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Assessing the measurement methods of post-harvest food loss and waste: opportunities and challenges

A. Shee, A. Parmar, S. Raut, B. Strum, and B. Bennett

Abstract: *Understanding the magnitude of food loss and waste (FLW), and where in the value chain it occurs, can provide policy perspectives for targeting innovations and business opportunities to reduce FLW. Since the seminal 2011 Food and Agriculture Organization (FAO) report on global FLW and the adoption of the UN Sustainable Development Goal (SDG) 12.3 (By 2030, halve per capita global food waste), there has been a surge of research efforts quantifying FLW in recent years. However, there is disagreement over how best to measure FLW. Without reliable data, it will be challenging to derive policy and action that target FLW hotspots. In this synthesis, we review the available tools for measuring FLW, their advantages and disadvantages, and comprehensively assess their ranking in terms of accuracy, cost, and meaningfulness. The methods for quantifying FLW may vary according to the stages and types of a food supply chain, for which different resources and technical capabilities are required. Therefore, a strong call to standardize FLW quantification methodologies is imperative in order to harmonize measurement tools and methods.*

Keywords: food loss, food waste, post-harvest losses, measurement methods, food security.

Introduction

Food loss and waste (FLW) reduction is an essential pathway to food and nutrition security (Food and Agriculture Organization (FAO), 2011; High Level Panel of Experts on Food Security and Nutrition (HLPE), 2020). The current global FLW has a significant impact on the environment, economy, and food security. The impact represents an estimated 8 per cent of annual greenhouse gas (GHG) emissions, an annual loss in the economy of an astounding US$940 billion, a loss of a quarter of all water used by agriculture, and a loss of 1 billion tonnes of food per year, where one in nine people are still undernourished (FAO et al., 2018). Such a large global impact of FLW is alarming. It highlights the urgent need to reduce post-harvest FLW. The recent report from the EAT-Lancet Commission (Willett et al., 2019) has

Apurba Shee, (A.Shee@greenwich.ac.uk), Natural Resources Institute, University of Greenwich, UK; Aditya Parmar, (a.parmar@ger.ac.uk), Natural Resources Institute, University of Greenwich, UK; Sharvari Raut, (SRaut@atb-potsdam.de), Leibniz Institute for Agricultural Engineering and Bioeconomy, Germany; Barbara Strum, (BSturm@atb-potsdam.de), Leibniz Institute for Agricultural Engineering and Bioeconomy, Germany; Ben Bennett, (Ben.Bennett@greenwich.ac.uk), Natural Resources Institute, University of Greenwich, UK

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identified halving FLW as a critical element in achieving a sustainable food future, which is in line with the target of UN Sustainable Development Goal (SDG) 12.3 (halving FLW rates by 2030).

Since the seminal 2011 FAO report on global FLW and the adoption of UN SDG 12.3 in 2015 (UN, 2015), there has been a surge of research efforts quantifying FLW in recent years (Xue et al., 2017; Spang et al., 2019). This body of research finds that a significant amount of FLW occurs at all the stages of various commodity supply chains. However, the volume of research is skewed towards a few countries (e.g. the United States and the United Kingdom; Spang et al., 2019). Overall, the reported loss figures from primary production to retail are more widespread in developing countries, while food waste is more dominant at the household-consumption level in developed countries (Hodges et al., 2011 World Resources Institute (WRI), 2016a; FAO, 2019).

Along with member countries, the FAO has placed a research priority on developing and improving cost-effective methodologies for estimating FLW (Global Strategy to Improve Agricultural and Rural Statistics (GSARS), 2017; FAO, 2018). Recent research identified insufficient quantification of FLW based on rigorous methods. Without reliable data on FLW, it will be challenging to derive policy and action that target hotspots of FLW. In this effort, the FAO has just published updated global and regional estimates of food loss. In contrast, food waste data are yet to be published (FAO, 2019). Kitinoja et al. (2018) conducted a meta-analysis of FLW studies from 2006 to 2017. They found that about 41 per cent of studies used surveys, about 37 per cent used mixed methods, and only 7 per cent used direct measurement methods to quantify FLW. Sheahan and Barrett (2017) found that about 20 per cent of FLW studies used empirical field-level primary data collection. Xue et al. (2017) reviewed global FLW data. They found that around only 20 per cent of existing publications were based on primary data collection, and called for the urgent need for FLW data collection based on direct measurement.

