

REVIEW OF RESEARCH FRAMEWORKS AND METHODOLOGICAL APPROACHES ON FOOD LOSS AND WASTE

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Abstract

Food loss and waste (FLW) quantification is critical for addressing global food security and sustainability challenges. This systematic review evaluates 27 studies focusing on methods used to quantify FLW, highlighting the diversity in definitions, frameworks, and methodological approaches. Of these, five studies lacked any explicit FLW definition, while others referenced diverse frameworks, including the Food Loss and Waste Protocol, Food and Agriculture Organization, and other organizations such as United States Department of Agriculture, High Level Panel of Experts, and the United Nations. Multiple definitions were mentioned in some studies, reflecting a fragmented landscape. Methodologically, 14 studies employed quantitative approaches, three used qualitative methods, and 10 adopted mixed methods, underscoring the complexity of FLW research. The dominance of quantitative approaches reflects the need for objective, measurable data, while mixed methods offer a more comprehensive understanding by integrating contextual insights. This review highlights significant methodological variability and a lack of standardization in FLW definitions and measurement practices. These results underscore the necessity for standardized frameworks and methodologies to enhance comparability and effectively direct global efforts for the reduction of FLW.

Key words: food loss and waste, quantification methods, systematic review, sustainability

INTRODUCTION

Food loss and waste (FLW) represent paramount concerns that exert a profound influence on the environment, economy, and society on a global scale. The phenomenon of food loss predominantly occurs during the production, post-harvest, and processing stages, with a notably increased prevalence in developing countries due to inadequate infrastructure and technological capabilities (Economou et al., 2024) [12]. Conversely, food waste transpires at the retail and consumption levels, where food deemed suitable for human consumption is discarded, frequently because of inadequate planning and consumer behaviour (Vaško & Jalić, 2024) [52]. The Food and Agriculture Organization (FAO) approximates that nearly one-third of all food produced for human consumption is either lost or wasted each year, which equates to roughly 1.3 billion tonnes and incurs an economic cost of around \$990 billion (Handoyo & Asri, 2023) [20]. The ramifications of FLW on the

environment are considerable, as it contributes significantly to greenhouse gas emissions and the wastage of vital resources, including water and land (Economou et al., 2024) [12]. Socially, reducing FLW can enhance food security and social justice by redistributing resources to those in need (Tahmaz & Aksoy, 2024) [47]. Economically, it can lower costs for households and businesses by reducing waste disposal expenses and improving resource efficiency (Sharmila Devi & Sundareshwar, 2023) [44]. Various digital technologies, such as the Internet of Things (IoT), Blockchain Technology (BCT), and Radio Frequency Identification (RFID), are being employed to manage and reduce FLW by tracking food conditions and extending shelf life (Kusolchoo & Ueasangkomsate, 2024) [29]. Additionally, artificial intelligence and donation platforms are being developed to predict expiry dates and redistribute surplus food to the needy, respectively (Weerasooriya & Kumar, 2022) [54].

Also, the studies of dynamics of food loss and waste as well as the statistical analysis provide valuable information in this field (Nakov et al., 2020; Nijloveanu et al., 2023) [35, 37].

Bibliometric studies measure the importance of food loss and waste in literature highlighting the journals, papers, top interested countries, and authors (Ştefan, 2024) [45].

Innovative strategies are developed to reduce food loss and waste and assure a sustainable development (Moldovan, 2024) [34].

The European Union and other regulatory bodies have mandated the measurement and monitoring of FLW to align with sustainable development goals, emphasizing the need for effective waste prevention measures (Economou et al., 2024) [12]. The measurement of food loss globally is a complex issue, and currently, there is no universally standardized metric for quantifying FLW. Various studies highlight the challenges and gaps in data collection and methodology. For instance, FAO and other organizations have made significant efforts to estimate food loss, but these efforts are often hampered by inconsistent definitions, scopes, and ad-hoc data collection methods (Kitinoja et al., 2018) [27]. The Food Loss Index, developed to monitor progress towards Sustainable Development Goal (SDG) 12.3, faces challenges due to the lack of comprehensive data, which affects the robustness of the modelling approaches used to estimate annual food losses by country and commodity (Mingione et al., 2021) [33]. Additionally, the global food waste indicator, which aggregates country-wise data, suffers from variances in data collection, methodology, and presentation, with only a small percentage of data available from direct sources (Waiker et al., 2020) [53]. The literature also points out that most studies are concentrated in a few industrialized countries and often rely on secondary data, leading to high uncertainties in the global FLW database (Xue et al., 2019) [58]. Efforts to develop standardized measurement techniques are ongoing, with some studies proposing the use of robust statistical techniques and Bayesian models to improve the accuracy of food loss estimates (Mingione et al., 2021) [33]. The FOODRUS

index, for example, is a recent attempt to create a sustainability index to assess the food supply chain (FSC) performance regarding FLW, incorporating expert and stakeholder feedback (Cervera et al., 2023) [8].

