced through prevention actions. Results indicate that innovative governance solutions yield the most positive impacts, avoiding climate change impacts by 9.8 and water use by 8.80 %. The salad with higher proportions of animal-based ingredients experienced the largest impact reductions. These findings highlight areas for targeted prevention efforts for decision makers. Primary production generated the most environmental impacts coming from FLW. However, the holistic perspective taken demonstrated that effective prevention should focus on downstream points of generation. In conclusion, the presented LCA approach accurately identifies the most promising FLW prevention opportunities to improve the environmental performance of food products. The enhanced data transparency improves accuracy and promotes openness and accountability in LCA and FLW research.

## 1. Introduction

Food loss and waste (FLW) represent a significant global challenge, posing substantial environmental, economic, and social consequences (Alonso-Muñoz et al., 2022). Each year, around one-third of all food produced for human consumption is lost or wasted (Gustavsson et al., 2011), contributing to unnecessary resource use and greenhouse gas emissions, among other impacts. This waste undermines efforts to ensure food security and strains natural resources, making FLW reduction a key priority for sustainable development. The importance of FLW prevention is further highlighted by Sustainable Development Goal (SDG) 12.3, which aims to "halve per capita global food waste at the retail and consumer levels, and reduce food losses along production and supply chains by 2030" (United Nations, 2022). The pursuit of this goal drives the need for comprehensive assessment methods like Life Cycle Assessment (LCA), which can evaluate the true environmental impacts of FLW and the potential benefits of FLW prevention strategies.

LCA is a standardised methodology defined by ISO in ISO 14040 and ISO 14044 for assessing environmental impacts (ISO, 2006a; ISO, 2006b). But although LCA is standardised, there are still additional efforts needed to be made with the aim of facilitating the task of comparing LCA studies, and so circular economy strategies based on LCA (Peña et al., 2021).

LCA has been widely applied in the field of waste management and, more recently, in the specific area of Food Loss and Waste (FLW) management. FAO (2013) conducted a reference study in this field, providing a comprehensive estimation of global FLW and its environmental impacts. Such a study reports that yearly environmental impacts

* Corresponding author.
*E-mail address:* manuel.amador@deusto.es (M. Amador-Cervera).

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due to FLW produce at global level a carbon footprint of 6 Giga tons of $CO_2$ eq, a blue water footprint of 250 $km^3$, and a land use impact of 1.4 billion hectares. This enables researchers and policymakers to determine which technologies or actions are most effective at reducing environmental impacts throughout the Food Supply Chain (FSC). Scherhaufer et al. (2018) assessed the environmental impact of FLW at the European level, considering nine different food products. Their findings reveal that FLW contributes significantly to the overall environmental footprint of the European food system. The study conducted by Omolayo et al. (2021) is also noteworthy, as they performed a comprehensive review of the state of the art in LCA applied to the FLW area focused on FLW management policies. They identified 10 different system boundaries among the 22 studies they reviewed. Furthermore, 3 different functional units (FUs) were employed across these studies: 14 articles used 1 tonne of FW, 6 articles adopted 1 tonne of food consumed, and 2 articles utilised as FU the food products consumed by 1 individual. Exploring nutritional-based functional units (particularly when assessing social impacts) and incorporating all FSC stages is recommended (Omolayo et al., 2021). Conversely, Cánovas Creus et al. (2018) suggest using "the net amount of food flow leaving a stage" as the functional unit to enable meaningful scenario comparisons. In such article a cradle-to-grave approach is strongly recommended to avoid underestimating the effects of FLW prevention actions (Cánovas Creus et al., 2018). More recently, Albizzati et al. (2022) evaluated the sustainability of FLW prevention actions, including the rebound effect resulting from monetary savings due to FLW avoidance. Their study employed 1 tonne of avoided FLW as the FU, and the system boundaries covered all lifecycle stages (cradle-to-grave). System expansion was used to account for the consequences of avoiding FLW and the associated financial savings. Their study found that household-level interventions had the highest potential for reducing climate change impacts, with a reported decrease of 16.4 Mt $CO_2$-eq per year.

As concerns the environmental impact of FLW prevention actions, Cánovas Creus et al. (2018) estimated that a 37.7 % reduction in FLW within a wheat FSC, using 1 kg of food eaten as the FU, resulted in an 18.75 % decrease in carbon footprint. Authors such as Caldeira et al. (2019a) have provided valuable insights into the potential of these actions to reduce impacts across various food products. They analysed 91 actions using surveys for data collection and proposed a tailored approach for conducting LCA of these actions, classifying the results according to the type of FLW prevention action. Their findings indicated that redistribution initiatives (predominantly targeting the retail and distribution stages) proved effective in preventing FLW, particularly when supported by intersectoral cooperation and low operational costs. However, consumer behaviour change interventions showed limited evidence of effectiveness, with only specific strategies, such as improving food management skills and adjusting portion sizes in restaurants, demonstrating measurable waste reductions. Sundin et al. (2023) evaluated the environmental, social, and economic effects of food donations using LCA too, analysing the trade-offs among these three dimensions of sustainability. The study suggested that better-aligned policy measures are needed to ensure that food donation supports prevention and reuse in line with the waste hierarchy. While surplus food donation is not a long-term solution to FLW, it can serve as a valuable short-term measure to enhance sustainability. Lévesque et al. (2023) focused specifically on measuring the environmental impacts of FLW prevention actions within the food service industry, assessing a total of 137 food products to identify key hotspots. Their results showed that, while vegetables constituted the largest share of FLW by weight (58 % of kitchen waste), the highest environmental impact came from meat and seafood (72–92 % of total environmental burden). This finding underscores the importance of targeting FLW categories with the highest environmental impact rather than focusing solely on volume-based waste reduction strategies. Additionally, their study highlighted the need to assess the trade-offs of FLW reduction measures, as some interventions might generate higher environmental costs than composting plate waste.

The state-of-the-art in the topic endorses LCA as an essential tool for assessing the environmental impacts of FLW prevention actions. Yet, this body of literature demonstrates a lack of consensus and limitations regarding key methodological choices, such as the selection of FUs and system boundaries (Bizcocho and Llatas, 2019). As is well recognised in LCA, these choices depend on the specific objective of each study, which is not always the same. For instance, while some studies aim to evaluate the impact of waste prevention actions, others focus on assessing waste valorisation technologies. In the latter case, using 1 kg of waste as the FU can be appropriate. However, even among studies that focus on LCA for FLW prevention (like those by Albizzati et al. (2022), Cánovas Creus et al. (2018), and Salemdeeb et al. (2017)) there are notable differences in scope. Furthermore, studies do not focus on prevention at the point of generation (PoG), nor do they ensure data transparency (Omolayo et al., 2021). This is critical, as the reproducibility and accuracy of LCA studies are essential for establishing benchmarks for effective FLW prevention actions. To fully harness the potential of LCA for FLW prevention, further research is needed to standardise methodologies and improve data accessibility. Additionally, to the best of the authors' knowledge, no comparative analysis has been conducted on the environmental benefits of different FLW prevention actions within the same case study and using primary data for all FLW across the entire life cycle, increasing uncertainty in current assessments. Moreover, while interest in FLW prevention's environmental impacts is growing, a clear understanding of the specific impacts of these actions remains limited, complicating the identification of the most effective strategies. Addressing this gap is essential to fully leverage LCA in guiding impactful FLW prevention measures.

Building on these gaps, the general goals of the study are: 1) to identify opportunities to improve the environmental performance of a prepared salad through FLW prevention actions across different stages of its life cycle; and 2) to provide actionable insights for decision makers, helping them target FLW prevention strategies that maximise environmental benefits. The relevance of the case study for the topic is due to the fact that vegetables is the food group with the highest FLW rate in the EU: accounting for 24 % of the total (Caldeira et al., 2019b). Moreover, Spain, the country where the case study takes place, is the 4th country in the EU that wastes more food according to the last report, with a total of 4.2 million tons of FLW per year (Eurostat, 2023).

A key innovation of this study lies in the extensive collection of primary data covering the entire life cycle of a prepared salad in Spain, offering a level of detail rarely achieved in previous research. This includes precise FLW data across all stages, identifying 15 distinct points of FLW generation (PoG), which allows for a more accurate assessment of the potential for FLW reduction. By addressing the need for more detailed data and transparency, this study offers a more robust foundation for understanding the real environmental benefits of FLW prevention, thus helping to bridge critical gaps in the literature. Moreover, in this paper, various FLW prevention actions are analysed, with a particular emphasis on those targeting prevention at the PoG. This focus is especially valuable as such actions, despite being the top priority in the FLW hierarchy, have received limited attention in existing research. Ultimately, the main reason driving the development of this study is the search for progress towards a circular economy that helps meet the SDG 12 by 2030.

## 2. Methodology

This study employed the LCA methodology to evaluate the environmental impact of a prepared salad product throughout its entire FSC: from Primary Production (PP) to final consumption at Household (HH), including FLW prevention or management at each point of FLW generation. The methodology followed the ISO 14040 and 14044 standards (ISO 2006a; ISO, 2006b), which involve four main phases: goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact

assessment (LCIA), and interpretation.

### 2.1. Goal and scope definition

The present LCA aims to compare the environmental impacts of a prepared salad in two different situations: (1) in the initial status quo, called "baseline scenario"; and (2) when a set of different FLW prevention actions are implemented, called "prevention action scenario". Furthermore, given that the analysed prepared salad represents a weighted average of 4 types of prepared salads, a secondary objective emerged. This additional objective consists of comparing the environmental impact avoided by the same reductions in FLW when the salad recipe is different. This stems from the understanding that different ingredients naturally yield different environmental impacts as the prevailing academic research suggests (Castellani et al., 2017; Lévesque et al., 2023). Conducting this analysis will shed light on the extent to which altering the salad recipe could amplify the environmental benefits brought by FLW prevention efforts. Besides, it will increase the data transparency as the recipes and impact of those salads will also be outlined. The recipe of the average salad corresponds to that of the 4 different types of prepared salad weighted by the production volumes of each of them, being.

- Salad recipe 1: 58.07 %
- Salad recipe 2: 21.26 %
- Salad recipe 3: 2.00 %
- Salad recipe 4: 18.67 %

The ingredient composition of these recipes is provided as part of the LCI in Table B of Annex II.

Given the objective of this LCA, the functional unit (FU) was defined as 1 kg of salad eaten by the consumers. This FU is in line with that suggested by the Product Environmental Footprint Category Rules (PEFCR) (European Commission, 2018), which eases comparisons with other products of the same group. Such a FU was deemed the most suitable one for the goal of the study because it allows for a fair comparison between the baseline and the prevention action scenario, and is in alignment with the cradle-to-grave approach. The objective of this LCA is to compare overall environmental impact between the baseline and prevention scenarios, not to identify which solution avoids more environmental impact per kg of FLW prevented. This distinction reinforces the appropriateness of using kgs of salad eaten as the FU instead of kgs of FLW avoided as done sometimes in the related literature. Employing 1 kg of FLW avoided as the FU would be useful to compare scenarios (or actions) that prevent an equivalent amount of FLW, which is not necessarily the case. The results show that the capability of each FLW prevention action to reduce FLW is crucial and must be accounted for in the analysis. Additionally, using mass of FLW avoided as the FU could bias the results. In the baseline scenario, the exact amount of FLW avoided at the PoG is unknown without a previous scenario for reference. Therefore, expressing impacts per kg of FLW avoided would underestimate the FLW avoided in the baseline, skewing comparisons with the prevention action scenario. For these reasons, the selected FU ensured a fair comparison between the baseline and the prevention action scenario. This aligns with the recommendation of Cánovas Creus et al. (2018), which suggests that using an output-based food flow FU ensures comparability between baseline and prevention scenarios. Additionally, regarding system boundaries, a cradle-to-grave approach is recommended (Cánovas Creus et al., 2018), reinforcing the choice of 1 kg of food eaten as the most appropriate FU for LCAs of FLW prevention actions.

