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A standardised framework for food loss and waste prevention: Integrating definitions, causes, destinations, and a circularity index

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ABSTRACT

This paper presents a standardised framework for food loss and waste prevention that harmonises operational definitions, a cause taxonomy, and a hierarchy of destinations aligned with EU regulatory guidance, and demonstrates its application through the full food supply chain case study of a prepared salad in Spain. The framework combines a selection of definitions, methodology to identify points of food loss and waste (FLW) generation using NACE codes, a decision-tree that identifies the feasible optimal destination for each FLW flow, and a FLW circularity index to measure FLW prevention/management performance. Such an index works by weighting destinations (prevention = 1; recycling ≈ 0.80; recovery ≈ 0.55; disposal = 0), with weights chosen via sensitivity analysis of multi-country data and LCA-based evidence. The framework was validated with data covering Primary production, Processing and manufacturing, and Retail and other distribution of food (1 year of data), as well as Households (4 months of data for 10 households), processed with two digital monitoring tools. Results show Processing and manufacturing contributes most to FLW avoided (≈ 60.5%), while Households generate the largest share of FLW (≈ 61.9% of generated flows). The FLW circularity score indicates that the producer achieved the highest efficiency, while households performed the poorest. The results confirm that the framework can be operationalised with existing data sources and digital tools, and is adaptable to diverse contexts and products. The study concludes that this approach provides a robust basis for characterising FLW prevention actions, measuring FLW related metrics, and allowing cross-case comparability.

1. Introduction

Food loss and waste (FLW) present a critical global issue with far-reaching sustainability implications (Alonso-Muñoz et al., 2022). Approximately one-third of all food produced for human consumption is discarded or lost annually (Gustavsson et al., 2011). The urgency of addressing this problem is emphasised by Sustainable Development Goal (SDG) 12.3, which seeks to halve FLW by 2030 (United Nations, 2022).

A major challenge is the lack of standardised definitions, causes, and destinations, limiting comparability across studies (Caldeira et al., 2019). Discrepancies persist in the literature and among policy frameworks, leading to inconsistencies in measurement and reporting (European Commission, 2021; FAO, 2014; WRAP, 2018).

Key terms like food, edible and inedible food, food loss, and food waste vary across studies. Most define food as any substance for human consumption (European Commission, 2021; FAO, 2014; Östergren et al., 2014), but edible and inedible components are treated differently, affecting FLW quantification across supply chain stages.

Distinguishing edible from inedible food is complex. Some sources treat them as absolute categories (WRAP, 2021), where edible food corresponds to avoidable waste and inedible food to unavoidable waste. Others highlight cultural dependence (European Commission, 2021; Teuber and Jensen, 2016). Garcia-Garcia et al. (2017) emphasise that food must be expected to be consumed to be classified as edible, implying that demand plays a role. Also, some definitions differ on whether inedible parts should be included in FLW quantification.

Although often used interchangeably, food loss and food waste have distinct meanings. Food loss occurs before retail due to supply chain inefficiencies, while food waste occurs at retail or consumer levels due to economic, stock, or cultural factors (FAO, 2023; FUSIONS, 2016; WRAP, 2020).

The European Commission (2021) excludes any by-products from food production and food not yet part of the supply chain, such as crops left unharvested. Teuber and Jensen (2016) go even further, arguing that a universal definition of food loss and waste may not be feasible, as they depend on research objectives.

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Ramaprasad and Kashyap (2024) proposed a FLW ontology, but it overlooks key policy definitions (from the European Commission and FAO), and does not address edible/inedible distinctions, which are essential for identifying viable prevention actions.

The most relevant definitions and therefore considered in the subsequent sections of this study are included in Appendix A. The specific definitions adopted for this study are formally established and detailed in section 2.

Understanding FLW causes is key to developing effective reduction strategies. These factors span the entire supply chain and involve multiple stakeholders.

Stakeholder decisions strongly drive FLW. Farmers often see overproduction losses as unavoidable (Peira et al., 2018). Supply chain agreements like take-back agreements (under which retailers only pay for the quantities sold, allowing them to return unsold goods to suppliers at no cost) can shift risks to suppliers, generating surplus (Ghosh and Eriksson, 2018). Limited consumer awareness also plays a role, as inefficient purchasing habits and poor food management increase household waste (Diaz-Ruiz et al., 2018).

Transport and logistics inefficiencies contribute significantly to FLW. Perishables are vulnerable to poor handling, temperature changes, and delays from storage, traffic, or weather, reducing quality and shelf life (Zhu, 2017). Packaging also matters: too little causes spoilage, while too much increases environmental impacts (Wohner et al., 2020).

Market and business practices also generate FLW. Retailers overorder to secure discounts or meet contracts, creating unsold surpluses (Ghosh and Eriksson, 2018). Strict aesthetic and quality standards lead to rejection of edible food (Gillman et al., 2019). Additionally, the "one-third rule," which divides shelf life between production, retail and consumption, often removes food prematurely (Mizuyama et al., 2022).

Consumer behaviour is another major source of FLW. Poor meal planning, date-label confusion, and limited cooking skills increase household waste (Diaz-Ruiz et al., 2018), while buffet service often leads to overserving (Gustavsson et al., 2011; Institution of Mechanical Engineers, 2013). Weather and seasonal fluctuations complicate demand forecasting, creating surplus stock and additional waste (Mena et al., 2011).

Poor demand forecasting often causes overproduction, which will then generate FLW (Pirani and Arafat, 2016). At the agricultural stage, crops may remain unharvested if prices fall below production costs (Muriana, 2017). Subsidies can also encourage overproduction, creating inefficiencies that generate avoidable FLW (Bengtsson et al., 2018).

A lack of financial and technological resources limits FLW prevention. Investments in storage, digital tracking, and training are often insufficient, especially in lower-income regions (Chauhan et al., 2021). Poor cold chain management (Tariq and Ali, 2026) and labour shortages (Parizeau, 2024) further increase waste across the supply chain.

A comprehensive synthesis of these causes, categorised systematically across each stage of the FSC, is provided in Table 2 in section 2.

FLW's final destination strongly affects its environmental, economic, and social impacts. Most models follow a hierarchy from the Waste Framework Directive (European Commission, 2008), prioritising prevention over recycling, recovery, and disposal, widely used in FLW research and policy.

A widely recognised hierarchy was proposed by WRAP (2018), which categorises FLW destinations into prevention, recycling, recovery, and disposal. Some approaches refine these categories: Teigiserova et al. (2019) treat reuse as prevention, while the EU Joint Research Centre includes nutrient recovery within recycling and adds wastewater disposal. These refinements show the evolving nature of FLW classifications and the need for a clear, standardised hierarchy that facilitates waste quantification and policy development.

These concepts are essential for coherent FLW quantification and assessing prevention impacts. Calculating these impacts requires measuring key performance indicators (KPIs) (Amador-Cervera et al., 2024; De Laurentiis et al., 2020), which often need extensive datasets, limiting application to well-resourced case studies. Among them, indicators such as those calculated via life cycle assessment (LCA) are commonly utilised, which are specially time and resource consuming. For quicker evaluations, recent studies use the FLW hierarchy to estimate prevention/management performance. Relevant methodologies include Pires and Martinho (2019), who proposed a Waste Hierarchy Index (WHI) to evaluate waste management performance within a circular economy context, and Garcia-Garcia et al. (2017), who developed a systematic nine-stage categorisation matrix combined with the food waste hierarchy to act as a decision-support tool for food manufacturers.

However, these approaches face limitations when applied to FLW. The Waste Hierarchy Index (Pires and Martinho, 2019) considers only generated waste, excluding prevention. Although it ranges from 0 to 1, it does not reflect the actual improvement potential of each context, limiting comparability across regions or stages. Applying the hierarchy as a decision tree to biowaste (Garcia-Garcia et al., 2017) also poses challenges, as no consensus exists on destinations' priority. In other words, there is an absence of a systematic procedure for determining weighting factors for each level or destination within the hierarchy based on their sustainability performance. Weighting factors are often applied without considering environmental, economic, or social effects. Establishing scientifically grounded weighting factors is crucial to developing a metric that objectively assesses FLW sustainability.

A standardised approach to FLW definitions, causes, and destinations is essential for accurate and comparable quantification.

Various methodologies exist for FLW quantification. A widely recognised standard is the FLW Standard (Hanson et al., 2016), which provides a structured method for tracking, reporting, and mitigating FLW, with flexible inventory boundaries, measurement methods, and reporting. Its adaptability allows application across sectors, supply chain stages, and regions. The FLW Protocol Ranking Tool helps users select the most suitable quantification method (https://www.flwprotocol.org/flw-standard/).

To harmonise FLW measurement, the European Union (EU) introduced the Delegated Decision 2019/1597 (European Commission, 2019), establishing a mandatory framework for Member States. It defines FLW and prescribes quantification methods for each supply chain stage: Primary production (PP), Processing and manufacturing (P&M), Retail and other distribution of food (RDF), Restaurants and food services (RFS) and Households (HH). It also recommends using NACE (statistical classification of economic activities in the European Community) codes and European Waste Codes for consistent classification and data harmonisation.

Despite these advancements, FLW quantification still faces major challenges (Afzal et al., 2022; Alshabanat et al., 2021; Amicarelli et al., 2021; Amicarelli et al., 2022; Bedoya-Perales and Dal' Magro, 2021; Fernandez-Zamudio et al., 2020; Herrera-Quinteros and Jara-Rojas, 2023; Ioannou et al., 2022; Thanomnim et al., 2022; Tóth et al., 2021). The main issues include:

1. Inconsistent definitions and classification systems: Studies vary in definitions (even after the publication of the Delegated Decision 2019/1597), temporal and geographical scopes, and FSC stage categorisations, which creates inconsistencies in comparative analyses. In some cases, definitions are not explicitly stated, hampering data validity evaluation.
2. Comprehensiveness of measurement methods: While the Delegated Decision 2019/1597 provides a comprehensive list of FLW quantification methodologies, some studies do not explicitly align with these guidelines, leading to methodological discrepancies.
3. Exclusion of preharvest FLW: Some studies exclude preharvest FLW, despite estimates suggesting that it accounts for 15% of global FLW (WWF, 2021). This data gap underestimates the real global picture.
4. Data accessibility and availability: Many studies struggle with limited access to reliable FLW data, often relying on assumptions to fill gaps, affecting accuracy and comparability.

These challenges highlight the need for a standardised FLW measurement framework. Aligning definitions, causes, and destinations within a structured quantification system, makes FLW data more reliable, comparable, and actionable, enabling effective evaluation of FLW prevention actions' impacts.