Varying definitions, data-collection techniques, and reporting practices make it difficult to compare results from different studies and contexts. This lack of standardization hinders the development of effective policies and interventions, particularly in the production and processing stages where substantial amounts of FLW can occur. To facilitate this extensive examination, the subsequent research inquiries are proposed:

(1)How do existing frameworks and definitions diverge in relation to the measurement FLW during the production and processing stages of the FSC?

(2)Which methodologies (quantitative, qualitative, mixed) are most efficacious in measuring FLW, and what are their respective merits and drawbacks in diverse settings?

(3)How can emerging digital technologies contribute to the precision, scalability, and stakeholder involvement in FLW quantification methodologies?

The primary purpose of this research, therefore, is to systematically review and analyse the existing frameworks, methodologies, and tools used to measure FLW to identify the most prevalent and reliable quantification approaches and examine how inconsistencies in definitions and scope affect measurement outcomes.

MATERIALS AND METHODS

The primary objective of a systematic review is to address particular inquiries, utilizing a clearly defined, methodical, and reproducible search strategy, accompanied by criteria for inclusion and exclusion that delineate the studies to be incorporated or omitted (Gough et al., 2017) [18]. Data is subsequently encoded and extracted from the studies that are included, with the aim of synthesizing the findings and elucidating their practical applications, in addition to identifying existing gaps or discrepancies. This contribution

delineates 27 scholarly articles concerning methodologies for quantifying FLW. The preliminary search string (Table 1) and the established criteria (Table 2) for the present systematic review encompassed peer reviewed scholarly articles published in English or Romanian, which add the methods used for quantifying FLW during the production and processing stages of the FSC, and were catalogued in two prominent international databases: Web of Science and Scopus (encompassing titles, abstracts, and keywords).

Table 1. Initial search string

Topic	Search terms
Food loss and waste	"food loss" OR "food waste" OR "FLW" OR "food loss and waste"
AND	
Quantifying method	"accounting method" OR "measurement method" OR "quantif*"
AND	
FSC stage	"production" OR "post-harvest" OR "post-production" OR "harvest"
AND	
FLW setting	"ranch" OR "farm" OR "homestead" OR "agricultural holding" OR "farmstead" OR "vineyard" OR "orchard" OR "dairy farm" OR "farmyard" OR "barnyard"

Source: Author's own elaboration

Table 2. Final inclusion and exclusion criteria

Inclusion criteria	Exclusion criteria
Published 2015 – June 2024	Published before 2015
English or Romanian language	Not in English or Romanian
Empirical, primary research	Not primary research (e.g. review)
Indexed in Web of Science or Scopus	Not a journal article
Quantifying methods of FLW	No quantifying methods of FLW
Harvest, post-harvest, on-farm processing or packaging stages	Not harvest, post-harvest, on-farm processing or packaging stages
FLW occurring in farms	No FLW setting or only FLW occurring outside of farms

Source: Author's own elaboration

It was determined to restrict the selection of articles to those published in 2015 or subsequently, as this particular year marked the adoption of the 2030 Agenda for Sustainable Development by all member states of the United Nations, which established 17 global SDGs.

Furthermore, it was resolved that the corpus would be confined to articles that examine methodologies for quantifying FLW specifically during the production or post-production phases of the FSC.

Upon the completion of the established inclusion and exclusion parameters, and after the removal of redundant entries employing the statistical software R in combination with the bibliometrix package, a cumulative total of 58 potential articles were discerned for comprehensive text evaluation (Figure 1).

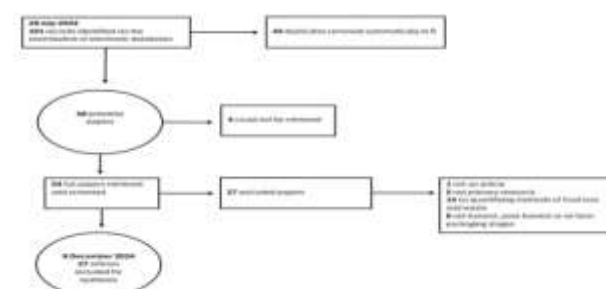


Fig. 1. PRISMA diagram

Source: modified after Brunton & Thomas (2012) [5]

Nevertheless, four articles could not be obtained via the library ordering system. Consequently, 54 articles were successfully retrieved and subjected to screening, and after the exclusion of 27 manuscripts, 27 articles were retained for synthesis.

RESULTS AND DISCUSSIONS

There was a discernible augmentation in the papers published from 2015 onwards (Figure 2). The quantity of incorporated articles expanded from none in 2015 to four in the first half of 2024, with a maximum of five articles between the years 2018 and 2022.