In accordance with the requirements given in the corresponding Product Category Rules (PCR) (Environdec, 2019), the product system under analysis is a whole FSC (cradle-to-grave approach), including all life cycle stages. The flowchart that represents all processes included within the system boundaries is provided in Figs. 1 and 2, where processes shaded in red indicate those where FLW is generated.

Along the lifecycle, a total of 15 PoGs were identified. In each of them different FLW prevention/management practices occur (in the baseline scenario), as it is showcased in Table 1.

As FLW is the main issue to be addressed in this LCA, a specific approach was designed to estimate its impact. Tracking this information permitted both the estimation of the amount of FLW going to each destination in the baseline, and that of the FLW reduction achieved by each FLW prevention solution, as it will be explained later. The FLW quantification methods employed are categorised according to the

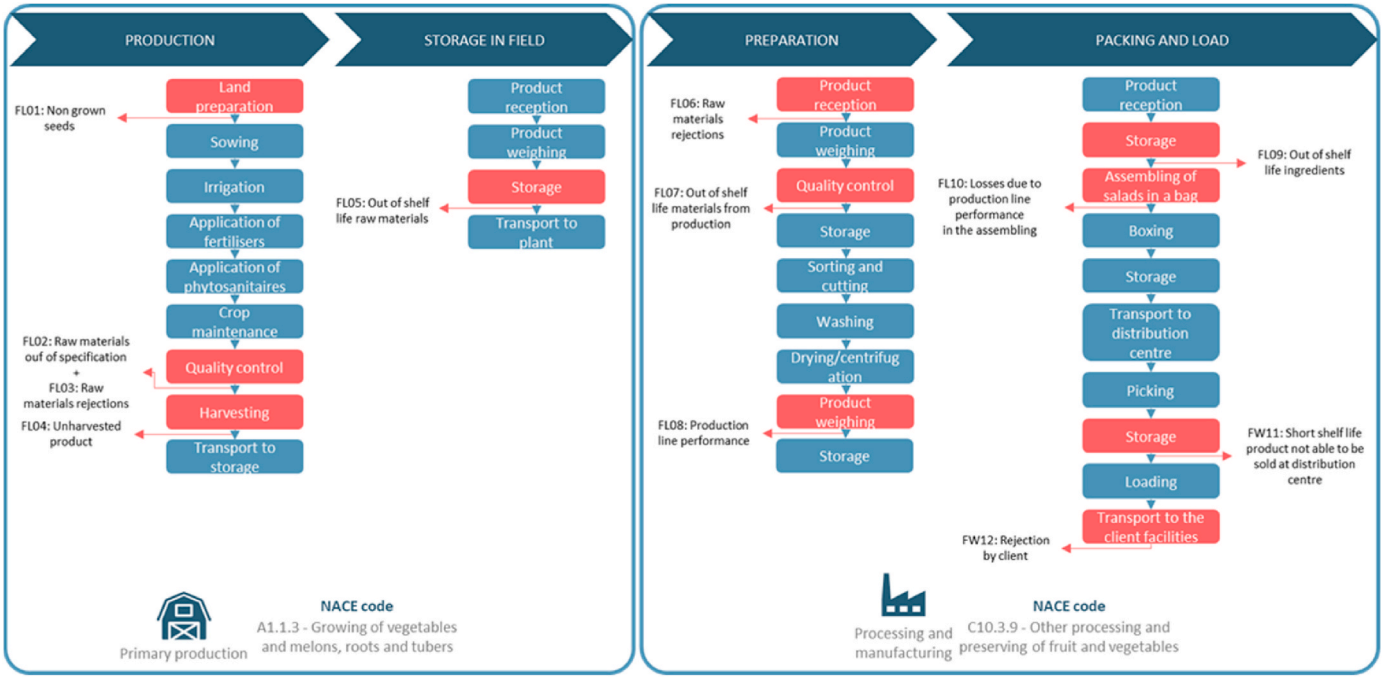


**Fig. 1.** Processes in Primary Production and in Processing and Manufacturing stages.

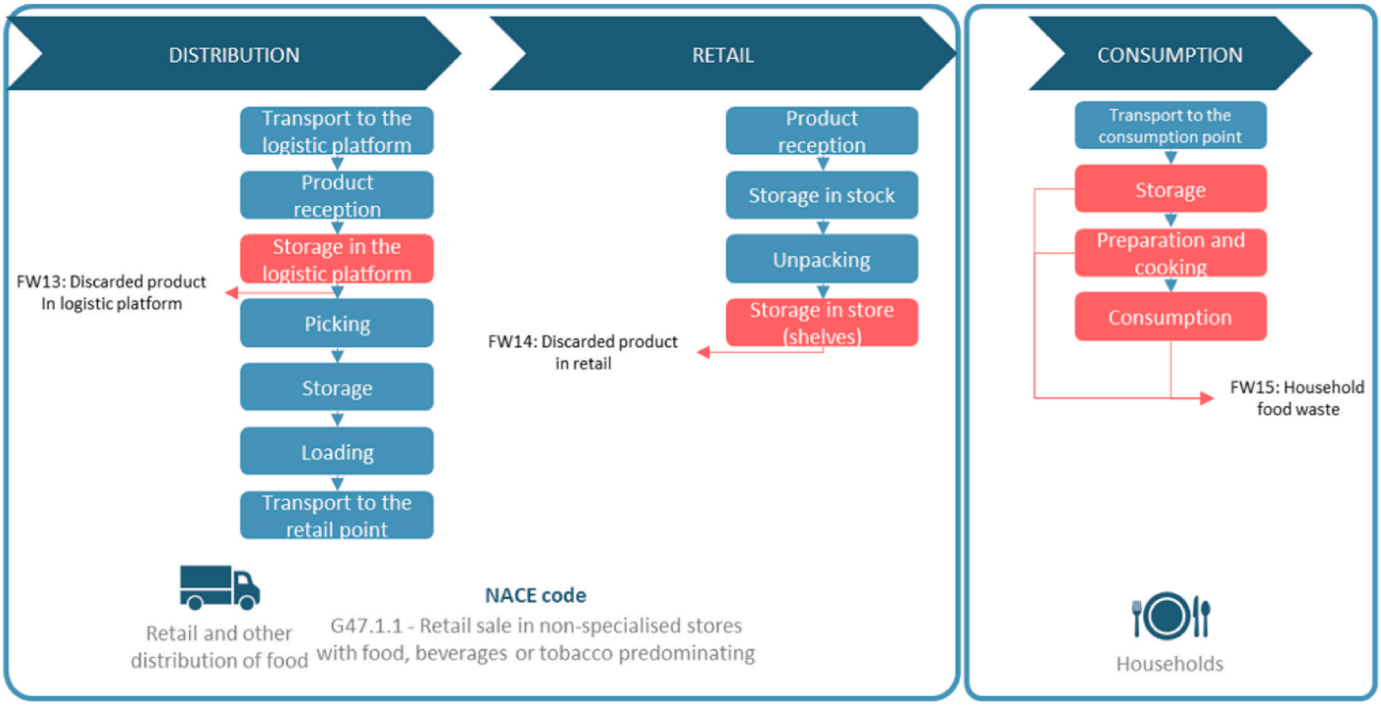


**Fig. 2.** Processes in Retail and other Distribution of Food and Household stages.

**Table 1**
Destination of the FLW in each PoG.

| FSC stage | PoG | FLW quantification method | Cause of FLW generation | Destination |
|---|---|---|---|---|
| Primary production | FL01 | – | – | Absorbed by the soil. |
| | FL02 | Coefficients and production statistics | Lack of/inaccurate demand forecasting.<br>Pests and diseases. | Left in the field. |
| | FL03 | Coefficients and production statistics | Food aspect requirements self-imposed by stakeholders (clients, consumers …). | Animal feeding. |
| | FL04 | Coefficients and production statistics | Lack of/inaccurate demand forecasting.<br>Inadequate climate conditions.<br>Pests and diseases. | Left in the field. |
| | FL05 | Mass balance | Lack of/inaccurate demand forecasting. | Animal feeding. |
| Processing and manufacturing | FL06 | Mass balance | Food aspect requirements self-imposed by stakeholders (clients, consumers …). | Animal feeding. |
| | FL07 | Mass balance | Lack of/inaccurate demand forecasting. | Animal feeding. |
| | FL08 | Mass balance | Presence of inedible parts. | Animal feeding. |
| | FL09 | Mass balance | Cold chain interruptions.<br>Product discarded because of an excessive delay (One-third rule). | Landfill. |
| | FL10 | Mass balance | Products are damaged due to bad practices in some processes (harvesting, cleaning, screening, processing …). | Landfill. |
| | FW11 | Counting/Scanning | Lack of/inaccurate demand forecasting.<br><br>Food quality and aspect requirements in standards and policies. | Donation.<br>Vending for staff.<br>Landfill. |
| | FW12 | Counting/Scanning | Cold chain interruptions. | Landfill. |
| Retail and other Distribution of Food | FW13 | Counting/Scanning | Food quality and aspect requirements in standards and policies. | Landfill. |
| | FW14 | Counting/Scanning | Lack of/inaccurate demand forecasting.<br>Packaging design favouring food spoilage.<br>Cold chain interruptions.<br>Food aspect requirements self-imposed by stakeholders (clients, consumers …).<br>Food quality and aspect requirements in standards and policies<br>Lack of/inaccurate demand forecasting. | Landfill.<br><br><br><br><br><br>Donation.<br>Sold with a discount. |
| Household | FW15 | Diaries | Consumers don't make an adequate purchasing plan.<br>Kitchen staff or consumers' ways to preserve food is inefficient.<br>Packaging design favouring food spoilage.<br>The amount of leftovers is so small that it is not worth keeping.<br>The product is not chosen because its image is not attractive enough (ugly food). | Composting or Landfill.<br><br><br><br>Composting, landfill, or animal feeding. |

classification of the Commission Delegated Decision (EU) 2019/1597 (European Commission, 2019), providing more clarity on the data quality at each PoG.

As concerns time boundaries, primary data collected for the baseline FLW belong to the period going from June 1, 2021 to May 31, 2022. However, primary data related to the production of lettuces and the salads corresponds to the year 2019. The rationale for this decision lies in the pre-existence of the data collected within the context of a prior project, which presented an advantageous opportunity. In the case of geographical boundaries, the modelled system is limited to the Spanish territory. The salad is produced, processed, marketed, and consumed within the Spanish geographical boundaries. And the FLW prevention/management processes are also assumed to occur in Spain.

As regards cut-off criteria, all known input and output flows which are declared in the PCR as being of relevance are included in the study unless otherwise stated. It is fair to say that at least a 1 % cut-off is respected in this LCA.