For the mentioned reasons, this study proposes a standardised framework for FLW terminology, causes, and destinations. This framework is validated through a real case study utilising a circularity index alongside two specific digital tools developed within the FOODRUS project to measure FLW (one designed for the entire FSC excluding consumers, and another tailored for consumers and the HORECA sector).

2. Methodology

2.1. Framework development

Before detailing the operational steps, it is necessary to define the structural boundaries of the proposed framework. In the context of this study, the framework is conceptualised as an integrated structural map designed to guide the standardised assessment of FLW. It is built upon four interconnected pillars: 1) a harmonised set of definitions to establish boundaries; 2) a categorised catalogue of root causes attributed to specific stakeholders; 3) a standardised classification of FLW destinations; and 4) a robust quantification methodology tailored to these elements. These components function as a single consolidated model, where the definitions dictate what is measured, the quantification tools capture the flows, and the mapped causes and destinations provide the diagnostic data necessary to trigger targeted FLW prevention actions.

The development of the framework was grounded in a comprehensive literature review, which informed the definition of its three core elements. The literature search was conducted up to 2024 across major academic databases, including Google Scholar, Scopus, and Web of Science. Studies were selected based on a scoping approach, with inclusion criteria focusing on papers that provided distinct definitions of FLW terms, unique (non-overlapping) causes of FLW generation, or classifications of waste destinations across the food supply chain. Additionally, key pieces of European legislation were analysed, specifically focusing on the legal definitions and authorised waste destinations they establish, as legislation typically does not codify the behavioural or operational causes of FLW. Unrelated studies or those replicating existing categories without adding conceptual novelty were excluded.

First, regarding definition of key terms, the literature review conducted consolidated insights from the scientific community and European legislation. The focus was on understanding and harmonising terminologies, specifically examining the terms: food, edible food, inedible food, food loss, and food waste. The comprehensive mapping of these definitions is provided in Appendix A. With this input an International Workshop on Food Loss and Waste Quantification (consumption stage) was conducted on November 18, 2022. This online workshop involved 19 professionals from 7 European countries who were directly invited via email. The participants were primarily partners and advisory board members from the FOODRUS project, alongside experts from related sister European FLW projects. This multi-disciplinary group comprised both research experts specialising in FLW quantification and practitioners directly involved in municipal or regional FLW management. Their role in this study was to engage in a co-creation process to resolve terminology discrepancies, evaluate literature-based definitions, and assess the practical feasibility of the framework. A set of questions was designed to determine which of the most widely used definitions in the literature (presented in Appendix A) for the terms “food”, “edible food”, “inedible food”, “food loss” and “food waste” best represents each concept, according to the participants who voted in a real-time survey. The sessions also facilitated in-depth discussions on terminology and conceptual nuances of such definitions. By contrasting the theoretical baselines from Appendix A with the real-time voting and stakeholder feedback, this participatory process directly guided the selection and adaptation of the final definitions adopted in our framework. Apart from that, the quantification of FLW at the consumption stage was also discussed, which is considered the most critical phase of the FSC since it generates the most FLW (Eurostat, 2025). So, the three quantification methodologies endorsed by the Delegated Decision 2019/1597 (European Commission, 2019) to measure FLW in that stage were discussed: surveys, diaries, and waste composition analysis. By integrating theoretical expertise and practical insights, the workshop aimed to create a synergy that would enhance both the quality and practical relevance of the results. This participatory process helped select the most appropriate definitions for the framework.

In the case of the causes of FLW generation, the initial list was extracted from the literature and then filtered, excluding those perceived as barriers instead and seeking the selection of root causes only. Then, they were classified according to the FSC stage(s) where they take place, which is where the FLW prevention action will be required.

To establish a comprehensive overview of FLW destinations, several studies have been reviewed, including those conducted by Girotto and Piazza, (2022), Pinto et al. (2022), Sánchez López et al. (2020), Caldeira et al. (2019), European Commission (2019), Filimonau and De Coteau, (2019), Beausang et al. (2017), Garcia-Garcia et al. (2017), and Garrone et al. (2016). These sources provide valuable insights into how FLW is managed and classified across different contexts. Destinations were classified according to the FLW hierarchy from WRAP (2018), since this is the approach that best aligns with the Waste Framework Directive (European Commission, 2008).

In summary, the final consolidated model of the framework bridges these four pillars into a unified operational sequence. The framework operates sequentially: the established definitions set the system boundaries, the quantification methodologies capture the empirical data, and the catalogues of causes and destinations translate those measurements into actionable insights. This integrated structure serves as the final conceptual map used to execute the FLW validation exercise detailed in the following case study.

2.2. Data collection in the case study

Once the framework was defined, an FLW quantification exercise was carried out in a case study. Such a case study took place in a region in northern Spain, covering the whole FSC of a prepared salad: the PP and P&M stages, which were covered by a food producer; the RDF stage, which was covered by a large retailer; and the HH stage, which involved the participation of 10 families from a municipality in the Basque Country. This territory was selected because it provided the necessary digital infrastructure, local stakeholder engagement, and data access required to validate the framework. The FLW quantification in the case study includes as a first step the identification of each point where FLW is generated (called point of generation i.e. PoG from now on), as well as the root cause and destination. For this purpose, a flowchart was first created to graphically illustrate the mass flow across the FSC. In this diagram the successive processes happening in each FSC stage were arranged, as well as the PoGs. This mapping was performed following on-site technical visits to the stakeholders' facilities (the food producer, the retailer, and the city council) in November 2021, supplemented by online interviews and email exchanges with key company representatives (such as operations and quality managers) throughout the data collection period. The interviews were recorded to ensure the accuracy of the compiled data. The information gathered from this process was analysed systematically to support the framework by: 1) constructing the process flow diagram (Fig. 1) (Amador-Cervera et al., 2025); 2) identifying and categorising the site-specific causes of FLW generation; 3) mapping the specific flows to their respective destinations; and 4) measuring the FLW and FLW avoided corresponding with each flow, as detailed in the subsequent sections.

In this way more specific information (essential for a proper FLW

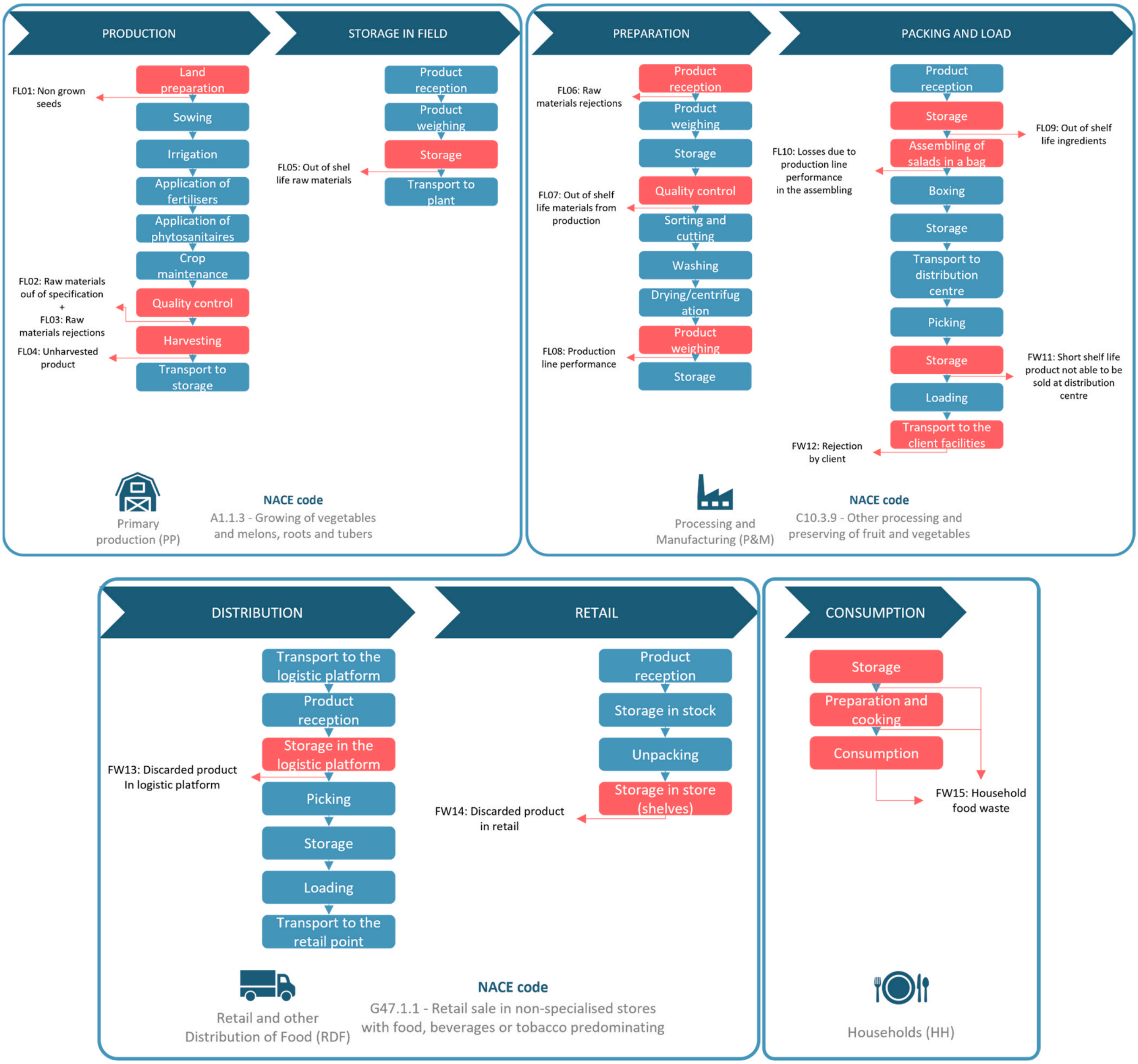

Fig. 1. a) Flowchart of the case study for the PP and P&M stages (Amador-Cervera et al., 2025). The processes where FLW is generated (points of generation) are shaded in red. b) Flowchart of the case study for the RDF and HH stages (Amador-Cervera et al., 2025). The processes where FLW is generated (points of generation) are shaded in red.

quantification) was extracted from each of them, which is presented in Table 1.

Collecting information for each PoG in this manner enabled a detailed identification of the causes of FLW generation within the case study, and thus the corresponding FLW prevention actions applicable at each stage of the FSC. Similarly, the edibility and eatability fields played a crucial role in determining viable solutions or destinations with the decision tree presented in section 2.3. For example, ensuring that only edible and eatable food surplus is considered for redistribution.