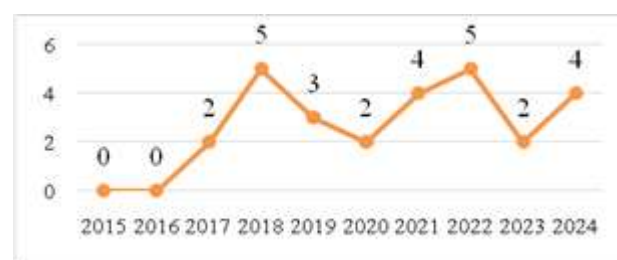


Fig. 2. Annual scientific production spanning from 2015 to June 2024

Source: Author's own calculation on the basis of data from Scopus and WoS.

The articles that comprised the sample were disseminated across 20 distinct academic journals (Table 3).

The highest frequency of publications was observed in Sustainability (n = 5), succeeded

by Resources, Conservation Recycling (n = 3) and Frontiers in Sustainable Food Systems (n = 2) show casing that only three journals have published two or more articles concerning methodologies for quantifying FLW during the stages of primary production, processing, or packaging from 2015 until June 2024.

Table 3. Number of included articles by journal

Rank	Journal	n
1	Sustainability	5
2	Resources, Conservation Recycling	3
3	Frontiers in Sustainable Food Systems	2
	others with one article	17

Source: Author's own calculation on the basis of data from Scopus and WoS.

For the geographical distribution analysis of scholarly articles (Table 4), the nation of origin of the first author was utilized (n = 16 nations), only four nations have contributed with two or more publications, indicating that half of the total articles are derived from merely three countries: South Africa, the United States of America and Germany.

Table 4. Distribution of articles by country

Rank	Country	n
1	South Africa	5
2	USA	4
	Germany	4
3	Brazil	2
	other	12

Source: Author's own calculation on the basis of data from Scopus and WoS.

Table 5. Affiliation of the first author

Rank	Affiliation	n
1	Agriscience	6
2	Sustainable Environment	4
	Agricultural Economics	4
3	Horticultural Sciences	3
4	Agricultural Engineering	2
	not mentioned	2
5	Bioscience Engineering	1
	Public Health	1
	Social Sciences	1
	Environmental Engineering	1
	Sustainable Agriculture	1
	Science and Technology	1

Source: Author's own calculation on the basis of data from Scopus and WoS.

The affiliation of the first author was taken into consideration, researchers predominantly hail from disciplines directly tied to agriculture and environmental sustainability (Table 5).

Among the 27 articles, most authors (n = 6) are affiliated with Agriscience departments, reflecting a strong emphasis on agricultural

research. The next most common affiliations, each appearing four times, are Sustainable Environment and Agricultural Economics, suggesting that environmental impact and economic considerations play key roles in how researchers approach FLW. Horticultural Sciences (n = 3) and Agricultural Engineering (n = 2) further expand the agricultural and technical focus of FLW studies. Meanwhile, a smaller group of authors representing Bioscience Engineering, Public Health, Social Sciences, and other fields highlights the interdisciplinary nature of FLW research, encompassing health, social factors, and engineering solutions. Overall, the distribution underscores that FLW quantification research is primarily conducted by specialists in agriculture-related fields, with notable contributions from environmental, economic, and social science perspectives. This multidisciplinary backdrop reflects the complex and wide-reaching implications of FLW, from on-farm production techniques to broader sustainability and public health considerations. A plethora of references and criteria for delineating FLW were discerned, revealing considerable discrepancies in methodology and precision (Table 6). It is noteworthy that five scholarly articles failed to cite any established definitions of FLW or to propose their own conceptualizations (Kumar & Underhill, 2019; Blanckenberg et al, 2021; Blanckenberg et al, 2022; Alzubi et al., 2023; Onwude et al., 2024) [28, 2, 3, 1, 39], while others referenced more than one definition, thereby indicating a potential deficiency in coherence or cognizance concerning standardized terminologies. This absence of reference may either signify an assumption of shared comprehension or reflect a shortcoming in methodological rigor within these investigations.

Table 6. Distribution of articles by definition, multiple mentions possible

Rank	Origin of the definition	n
1	FAO	11
2	FLW Protocol	10
3	No definition	5
4	FUSIONS	4
5	USEPA	2
	Other	6

Source: Author's own calculation on the basis of data from Scopus and WoS.

FAO offers precise definitions aimed at differentiating between food loss and food waste, acknowledging the distinct factors and phases at which these phenomena manifest within the FSC.

As per the FAO's classification, food loss is defined as the reduction in the quantity of edible food during the phases of production, post-harvest management, and processing within the FSC (FAO, 2019) [14]. This phenomenon is predominantly observed in developing countries and is often attributed to technical, managerial, and infrastructural limitations. In contrast, food waste pertains to the discard of edible foods at the retail and consumer levels, primarily in developed countries (FAO, 2019) [14]. This waste is largely influenced by consumer behaviour and decisions made by retailers and food service providers.