An attributional approach was undertaken as it was deemed the most appropriate perspective to the defined objectives. In spite of this, the avoided substitute products due to FLW prevention actions, recycling of the packaging, redistribution of food surplus, etc, were included in the LCA to account for the credits from more sustainable practices. This same approach is undertaken by other authors like Sundin et al. (2022), who carried out an attributional LCA including system expansion for substituted products to assess the environmental impacts of food donations. The assumptions made to model such substitutions are provided in Annex I.

To distribute the environmental burdens in combined production processes mass allocation was employed. It was utilised in the PP stage to distribute the environmental burdens among the lettuces used as ingredients in the assessed salad (Curly endive, Green Lamb's lettuce, and Radicchio) and those lettuces cultivated in the same plots but used as ingredients for other salads. In the P&M stage, mass allocation had to be done in order to assign the environmental burdens to the salad, since data received for salad processing encompassed all products processed in the industrial plant.

Regarding the prevention action scenarios, five different ones were assessed, grouping up the case study FLW prevention solutions according to the classification designed by the European Commission's Joint Research Centre (Caldeira et al., 2019a). These scenarios are.

1. Scenario 1 (S1) – Improvement of supply chain efficiency: In this scenario different solutions were modelled to: quantify and monitor FLW along the FSC (except at HH stage) (S1.1), plan and monitor the impact of FLW prevention actions (S1.2), assess the impacts with a holistic view (S1.3), forecast the food demand (S1.4), track and monitor the cold chain (S1.5), predict the food quality and suggest preventive measures (S1.6), and certify the FLW prevention effort via blockchain (S1.7).
2. Scenario 2 (S2) – Redistribution: This scenario models the implementation of a refrigerated box to enable food donations (S2.1), and a digital system to notify food offers (S2.2).
3. Scenario 3 (S3) – Consumer behaviour change: In this scenario a set of social actions are assumed, where several digital solutions are modelled to: quantify and monitor FLW at the HH stage (S3.1), provide consumers with knowledge on how to prevent FLW (S3.2), and inform consumers about food traceability and the environmental impact avoided with all the FLW prevention solutions (S3.3).
4. Scenario 4 (S4) – FLW prevention governance: This scenario includes the impact of a FLW monitoring solution for municipalities (S4.1), and an innovative Pay-As-You-Throw (PAYT) system (S4.2).
5. Scenario 5 (S5) – Comprehensive FLW prevention strategy: In this scenario all the solutions contained in the previous scenarios are deployed simultaneously.

This higher granularity analysis will further illustrate the type of FLW prevention actions with lower environmental impact for the case study. To this end, the environmental impacts of the prepared salad will be calculated in terms of carbon footprint and water footprint. They have been chosen in accordance with the goal of the study, as they are identified as the most important LCA impact categories to assess the sustainability of FLW prevention actions according to the study conducted by Amador-Cervera et al. (2024). This is justified by the fact that the agriculture sector is liable for 36 % of the total water footprint in Europe (European Environment Agency, 2017). Indeed, this sector consumes 70 % of the freshwater globally, and the industry 19 % of it (World Resources Institute, 2020). In terms of climate change, agriculture represents around 13.5 % of total human GHG emissions (Pandey and Agrawal, 2014). To calculate those footprints, the LCIA phase utilised the Environmental Footprint EF v3.0 method within Simapro version 9.3.0.3.

### 2.2. Life cycle inventory (LCI) analysis

To create the LCI, first the PCR criteria was set as the reference to establish which data should come from primary data sources. Additionally, a literature review of scientific articles conducting an LCA for agricultural products (preferable salad or lettuce) was carried out to obtain a list of variables that typically come from primary data sources and aim to maximise the representativeness of the model. The only papers accepted were those clearly indicating: 1) the data source used for each variable; and 2) the percentage of the carbon footprint or water footprint attributed to each process. The selected articles were those authored by: Manfredi and Vignali (2014), Fusi et al. (2016), Cheng et al. (2015) , Wang et al. (2015), Meisterling et al. (2009), Bartzas et al. (2015) and Ryu et al. (2011) . From these studies, variables extracted from primary data sources include: Amount of seeds used, amount and type of chemicals (fertilisers, pesticides …) used, machinery operations data, water consumption, electricity consumption, fuel consumption, amount and type of plastic used for the greenhouse, amount and type of plastic used for the packaging, amount of wastewater generated, and amount of waste generated. So, gathering primary data for these variables was the adopted approach to enhance the study's robustness and ensure that the impact was as representative as possible of the case under investigation.

Finally, the primary data utilised to build the LCI was gathered from the salad producer and from a large retailer through interviews, questionnaires, and file sharing. Household consumer data was collected using diaries to track consumption and FLW disposal behaviour, with corrections applied to account for potential underestimation using factors from Quested et al. (2020). Additionally, data from a parallel waste composition analysis in the same Spanish municipality was used to adjust for disposal habits. The LCI created with this primary data collected is provided in Annex II and the data sources are summarised in Table 2. On the other hand, Table 3 showcases the data sources of those variables modelled with secondary data. Transparency in the LCI provided in Annex II has been promoted whenever data privacy has not been compromised.

For a comprehensive understanding of the system modelling, including the specific FLW prevention solutions applied, please refer to Annex I, which details the assumptions made.

Data preprocessing included mass balance calculations to account for FLW at each stage of the 15 PoGs, which were integrated into the FU. The mass balance (Fig. 3) also adjusted related matter and energy flows (such as water consumption, packaging input, waste, etc) in each part of the model to reflect the impact of FLW, achieving a comprehensive resolution of the system. Annual average values were calculated to account for seasonality in agricultural production. A nutrient balance completed this exercise, which served to calculate the amount of fertiliser needed for the cultivation of lettuce.

The modelling of the 5 prevention action scenarios was done similarly to how Caldeira et al. (2019a) propose to calculate the so-called

**Table 2**
Primary data sources utilised.

| FSC stage | Data | Source |
|---|---|---|
| Primary Production (PP) | Seeds/plants used<br>Land used<br>Water consumption<br>Electricity consumption<br>Fuel consumption<br>FLW generated and avoided<br>Lettuce production<br>Transport distances from the farms to the processing plants | Producer company |
| Processing and Manufacturing (P&M) | Water consumption<br>Electricity consumption<br>Chemicals used for the washing process<br>FLW generated and avoided<br>Salads production<br>Different salads recipes<br>Packaging data (weight and type of plastic)<br>Transport distances from the packaging production plant to the processing plants | |
| Retail and other Distribution of Food (RDF) | Electricity consumption for storage<br>FLW generated and avoided<br>Salads sold | Retail company |
| Household (HH) | Salads/lettuces purchased<br>FLW generated and avoided | Consumers |
| Solutions | Data stored during one year<br>Hardware used | Solutions developers |

**Table 3**
Secondary data sources utilised.

| FSC stage | Data | Source |
|---|---|---|
| Primary Production (PP) | Meteorological data | SIAR (Ministerio de Agricultura Pesca y Ganadería, 2023) & AEMET (Ministerio para la transición ecológica y el reto demográfico, 2023) |
| | Chemicals production<br>Production of fertilisers and pesticides | Ecoinvent (Ecoinvent, 2023) & Agribalyse (ADEME, 2023) |
| | Lettuce production<br>Fuel production and use<br>Water extraction and use | Ecoinvent (Ecoinvent, 2023) |
| | Compost composition | Phyllis2 (TNO: Innovation for life, 2023) |
| Processing and Manufacturing | Salad production<br>Plastic bag production | Agribalyse (ADEME, 2023) |
| | Fuel production and use<br>Water extraction and use | Ecoinvent (Ecoinvent, 2023) |
| Retail and other Distribution of Food (RDF) | Electricity consumption for storage<br>Transport from processing plant to RDF | PEFCR guidance (European Commission, 2018) and PEFCR for Dairy products (Bengoa et al., 2018) |
| Household (HH) | Transport from RDF to HH<br>Transport from HH to composting plant<br>Electricity consumption for storage | |
| Solutions | Data storage of blockchain solutions<br>Electricity consumption per hour of usage<br>Electricity consumption per terabyte of data and year | Scientific literature references (Specified in Annex I) |

"net environmental savings". So, two main modifications were made with respect to the baseline scenario model. First, the mass balance was modified in order to incorporate the percentage of FLW reduction achieved by the implemented FLW prevention solutions at each PoG. In that way, the impacts coming from the avoided food production, and the avoided FLW treatment was accounted for. In Table 4 a summary of the FLW reductions achieved in each FSC stage is provided for each scenario.

Reductions in S1 were calculated based on the specific causes of FLW that these solutions could address, such as inaccurate demand forecasting, cold chain interruptions, and issues related to food appearance and quality. In S2, only FLW that is edible, eatable, and lower in the FLW hierarchy than donation was considered as reducible through these redistribution solutions to human consumption. For S3, a 20 % reduction in FLW at households was assumed, which has an upstream effect in terms of kilograms of FLW avoided. This positions S3 as the second least optimistic scenario for FLW reduction, which aligns with findings from Caldeira et al. (2019a), who indicate that such interventions demonstrate limited effectiveness regarding measurable FLW reduction. In S4, the PAYT system's FLW reduction capacity was adjusted according to edibility and eatability criteria, and assuming an optimal 90 % waste separation rate (European Commission, 2022). Finally, in S5, all previous calculations were applied following a cascade approach in line with the waste hierarchy to realistically account for overlapping and interacting effects of multiple solutions. This ensures that FLW prevention actions at the PoG are prioritised, followed in order by the subsequent options in the FLW hierarchy.

Given such a mass balance, Table 5 presents the total initial input of lettuce (before FL02) and other ingredients (before FW11) entering the system for each scenario and salad recipe.

And secondly, the solutions themselves were also modelled to include the environmental impact they add. Annex I and Annex II outline the details of the primary data LCI and the assumptions made to model the solutions, respectively.

## 3. Results and discussion

This section presents the LCA results for both the baseline scenario and the five proposed prevention action scenarios. First, results are shown for the average salad and for each of the 4 different salad recipes in the baseline scenario. Then, the prevention action scenarios are analysed for the average salad, with S5, which combines all solutions, also evaluated for the 4 salad recipes.

### 3.1. Baseline scenario results

The results of the baseline for 1 kg of average salad eaten by consumers are 4.571 kgs $CO_2$ eq and 5.345 $m^3$ water deprivation. The distribution across the FSC stages is depicted in Fig. 4 for climate change and in Fig. 5 for water use.

The results clearly show that PP is the most impactful FSC stage for both footprints in spite of the FLW being generated all along the FSC. In the case of the water footprint this FSC stage holds 97.48 % of the total impact of the product. Also, in both footprints the RDF stage and the HH stage represent the lowest contributions to the environmental impact.