With this information the FLW generated as well as the FLW avoided (i.e. FLW prevented) at each PoG were quantified following the specifications given in the Delegated Decision 2019/1597 (European Commission, 2019), with the tailored modifications outlined in the framework proposed in this study.

The data employed to calculate both the FLW generated and FLW avoided in the case study was collected through the sharing of online files (especially worksheets) and folders facilitated by the FSC stakeholders (the food producer, the retailer, and the city council), which included huge datasets with daily data. The determination of the temporal scale was guided by data availability within each institution's system, resulting in the following periods:

- From 1st June 2021 until 31st May 2022 for the organisations that covered PP, P&M, and RDF (1 calendar year).
- From 1st November 2022 until 28th February 2023 in the case of the data collected from the HH stage through diaries (4 months).

One full year was targeted in order to account for seasonality. However, in the case of the HH stage it was not possible to monitor end consumers for such a long period. So, data was extrapolated to 1 year time in that case.

A substantial volume of data was collected to facilitate the

Table 1
Information from the points of generation.

FSC stage (NACE code)	PoG code	Cause of FLW /food surplus generation	Process	Unit	FLW quantification method	Edibility	Eatability	Destination
Primary production (A1.1.3 - Growing of vegetables and melons, roots and tubers)	FL01	-	Land preparation	-	-	-	-	-
	FL02	1 - Lack of/inaccurate demand forecasting 54 - Pests and diseases	Quality control	Tn	C&PS	Edible	Uneatable	Left in the field
	FL03	15 - Food aspect requirements self-imposed by stakeholders (clients, consumers…).		Tn	C&PS	Edible	Uneatable	Animal feeding
	FL04	1 - Lack of/inaccurate demand forecasting 4 - Inadequate climate conditions 54 - Pests and diseases	Harvesting	Tn	C&PS	Edible	Eatable	Left in the field
	FL05	1 - Lack of/inaccurate demand forecasting	Storage	Tn	MB	Edible	Uneatable	Animal feeding
Processing and manufacturing (C10.3.9 - Other processing and preserving of fruit and vegetables)	FL06	15 - Food aspect requirements self-imposed by stakeholders (clients, consumers…).	Product reception	Tn	MB	Edible	Uneatable	Animal feeding
	FL07	1 - Lack of/inaccurate demand forecasting	Quality control	Tn	MB	Edible	Uneatable	Animal feeding
	FL08	55 - Presence of inedible parts.	Product weighing	%	MB	Inedible	Uneatable	Animal feeding
	FL09	19 - Cold chain interruptions 25 - If there is an excessive delay, the product is withdrawn prematurely.	Storage	Tn	MB	Edible	Uneatable	Landfill Landfill
	FL10	6 - Products are damaged due to bad practices in some process (harvesting, cleaning, screening, processing…).	Assembling of salads in a bag	%	MB	Edible	Eatable	Landfill
	FW11	1 - Lack of/inaccurate demand forecasting	Storage	Kg and units	C/S	Edible	Eatable	Donation Vending for staff
		14 - Food quality and aspect requirements in standards and policies				Edible	Uneatable	Landfill
	FW12	19 - Cold chain interruptions	Transport to the client's facilities	Kg and units	C/S	Edible	Uneatable	Landfill
Retail and other distribution of food (G47.1.1 - Retail sale in non-specialised stores with food, beverages or tobacco predominating)	FW13	14 - Food quality and aspect requirements in standards and policies	Storage in logistic platform	Kg and units	-	Edible	-	Landfill
	FW14	1 - Lack of/inaccurate demand forecasting 28 - Packaging design favouring food spoilage 19 - Cold chain interruptions 15 - Food aspect requirements self-imposed by stakeholders (clients, consumers…). 14 - Food quality and aspect requirements in standards and policies	Storage in the retail point (shelves)	Kg and units	C/S	Edible	Uneatable	Landfill
		1 - Lack of/inaccurate demand forecasting					Eatable	Donation Sold with a discount in price
Households	FW15	43 - Consumers don't make an adequate purchasing plan.	Consumption in households	Kg	D	Edible	Uneatable	Composting Landfill
		47 - Kitchen staff or consumers' ways to preserve food is inefficient.						Composting Landfill
		28 - Packaging design favouring food spoilage						Composting Landfill
		38 - The product is not chosen because its image is not attractive enough (ugly food).					Eatable	Composting Landfill
		41 - The amount of leftovers is so small that is not worth keeping.						Composting Landfill Animal feeding

calculation of the KPIs. Initially, this process involved manual compilation, allowing for a deeper understanding of how the involved institutions store and organise their data, as well as the terminology they use to label and classify it. This led to the creation of several data models, which shaped the digital tools used to facilitate the collection, analysis and visualisation of such KPIs. This co-creation approach, based on citizen science activities, aimed to tailor the tools' functionalities to the needs of the FSC stakeholders, who are the primary end users.

Finally, it must be remarked that the data collection process was an iterative procedure in which the required data was redefined as it was received and checked, or as new data availability challenges were encountered.

2.3. FLW circularity index

The FLW hierarchy provides a widely recognised structure for classifying the potential destinations or management options applicable to food surplus and FLW. Building on this concept, the Waste Hierarchy Index (WHI) developed by Pires and Martinho (2019) and the decision-tree approach proposed by Garcia-Garcia et al. (2017) were adopted as foundational references to develop a robust circularity index for assessing FLW performance. The resulting metric, referred to as the FLW circularity index, was designed to quantify how well a system is performing in terms of FLW management/prevention according to its possibilities and the sustainability impacts of such destinations. The formula for the index is expressed as follows:

$$FLW\ Circularity\ Index = \frac{\Sigma_i^n (Q_i \times WF_i)}{\Sigma_i^n (Q_i \times WF_i{}^*)}$$

Where:

- Q_i = Quantity of FLW/food surplus going to destination i
- WF_i = Weighing factor of destination i
- $WF_i{}^*$= Weighing factor of the optimal destination for such a FLW flow i considering its characteristics

To define the weighting factors (WF_i) associated with each destination in the hierarchy, an analytical process was conducted using FLW generation data from 6 countries reported in the Food waste index report (United Nations Environment Programme, 2024). These specific countries (Australia, Belgium, France, Netherlands, United States and Slovenia) were selected based on a two-step criterion: 1) they were classified within the report as having a "medium" or "high" data confidence level; 2) they provided the necessary data granularity required to extract the distribution of FLW across the 4 primary tiers of the FLW hierarchy. Based on this information, and assuming a score of 1 for prevention and 0 for disposal, a sensitivity analysis was performed to evaluate different configurations of the weighting factors for recycling and recovery. This analysis aimed to ensure that the proposed index is sufficiently sensitive to distinguish between case studies exhibiting similar performance levels. To this end, the standard deviation among the 6 countries was calculated for each variation of the 2 weighting factors.

As a reference for defining the weighting factors, the study conducted by Albizzati et al. (2021) was used. This research evaluated the environmental, social, and economic impacts of different FLW destinations through a life cycle assessment (LCA) approach. For each destination, the results of the 5 end-point indicators assessed in their study were first averaged. These values were then aggregated by hierarchy level (recycling and recovery) to calculate a mean performance score for each level. Finally, these mean scores were normalised, setting prevention as the reference value (equal to 1).

However, for this methodology to be of practical use it is important to highlight that the feasible destinations in the case study must be considered. Otherwise, the optimal destination from a pragmatic point of view would not be achievable.

To determine the optimal destination for each case, a decision tree was developed, drawing inspiration from the framework proposed by Garcia-Garcia et al. (2017). At each branch, specific conditions and characteristics of the FLW stream guide the selection process by ruling out unsuitable destinations within the FLW hierarchy. For example, if "Uneatable" or "Uneatable for humans, eatable for animals" is selected, the destinations that aim to redistribute food for human consumption will not be considered a possibility. This sequential elimination enables a transparent prioritisation of destination options, where the top-ranked destination represents the most appropriate and sustainable solution for the given case. Consequently, this destination determines the corresponding $WF_i{}^*$ value applied in the calculation of the FLW circularity index.

The full set of decision tree pathways, including all branching conditions and resulting applicable destinations, is provided in Appendix B.

3. Results and discussion

Based on the results of the literature review conducted in the state of the art, and the workshop previously described, the following definitions are proposed as a fundamental part of the methodological framework.

3.1. Definitions

During the review of definitions in the literature, inconsistencies and variations in definitions were observed across different sources. However, certain terms did exhibit widely accepted definitions that were consistently referenced in multiple sources. In summary, the review yielded several noteworthy findings:

- Consistently across the sources consulted, the requirement for a product to be intended for human consumption emerged as a defining characteristic of "food." However, in some sources this criterion also serves to distinguish between edible and inedible food.
- Edible and inedible food are often equated with avoidable and unavoidable FLW, respectively.
- As noted by FAO (2023), FL is frequently associated with a decline in quality or quantity of food along the FSC.
- The influence of culture is a significant factor in determining the boundary between edible and inedible food in each region.

The final point merits special attention, as it implies that the quantification of FLW may not be possible to become completely standardised across regions. Consequently, the applicable solutions for managing potential FLW would also vary. In other words, the optimal approach to managing the same type of food surplus with the goal of minimising the environmental impact may differ between geographical areas.

The definition of "food" selected by most workshop participants (66.66%) was the one proposed by the European Commission (2002). Although the international workshop results suggested an alternative approach for defining "food loss" and "food waste," the European Commission's framework was also adopted in this study. This decision was made because, although the two terms may differ conceptually, in practice they are quantified in the same way. Therefore, since no meaningful differences emerged in the FLW quantification exercise, both concepts were unified under a single definition for practical purposes.

The selected definition for edible food (chosen by 87.5% of the workshop respondents) is the one provided by the European Commission (2021): "components associated with a food, in its fresh mass status, that are usually consumed by humans in the Member States, either as is (raw consumption) or after processing or cooking." For inedible food, the definition most voted for in the international workshop (68.75%) and adopted in this study is that proposed by WRAP (2021): 'those parts associated with food that are not intended to be consumed (such as bones, eggshells).' However, as highlighted in the state-of-the-art section, cultural factors strongly influence perceptions of edibility, and therefore these definitions are not totally rigid.

Besides the definitions discussed during the workshop, several additional concepts were identified as important to clarify in order to prevent confusion. First, the term "eatable food" will be defined to distinguish it from "edible food." Eatable food refers to food that possesses the necessary qualities to be sold for human consumption (Garcia-Garcia et al., 2017). Consequently, the edible portion of a food item, such as an apple, may become uneatable if its condition deteriorates due to external factors.