Both food loss and food waste signify substantial inefficiencies embedded within the food system, resulting in economic detriments, environmental degradation, and detrimental consequences for food security and nutritional standards (FAO, 2019) [14]. The resolution of these challenges necessitates the implementation of targeted interventions specifically designed to address the distinct causes and phases of the supply chain where losses and waste manifest.

The definitions established by the FAO were explicitly referenced in 11 articles (Parmar, 2017; Johnson et al., 2018; Fernandez-Zamudio et al., 2020; Winans et al., 2020; Cooreman-Algoed, 2022; Hook & Soma, 2022; Tóffano Pereira et al., 2022; Herrera-Quinteros & Jara-Rojas, 2023; Lana, 2023; Canan & Uluişik, 2024; Channiyamathorn et al., 2024) [43, 25, 26, 15, 55, 10, 24, 48, 22, 30, 7, 9] rendering them the most frequently cited conceptual framework among the articles subjected to review. This predominance underscores the FAO's significant role as a preeminent authority in the domains of FLW research and policy formulation.

The recurrent invocation of FAO definitions underscores their significance in establishing a uniform comprehension of FLW. By functioning as a shared reference framework, these definitions allow scholars to

contextualize their investigations within a globally acknowledged framework, thereby promoting comparability and uniformity across diverse research endeavours. This aspect is especially crucial in a domain marked by methodological and definitional inconsistencies. These definitions are particularly valued in research contexts for their alignment with global food security and sustainability priorities.

Nevertheless, the observation that the FAO definitions were cited in only 11 of the 27 studies signifies the disjointed character of FLW research, as numerous investigations depend on alternative frameworks or fail to expressly cite any definitions. This highlights the imperative for more extensive implementation and standardization to improve coherence within the discipline.

The FLW Protocol, along with its corresponding Accounting and Reporting Standard, establishes a robust framework for the measurement and reporting of food loss and waste (FLW) in a consistent manner across diverse contexts. This initiative was formulated by a collaborative partnership comprising multiple stakeholders, including the World Resources Institute (WRI), the FLW Protocol is designed to address the need for standardized methodologies in a field often characterized by fragmented and inconsistent definitions and practices. The FLW Protocol defines FLW as any food and associated inedible parts removed from the FSC that was originally intended for human consumption (WRI, 2016) [57].

The FLW Protocol enables users to delineate the parameters of their measurement endeavours (e.g., phases of the supply chain, geographical constraints, and food categories) (WRI, 2016) [57]. The framework accommodates an assortment of methodologies, including direct measurement, mass balance techniques, and surveys, thereby permitting users to identify the most suitable strategy for their specific context. Ascertaining what to incorporate within the inventory (e.g., inedible components, particular phases) can pose challenges and may differ among users. The precision of FLW quantification is significantly contingent upon the accessibility

and dependability of the foundational data, which can exhibit inconsistency across numerous regions.

In the reviewed studies, ten papers explicitly referenced the FLW Protocol (Tostivint et al., 2017; Johnson et al., 2018a, 2018b; Neff et al., 2018; Parmar et al., 2018; March et al., 2019; Caldeira et al., 2021; Opara et al., 2021a, 2021b; Dong et al., 2022) [49, 25, 26, 36, 42, 32, 6, 40, 41, 11] demonstrating its influence as a standard-setting framework in FLW research. Its comprehensive and systematic approach makes it particularly valuable for academic studies aiming for methodological rigor and comparability. The Protocol's emphasis on transparent reporting also aligns well with the scientific community's need for reproducibility and accountability.

The FLW Protocol represents a significant step toward harmonizing FLW quantification efforts, helping to bridge gaps in definitions and methodologies while fostering actionable insights for reducing FLW globally.

The Food Use for Social Innovation by Optimizing Waste Prevention Strategies (FUSIONS) initiative, which receives funding from the European Union, has established a widely acknowledged definition of FLW that has significantly impacted discourse, particularly within European frameworks. According to FUSIONS food waste consists of the disposal or alternative (non-food) utilization of both food items and inedible portions that were initially designated for human consumption (FUSIONS, 2016) [17]. This definition explicitly incorporates both edible and inedible elements, thereby underscoring a holistic methodology for FLW assessment.

The FUSIONS definition is distinguished by its focus on prevention strategies, which is congruent with the sustainability objectives delineated in EU policy frameworks. Furthermore, it facilitates harmonization among member states, thereby promoting uniformity in reporting and comparative analysis (FUSIONS, 2016) [17].