The impacts coming from FLW were then isolated. This analysis serves to show the maximum room for improvement in the product's impacts in the ideal situation that there were no inefficiencies and all FLW was avoided with prevention at the PoG. This analysis revealed that impacts resulting from FLW amount to 0.87 kg $CO_2$ eq, representing 19.06 % of the total carbon footprint in the baseline, and 1.32 $m^3$ water deprivation, accounting for 24.68 % of the water footprint in the baseline. It is important to note that these impacts encompass not only those related to the FLW management that would be avoided, but also the impacts from the food production that would no longer be necessary to fulfil the FU. That is why most of these potentially avoidable

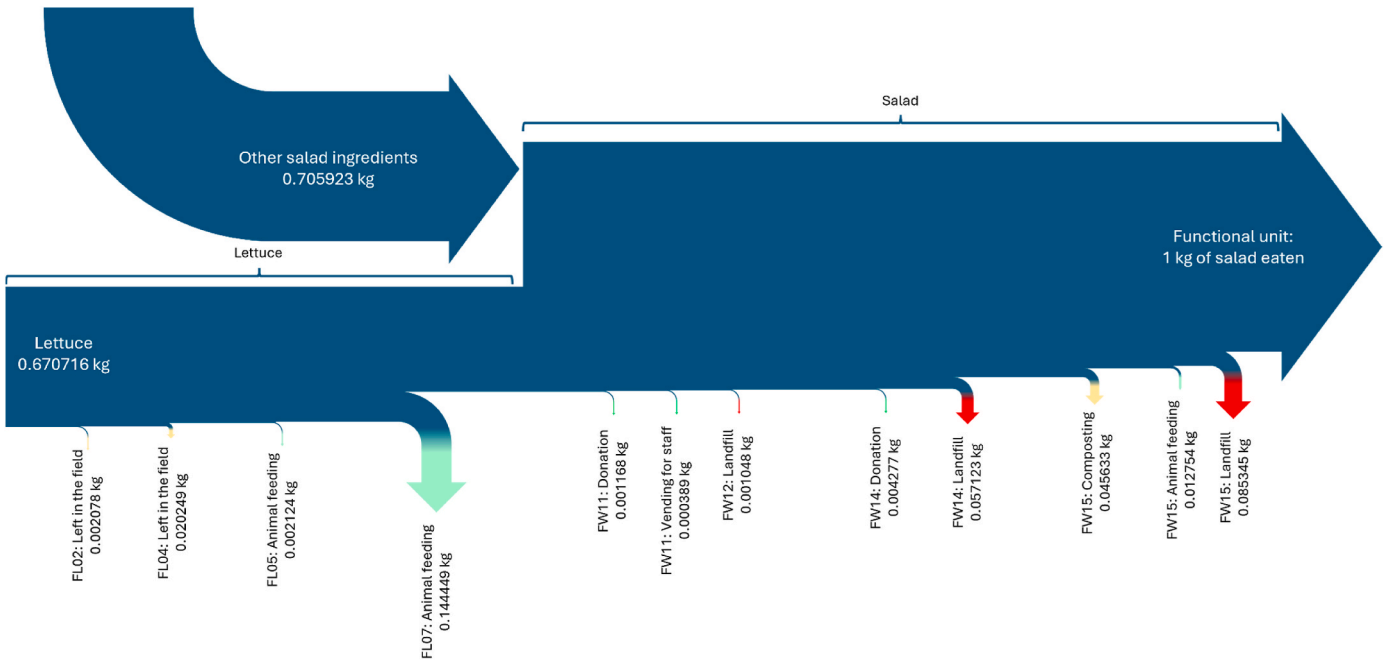


**Fig. 3.** Mass balance to provide the functional unit of 1 kg of salad eaten.

**Table 4**
Kilograms of FLW avoided per FU in each scenario with respect to the baseline scenario.

| Scenario | Primary production | Processing and manufacturing | Retail and other distribution of food | Household | Total |
|---|---|---|---|---|---|
| Scenario 1 | 0.009284 | 0.000032 | 0.033773 | 0 | 0.043088 |
| Scenario 2 | 0.015453 | 0 | 0.005418 | 0 | 0.020871 |
| Scenario 3 | 0.002748 | 0.000029 | 0.001596 | 0.029124 | 0.033497 |
| Scenario 4 | 0.017505 | 0.000946 | 0.048843 | 0.025142 | 0.092435 |
| Scenario 5 | 0.019314 | 0.000951 | 0.053773 | 0.048205 | 0.122244 |

environmental impacts occur during PP (63 % of the carbon footprint and nearly 100 % of the water footprint), despite it being the stage where the least FLW is generated. Therefore, FLW prevention actions should focus on PoGs in downstream FSC stages (especially FW14 in the RDF stage and FW15 in the HH stage) to effectively address this issue, as most of the FLW related impact at PP is a consequence of the additional food production needed to fulfil the FU. This emphasises the importance of having a holistic vision of the food system (cradle-to-grave approach) to fairly assign the responsibility of the environmental impacts due to FLW generation to the adequate FSC actors/decision makers. However, it must be considered that the impact added by the required solutions to achieve this ideal FLW reduction should also be factored in, which will reduce the overall room for improvement.

The assessment of the impacts was repeated for the 4 types of salad in the baseline first, as this is a necessary step to address the secondary objective of the LCA. In Table 6 the results expressed as percentages compared to the average salad are shown.

As can be seen, prior to the implementation of the FLW prevention actions the Salad recipe 3 (vegetarian) reduces both footprints, offering the most beneficial results. Salad recipe 2 reduces the water footprint but increases the carbon footprint. This is mainly due to the increase in cooked bacon, which has a higher carbon footprint, and the decrease in toasted bread, which has a lower water footprint. And both recipe 1 and recipe 4 reduce the carbon footprint but increase the water footprint of the average salad. In both cases, the rise in water footprint is primarily attributed to the higher amount of toasted bread. However, in Salad recipe 1, the reduction in carbon footprint is driven by a decrease in Caesar sauce and the absence of bacon, while in Salad recipe 4, it is also due to a reduction in Caesar sauce.

### 3.2. Prevention action scenarios results

The results of the scenarios where the FLW prevention solutions are implemented are presented in Fig. 6, along with its comparison to the baseline.

In S1, the FLW reduced due to the implementation of the solutions grouped under supply chain efficiency would reduce the carbon footprint by 0.15 kg $CO_2$ eq and the water footprint by 0.17 $m^3$ depriv. water. However, when accounting for the direct impact of the solutions, while the water footprint still shows a improvement compared to the baseline, the carbon footprint increases by nearly. An analysis of the contributing processes revealed that the solution for cold chain monitoring is responsible for this increase. The considerable number of devices required for this solution introduces a significant environmental impact, which is not justified by the limited amount of FLW that could be prevented in this specific case study. Cold chain interruptions, the issue targeted by this solution, were minimal, as effective cold chain management was already in place.

In S2, a slight reduction in impacts compared to the baseline is achieved, with a 0.1 decrease in the carbon footprint and a 2. decrease in the water footprint. Despite the use of a considerably sized refrigerated box, the impact avoided due to the redistribution of these salads compensates for it according to these results.

Similar to S1, S3 sees a reduction in water footprint but an increase in carbon footprint when the impact of the solutions is considered. This increase is especially due to the impact of using the FLW monitoring solution for the HH stage, which contributes 74.9 to the total carbon footprint of the solutions in S3. It should be noted that this impact depends on the assumed hours of use (as indicated in Annex I), and thus

**Table 5**
Total mass input per FU for each scenario and salad recipe.

| Scenario | Lettuce input (kg) | Other ingredients input (kg) | Lettuce share of total input (%) | Lettuce percentage in the recipe (%) |
|---|---|---|---|---|
| Average salad recipe in the Baseline | 0.670716 | 0.705923 | 48.7 | 41.5 |
| Average salad recipe in S1 | 0.642334 | 0.684129 | 48.4 | |
| Average salad recipe in S2 | 0.670716 | 0.705923 | 48.7 | |
| Average salad recipe in S3 | 0.651974 | 0.686197 | 48.7 | |
| Average salad recipe in S4 | 0.653595 | 0.687903 | 48.7 | |
| Average salad recipe in S5 | 0.611920 | 0.651736 | 48.4 | |
| Salad recipe 1 in the Baseline | 0.677173 | 0.705923 | 48.9 | 41.9 |
| Salad recipe 2 in the Baseline | 0.645695 | 0.705923 | 47.7 | 40.0 |
| Salad recipe 3 in the Baseline | 0.677980 | 0.705923 | 48.9 | 42.0 |
| Salad recipe 4 in the Baseline | 0.677980 | 0.705923 | 48.9 | 42.0 |
| Salad recipe 1 in S5 | 0.617811 | 0.651736 | 48.6 | 41.9 |
| Salad recipe 2 in S5 | 0.589092 | 0.651736 | 47.4 | 40.0 |
| Salad recipe 3 in S5 | 0.618547 | 0.651736 | 48.6 | 42.0 |
| Salad recipe 4 in S5 | 0.618547 | 0.651736 | 48.6 | 42.0 |

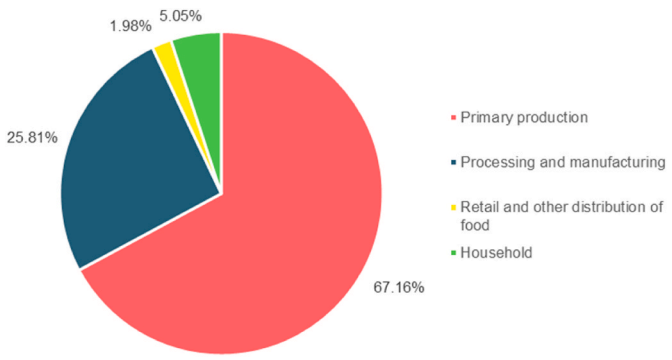


**Fig. 4.** Share of climate change impacts in the baseline per FU for the average salad.

may vary significantly with the case study. Importantly, this analysis considers only the FLW avoided for the salad, not for other foods also consumed at the HH stage that may be affected by these FLW prevention actions. Solution S3.1, if implemented appropriately, is designed to reduce FLW for any food at the consumption stage, not just salads. Therefore, in a realistic scenario, the use of this tool would result in much greater FLW reductions, potentially offsetting the added impact of its use.

In S4, the impact of the FLW prevention governance solutions was analysed. The results show that the FLW reduction achieved by the innovative PAYT system alone could significantly reduce impacts under the given conditions, achieving a 9.8 reduction in the carbon footprint and an 8.8 reduction in the water footprint.

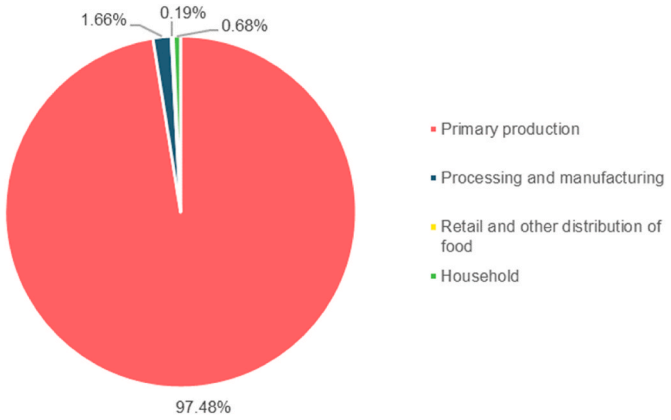


**Fig. 5.** Share of water use impacts in the baseline per FU for the average salad.

**Table 6**
Baseline results of the 4 salad recipes in comparison to the average salad.

| Salad | Climate change (%) | Water use (%) |
|---|---|---|
| Salad recipe 1 | −1.7 | 2.5 |
| Salad recipe 2 | 6.5 | −10.5 |
| Salad recipe 3 | −4.8 | −13.5 |
| Salad recipe 4 | −0.4 | 4.4 |

Finally, in S5, where all solutions are applied together as previously explained, a 2.0 increase in the carbon footprint and a 7.6 reduction in the water footprint were observed. Again, the increase in the carbon footprint is due to the production and transportation of the sensors needed for the cold chain solution, as in S1.