Additionally, the term "food surplus" will refer to food that is diverted to a prevention destination (Teigiserova et al., 2019), except when prevention occurs at the PoG, as this would not constitute a food surplus. The use of the term "food surplus" aims to highlight the value and usability of this food, encouraging its consumption and reducing unnecessary waste. This distinction is important because labelling such food as "waste" or "loss" may discourage consumers from eating it, even when it is fully eatable.

Finally, the terms "avoidable" and "unavoidable" as synonyms of "edible" and "inedible", respectively, will not be used in this study. The rationale behind is that inedible FLW can also be avoided when the cause of FLW/food surplus generation is an inaccurate demand forecasting (i.e. when there is overproduction). Effective demand forecasting solutions would prevent the production of a certain amount of food in those cases, which includes the inedible part. Consequently, the resulting impacts of that inedible FLW would be avoided too. Referring to this fraction as unavoidable would therefore not accurately reflect the actual improvement potential and could lead to a misleading interpretation. Although the interchangeable use of these terms is common in the literature, they are considered conceptually inequivalent by the authors of this work and thus are not adopted in the present study.

3.2. Causes of FLW generation

A classification of FLW generation causes is now presented, attributing them to the relevant stakeholders within the FSC. As shown in Table 2, this approach acknowledges that multiple stakeholders may operate within the same FSC stage. For instance, in the RDF stage, both retailers and consumers contribute to FLW generation, each with distinct underlying causes. Consequently, the strategies required to address FLW vary depending on the stakeholder involved, making this distinction mandatory for designing effective and targeted FLW prevention actions. The causes compiled in Table 2 represent general factors identified across diverse food supply chains, synthesised from the literature (with specific authors cited directly within the table) alongside a few unique causes proposed by the authors.

To give a proper solution to a problem, the root cause must be detected. This is why in order to compile this catalogue of root causes the previous work developed by Williams (2001) served as a reference. The "Ask 5 times why" technique pointed out by Williams (2001) served as inspiration to avoid identifying causes at a too superficial level. Falling into this mistake could make it very challenging to establish connections between the proposed solutions and the causes. Hence, when the consulted literature put forward causes that were too general, spotted as redundant or as a consequence of previously recognised causes, they were ruled out.

Out of the 55 reasons for FLW generation, there is a portion that was actually proposed by the authors of this study. Specifically, causes number 12, 21, 37, 41, 42, 49, 50, 51, 52 and 53 in the table. These particular causes emerged through extensive discussions and deliberations encompassing various scenarios and instances where FLW occurs. As a result, some new causes that were not among the ones found in the literature arose.

This list of root causes of FLW generation allows to recognise the underlying factors driving FLW at each stage of the FSC. By identifying these causes, it becomes possible to estimate the potential FLW reductions achievable through targeted FLW prevention actions with higher accuracy, ensuring a more effective and strategic approach.

3.3. Destinations

The selected destinations are classified within the different levels of the hierarchy (WRAP, 2018) and assigned a priority order. Moreover, the FSC stages in which each destination may be viable to be applied are displayed. All this information is illustrated in Table 3.

The first three destinations require special clarification, as they will be referred to as "prevention at the PoG." These destinations encompass all solutions designed to prevent FLW before food surplus materialises, they do directly address the root causes of FLW/food surplus generation in each case. That is why these destinations are also referred to as "solutions": their appropriateness will depend on the cause that is intended to be tackled. This distinguishes them from other prevention destinations, where food surplus has already been generated, such as the two additional types of FLW prevention actions identified by Caldeira et al. (2019): Redistribution for human consumption, and Food valorisation.

Moreover, a slight modification could be applied to the "Improvement of supply chain efficiency" destination put forward by Caldeira et al. (2019). As they present this destination or group of solutions, it combines prevention at the PoG solutions with broader prevention measures. For instance, "price discounts" and "imperfect product sales" are included, which do not directly address the root causes of FLW (inaccurate demand forecasting and consumer perception on ugly food, respectively). Similarly, the "Food valorisation" category proposed by Caldeira et al. (2019) presents certain inconsistencies when aligned with the definitions established in the Waste Framework Directive. In this study, a refined approach was adopted whereby "Remaking the same product" and "Revalorising FLW into new food products" are classified under Recycling rather than Prevention, ensuring coherence with the Directive's conceptual definitions of these two terms. Classifying these activities as prevention may otherwise lead to misleading interpretations of some case studies, giving the impression of higher prevention performance than what is actually achieved. Therefore, a revision of either the classification proposed by Caldeira et al. (2019) or of the definitions provided in the Waste Framework Directive would be necessary to achieve full conceptual coherence between both frameworks.

3.4. Stakeholders

The classification of FSC stakeholders is also part of the framework. An international standard classification was employed for this. This standard classification plays a crucial role in facilitating the tracking of mass flows throughout the FSC in a reliable manner.

In line with the proposal set forth by the Delegated Decision 2019/1597 (European Commission, 2019), the NACE codes were employed for the classification of stakeholders. This code system is supported by the EU to carry out data collection, analysis and reporting activities.

3.5. FLW quantification and FLW circularity index results

The proposed framework was validated through a real case study focused on prepared salad production in Spain, encompassing the entire FSC, including PP, P&M, RDF, and HH stages. A leading European food producer covered both PP and P&M stages. For the RDF stage, collaboration was established with one of Spain's largest supermarket chains. Finally, for the HH stage, the study engaged 10 households from a municipality in the Basque Country.

The results of the FLW generated and FLW avoided in each PoG of the case study is shown in Table 4. This table presents a summary of the case

Table 2
FLW/food surplus generation causes and responsible FSC stakeholders.

Cause of FLW/food surplus generation		PP	P&M	RDF		RFS		HH	
N°	**Cause**	**Primary producer**	**Processor or manufacturer**	**Wholesaler or retailer**	**Consumer**	**Service provider**	**Consumer**	**Consumer**	**Reference**
1	Lack of/inaccurate demand forecasting.	✓	✓	✓		✓			Pirani & Arafat (2016)
2	Farmers grow most profitable crops according to last season's prices, which generates food surplus.	✓							Diaz-Ruiz et al. (2018)
3	Farmers' individualistic decisions not aligned with cooperative's, whose capacity to deal with food surplus is reduced.	✓							Diaz-Ruiz et al. (2018)
4	Inadequate climate conditions.	✓							Diaz-Ruiz et al. (2018)
5	Farmers collect products that are not mature enough or overmatured.	✓							Arivazhagan et al. (2016)
6	Products are damaged due to bad practices in some process (harvesting, cleaning, screening, processing…).	✓	✓						Arivazhagan et al. (2016)
7	Supermarkets' hoarding leads to more food waste since they are less flexible and don't accept to purchase some seasonal and diverse products in comparison to other buyers.	✓							Ghosh & Eriksson (2018)
8	Subsidies for production promoting overproduction, which generates food surplus.	✓							Bengtsson et al. (2018)
9	Low market prices for some products forcing farmers to waste them because it's less expensive.	✓							Muriana (2017)
10	Lack of innovative technologies and solutions for more efficient harvesting and processing.	✓	✓						Balaji & Arshinder (2016)
11	Labour shortage.	✓	✓						Parizeau (2024)
12	Equipment and systems breakdowns.	✓	✓	✓		✓			Proposed by the authors of this article.
13	Poor investment in food waste prevention innovations and technical specialisation.	✓	✓	✓		✓			Chauhan et al. (2021)
14	Food quality and aspect requirements in standards and policies.	✓	✓	✓		✓			Diaz-Ruiz et al. (2018)
15	Food aspect requirements self-imposed by stakeholders (clients, consumers…).	✓	✓	✓		✓			Gillman et al. (2019)
16	Lack of/insufficient standards, policies or regulations for food surplus management.	✓	✓	✓		✓			Beausang et al. (2017)
17	Standards, policies or regulations for food surplus management are too rigid (their requirements are too demanding).	✓	✓	✓		✓			Institution of Mechanical Engineers (2013)
18	Standards are uncertain or difficult to interpret.	✓	✓	✓		✓			Diaz-Ruiz et al. (2018)
19	Cold chain interruptions.	✓	✓	✓		✓			Tariq & Ali (2026)
20	Political changes resulting in food waste generation in international trades.	✓	✓	✓		✓			AL-Dalaeen et al. (2021)
21	Absence of a corporate social responsibility policy that leads to food waste generation.	✓	✓	✓		✓			Proposed by the authors of this article.
22	Lack of awareness concerning food waste.	✓	✓	✓	✓	✓	✓	✓	Diaz-Ruiz et al. (2018)
23	Lack of/inefficient coordination and communication of information between actors in the value chain.	✓	✓	✓	✓	✓	✓	✓	Kaipia et al. (2013)
24	Inappropriate food sourcing strategies (i.e. selection of providers) that lead to food waste generation.		✓						Rijpkema et al. (2014)
25	If there is an excessive delay, the product is withdrawn prematurely.		✓	✓		✓			Mizuyama et al. (2022)
26	Shelf life losses due to logistics obstacles: Traffic congestion, hostile weather, long distances…			✓					Rijpkema et al. (2014)

(*continued on next page*)

Table 2 (*continued*)