The FUSIONS definition was explicitly cited in four of these studies (Tostivint et al., 2017; March et al., 2019; Fernandez-Zamudio et al., 2020; Caldeira et al., 2021) [49, 32, 15, 6]. This

comparatively modest frequency of citation implies that although the FUSIONS framework holds considerable importance in specific geographic or contextual settings, it has not attained extensive utilization in the realm of global FLW research when juxtaposed with frameworks such as those proposed by FAO.

The limited references to definitions of FUSIONS within the examined literature indicate a regional focus, given that the FUSIONS initiative is predominantly European, its definitions may be less recognized or relevant to scholars in other locales. Considering the existence of various organizations that propose definitions of FLW, such as FAO and the FLW Protocol, researchers might select frameworks that align with their specific geographical context or the objectives of their investigations.

Despite its limited use in the reviewed papers, the FUSIONS definition remains a critical contribution to the discourse on FLW, particularly in advancing strategies for prevention and harmonized reporting across European countries. Its influence is likely stronger in studies or policies with a European context or focus on sustainability and waste prevention.

The United States Environmental Protection Agency (USEPA) provides a practical and action-oriented framework for understanding and addressing FLW, focusing on waste prevention and resource recovery. According to the USEPA, FLW encompasses food products that were designated for human consumption but have been extricated from the FSC, regardless of their edibility (surplus or spoiled food) or inedibility (peels, rinds) (USEPA, 2020) [51].

The definitions provided by the USEPA are especially pertinent for research endeavours conducted within the United States or those that concentrate on waste management strategies, as they delineate a comprehensive blueprint for the reduction of waste and the enhancement of resource recovery.

The USEPA definitions were explicitly referenced in two studies (Winans et al., 2020; Dong et al., 2022) [55, 11]. This limited citation frequency indicates that while the USEPA framework is significant, its use is

geographically concentrated and primarily relevant to research or policy work within the U.S. context.

Despite its limited global adoption, the USEPA definitions are influential in the U.S. and provide valuable guidance for reducing FLW in line with environmental sustainability goals. Their hierarchical approach offers practical solutions that are often incorporated into local, state, and federal policies, as well as corporate sustainability initiatives.

A significant variety of definitions not associated with prominent frameworks such as the FAO, USEPA, or FUSIONS were employed throughout the research landscape; these alternative definitions were referenced in six distinct studies (Ludwig-Ohm et al., 2019; Winans et al., 2020; Eičaitė et al., 2022; Herrera-Quinteros & Jara-Rojas, 2023; Lana, 2023; Canan & Uluişik, 2024) [31, 55, 13, 22, 30, 7], coming from organizations such as United States Department of Agriculture (USDA, 2024) [50], Organisation for Economic Co-operation and Development (OECD, 2024) [38], The High Level Panel of Experts (HLPE, 2014) [23] and The Waste and Resources Action Programme (WRAP, 2017) [56], also from other researchers such as Franke et al. (2016), Hafner et al. (2013), Hartikainen et al. (2018), and Strid & Eriksson (2014) [16, 19, 21, 46]. This heterogeneity underscores the fragmented and contextually contingent attributes inherent in food loss and waste (FLW) research.

A multitude of academic studies have either established or refined definitions relevant to their particular research frameworks, which encompass a focus on the discrete phases of the supply chain (Winans et al., 2020; Eičaitė et al., 2022) [55, 13], geographic locales (Ludwig-Ohm et al., 2019; Winans et al., 2020; Herrera-Quinteros & Jara-Rojas, 2023) [31, 55, 22] or specific categories of food products (Ludwig-Ohm et al., 2019; Eičaitė et al., 2022) [31, 13]. Certain research endeavours have opted for streamlined, operational definitions to meet the exigent demands of their methodologies, especially in instances where comprehensive measurement frameworks were impractical (Eičaitė et al., 2022) [13].

The absence of a universally accepted definition of FLW often compels scholars to construct their own frameworks tailored to the unique objectives of their investigations. Customized definitions facilitate the adaptation of methodologies to regional, sectoral, or institutional contexts, especially when existing international frameworks, such as those articulated by FAO, are perceived as excessively broad or convoluted. In emergent domains of FLW research, including circular economy applications or urban food systems, prevailing definitions may inadequately encompass the dynamic aspects associated with FLW.

The utilization of varied, ad hoc definitions impedes the comparability of research findings, thereby complicating efforts to synthesize or generalize results across the field. In certain instances, these definitions may not be fully articulated or may lack precision, thereby undermining the replicability and credibility of the scholarly inquiry.

The widespread presence of alternative definitions underscores a significant imperative for standardization within the domain of FLW research. Although flexibility can be advantageous in addressing distinctive contexts, a more uniform application of standardized definitions, such as those established by FAO or the FLW Protocol, would augment the comparability and efficacy of FLW studies. As the body of research on FLW continues to grow, promoting dialogue and collaboration among various stakeholders may facilitate the bridging of gaps and encourage the development of more cohesive frameworks.