Since the cold chain solution appears to be unsuitable for the case study based on these results, the analysis was repeated excluding this solution and its effect on the FLW avoided. The results are shown below in Fig. 7.

As can be seen, both S1 and S5 achieve better environmental performance once the cold chain monitoring solution is excluded. In S1, the avoided footprints in the two analysed impact categories exceed , while in S5, these reductions are 4.0 and 8.8 for climate change and water use, respectively.

Comparing the scenarios, it is noteworthy that S4, where only the prevention solution categorised as “FLW prevention governance” was modelled, nearly matches the water footprint reduction of S5 and significantly exceeds its carbon footprint reduction (more than double). As shown in the table, the impact reduced by the FLW avoided in S5 is still higher, but the additional impacts from all the solutions included in this scenario allow S4 to close the gap. Once again, these results heavily depend on the assumptions being met. This means that in S4, the aforementioned FLW reductions should occur, which are expected to affect the entire FSC and at a low environmental cost for implementing the governance solutions.

When comparing the cumulative sum of environmental savings from Scenarios S1, S2, S3, and S4 (resulting in an 8.9 reduction in carbon footprint and a 14.8 reduction in water footprint) with S5, which combines these efforts but results in a 4.0 and 8.8 reduction in carbon footprint and water footprint respectively, it becomes clear that the sum of the individual impacts does not equal the impact of S5. This discrepancy arises due to the cascade approach followed in S5. For example, solutions applied in S3, which target the last FSC stage, achieve less FLW reduction when combined with solutions from the other scenarios. This is because downstream solutions (Scenarios 1, 2, and 4) already reduce an amount of FLW that alters the mass balance upstream to fulfil the FU. Therefore, the efficiency of the solutions happening upstream translates now to a smaller absolute reduction in kilograms due to the decreased FLW available for reduction. Thus, the overall

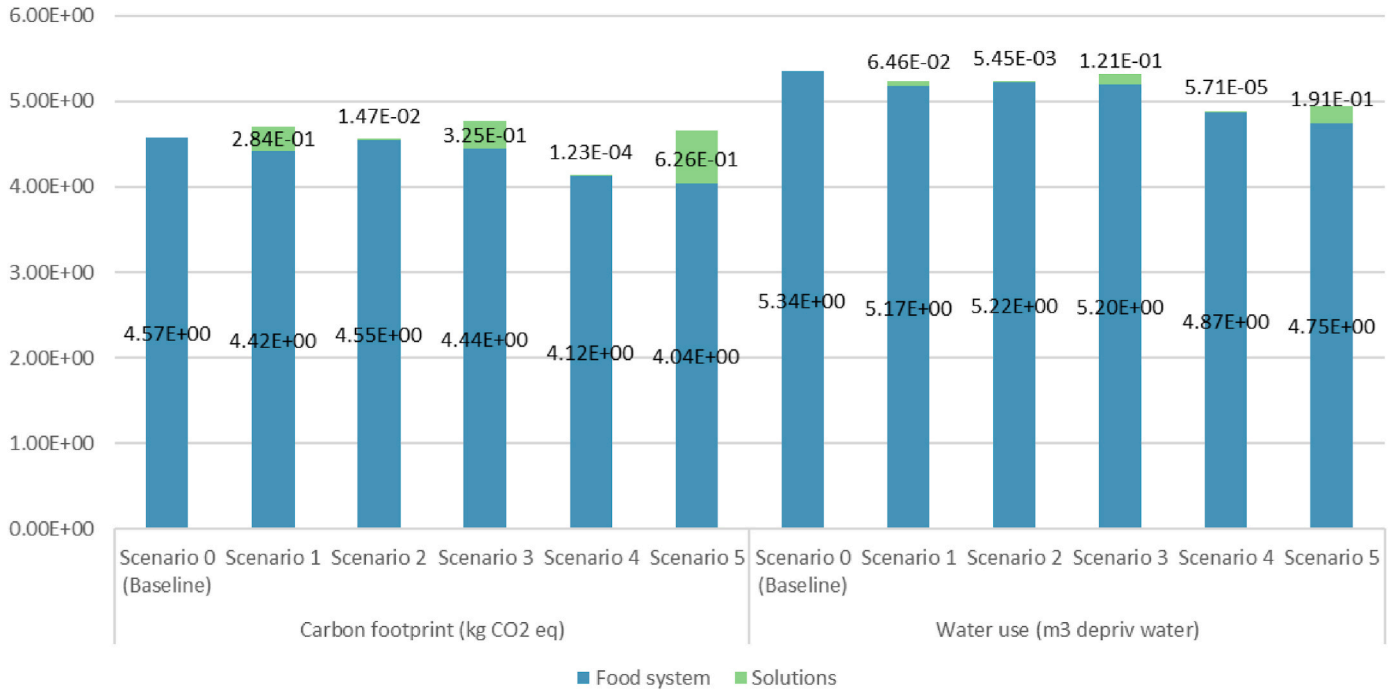


**Fig. 6.** Results of each scenario for the average salad.

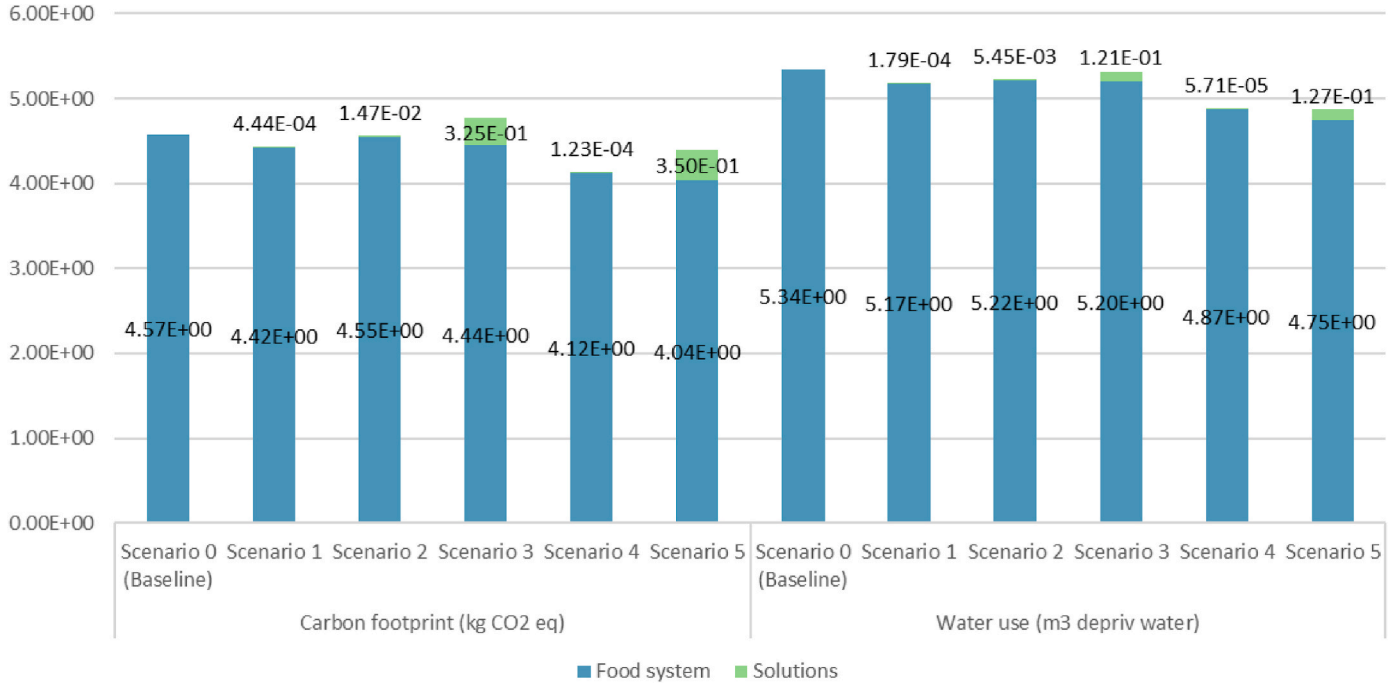


**Fig. 7.** Results of each scenario for the average salad without the cold chain solution.

impact reduction in S5 is not merely the additive sum of the individual scenarios but rather a result of the synergistic and sequential interactions among the solutions across the entire FSC. This cascade approach leads to a more reliable reflection of potential FLW reductions and their corresponding environmental impacts.

In order to achieve the second goal of the LCA, S5 was modelled again for each of the 4 types of salad. These results are presented in Fig. 8.

When comparing the impact of S5 across the different salad recipes, it is observed that the avoided impact is within a similar range for all 4 studied salads. Regarding the carbon footprint, the Salad recipe 2 shows the greatest benefit from these FLW prevention actions, with a 4.6 reduction compared to its baseline. For the water footprint, although recipe 2 is very close, recipe 3 (vegetarian) sees the most significant reduction, avoiding 8.8 of its water footprint under S5.

These results offer valuable insights into the importance of applying FLW prevention actions to specific food products. Salad recipe 2 contains a lower percentage of lettuce (4), but the highest percentage of animal-based ingredients (56.) compared to the rest. In contrast, recipe 3 (vegetarian) contains the highest percentage of plant-based