Cause of FLW/food surplus generation		PP	P&M	RDF		RFS		HH	
N°	**Cause**	**Primary producer**	**Processor or manufacturer**	**Wholesaler or retailer**	**Consumer**	**Service provider**	**Consumer**	**Consumer**	**Reference**
27	Product damage due to bad roads conditions and lack of a protector packaging.			✓					Arivazhagan et al. (2016)
28	Packaging design favouring food spoilage (for example: it favours the spread of a disease among food units, it hampers food extraction…).			✓		✓		✓	Wohner et al. (2020)
29	Stocking policy favouring overstock, which leads to food waste generation.			✓		✓			Teller et al. (2018)
30	In order to obtain discounts oversised orders are placed, which leads to overstocking.			✓		✓			Institution of Mechanical Engineers (2013)
31	Our sales strategy promotes the stock of an excessive amount of products during promotions, which leads to food waste generation.			✓					Diaz-Ruiz et al. (2018)
32	Overstocking due to offering a wide variety of products.			✓		✓			Diaz-Ruiz et al. (2018)
33	The purchasing strategy exempts the company from the responsibility of food surplus generation (take-back agreements).			✓		✓			Ghosh & Eriksson (2018)
34	Keeping total on-shelf availability of products, which leads to overstocking.			✓					Teller et al. (2018)
35	Improper manipulation of fresh food by consumers.			✓					Diaz-Ruiz et al. (2018)
36	Weather fluctuations changing expected consumers' orders.			✓		✓			Mena et al. (2011)
37	Food waste due to spills and other mishandling by the employees.			✓		✓			Proposed by the authors of this article.
38	The product is not chosen because its image is not attractive enough (ugly food).				✓		✓	✓	Diaz-Ruiz et al. (2018)
39	Consumers purchase/order/take more food because they don't calculate well the quantity they will eat.				✓		✓		Diaz-Ruiz et al. (2018)
40	Consumers' diets don't allow them to eat some edible parts of the food they purchase/order/take.							✓	Diaz-Ruiz et al. (2018)
41	The amount of leftovers is so small that is not worth keeping.						✓	✓	Proposed by the authors of this article.
42	The packaging design is inadequate for food preservation once opened.					✓		✓	Proposed by the authors of this article.
43	Consumers don't make an adequate purchasing plan.					✓		✓	Diaz-Ruiz et al. (2018)
44	The difference between "use by" and "best before" dates is not always clear to consumers.					✓		✓	Diaz-Ruiz et al. (2018)
45	Kitchen staff or consumers cook/order/take more than necessary because they don't calculate well the quantity they will cook/they don't have to pay more for it.					✓	✓	✓	Diaz-Ruiz et al. (2018)
46	Kitchen staff or consumers don't know how to make the most of the leftovers.					✓		✓	Diaz-Ruiz et al. (2018)
47	Kitchen staff or consumers' ways to preserve food is inefficient.					✓		✓	Diaz-Ruiz et al. (2018)
48	Even if consumers know how, they don't make the most of food because of their limited cooking abilities.					✓		✓	Diaz-Ruiz et al. (2018)
49	Consumers' lack of time to cook more efficiently.					✓		✓	Proposed by the authors of this article.
50	The packaging size obliges me to buy more food than needed.					✓		✓	Proposed by the authors of this article.
51	The menu's flexibility/description doesn't fit my diet/taste.						✓		Proposed by the authors of this article.

(*continued on next page*)

Table 2 (*continued*)

Cause of FLW/food surplus generation		**PP**	**P&M**	**RDF**		**RFS**		**HH**	
N°	**Cause**	**Primary producer**	**Processor or manufacturer**	**Wholesaler or retailer**	**Consumer**	**Service provider**	**Consumer**	**Consumer**	**Reference**
52	Consumers don't take into account the "use by" date when managing the fridge/pantry.					✓		✓	Proposed by the authors of this article.
53	Consumers don't have the possibility to bring the leftovers home.						✓		Proposed by the authors of this article.
54	Pests and diseases.	✓							Joardder & Masud (2019)
55	Presence of inedible parts.	✓	✓	✓		✓	✓	✓	Teigiserova et al. (2019)

Table 3
Destinations and FSC stakeholders to which they are applicable.

Destination	FLW hierarchy level	PP	P&M	RDF	RFS		HH
		Primary producer	Processor or manufacturer	Wholesaler or retailer	Service provider	Consumer	Consumer
Improvement of the supply chain efficiency	Prevention	✓	✓	✓	✓		
Consumer behaviour change	Prevention					✓	✓
FLW prevention governance	Prevention	✓	✓	✓	✓	✓	✓
Sales with promotion and discounts	Prevention	✓	✓	✓	✓		
Sales in secondary markets	Prevention	✓	✓	✓			
Internal distribution	Prevention	✓	✓	✓	✓		
Marketing actions and sponsorships	Prevention	✓	✓	✓	✓		
Donation	Prevention	✓	✓	✓	✓		✓
Animal feeding	Prevention	✓	✓	✓	✓	✓	✓
Remaking the same product	Recycling	✓	✓	✓			
Revalorise FLW into new food products	Recycling	✓	✓	✓	✓	✓	✓
Revalorise FLW into added value products	Recycling	✓	✓	✓	✓	✓	✓
Left in the field	Recycling	✓					
Ploughing back into the soil	Recycling	✓					
Composting	Recycling	✓	✓	✓	✓	✓	✓
Anaerobic digestion	Recycling	✓	✓	✓	✓	✓	✓
Gasification	Recovery	✓	✓	✓	✓	✓	✓
Pyrolysis	Recovery	✓	✓	✓	✓	✓	✓
Incineration with energy recovery	Recovery	✓	✓	✓	✓	✓	✓
Incineration without energy recovery	Disposal	✓	✓	✓	✓	✓	✓
Landfill	Disposal	✓	✓	✓	✓	✓	✓
Drained as or with wastewaters	Disposal	✓	✓	✓	✓	✓	✓

study results, organised by the stages of the FSC and utilising NACE codes along with the PoGs previously identified. The tables indicate that certain PoGs recorded zero FLW generation based on the data provided by the partners. Specifically, at FL03 zero kilograms of FLW were reported in the studied period for the target product. Similarly, FL05 and FL06 (included in the same dataset) were found to generate no FLW since the lettuces used in the prepared salad are also utilised in other salads produced by the same company, ensuring no wastage at that point. Additionally, during the studied period, no other ingredients were wasted in FL09, such as chicken meat, cheese, or bread. Regarding FL10, the producer company stated that most of the problems in this PoG have been resolved and that minimal FLW is generated. They also mentioned that this minimal FLW is already quantified in other PoGs. Last, FW13 produced such a negligible amount of FLW that it is not quantifiable according to the retailer company.

As observed in the tables, the studied FSC demonstrates a high level of efficiency in terms of FLW/food surplus generation. Which leaves little room for improvement. Only FL08, FW14, and FW15 exceed 10% of FLW/food surplus generated relative to the food input. Distributing the food surplus and FLW generated in the baseline across the FSC stages, the results obtained are depicted in Fig. 2.

P&M is the FSC stage where most FLW is avoided in the case study, accounting for 60.52% of the total. At FL08, the main contributor in this stage, this is primarily due to the removal of the inedible parts of lettuce during processing. However, most of this food is diverted to animal feeding, which falls into the prevention level and is thus considered FLW avoided. The second highest contributor is the RDF stage, which contributes 33.31% to FLW avoided. Here FW14 shows that demand forecasting errors are responsible for 97% of the FLW/food surplus generated at that PoG. Although in this case more than half of it is either donated or sold with a discount, avoiding wastage. The results obtained for FW14 support the earlier observation that the FLW classification proposed by Caldeira et al. (2019) could be refined by distinguishing between actions that directly address the root causes of FLW (solutions at the PoG) and those that do not. In this case, price discounts were already implemented at PoG FW14, where inaccurate demand forecasting was identified as the root cause of FLW for that specific flow.

Households are clearly where most FLW is generated, accounting for 61.94% of the total. In this PoG (FW15), consumers waste approximately 12% of the salad mass purchased, primarily due to appearance related issues. And this FLW is managed mostly by bumping it into the residual waste bin, which will end up in landfill. In second place, the RDF stage appears again, being responsible for 27.01% of the total FLW generated. When examining this KPI, the results are comparable to some degree to the FLW reported by the European Union (Eurostat, 2025). The disparity mainly arises in the P&M and RDF stages. Although it is

Table 4
Results of the quantification KPIs in the baseline.

FSC stage (NACE code)	PoG code	Cause of FLW /food surplus generation	% FLW or food surplus	Destination
Primary production (A1.1.3 - Growing of vegetables and melons, roots and tubers)	FL01	-	-	-
	FL02	1 - Lack of/inaccurate demand forecasting 54 - Pests and diseases	0.31%	Left in the field
	FL03	15 - Food aspect requirements self-imposed by stakeholders (clients, consumers…).	0.00%	Animal feeding
	FL04	1 - Lack of/inaccurate demand forecasting	1.36%	Left in the field
		4 - Inadequate climate conditions	0.86%	
		54 - Pests and diseases	0.81%	
	FL05	1 - Lack of/inaccurate demand forecasting	0.33%	Animal feeding
Processing and manufacturing (C10.3.9 - Other processing and preserving of fruit and vegetables)	FL06	15 - Food aspect requirements self-imposed by stakeholders (clients, consumers…).	0.00%	Animal feeding
	FL07	1 - Lack of/inaccurate demand forecasting	0.00%	Animal feeding
	FL08	55 - Presence of inedible parts.	22.35%	Animal feeding
	FL09	19 - Cold chain interruptions	0.00%	Landfill
		25 - If there is an excessive delay, the product is withdrawn prematurely.		Landfill
	FL10	6 - Products are damaged due to bad practices in some process (harvesting, cleaning, screening, processing…).	0.00%	Landfill
	FW11	1 - Lack of/inaccurate demand forecasting	0.10%	Donation
			0.03%	Vending for staff
		14 - Food quality and aspect requirements in standards and policies	0.00%	Landfill
	FW12	19 - Cold chain interruptions	0.09%	Landfill
Retail and other distribution of food (G47.1.1 - Retail sale in non-specialised stores with food, beverages or tobacco predominating)	FW13	-	-	-
	FW14	1 - Lack of/inaccurate demand forecasting	4.48%	Landfill
		28 - Packaging design favouring food spoilage	0.01%	
		19 - Cold chain interruptions	0.00%	
		15 - Food aspect requirements self-imposed by stakeholders (clients, consumers…).	0.01%	
		14 - Food quality and aspect requirements in standards and policies	0.23%	
		1 - Lack of/inaccurate demand forecasting	0.35%	Donation
			6.31%	Sold with a discount in price
Households	FW15	38 - The product is not chosen because its image is not attractive enough (ugly food).	1.12%	Animal feeding
			1.62%	Composting
			3.03%	Landfill
		43 - Consumers don't make an adequate purchasing plan.	0.18%	Composting
			0.34%	Landfill
		47 - Kitchen staff or consumers' ways to preserve food is inefficient.	0.25%	Composting
			0.47%	Landfill
		28 - Packaging design favouring food spoilage	1.29%	Composting
			2.41%	Landfill
		41 - The amount of leftovers is so small that is not worth keeping.	0.65%	Composting
			1.22%	Landfill