A clear preference for quantitative methods emerges, with 14 papers employing these techniques to address FLW quantification (Table 7). Quantitative methods dominate due to their ability to provide objective, measurable, and replicable data—a critical aspect when attempting to capture the scope and scale of FLW accurately. This quantitative emphasis aligns well with the goals of many researchers in the field, who seek reliable, data-driven insights that can inform policies and interventions.

Table 7. Distribution of articles by methodological approach

Rank	Methodological approach	n
1	Quantitative	14
2	Mixed	10
3	Qualitative	3

Source: Author's own calculation on the basis of data from Scopus and WoS.

The use of mixed methods, seen in 10 papers, highlights a growing trend towards methodological integration. Mixed methods studies combine the precision of quantitative data with the contextual depth of qualitative findings, potentially offering a more holistic view of FLW issues. By leveraging both types of data, mixed methods provide a comprehensive approach that can enhance understanding across different dimensions of FLW.

Three studies employed qualitative methods exclusively, a smaller subset that underscores the value of in-depth, context-rich information. These approaches, though less common, offer a nuanced understanding of FLW, capturing stakeholder perspectives, socio-cultural factors, and contextual nuances that may not be easily quantified. Qualitative studies can complement quantitative approaches by offering deeper insights into the reasons behind FLW, thus broadening the scope of FLW research (Ludwig-Ohm et al., 2019; Opara et al., 2021; Hook & Soma, 2022) [31, 40, 24]. This varied approach reflects the complexity of FLW as a research topic, requiring both quantifiable data and insights into the underlying factors that contribute to waste. The examination of methodologies employed for data collection exposes a heterogeneous array of strategies utilized to quantify FLW, underlines the complexity of FLW and directly addresses the research questions regarding (1) diverse definitions and frameworks, (2) methodological strengths and limitations, and (3) the role of technology in improving FLW measurement.

Field measurement emerged as the predominant methodology, being employed in 15 investigations. This technique entails the direct, on-site acquisition of data through empirical observation, measurement, or sampling at various junctures of the FSC. Its extensive application signifies its

dependability and accuracy in capturing authentic FLW data. Nonetheless, field measurement may prove to be resource-intensive, necessitating considerable time, labour, and access to research locales, which could constrain its practicability in specific contexts.

In studies such as (Opara et al., 2021a, 2021b) [40, 41] the quantification of FLW was conducted utilizing a direct measurement methodology, which entailed the systematic identification of the underlying causes of loss in individual pomegranates. The evaluation encompassed the daily monitoring of bins containing harvested fruit, where physical examination facilitated the categorization of the fruits based on a range of defects, including sunburn, fissures, bruising, and insect infestation.

This quantification process necessitated the calculation of the fruit lost in relation to the quantity introduced into the packhouse processing line, culminating in an average loss of 328.79 t/production season at the examined packhouse (Opara et al., 2021a) [40]. The quantification process also involved interaction with farm workers to gather qualitative data during harvesting (Opara et al., 2021b) [41].

Researchers employed systematic sampling techniques to assess food loss in designated plots or field segments, focusing on unharvested, discarded, or leftover produce (Johnson et al., 2018; Fernandez-Zamudio et al., 2020; Blanckenberg et al., 2021; Blanckenberg et al., 2022; Lana, 2023) [25, 26, 15, 2, 3, 30]. The data collected from these sampled areas were extrapolated to estimate total losses across entire fields. For instance, in North Carolina's vegetable fields, researchers evaluated 68 fields across nine farms (Johnson et al., 2018) [25, 26], physically weighing unharvested crops to estimate an average of 2,909 kg/ha of marketable weight left in the field. Similarly, in South Africa, table grape losses were measured at various stages, including farm, cold storage, and retail scenarios, using portable scales (Blanckenberg et al., 2021) [3]. Harvest losses ranged from 7.5% to 23.3%, with variations attributed to

vineyard management practices and the timing of harvest.

In Ethiopia's cassava production, losses were tracked during drying and stockpiling processes. Critical loss stages were identified, with up to 50% of the produce lost due to insect infestations and inadequate storage conditions (Parmar et al., 2018) [42]. Meanwhile, a study on leafy vegetables in Brazil adapted its methods to different crop types, revealing losses that varied from 1,4% to 84,8% of plant populations, largely influenced by farming practices and market demands (Lana, 2023) [30]. In Thailand, researchers examined banana pepper production, conducting visual assessments of mechanical damage, pest infestations, and disease impacts (Channiyamathorn et al., 2024) [9]. The total loss was 55,21%, which amounted to 1,189.62 kg/rai (1,600 m²). In Canada, researchers explored the potential of app-based technology for measuring food loss (Hook & Soma, 2022) [24]. Farmers participated in training sessions to familiarize themselves with a farm management app, which they then used to record their yields and sales. This approach provided a practical and efficient method for quantifying food loss by tracking the difference between the initial harvest and recorded sales. However, a notable challenge emerged as farmers' interpretations of food loss often differed from academic definitions, introducing complexities in standardizing and quantifying the data (Hook & Soma, 2022) [24]. Despite this, the app-based method demonstrated promise as a tool for engaging farmers in the measurement process and generating valuable insights into food loss at the farm level.