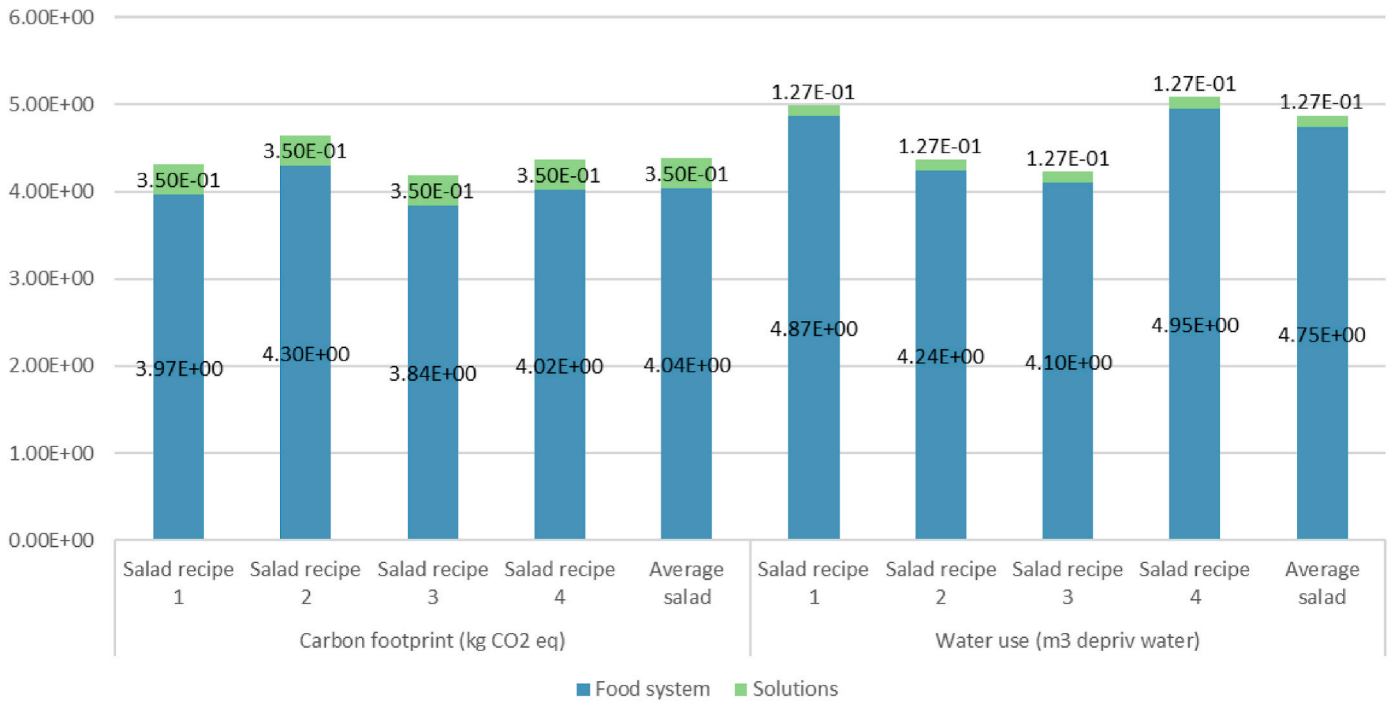


**Fig. 8.** Results of each salad for Scenario S5.

ingredients among the salads (63.), with lettuce comprising 4 of the total salad.

## 4. Conclusion

In this study, the environmental impacts of FLW prevention actions were assessed using a cradle-to-grave LCA approach in a prepared salad case study. The baseline scenario identified 15 points of FLW generation. Four different salad recipes were analysed, allowing for the exploration of how various ingredients influence the potential environmental benefits. The study also categorised FLW prevention actions into 5 distinct scenarios, based on a classification by Caldeira et al. (2019a), to assess the potential impacts of different types of solutions.

The main conclusion drawn from this research work is that this LCA approach was capable of thoroughly assessing different FLW prevention actions at the PoG, spotting not only the most promising solutions to improve the environmental performance, but also those whose impact overweighs the impact reduction achieved by the FLW avoided. In addition, the comprehensive primary data LCI built and enhanced data transparency achieved in this LCA not only provides a more accurate assessment of the environmental impacts of FLW prevention actions, but also sets a benchmark for future studies and eases replicability. By openly sharing detailed data and methodologies, this study promotes a culture of openness and accountability in the research field of LCA and FLW.

More specific conclusions, aligned with the study's goals, include.

1. The assessed FLW prevention actions exhibit substantial potential to reduce environmental impacts, particularly those within the category of FLW prevention governance. More importantly, implementing all solutions together achieves the most significant reductions. This is noteworthy given that the baseline scenario already incorporated various FLW prevention actions (e.g., donation, vending for staff, animal feeding, and discounted salads), which limited the potential additional benefits of the assessed interventions. This suggests that similar FLW prevention actions could achieve even greater environmental impact reductions in a more conventional salad FSC, as the studied FSC was already highly optimised in terms of FLW.
2. The cold chain monitoring solution does not represent a viable opportunity in the case study, as its environmental savings do not outweigh its additional impact. This is due to FLW caused by cold chain interruptions representing a very small quantity in the studied system. This finding underscores the need to assess the effectiveness of solutions within specific case studies and adapt their scope accordingly. For example, in this case, optimising the solution by reducing the number of devices (if technically feasible) could maintain its effectiveness while enhancing its environmental performance.
3. Innovative PAYT systems, such as the one assessed in this paper, can serve as a mechanism to encourage FSC actors to commit to FLW prevention efforts that deliver the most beneficial environmental results.
4. Decision makers should consider that FLW prevention actions lose cost effectiveness when applied together. Since each action reduces the total FLW available for subsequent interventions, implementing multiple solutions in combination can result in lower FLW reduction per action in absolute terms. This highlights the need for strategic planning and prioritisation to maximise impact.
5. FLW prevention actions have a greater impact when applied to animal-based products, as these FSCs typically exhibit higher environmental footprints. Consequently, prioritising FLW prevention actions for animal-based food products would yield the highest environmental impact reductions, suggesting that investors should allocate more funds to FLW prevention actions tailored to animal-based products, which aligns with Lévesque et al. (2023) findings.

During the course of the study there were several limitations that should be mentioned. The main limitation to carry out this study more effectively was the lack of means to test the solutions at real scale and calculate the FLW reductions actually achieved. Data on the actual effectiveness of the solutions was instead estimated through assumptions. This real testing exercise would be key to reducing the uncertainty of the LCA results.

Deepening into the methodological decisions made, there are some factors that could be explored with a sensitivity analysis to assess their influence on the final result. Firstly, the assumption that the substituted

product for redistributed salads is a similar type of salad could be further investigated. To achieve a more representative outcome, a set of different food products could be employed instead. For instance, the composition of the European basket of products (Castellani et al., 2017) could be a trustworthy representation of the average of products that would be displaced by FLW prevention actions. Additionally, the recently published PEFCR for fruits and vegetables (Weststrate et al., 2024) could help refine certain methodological decisions or parameters within the model. However, the main contributions of this study, which focuses on FLW prevention actions, remain unaffected, as this aspect is not explicitly addressed in the PEFCR.

As another consideration, it is worth noting that in the specific case of the demand forecasting solution, better demand prediction may not lead to a reduction in impacts but rather a displacement of them to another system. Those salads the algorithm predicts will exceed demand and therefore become food surplus, may still be produced by the producer company to sell them to a different customer than the one studied. This looks like a fair assumption, since industry seeks to maximise economic incomes. Analysing this requires a much more complex analysis, where the effect of these FLW reduction actions on the economic system is studied with a consequential LCA approach, which is beyond the scope of the present LCA.

Last, the rebound effect mentioned earlier is not being considered either in this analysis since it is out of scope. Some authors indicate that this rebound effect may result in a 3 offset of carbon and water footprints (Albizzati et al., 2022).

## CRediT authorship contribution statement

**M. Amador-Cervera:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **S. Scherhaufer:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **S. Gollnow:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **A. Alonso-Vicario:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

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## 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.

Manuel Amador Cervera, Silvia Scherhaufer, Sebastian Gollnow, and Ainhoa Alonso Vicario reports financial support was provided by European Commission.

## Annex I. Assumptions and limitations

This LCA is built and developed for the specific case study of a packaged and ready-to-eat salad. Although standardisation was sought and results were revised, it might not be always applicable to similar products depending on the context. Even if primary data was always the priority, literature data and data from software databases were compiled as well. Such condition must be carefully explored when interpreting the results or using them for any application.

As in any LCA, either due to lack of data, to avoid double counting, or to ensure coherence, assumptions were made and limitations were encountered. Key assumptions made as regards different processes are here organised according to the FSC stage, with an additional point for the applied solutions (i.e. FLW prevention actions).

For donation (FW11, FW14) and vending for staff (FW11) the substitution of the avoided product was done assuming that salads donated avoid the production of the same amount of salads.

As regards the Primary production stage.

- For lettuce left in the field (FL02, FL04) the substitution of the avoided product was calculated on a dry matter basis. Given that the average moisture content of the lettuces is 93.9 (93.7 for Green Lamb’s lettuce, 93.1 for Radicchio, and 9 for Curly Endive), the resulting average dry matter content was assumed to be 6.1. This value was used to estimate the amount of mineral fertiliser that is substituted (avoided) by the lettuce remaining in the field.
- For lettuce sent to animal feeding (FL03, FL05) the substitution of the avoided product was done on a dry matter basis. The 3 types of lettuce (with an average dry matter content of 6.1) were assumed to avoid the production of a conventional animal feed product like forage barley, which has a dry matter content of 3 (Grill and Omokanye, 2018.
- It was assumed that primary data from 2019 for production and transport processes can be used because there is not a significant difference between that period and the baseline period regarding technology or climatological conditions.
- It is assumed that the rainfall is the same for every plot inside a plot group, as the obtained data is general meteorological data for the region.
- In the plots where more than 1 type of lettuce was cultivated at the same time, it is assumed that the inputs per kg of lettuce are the same for all types of lettuces in the plots as data is aggregated.
- The data provided by the producer company on the salad’s production pertains to a different salad, which includes 2 of the 3 lettuces found in the assessed prepared salad. The 3rd lettuce, Green Lamb’s lettuce, is not included in that dataset, for which reason Curly endive was used as a proxy. Based on the results of a previous LCA conducted for the producer company, it was assumed that the production processes for Green Lamb’s lettuce are similar to that of Curly endive, with the exception of irrigation water consumption, which is higher for Green Lamb’s lettuce. The producer company provided the percentage difference in water consumption between these two lettuces, enabling a reliable modelling of Green Lamb’s lettuce impact.
- It was assumed that the PP of Green Lamb’s lettuce results in 4 more carbon footprint than that of Curly endive. This is based on another LCA study that was recently carried out for the same producer company.
- Data from Agribalyse database was used for fertilisers and pesticides usage since primary data was incomplete and would require extensive time for accurate modelling.

- Since electricity and fuel are utilised in various processes and the data is aggregated for the entire PP stage, it was assumed that 10 of these inputs are allocated to "Irrigation + Application of fertilisers and pesticides". This ensures that the energy and fuel consumption is accounted for when FLW is generated at FL02 or in a subsequent PoG. This assumption is based on the likelihood that irrigation, application of fertilisers and pesticides, and harvesting are the primary consumers of energy and fuel. However, since the exact consumption during harvesting is unknown, all energy and fuel inputs were allocated to the preceding processes.
- It was assumed that the production of seeds takes place in the same location as the PP stage of the prepared salad. Despite collecting primary data, data from the Ecoinvent database was utilised instead. This decision was made because the Ecoinvent lettuce production process, which served as the foundation for the model to account for all additional impacts lacking primary data, already incorporated data on seed production. Therefore, since it was not feasible to substitute this data with the primary data in the model, the primary data was omitted to avoid double counting.
- For each farm, it is assumed that the first sowing date and the last harvest date represent the temporal period during which complete batches of crops were cultivated. This period encompasses the dates within which input and output data are considered.
- Data from batches of crops where the initial process corresponds to a harvest are excluded, as it suggests that sowing occurred in the previous year (2018), placing inputs and outputs related to that batch beyond the designated scope. Similarly, data from batches where the final date is a sowing rather than a harvest date are also disregarded, as it is assumed that the batch continued into 2020. This assumption resulted in the exclusion of numerous crops, including several entire farms.
- In order to allocate the consumption of fuel, electricity, and water for each plot, a mass-based criterion has been employed. Initially, calculations provided by the producer company for the consumption of fuel, electricity, and water per kilogram of total production were utilised. These calculations served as the basis to estimate the consumption for each type of lettuce and each individual plot.
- The production data for fertilisers and phytosanitary products surpassed the limits for primary data collection. Hence, for the analysis, it was assumed that these chemicals were manufactured within Spain's national borders whenever feasible, with Europe as a secondary option, and globally if no other data were available. To estimate the chemical products applied to complete plots dedicated to lettuce production, the percentage of lettuce in the plots (53.1 of the total) was considered. Subsequently, the chemical products applied to each of the 16 plots included in the study were individually calculated, with the 53.1 share factored into these quantities. The percentage of p/v in fertilisers and phytosanitary products was taken to represent the concentration of that component in grams per litre (g/l). Despite instances where chemicals were applied outside the defined time segment, corresponding to the dates of lettuce harvest, they were still included in the analysis. It was assumed that these applications represented post-harvest treatments and other related processes stemming from the production practices of those lettuces.
- It was assumed that the lettuces used for animal feeding avoid the production of conventional animal feed products. To establish the relationship between the amount of lettuce used for animal feeding and the avoided product, it was assumed that forage barley is the product being substituted. Forage barley has a moisture content of approximately 7, resulting in a dry matter content of 3. Source: Gill and Omokanye (2018). This figure was used to determine the amount of animal feed product that is substituted (avoided) through the use of lettuce to feed animals.
- It was assumed that the distance travelled by trucks to send the food to a farm for animal feeding is 38 km. This distance was taken from the study performed by Jayathilake et al. (2022).
- It was assumed that the lettuces that are left in the field do not imply any additional process, they are just not harvested. They would avoid the production of fertiliser.