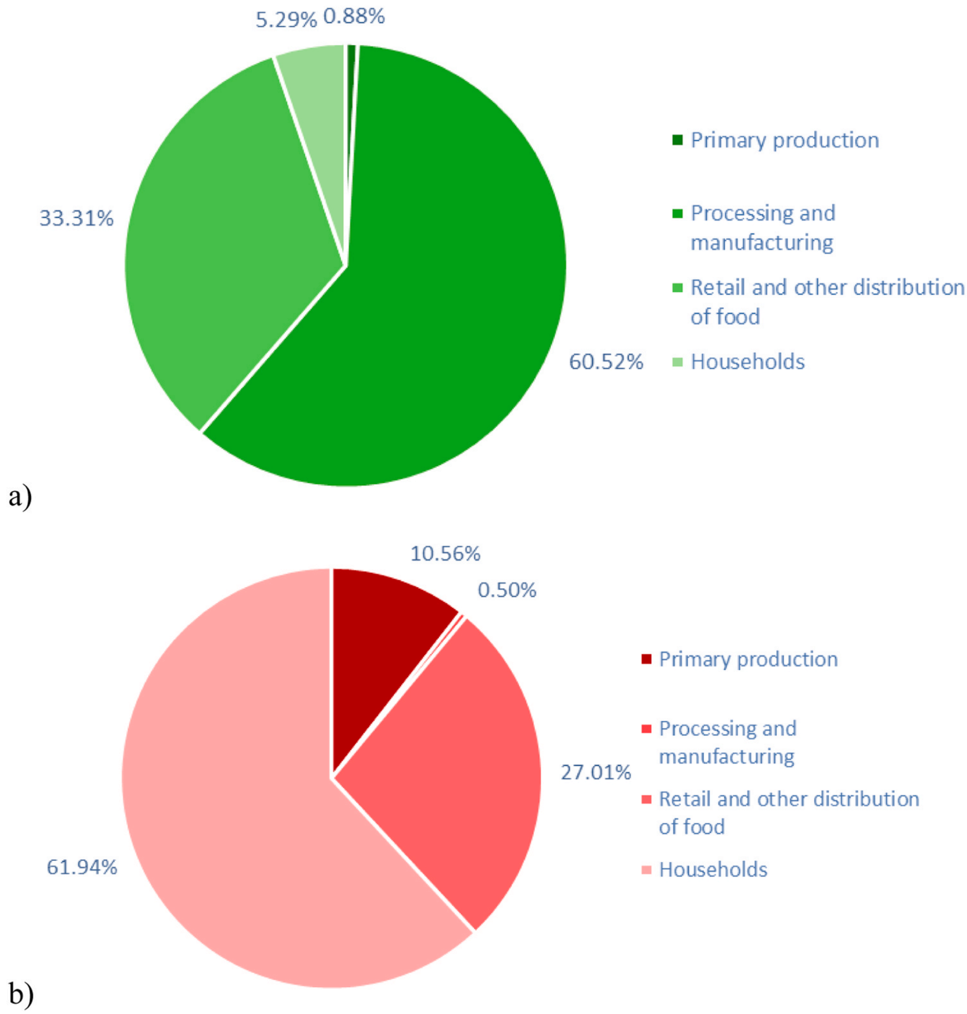

Fig. 2. a) FLW avoided per FSC stage. B) FLW generated per FSC stage.

important to note that this case study focuses on a specific product, whereas the EU results encompass the total FLW generated by all types of food products in the EU. This broader perspective may explain a notable portion of the difference.

Regarding the FLW circularity index, the sensitivity analyses performed resulted in the graph shown in Fig. 3. The analysis compared the standard deviation of the index values under both baseline conditions and several what-if improvement scenarios.

The results showed that when assigning weighting factors of approximately 0.8 for recycling and 0.55 for recovery, the standard deviation across the countries remained relatively stable (around 0.27) between baseline and what-if conditions. In contrast, other combinations (such as assigning 0.9 and 0.1 or 0.2 and 0.1 to recycling and recovery, respectively) produced greater variability between scenarios, reducing the comparability of results.

On the other hand, the weighting factors derived from the analysis of Albizzati et al. (2021) were 0.8041 for recycling and 0.5509 for recovery. These values were obtained by analysing the results of their sustainability performance assessment, which evaluated the environmental, social, and economic impacts of different FLW destinations from a life cycle perspective. The results indicated that in general terms recycling performed better than recovery, aligning with the hierarchy's logic that prioritises material circularity over energy recovery. Importantly, these values closely match those obtained through the sensitivity analysis (approximately 0.8 and 0.55, respectively), which further supports their suitability as the weighting factors. Using these values is therefore consistent with the waste hierarchy and allows for greater comparability across case studies.

The calculation of the KPIs with the digital tools enabled the following diagnosis of the case study, where both critical points and possibilities for improvement were identified.

With the FLW monitoring solution for the FSC both the producer and the retailer's systems were assessed. For the producer, which covered both PP and P&M stages, although 12 PoGs were identified during the analysis, only 4 of them (FL02, FL04, FW11, and FW12) actually resulted in the generation of FLW or a food surplus. The food losses due to production line performance emerges as the primary source of FLW/food surplus generation, constituting 84% of the total generated at these stages. In terms of underlying causes, the presence of inedible parts accounts for a significant 47% of this issue. Considering all FLW generated and food surplus, it is noteworthy that most of it (51%) is sent to animal feeding. The FLW circularity index score obtained in this case was 0.906.

At the RDF stage, only one PoG was identified as an actual point of FLW generation in the retailer's facilities (FW14) according to the data. This PoG corresponds to the storage process at the retail point, specifically the supermarket shelves. The predominant issue contributing to FLW and food surplus in this scenario is inaccurate demand forecasting, accounting for a significant 98% of FLW mass in this stage. The destination for a large portion of this FLW/food surplus, approximately 59%, is the application of discounts to sell the salads to end consumers. The index score obtained for this stage was 0.833.

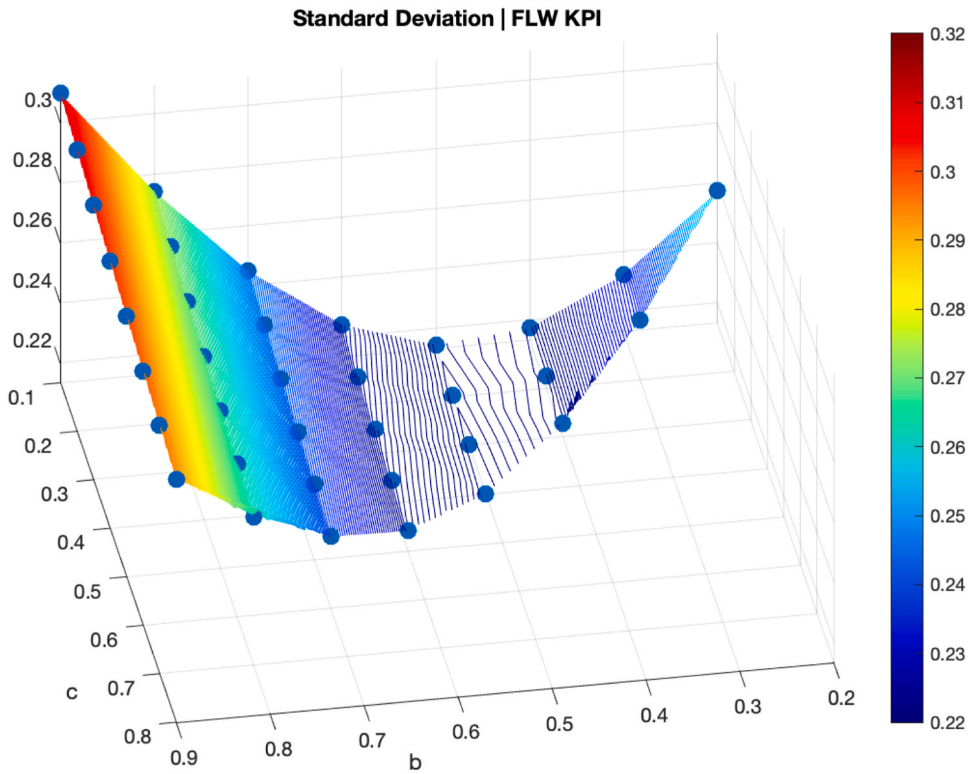

Fig. 3. Standard deviation of the 6 case studies for different weighting factors of recycling (b) and recovery (c).

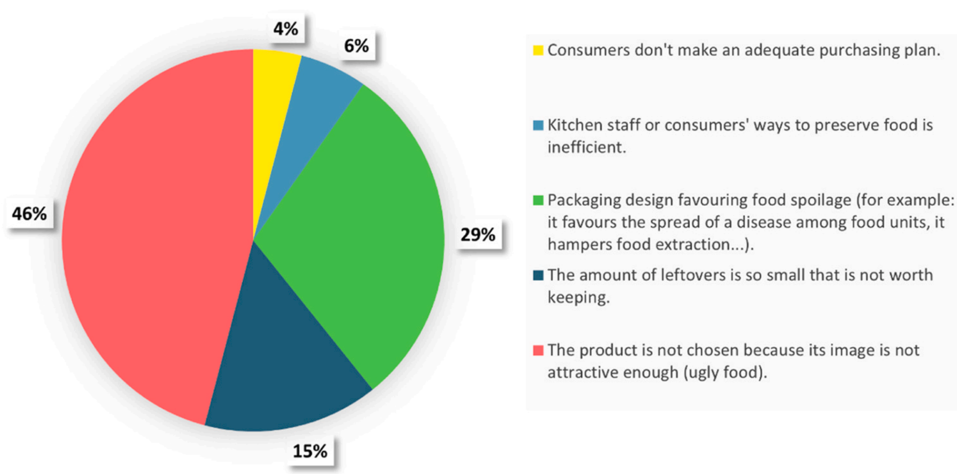

Fig. 4. Cause distribution at the HH stage.

Moving to the HH stage, which assessment was carried out with the FLW monitoring solution for the consumption stage, a total of 10 families were monitored in a municipality within the Basque Country. Over a 4-month period, during which the program was active, a total of 1758 g of salad were quantified as either FLW or food surplus. This amount represented 3.77% of the salads purchased by the studied families. The main reasons for this were concerns related to the appearance of the salad and packaging issues (Fig. 4). The index score obtained for this stage was 0.344.