Together, these studies through direct field measurements, highlight the variability in food loss across regions and crops, emphasizing the influence of management practices, environmental conditions, and market requirements. By pinpointing the causes of loss—such as sunburn, bruising, or pest damage—field measurement offers valuable, granular data that can inform standardized frameworks for FLW quantification, but also highlights practical constraints, including

labour intensity and the need for direct field access.

Survey-derived data was implemented in 13 studies, emphasizing the significance of stakeholder-reported data within FLW research. Surveys offer scalable and cost-effective mechanisms for gathering data from a multitude of participants within the FSC, including producers, retailers, and consumers. Survey-based approaches are a widely used method for quantifying FLW in research, particularly when direct field measurements or secondary data are unavailable. However, this methodology introduces challenges such as recall bias, inaccuracies arising from self-reporting, and limitations in survey design, which may compromise data integrity.

Researchers such as Eiçaitė et al. (2022) [13] used surveys to gather self-reported data from farmers in Central and Eastern Europe, focusing on on-farm losses for crops and livestock. In Chile surveys were used to obtain data from small-scale farmers to assess food losses during harvest and commercialization stages (Herrera-Quinteros & Jara-Rojas, 2023) [22].

Surveys often identify hotspots of food loss, such as harvesting inefficiencies (Kumar & Underhill, 2019; Canan & Uluişik, 2024) [28, 7] or inadequate storage and transportation (Parmar et al., 2017) [43]. They reveal stakeholder perceptions of causes, including labour shortages, market constraints, or cosmetic standards (Neff et al., 2018) [36]. Farm-level losses were attributed to incorrect spraying practices, pests, diseases, and manual harvesting errors (Canan & Uluişik, 2024) [7]. Some studies combined survey data with secondary datasets or field measurements for validation, improving robustness (March et al., 2019; Eiçaitė et al., 2022; Tóffano Pereira et al., 2022) [32, 13, 48].

Most articles report substantial food losses at various stages of the supply chain, often ranging between 15% and 30% depending on the crop or region. Vermont farms reported 16% vegetable losses (Neff et al., 2018) [36], and Fijian tomato farmers experienced 26% postharvest losses (Kumar & Underhill, 2019) [28]. Sweet potato value chains in Ethiopia showed up to 25% losses at various stages

(Parmar et al., 2017) [43]. In Turkey, farmers reported losses 2,2% and 3%, whereas at the retail stage, losses varied between 16,8% and 20,3% (Canan & Uluişik, 2024) [7].

Lack of detailed or consistent record-keeping can limit the reliability of responses. Respondents may not accurately recall the amount of food lost or wasted, leading to under or, over-estimation and perceptions of "loss" or "waste" can vary, especially when clear definitions are not provided (Neff et al., 2018) [36].

Secondary data was employed in three studies, leveraging existing government reports and industry statistics. While this approach supports broader, cross-country comparisons—aligned with efforts to explore how definitions and measurements vary under different frameworks—its reliability hinges on the quality and availability of the original datasets. Inconsistencies across sources mirror the core challenge of lacking global standardization.

The concept of material flow analysis (MFA) is distinctly employed in three articles (Caldeira et al., 2021; Cooreman-Algoed et al., 2022; Dong et al., 2022) [6, 10, 11]. MFA analyses the throughput of processes including extraction, transformation, manufacturing, consumption, recycling, and disposal. It utilizes physical unit accounts to quantify process inputs and outputs (Brunner & Rechberger, 2004) [4]. Ultimately, MFA offers a system-analytical perspective of interconnected processes to facilitate strategic management design. It can be used to track the flow of materials (food and associated losses) from production to consumption, encompassing intermediate stages like processing, distribution, and retail.

To estimate FLW in European Union countries, one study adapted MFA to the EU level, employing harmonized coefficients to compare FLW among member states (Caldeira et al., 2021) [6]. MFA was used to identify critical loss points across the FSC, including on-farm losses caused by market rejections, harvesting inefficiencies, unharvested crops, and environmental factors. It also tracked processing losses from by-products and discarded materials, as well as consumer-level

waste driven by behaviour and improper storage practices.

MFA further provided a framework to quantify FLW while linking it to environmental impacts, including greenhouse gas emissions, water usage, and energy consumption, thereby offering a comprehensive perspective on the broader implications of FLW (Caldeira et al, 2021) [6].