As regards the Production and manufacturing stage.

- For lettuce sent to animal feeding (FL06, FL07, FL08) the substitution of the avoided product was done on a dry matter basis. The 3 types of lettuce (with an average dry matter content of 6.1) were assumed to avoid the production of a conventional animal feed product like forage barley, which has a dry matter content of 3 (Grill and Omokanye, 2018).
- For donation and vending for staff (FW11) the substitution of the avoided product was done assuming that salads donated avoid the production of the same amount of salads.
- Since there was little variation among the lettuces in the salad and raw data did not distinguish between them, a single type of lettuce was assumed for the analysis in this FSC stage. Consequently, all processes occurring until the mixing of the vegetables have been streamlined by attributing them to one virtual vegetable representing the completed salad. The exception to this is PoG FL07, where FLW data is differentiated per lettuce type, and thus the percentage of each of the 3 lettuces in the salad recipe was considered to apply the corresponding percentages of FLW to the mass flow.
- In order to calculate the average transport distance of the lettuces coming from the PP stage, only the distance between each plot group and each processing plant was deemed.
- As in the PP stage, it was assumed that the inputs per kilogram of salad are the same for all types of salads in the processing plants as collected primary data is aggregated.
- Considering the utilisation of electricity and fuel across various processes and the aggregation of data for the entire P&M stage, it was assumed that 10 of these inputs are assigned to "Sorting and cutting + Washing + Drying/centrifugation". This allocation ensures that energy and fuel consumption are taken into account when FLW is generated at FL08 or in subsequent PoGs. This assumption is grounded in the understanding that sorting and cutting, washing, and drying/centrifugation are the primary consumers of energy and fuel during this stage. However, due to uncertainty surrounding the exact consumption during other processes, all energy and fuel inputs were attributed to these processes.
- It was assumed that the other ingredients in the salad (meat, bread, sauce, cheese …) enter the assembling process before the generation of FLW in the PoG FL10. In other words, it is assumed that this FLW generation occurs once the salad is already assembled, and therefore it includes the other ingredients as well in the waste.
- It is assumed that from FL10 onwards, the weight of the packaging must be also added to the FLW flows as the salad is already packaged. Except for the FL10 that goes to animal feeding, which is assumed to be sent to such a destination because the food is still not packaged.
- It is assumed that PoG FW12 takes place after the product has gone from the processing plant to the logistic platform, and then back to the processing plant. So that transport distance was included twice in this PoG.
- It was assumed that the quantities of chemical products used in the processing plants represent the total amounts (in kilograms or litres). Additionally, in cases where insufficient information regarding the composition of these chemical products was available, it was assumed that they matched the compositions indicated in the technical specification sheets sourced online. If such documents were unavailable for a specific product,

it was assumed that they shared the same composition as the most similar product in the list for which data was available.
- It was assumed that lettuces used for animal feeding substitute the production of conventional animal feed products. The correlation between the two products was again determined by their dry matter content.
- It was assumed that salads donated and salads sold to the staff avoid the production of the same amount of salads.

As regards the Retail and other distribution of food stage.

- For donation (FW14) the substitution of the avoided product was done assuming that salads donated avoid the production of the same amount of salads.
- It was assumed that the transport distance from the P&M stage to the RDF is 1200 km, based on the PEFCR for Dairy Products (Bengoa et al., 2018).
- It was assumed that the salads spend on average around 4 days in the supermarket facilities, which was employed to estimate the electricity consumption according to secondary data. This average number of days was calculated from the data on the inventory turnover rate of the salads in the retailer facilities.
- It was assumed that salads donated avoid the production of the same amount of salads.
- It was assumed that the average transport distance from RDF to HH is 5 km, based on the PEFCR for Dairy Products (Bengoa et al., 2018).

As regards the "Household" stage.

- For salads sent to composting from households (FW15) the substitution of the avoided product was done on a dry matter basis. The FLW generated at the household was assumed to have a dry matter content of 12.5 (Vich et al., 2017).
- For lettuce sent to animal feeding (FW15) the substitution of the avoided product was done on a dry matter basis. The 3 types of lettuce (with an average dry matter content of 6.1) were assumed to avoid the production of a conventional animal feed product like forage barley, which has a dry matter content of 3 (Grill and Omokanye, 2018).
- Regarding waste management, consumers do not always know the final destination of the waste they generate. For that reason, it was assumed that: 1) FLW generated in HH is treated via industrial composting when disposed of in the biowaste bin; 2) packaging discarded in the corresponding packaging bin is recycled; and 3) FLW thrown away in the remainder waste bin is landfilled.
- It was assumed that the salads thrown in the biowaste bin end up being composted and then the production of mineral fertiliser is avoided. The average dry matter content of the FLW generated in the household in which the wasted salads are contained is assumed to be 12.5 (Vich et al., 2017).
- It was assumed that salads used as animal feed do not replace other products in the market and therefore do not offset the production of conventional animal feed products.
- It was assumed that the plastic bag sent to recycling avoids the production of the plastic packaging.
- For the energy consumption derived from the chilled storage in the fridge, based on the PEFCR for Dairy products (Bengoa et al., 2018), it was assumed that: 1) the salad spends 5 days in the fridge on average; 2) 0.0037 kWh/litre·day is the factor for energy consumption.
- It was assumed that the compost resulting from the composting of the FLW in HH is 2 of the FLW mass. This decision was made in consideration of the 7 average moisture content of FLW according to Zhang and Matsuto (2010).

As regards assumptions that are applicable to all FSC stages.

- Transport impact is highly dependent on the distance travelled and the loading weight. Not to mention the means of transport themselves. Emissions vary as such factors do. In this LCA, transport data was assumed to be performed by long distance 7.5–16 metric ton trucks. Besides, in the journey of some of the distances travelled the product may be delivered to an intermediate warehouse which was not considered in these processes. The transport distances data that were not supplied by the stakeholders were estimated according to Google maps distances by road between the sending point and the delivery point.
- It was assumed that the recycling process efficiency for the plastic packaging components was 7 for Polyethylene Terephthalate (PET) and 6 for Polypropylene. This decision was based on the average recycling rates of the analysed recycling plants, according to Antonopoulos et al. (2021). From this reference study, REC1 was excluded because it only treated plastic films, which represent a small portion (approximately) of the packaging modelled in the present LCA. Similarly, REC8 was excluded because it treated a mix of High-Density Polyethylene (HDPE), Polypropylene, and Polystyrene (PS), which did not include PET, the predominant material (approximately 9) in the packaging modelled in this LCA.
- It was assumed that the plastic packaging that is not recycled is disposed of in accordance with Antonopoulos et al. (2021). Consistent with the rest of the case study, the disposal of this waste was assumed to occur in landfill.

And as regards the solutions, for which a description is given in Section6.5.

- The environmental impact added by social actions was not considered due to difficulty and uncertainty in quantifying the impacts of these actions. In the context of LCA, focusing on the most significant impacts is a common practice to maintain the study's feasibility and relevance (ISO, 2006b). An example of one of these omitted processes can be the transport of consumers participating in a cooking show workshop to the facilities where the workshop takes place. To justify this decision, it is assumed that these impacts are negligible when compared with the total FLW these actions would avoid in the long term.
- It was assumed that social actions have a joint impact on FLW prevention, so the individual effect of each was not separately calculated. This decision was made because it is challenging to attribute specific reductions in FLW to individual social actions.
- S1.1 – FLW monitoring solution for the FSC: The user does not need to upload the data daily, but frequent usage is expected to assess the data and have an overview of the whole system. 200 h of yearly usage are assumed.
- S1.2 – Planning and monitoring solution for FLW prevention actions: 200 h of yearly usage are assumed.
- S1.3 – Food system assessment tool: 1 h of weekly usage is assumed. Which implies 52 h of yearly usage. This tool primarily aids in visualising data for the entire FSC rather than directly preventing FLW. The usage of other apps from which this solution extracts data is already accounted for in

both scenarios 1 and 5, so minimal additional time is expected to be spent by users on this tool.