4. Conclusions

The methodology proposed in this study provides a robust and standardised approach to quantify FLW. Grounded in the specifications of Delegated Decision 2019/1597 (European Commission, 2019), the proposed framework introduces refinements in definitions and quantification methodologies that enhance representativeness and enable a more realistic measurement of progress towards SDG 12.3. By integrating food characteristics, root causes and destinations based on scientific literature, the framework enriches the FLW quantification process, supporting a more exhaustive identification of FLW prevention opportunities and the evaluation of its performance according to the FLW hierarchy. More specific conclusions include:

1. The definitions used for the reference terms in the FLW domain ensure FLW quantification in alignment with the European regulatory framework. However, these definitions extend beyond such regulations by including preharvest FLW and FLW collected in other

waste fractions, which is essential for a representative quantification of FLW. Additionally, the precise classification of edible/inedible and eatable/uneatable food is essential for identifying prevention opportunities in line with the FLW hierarchy. Last, the use of the term "food surplus" provides the framework with a social criterion needed to encourage redistribution actions.
2. The standardised list of causes effectively categorises the diverse reasons for FLW/food surplus generation across FSC stages, attributing responsibility to specific stakeholders. This detailed list of causes has proven essential for determining the appropriate solutions for each PoG and quantifying the FLW that can be effectively addressed and potentially avoided by them.
3. The standardised list of destinations maintains consistency by adhering to the terminology of the hierarchy levels outlined in the Waste Framework Directive and aligns with the JRC's approach to classifying FLW prevention actions. This consistency provided a solid foundation for classifying the quantified FLW/food surplus flows in the case study, avoiding contradictions and ensuring a scientifically sound approach.
4. The quantification of FLW following the proposed methodological framework, supported by the presented digital tools, provides stakeholders with a structured and standardised approach to measuring FLW in alignment with current EU regulatory frameworks. Moreover, it enables comparability across case studies by ensuring a harmonised approach to causes and destinations. While the study proposes well-founded definitions of key concepts, the final selection of definitions remains at the choice of the user. To ensure transparency and comparability across case studies, it is essential to document these choices explicitly. This approach enhances the robustness of FLW quantification, reinforcing the reliability of the methodology and its applicability across diverse contexts.

Limitations and future work

Although this framework represents an advance over the current state of the art, several areas for improvement remain. Regarding definitions, while the proposed criteria are justified and contribute to standardising measurement, cultural differences continue to be an unavoidable source of variation. Moreover, because data entry ultimately relies on the user (regardless of the tool employed) some degree of subjectivity persists. To minimise this and achieve fully objective data collection, the use of robotic or AI-based tools could be a promising avenue (Musslick et al., 2025).

The standardised list of causes of FLW and food surplus generation proposed in this study establishes a solid foundation for identifying the underlying factors contributing to FLW. However, future work could aim to confirm that all identified causes are indeed root causes, and that no root causes have been overlooked. To achieve this, an exhaustive methodological approach could be employed particularly by enhancing and systematically applying the "5 Whys" methodology (Williams, 2001). This iterative questioning technique, when combined with a structured validation exercise involving FSC stakeholders, could lead to a more comprehensive and precise identification of root causes. Alongside a testing exercise with FSC actors, this approach would elaborate a more comprehensive list of causes. Further refinement could also benefit from the EFFICIENT protocol proposed by Kok et al. (2021), which categorises causes into three hierarchical levels (micro, meso, and macro) and defines relationships between them. Implementing this framework would not only enhance the structure of the cause list but also improve the identification of targeted FLW prevention actions, as each hierarchical level aligns with specific intervention measures.

In addition, the analysis highlights the need for greater conceptual consistency between the FLW destination categories defined by Caldeira et al. (2019) and the hierarchical definitions established in the Waste Framework Directive. These refinements would contribute to a more accurate interpretation of prevention performance and support the harmonisation of European methodologies for FLW assessment.

Concerning the circularity index, its accuracy would benefit from destination-specific rather than level-based weighting factors. This requires analysing a larger number of case studies, particularly those involving prevention actions, which are still relatively understudied. Additionally, exploring how these factors (and the resulting index values) may vary across different food categories would also be of interest.

CRediT authorship contribution statement

M. Amador-Cervera: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing and Visualization. **J. Legarda Macon:** Conceptualization and Investigation. **A. Alonso Vicario:** Conceptualization, Methodology, Validation, Investigation, Resources, Supervision, Project Administration and Funding acquisition.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT in order to improve the clarity and readability of the text. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

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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.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.clwas.2026.100556.

Data availability

The data that has been used is confidential.

References

Afzal, N., Basit, A., Daniel, A., Ilyas, N., Imran, A., Awan, Z.A., Papargyropoulou, E., Stringer, L.C., Hashem, M., Alamri, S., Bashir, M.A., Li, Y., Roy, N., 2022. Quantifying food waste in the hospitality sector and exploring its underlying reasons—A case study of Lahore, Pakistan. Sustainability 14 (11), 6914. https://doi.org/10.3390/su14116914.

Albizzati, P.F., Tonini, D., Astrup, T.F., 2021. A quantitative sustainability assessment of food waste management in the European Union. Int. J. Geogr. Inf. Sci. 55 (23), 16099–16109. https://doi.org/10.1021/acs.est.1c03940.

AL-Dalaeen, Q.R., Sivarajah, U., Irani, Z., 2021. Determining sustainability key performance indicators for food loss reduction. J. Enterp. Inf. Manag. 34 (3), 733–745. https://doi.org/10.1108/jeim-04-2021-424.

Alonso-Muñoz, S., García-Muiña, F.E., Medina-Salgado, M.-S., González-Sánchez, R., 2022. Towards circular economy practices in food waste management: a retrospective overview and a research agenda. Br. Food J. 124, 478–500. https://doi.org/10.1108/BFJ-01-2022-0072.

Alshabanat, Z., Alkhorayef, A., Ben Haddad, H., Mezghani, I., Gouider, A., Tlili, A., Allouche, M.A., Gannouni, K.A., 2021. Quantifying Food Loss and Waste in Saudi Arabia. Sustain. (Basel Switz.) 13 (16), 9444. https://doi.org/10.3390/su13169444.

Amador-Cervera, M., Angarita-Zapata, J.S., de la Calle Vicente, A., Alonso-Vicario, A., 2024. The FOODRUS index: Assessing suitability for effective food loss and waste prevention management under an integral perspective. Waste Manag. (New. Y. N. Y.) 179, 32–43. https://doi.org/10.1016/j.wasman.2024.02.050.

Amador-Cervera, M., Scherhaufer, S., Gollnow, S., Alonso-Vicario, A., 2025. Carbon and water footprint of food loss and waste prevention actions: Cradle-to-grave life cycle assessment of a prepared salad, 145331 J. Clean. Prod. 501, 145331. https://doi.org/10.1016/j.jclepro.2025.145331.

Amicarelli, V., Rana, R., Lombardi, M., Bux, C., 2021. Material flow analysis and sustainability of the Italian meat industry. J. Clean. Prod. 299, 126902. https://doi.org/10.1016/j.jclepro.2021.126902.

Amicarelli, V., Roe, B.E., Bux, C., 2022. Measuring Food Loss and Waste Costs in the Italian Potato Chip Industry Using Material Flow Cost Accounting. Agric. (Basel) 12 (4), 523. https://doi.org/10.3390/agriculture12040523.

Arivazhagan, R., Geetha, P., Ravilochanan, P., 2016. Assessment of wastages in fruit supply chain with respect to fruit processing units in Tamilnadu, India. Int. Food Res. J. 23 (2), 723–732.

Balaji, M., Arshinder, K., 2016. Modeling the causes of food wastage in Indian perishable food supply chain. Resour. Conserv. Recycl. 114, 153–167. https://doi.org/10.1016/j.resconrec.2016.07.016.

Beausang, C., Hall, C., Toma, L., 2017. Food waste and losses in primary production: Qualitative insights from horticulture. Resour. Conserv. Recycl. 126, 177–185. https://doi.org/10.1016/j.resconrec.2017.07.042.

Bedoya-Perales, N.S., Dal' Magro, G.P., 2021. Quantification of Food Losses and Waste in Peru: A Mass Flow Analysis along the Food Supply Chain. Sustain. (Basel Switz.) 13 (5), 2807. https://doi.org/10.3390/su13052807.

Bengtsson, M., Alfredsson, E., Cohen, M., Lorek, S., Schroeder, P., 2018. Transforming systems of consumption and production for achieving the sustainable development goals: moving beyond efficiency. Sustain. Sci. 13 (6), 1533–1547. https://doi.org/10.1007/s11625-018-0582-1.

Caldeira, C., De Laurentiis, V., Sala, S., 2019. Assess. Food Waste Prev. Actions. https://doi.org/10.2760/9773.

Chauhan, C., Dhir, A., Akram, M.U., Salo, J., 2021. Food loss and waste in food supply chains. A systematic literature review and framework development approach. J. Clean. Prod. 295, 126438. https://doi.org/10.1016/j.jclepro.2021.126438.

De Laurentiis, V., Caldeira, C., Sala, S., 2020. No time to waste: assessing the performance of food waste prevention actions, 104946 Resour. Conserv. Recycl. 161, 104946. https://doi.org/10.1016/j.resconrec.2020.104946.

Diaz-Ruiz, R., Costa-Font, M., López-i-Gelats, F., Gil, J., 2018. A Sum of Incidentals or a Structural Problem? The True Nature of Food Waste in the Metropolitan Region of Barcelona. Sustainability 10 (10), 3730. https://doi.org/10.3390/su10103730.

European Commission. (2008). Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32008L0098.

European Commission. (2019). Commission Delegated Decision (EU) 2019/1597 of 3 May 2019 supplementing Directive 2008/98/EC of the European Parliament and of the Council as regards a common methodology and minimum quality requirements for the uniform measurement of levels of food waste. https://eur-lex.europa.eu/eli/dec_del/2019/1597/oj.

European Commission. (2021). Guidance on reporting of data on food waste and food waste prevention according to Commission Implementing Decision (EU) 2019/2000. https://ec.europa.eu/eurostat/documents/342366/351811/Guidance+on+food+waste+reporting/5581b0a2-b09e-adc0-4e0a-b20062dfe564.

European Commission (2002), 2002. Regulation (EC) No 178/2002 of the European Parliament and of the Council of 28 January 2002 laying down the general principles and requirements of food law, establishing the European Food Safety Authority and laying down procedures in matters of food safety. Off. J. Eur. Communities 1–24. https://eur-lex.europa.eu/eli/reg/2002/178/oj/eng.

Eurostat. (2025). Food waste and food waste prevention - estimates - Statistics Explained. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Food_waste_and_food_waste_prevention_-_estimates#Amounts_of_food_waste_at_EU_level.

FAO. (2014). SAVE FOOD: Global Initiative on Food Loss and Waste Reduction Definitional framework of food loss. https://www.ipcinfo.org/fileadmin/user_upload/save-food/PDF/FLW_Definition_and_Scope_2014.pdf.

FAO, 2023. *Technical Platform on Food Loss and Waste Reduction*. United Nations. https://www.fao.org/platform-food-loss-waste/en/.

Fernandez-Zamudio, M.-A., Barco, H., Schneider, F., 2020. Direct Measurement of Mass and Economic Harvest and Post-Harvest Losses in Spanish Persimmon Primary Production. Agric. (Basel) 10 (12), 581. https://doi.org/10.3390/agriculture10120581.