For instance, a Belgian case study on chicken meat combined MFA with consumer behaviour analysis, highlighting the role of packaging efficiency and household practices in contributing to FLW (Cooreman-Algoed et al., 2022) [10]. Another study focused on the U.S. FSC, integrating life cycle assessments with MFA to explore recycling and recovery opportunities, demonstrating how complementary methods can enrich FLW analysis (Dong et al., 2022) [11]. These studies relied on extensive datasets such as national waste statistics, food balance sheets, and trade data, ensuring robust and reliable estimations.

Overall, MFA emerges as a powerful tool for identifying FLW hotspots and understanding the underlying drivers of losses. By pinpointing specific stages of inefficiency, MFA enables targeted interventions and provides actionable data to design policies that enhance sustainability across food systems. These studies consistently underscore its utility in supporting the transition toward more sustainable and efficient FSCs.

Certain studies used more than one methodology, capitalizing on the advantages of each approach to enhance data quality and robustness (Parmar et al., 2017; Parmar et al., 2018; Winans et al., 2020; Alzubi et al., 2023; Channiyamathorn et al., 2024) [42, 43, 55, 1, 9]. For instance, survey-derived data may serve to complement field measurements, thereby addressing gaps or corroborating findings. This integrative methodology signifies an acknowledgment of the multifaceted nature of FLW, and the drawbacks associated with reliance on a singular approach.

The predominance of field measurement and survey-derived data accentuates the necessity for both empirical precision and stakeholder perspectives in FLW research. While direct field measurement continues to be the most

trustworthy methodology for quantifying losses, its resource-intensive characteristics may elucidate the considerable dependence on surveys and secondary data. The adoption of mixed methods illustrates an emerging trend towards methodological integration, which enriches data completeness and accuracy.

The observed heterogeneity in data collection strategies though reflective of different local contexts further validates the research purpose of identifying gaps and promoting the development of universal protocols. By systematically examining and synthesizing these approaches, the review highlights the imperative of aligning them with established or emerging frameworks, integrating digital technologies, and ensuring interdisciplinary collaboration to address the environmental, economic, and social dimensions of FLW.

CONCLUSIONS

The systematic review highlights how a broad range of FLW quantification methods—from field measurements to emerging digital platforms—responds to the multifaceted nature of FLW and the research questions regarding (1) the variability of frameworks and definitions, (2) the strengths and limitations of common data-gathering techniques, and (3) the role of digital innovation in improving measurement accuracy. Despite significant progress in developing quantification methods, persistent gaps and inconsistencies underscore the purpose of this research: to propose universal guidelines that align with existing global frameworks and to explore participatory, stakeholder-focused approaches that advance sustainability and food security goals.

The review further demonstrates that while field-based measurements, surveys, MFA, and app-based technologies can capture valuable FLW data, their application varies widely due to differences in definitions, resource availability, and technical capacity. This lack of standardization hinders comparability across studies and contexts—an issue central to the research questions aimed at improving methodological coherence. Similarly, farm management apps and IoT-based systems show

promise but are often limited by user knowledge and infrastructure constraints, suggesting that training programs, particularly in developing regions, could help overcome these barriers.

By placing educational research at the forefront, through initiatives such as universal measurement protocols, open-access tools, and participatory research modules, the findings underscore the purpose of strengthening interdisciplinary skills, bridging academic-practitioner divides, and equipping stakeholders to integrate digital solutions with on-the-ground realities. In addressing these challenges, educational initiatives can prioritize mixed-methods training, thereby enabling students and researchers to capture both the quantitative scope of losses and the qualitative factors driving FLW.

Ultimately, these strategies and tools respond directly to the research questions on standardization and methodological rigor, while also bolstering capacity-building efforts in under-researched regions. As a result, researchers, policymakers, and practitioners can more effectively compare FLW data, implement evidence-based interventions, and support the global push for sustainability and food security.

While this systematic review was conducted with utmost rigor, each review is inherently constrained by its search methodology. Although the two selected educational research databases are extensive and globally encompassing, the application of criteria restricting inclusion to peer-reviewed articles published solely in English or Romanian precluded the incorporation of research disseminated in other languages pertaining to the quantification of FLW. This limitation similarly pertains to studies presented in conference proceedings, book chapters, or grey literature, as well as articles that were not disseminated in journals indexed within the three consulted databases. Furthermore, despite the inclusion of Romanian peer-reviewed articles based on established criteria, the absence of a specific search string in the Romanian language constrains the potential to incorporate Romanian papers that were not indexed using the selected keywords. Future

investigations might contemplate employing a broader array of databases, types of publications, and languages of publication, thereby enhancing the breadth of the review. Nevertheless, significant attention would necessitate to be directed towards project resources and the feasibility of managing the review effectively.

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