- S1.4 – Demand forecasting solution: 1 h of daily use for the 260 working days of the year. Which implies 260 h per year for this solution.
- S1.5 – Cold chain monitoring and traceability solution and S1.6 – Quality forecasting tool: 1 h of daily use for the 260 working days of the year. Which implies 260 h per year for these 2 solutions, which act as one in terms of usage. To extrapolate the solution to the system level, it was assumed that one additional logger would be needed for each box of salads (each box contains 12 salads), and one additional anchor and one additional sentry would be required for each supermarket in the system.
- S1.7 – Environmental management system for FLW certification: 200 h of yearly usage are assumed.
- S2.2 – Notification system for product offers: 100 h of yearly usage are assumed. In Scenario 5 this usage will be 0 as it is assumed that it is included in the hours of usage of solution S1.1.
- S3.1 – FLW monitoring solution for the consumption stage and S3.2 - Digital recipe book: 60 h of yearly usage are assumed for both solutions together. This number of hours was then multiplied by the estimated number of users (consumers) that would use the apps. This number of users was estimated according to the FU at system level (46,771.286 kg of salads eaten) and the reported amount of FLW generated per consumer in the case study.
- S3.3 – QR code with sustainability information: Energy consumption due to usage of this solution is considered negligible.
- S3.4 – FLW prevention online course: 20 h of usage of the solution per person are assumed. It corresponds to the estimated duration of this online course. The number of consumers making use of it is the same as estimated for the solutions S3.1 and S3.2
- S4.1 – FLW monitoring solution at municipal level: 150 h of yearly usage are assumed.
- S4.2 – Pay-As-You-Throw (PAYT) system: 100 h of yearly usage are assumed.
- For the two solutions based on blockchain technology (S1.7 and S4.2), the yearly data storage was calculated according to Muller et al. (2020). This calculation took into account the number of nodes in each blockchain and the number of transactions per year, which was assumed to be 100.
- The energy consumed by the use of the digital solutions of the project was assumed to be 0.019 kW per hour of usage, based on an Ecoinvent dataset for the operation of a laptop. Additionally, 1 h of internet usage was included in the model for each hour of usage of the digital solution.
- The energy consumed by data storage for each solution was assumed to be 46.33 kWh per terabyte (TB) of data per year, according to Corbett (2018).
- It was assumed that the FLW prevention actions, such as donations and vending for staff, represent an inefficiency in delivering the salads to the intended end consumers. In other words, these actions affect the demand for the product in the case study. Consequently, they were modelled as an output of the system that is ultimately consumed by different individuals, and the corresponding percentage of the food input they represent was incorporated into the mass balance. Furthermore, it was assumed that an equivalent amount of a similar product is substituted by these salads. Donations and staff sales were considered inefficiencies, as they constitute a percentage of food surplus exiting the system and reaching consumers different from those defined by the retailer demand. Consequently, the retailer will likely request more salads because these do not fulfil their order. Nevertheless, these salads were assumed to replace the consumption of other salads, thereby avoiding the associated impact.
- It was assumed that the specific FLW prevention action of sales with discounts at the RDF stage does not influence the supply-demand dynamics in the case study. The rationale is that these salads are delivered to the target end consumer, thereby following the usual mass flow along the FSC. Consequently, this FLW prevention action was not included in the LCA model as an inefficiency but rather as a solution that directly reduces the percentage of FLW at that PoG. Although it is true that the lower price might attract more consumers who normally would not buy the salads, thereby creating additional demand (rebound effect), this complexity was not incorporated into the analysis to maintain simplicity and keep the attributional approach.
- It is important to note that the actual benefits of some solutions would be even greater if they are implemented beyond a pilot phase. This is because in a real scenario they will not only be applied to the analysed food product but also to other products produced by the same producer, sold by the same retailer, or consumed by the same consumer, with the higher reduction of FLW it will lead to. In contrast, the increase in electricity consumption due to the use of the digital solutions would not scale proportionately, resulting in a more positive net environmental impact.

## Annex II. Life Cycle Inventory (LCI) created with primary data

**Table A**
Primary data used for the LCI of the Primary production stage.

| Inputs | | | Outputs | | |
|---|---|---|---|---|---|
| Input | Amount | Unit | Output | Amount | Unit |
| Diesel | 0.006558 | litres | Lettuce 1 | 1 | kg |
| Electricity | 0.026471 | kWh | | | |
| Irrigation water | 0.105932 | m3 | | | |
| Land use | 1.53E-05 | ha | | | |
| Seeds | 0.595808 | nº | | | |
| Plants | 0.549274 | nº | | | |
| Rain water | 0.016516 | m3 | | | |
| Mineral fertiliser | 0.003284 | kg | | | |
| Organic fertiliser | 0.207692 | kg | | | |
| Pesticides | 7.28E-05 | kg | | | |
| Diesel | 0.006891 | litres | Lettuce 2 | 1 | kg |
| Electricity | 0.031871 | kWh | | | |
| Irrigation water | 0.121844 | m3 | | | |
| Land use | 2.25E-05 | ha | | | |
| Seeds | 1.275256 | nº | | | |
| Plants | 1.165183 | nº | | | |
| Rain water | 0.016516 | m3 | | | |

(*continued on next page*)

**Table A** (*continued*)

| Inputs | | | Outputs | | |
|---|---|---|---|---|---|
| Mineral fertiliser | 0.003284 | kg | | | |
| Organic fertiliser | 0.207692 | kg | | | |
| Pesticides | 7.28E-05 | kg | | | |
| Diesel | 0.006558 | litres | Lettuce 3 | 1 | kg |
| Electricity | 0.026471 | kWh | | | |
| Irrigation water | 0.4461 | m3 | | | |
| Land use | 1.53E-05 | ha | | | |
| Seeds | 0.595808 | nº | | | |
| Plants | 0.549274 | nº | | | |
| Rain water | 0.016516 | m3 | | | |
| Mineral fertiliser | 0.003284 | kg | | | |
| Organic fertiliser | 0.207692 | kg | | | |
| Pesticides | 7.28E-05 | kg | | | |
| Lettuce | 1 | kg | FLW in FL02 (Landspreading) | 0.0031 | kg |
| Lettuce | 1 | kg | FLW in FL03 (Animal feeding) | 0 | kg |
| Lettuce | 1 | kg | FLW in FL04 (Landspreading) | 0.03028 | kg |
| Lettuce | 1 | kg | FLW in FL05 (Animal feeding) | 0.00328 | kg |
| Lettuce | 1 | kg | FLW in FL06 (Animal feeding) | 0 | kg |
| Average transport distance of the lettuce to the processing plant | 164.843 | km | – | – | – |
| Recycled PET | 0.0304 | kg | Plastic packaging | 0.0364 | kg |
| Virgin PP | 0.002 | kg | | | |
| Virgin PET | 0.003 | kg | | | |
| PET + Etilen-Vinil-Alcohol + PE | 0.001 | kg | | | |
| Average transport distance of the packaging to the processing plant | 555.667 | km | – | – | – |

**Table B**
Primary data used for the LCI of the Production and Manufacturing stage.

| Inputs | | | Outputs | | |
|---|---|---|---|---|---|
| Input | Amount | Unit | Output | Amount | Unit |
| Average transport distance for the packaging | 555.667 | km | – | – | – |
| Electricity | 0.20077271 | kWh | Average salad | 1 | kg |
| Water | 0.003311406 | m3 | | | |
| Sodium hypochlorite | 0.000665764 | kg | | | |
| Chlorine gas | 2.66532E-06 | litres | | | |
| Chemical product 1 | 0.00023789 | kg | | | |
| Chemical product 2 | 6.25978E-05 | kg | | | |
| Chemical product 3 | 0.000134036 | kg | | | |
| Chemical product 4 | 1.29955E-06 | kg | | | |
| Chemical product 5 | 2.88789E-06 | kg | | | |
| Chemical product 6 | 1.67498E-06 | kg | | | |
| Chemical product 7 | 1.67498E-06 | kg | | | |
| Chemical product 8 | 4.59175E-06 | kg | | | |
| Chemical product 9 | 4.29361E-05 | litres | | | |
| Chemical product 10 | 3.40846E-05 | kg | | | |
| Chemical product 11 | 0.000111542 | kg | | | |
| Mix of lettuces | 0.086 | kg | Salad recipe 1 | 0.205 | kg |
| Sauce | 0.05 | kg | | | |
| Chicken breast | 0.028 | kg | | | |
| Cheese | 0.023 | kg | | | |
| Toasted wheat bread | 0.018 | kg | | | |
| Mix of lettuces | 0.08 | kg | Salad recipe 2 | 0.2 | kg |
| Modern sauce | 0.045 | kg | | | |
| Chicken breast | 0.028 | kg | | | |
| Cheddar cheese | 0.025 | kg | | | |
| Cooked bacon | 0.015 | kg | | | |
| Toasted wheat bread with cheese and sesame seeds | 0.007 | kg | | | |
| Mix of lettuces | 0.084 | kg | Salad recipe 3 | 0.2 | kg |
| Vegetarian sauce | 0.05 | kg | | | |
| Soybean and wheat strips | 0.025 | kg | | | |
| Cheese | 0.023 | kg | | | |
| Toasted wheat bread | 0.018 | kg | | | |
| Mix of lettuces | 0.084 | kg | Salad recipe 4 | 0.2 | kg |
| Light sauce | 0.045 | kg | | | |
| Chicken breast | 0.028 | kg | | | |
| Gouda light cheese | 0.025 | kg | | | |
| Toasted wheat bread | 0.018 | kg | | | |
| Salad recipe 1 | 58.07 | % | Production volume | 100 | % |
| Salad recipe 2 | 21.26 | % | | | |
| Salad recipe 3 | 2.00 | % | | | |
| Salad recipe 4 | 18.67 | % | | | |
| Height | 0.088 | m | Prepared salad | 1 | unit |

(*continued on next page*)

**Table B** (*continued*)

| Inputs | | | Outputs | | |
|---|---|---|---|---|---|
| Diameter | 0.185 | m | | | |
| Volume | 0.002365462 | m3 | | | |
| Processing plant 1 | 63.75 | % | Production volume | 100 | % |
| Processing plant 2 | 18.68 | % | | | |
| Processing plant 3 | 17.57 | % | | | |
| Lettuce | 1 | kg | FLW in FL07+FL08 (Animal feeding) | 0.22351 | kg |
| Lettuce | 1 | kg | FLW in FL09 | 0 | kg |
| Lettuce | 1 | kg | FLW in FL10 | 0 | kg |
| Lettuce | 1 | kg | FLW in FW11 (Donation) | 0.00097 | kg |
| Lettuce | 1 | kg | FLW in FW11 (Vending for staff) | 0.00032 | kg |
| Lettuce | 1 | kg | FLW in FW12 | 0.00087 | kg |

**Table C**
Primary data used for the LCI of the Retail and other distribution of food stage.

| Inputs | | | Outputs | | |
|---|---|---|---|---|---|
| Input | Amount | Unit | Output | Amount | Unit |
| Average number of days the Cesar salad spends in the retail | 4 | day | – | – | – |
| Lettuce | 1 | kg | FLW in FW13 (Landfill) | 0 | kg |
| Lettuce | 1 | kg | FLW in FW14 (Landfill) | 0.0474 | kg |
| Lettuce | 1 | kg | FLW in FW14 (Donation) | 0.00355 | kg |
| Lettuce | 1 | kg | FLW in FW14 (Sold with a discount) | 0.06312 | kg |

**Table D**
Primary data used for the LCI of the Household stage.

| Inputs | | | Outputs | | |
|---|---|---|---|---|---|
| Input | Amount | Unit | Output | Amount | Unit |
| Lettuce | 1 | kg | FLW in FW15 (Animal feeding) | 0.00178 | kg |
| Lettuce | 1 | kg | FLW in FW14 (Composting) | 0.03721 | kg |

**Table E**
Primary data used for the LCI of the FLW prevention solutions.

| Inputs | | | Outputs | | |
|---|---|---|---|---|---|
| Input | Amount | Unit | Output | Amount | Unit |
| Refrigerated box production (S2.1) | 1500 | kg | Salads eaten by consumers (FU at system level) | 46,771.286 | kg |
| MB of data storage (S1.4) | 0.913 | Megabyte | | | |
| MB of data storage (S1.5) | 25.85 | Megabyte | | | |
| Temperature loggers and anchors production (S1.5) | 27.54 | kg | | | |
| Sentries production (S1.5) | 46.6 | kg | | | |
| MB of data storage (S1.1) | 23.487 | Megabyte | | | |
| Nodes in the blockchain (S1.7) | 5 | nº | | | |
| MB of data storage (S3.1) | 483.472 | Megabyte | | | |
| MB of data storage (S3.2) | 0.156 | Megabyte | | | |
| MB of data storage (S3.3) | 2.97 | Megabyte | | | |
| MB of data storage (S4.1) | 7.55 | Megabyte | | | |
| Nodes in the blockchain (S4.2) | 4 | nº | | | |
| MB of data storage (S1.3) | 0.046 | Megabyte | | | |
| MB of data storage (S1.2) | 0.067 | Megabyte | | | |

## Data availability

The data that has been used is confidential.

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