Filimonau, V., De Coteau, D.A., 2019. Food waste management in hospitality operations: A critical review. Tour. Manag. 71, 234–245. https://doi.org/10.1016/j.tourman.2018.10.009.

FUSIONS. (2016). Food waste definition. https://www.eu-fusions.org/index.php/about-food-waste/280-food-waste-definition.

Garcia-Garcia, G., Woolley, E., Rahimifard, S., Colwill, J., White, R., Needham, L., 2017. A methodology for sustainable management of food waste. Waste Biomass-.-. Valoriz. 8 (6), 2209–2227. https://doi.org/10.1007/s12649-016-9720-0.

Garrone, P., Melacini, M., Perego, A., Sert, S., 2016. Reducing food waste in food manufacturing companies. J. Clean. Prod. 137, 1076–1085. https://doi.org/10.1016/j.jclepro.2016.07.145.

Ghosh, R., Eriksson, M., 2018. Food waste due to retail power in supply chains: Evidence from Sweden. Glob. Food Secur. 20, 1–8. https://doi.org/10.1016/j.gfs.2018.10.002.

Gillman, A., Campbell, D., Spang, E., 2019. Does on-farm food loss prevent waste? Insights from California produce growers. Resour. Conserv. Recycl. 150. https://doi.org/10.1016/j.resconrec.2019.104408.

Girotto, F., Piazza, L., 2022. Food waste bioconversion into new food: A mini-review on nutrients circularity in the production of mushrooms, microalgae and insects. Waste Manag. Res. 40 (1), 47–53. https://doi.org/10.1177/0734242X211038189.

Gustavsson, J., Cederberg, C., Sonesson, U., van Otterdijk, R., Meybeck, A., 2011. Global food losses and food waste – Extent, causes and prevention. Technical Report Food and Agriculture Organization of the United Nation.

Hanson, C., Lipinski, B., Robertson, K., Dias, D., Gavilan, I., Greverath, P., Ritter, S., Fonseca, J., Van Otterdijk, R., Timmermans, T., Lomax, J., O'connor, C., Dawe, A., Swannell, R., Berger, V., Reddy, M., Somogyi, D., Tran, B., Leach, B., & Quested, T. (2016). Food Loss and Waste Accounting and Reporting Standard. In Policy File. https://flwprotocol.org/wp-content/uploads/2017/05/FLW_Standard_final_2016.pdf.

Herrera-Quinteros, G., Jara-Rojas, R., 2023. Food losses perceived by family farms: Challenges and policy implications from a micro-approach quantification. Front. Sustain. Food Syst. 6. https://doi.org/10.3389/fsufs.2022.961120.

Institution of Mechanical Engineers. (2013). Global Food: Waste Not, Want Not. https://www.imeche.org/policy-and-press/reports/detail/global-food-waste-not-want-not.

Ioannou, A., Georgali, P.-Z., Fokaides, P.A., 2022. Quantification of food waste in an insular island state for all stages of the food supply chain. Resour. Conserv. Recycl. 185, 106486. https://doi.org/10.1016/j.resconrec.2022.106486.

Joardder, M.U.H., Masud, M.H., 2019. Causes of food waste. Food Preservation in Developing Countries: Challenges and Solutions. Springer International Publishing, pp. 27–55.

Kaipia, R., Dukovska-Popovska, I., Loikkanen, L., 2013. Creating sustainable fresh food supply chains through waste reduction. Int. J. Phys. Distrib. & Logist. Manag. 43 (3), 262–276. https://doi.org/10.1108/ijpdlm-11-2011-0200.

Kok, M.G., Castelein, R.B., Broeze, J., Snels, J.C.M.A., 2021. A pragmatic and integrated methodology for food loss and waste quantification, analysis of causes and intervention design. EFFICIENT Protoc. https://doi.org/10.18174/556214.

Mena, C., Adenso-Diaz, B., Yurt, O., 2011. The causes of food waste in the supplier–retailer interface: Evidences from the UK and Spain. Resour. Conserv. Recycl. 55 (6), 648–658. https://doi.org/10.1016/j.resconrec.2010.09.006.

Mizuyama, H., Yamaguchi, S., Suginouchi, S., Sato, M., 2022. Simulation-based game theoretical analysis of Japanese milk supply chain for food waste reduction. IFIP Advances in Information and Communication Technology. Springer Nature Switzerland, pp. 107–115.

Muriana, C., 2017. A focus on the state of the art of food waste/losses issue and suggestions for future researches. Waste Manag. 68, 557–570. https://doi.org/10.1016/j.wasman.2017.06.047.

Musslick, S., Bartlett, L.K., Chandramouli, S.H., Dubova, M., Gobet, F., Griffiths, T.L., Hullman, J., King, R.D., Kutz, J.N., Lucas, C.G., Mahesh, S., Pestilli, F., Sloman, S.J., Holmes, W.R., 2025. Automating the practice of science: Opportunities, challenges, and implications. Proc. Natl. Acad. Sci. USA 122 (5), e2401238121. https://doi.org/10.1073/pnas.2401238121.

Östergren, K., Gustavsson, J., Bos-Brouwers, H., Timmermans, T., Hansen, O.-J., Møller, H., Anderson, G., O'Connor, C., Soethoudt, H., Netherlands, T., Quested, T., Easteal, S., Politano, A., Bellettato, C., Canali, M., Falasconi, L., Gaiani, S., Vittuari, M., Schneider, F., & Redlingshöfer, B. (2014). FUSIONS definitional framework for food waste. Full report.

Parizeau, K., 2024. The dangers of rationalizing temporary foreign worker programs as a solution to food waste. Geoforum, 103911 J. Phys. Human. Reg. Geosci. 148, 103911. https://doi.org/10.1016/j.geoforum.2023.103911.

Peira, G., Bollani, L., Giachino, C., Bonadonna, A., 2018. The Management of Unsold Food in Outdoor Market Areas: Food Operators' Behaviour and Attitudes. Sustainability 10 (4), 1180. https://doi.org/10.3390/su10041180.

Pinto, J., Boavida-Dias, R., Matos, H.A., Azevedo, J., 2022. Analysis of the Food Loss and Waste Valorisation of Animal By-Products from the Retail Sector. Sustain. (Basel Switz.) 14 (5), 2830. https://doi.org/10.3390/su14052830.

Pirani, S.I., Arafat, H.A., 2016. Reduction of food waste generation in the hospitality industry. J. Clean. Prod. 132, 129–145. https://doi.org/10.1016/j.jclepro.2015.07.146.

Pires, A., Martinho, G., 2019. Waste hierarchy index for circular economy in waste management. Waste Manag. (New. Y. N. Y.) 95, 298–305. https://doi.org/10.1016/j.wasman.2019.06.014.

R. Teuber J. D. Jensen *Food losses and food waste: Extent, underlying drivers and impact assessment of prevention approaches* 2016.https://curis.ku.dk/ws/portalfiles/portal/169753425/IFRO_Report_254.pdf.

Ramaprasad, A., Kashyap, S., 2024. Definition of food consumption, loss, and waste. Sustainability 16 (11), 4846. https://doi.org/10.3390/su16114846.

Rijpkema, W.A., Rossi, R., van der Vorst, J.G.A.J., 2014. Effective sourcing strategies for perishable product supply chains. Int. J. Phys. Distrib. & Logist. Manag. 44 (6), 494–510. https://doi.org/10.1108/ijpdlm-01-2013-0013.

Sánchez López, J., Patinha Caldeira, C., De Laurentiis, V., Sala, S., & Avraamides, M. (2020). Brief on Food Waste in the European Union. In Joint Research Centre.

Tariq, H., Ali, M.H., 2026. Reducing food loss and waste within cold food supply chains – empirical evidence from developing economies. Br. Food J. (Croydon Engl.) 128 (4), 1535–1554. https://doi.org/10.1108/bfj-01-2025-0096.

Teigiserova, D., Hamelin, L., Thomsen, M., 2019. Towards transparent valorization of food surplus, waste and loss: Clarifying definitions, food waste hierarchy, and role in the circular economy. Sci. Total. Environ. 706, 136033. https://doi.org/10.1016/j.scitotenv.2019.136033.

Teller, C., Holweg, C., Reiner, G., Kotzab, H., 2018. Retail store operations and food waste. J. Clean. Prod. 185, 981–997. https://doi.org/10.1016/j.jclepro.2018.02.280.

Thanomnim, B., Papong, S., Onbhuddha, R., 2022. The Methodology to Evaluate Food Waste Generation with Existing Data in Thailand. Thai Environ. Eng. J. 36 (1), 1–9.

Tóth, K., Borbély, C., Nagy, B., Szabó-Szentgróti, G., Szabó-Szentgróti, E., 2021. Measurement of Food Losses in a Hungarian Dairy Processing Plant. Foods 10 (2), 229. https://doi.org/10.3390/foods10020229.

United Nations (2022). SDG Indicators metadata repository. https://unstats.un.org/sdgs/metadata/.

United Nations Environment Programme. (2024). Food Waste Index Report 2024. https://www.unep.org/resources/publication/food-waste-index-report-2024.

Williams, P.M., 2001. Techniques for Root Cause Analysis. Bayl. Univ. Med. Cent. Proc. 14 (2), 154–157. https://doi.org/10.1080/08998280.2001.11927753.

Wohner, B., Gabriel, V.H., Krenn, B., Krauter, V., Tacker, M., 2020. Environmental and economic assessment of food-packaging systems with a focus on food waste. Case study on tomato ketchup. Sci. Total. Environ. 738, 139846. https://doi.org/10.1016/j.scitotenv.2020.139846.

WRAP. (2018). Food waste measurement principles and resources guide. https://food.ec.europa.eu/system/files/2018-04/fw_lib_fwp-guide_food-waste-measurement_wrap-2018.pdf.

WRAP (2020). Food surplus and waste measurement and reporting. UK Guidelines. https://wrap.org.uk/resources/guide/uk-food-surplus-and-waste-measurement-and-reporting-guidelines.

WRAP. (2021). Food surplus and waste in the UK – key facts. https://wrap.org.uk/resources/report/food-surplus-and-waste-uk-key-facts.

WWF. (2021). Driven to waste: The global impact of food loss and waste on farms. https://wwfint.awsassets.panda.org/downloads/technical_report__wwf_farm_stage_food_loss_and_waste.pdf.

Zhu, L., 2017. Economic Analysis of a Traceability System for a Two-Level Perishable Food Supply Chain. Sustainability 9, 682. https://doi.org/10.3390/su9050682.