Lack of understanding of the location of losses and associated factors within the food supply chains remains a significant challenge for operationalizing FLW-mitigation strategies. Overall, food losses can be measured in quantitative and qualitative terms, although most research has focused on quantitative measures (Sheahan and Barrett, 2017). Quantitative losses occur when actual physical losses of food happen, while qualitative losses occur through the loss of nutrients, visual aesthetic appeal, or food contamination, amongst other factors (Sheahan and Barrett, 2017). Affognon et al. (2015) highlight the importance of understanding at which nodes in the value chain losses occur, at what levels, and what socio-economic factors influence such losses.

To decide on various FLW-reduction strategies along the food supply chain, it is important to measure FLW with varying levels of precision and granularity. Quantifying FLW information can provide an evidence-based foundation for prioritizing FLW hotspots in a food supply chain and help make policies to reduce FLW. Moreover, it will also help valorize waste and seek to create enterprise opportunities in this space based on evidence from FLW studies.

Methods for quantifying FLW may vary according to the stages and types of a food supply chain, for which different resources and technical capabilities are required. For example, understanding hotspots of losses in a smallholder's value

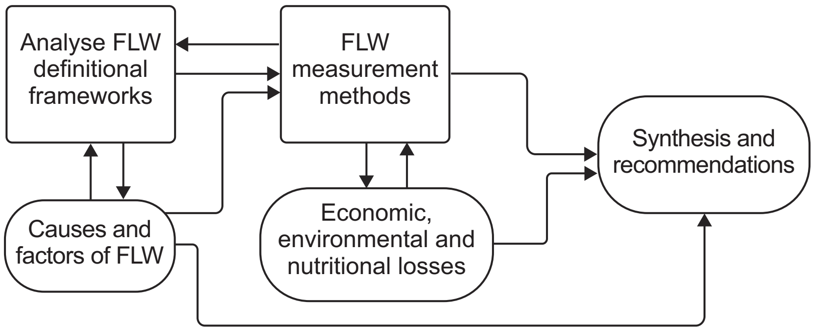

Figure 1 Research scope and framework of the review paper

chain may require fine-tuned data on types of loss (due to insects, spillage, etc.) and their location of occurrence in the value chain. On the other hand, to monitor a country's progress toward a policy target may only need a rough estimate of aggregated FLW figures.

Despite abundant recent literature on quantifying FLW, comparability between FLW estimates remains limited. This is mainly attributed to the lack of an internationally agreed FLW standard. Identified shortcomings include inconsistent FLW definitions and measurement methods. In response to this issue, in 2016, the Food Loss and Waste Accounting and Reporting Standard (FLW Standard) (WRI, 2016b) provided guidance on measuring and reporting FLW. It defined the term 'FLW' as a reduction in the weight of edible products available for consumption. This definition is convenient, simple, and practical for researchers and institutions. It has proven adequate for uniform application.

In this review, we investigate the available FLW definitions and measurement methods, their advantages and disadvantages, and our recommendations for improving the efficiency of such methods. The primary objective of this paper is to synthesize current knowledge on FLW definitional frameworks and widely accepted measurement methods. Figure 1 depicts the framework that was followed for this review paper.

Causes and factors of FLW across the food supply chain

Understanding the root causes of FLW along the food supply chain is very important for determining what methods can effectively capture the quantity lost or wasted for a specific food crop. A cause is defined as an immediate reason for FLW, while a factor is defined as an underlying driver of creating the reason (WRI, 2016a; Commission for Environmental Cooperation (CEC), 2019). Globally, there has been a rapid transformation of food supply chains, especially in developing countries (Reardon et al., 2018). These changes influence the quantity of FLW at the supply chain stages. The drivers behind these transformations include globalization, infrastructure improvement, urbanization, and specialization in the food industry, which shift the technology, access, and food preferences (Parfitt et al.,

Table 1 Examples of causes and factors of FLW in a food supply chain (FSC). (Source: Author's analysis)

Steps in food supply chain	*Production*	*Storage, processing, and packaging*	*Distribution and wholesale*	*Retail*	*Household consumption*
	During or immediately after harvest on the farm	*After leaving the farm for storage, processing, and packaging*	*During distribution to wholesale market*	*Food service and retail market*	*Cooking and consumption at home*
Direct causes of food loss and waste (FLW)	Spillage	Eaten by pests	Physical damage	Food cooked but not eaten	Food cooked but not eaten
	Physical damage	Spillage	Spoilage	Spoilage	Spoilage
	Damage from pests and animals	Trimming during processing	Rejected from the market	Product recall	Past sell-by date
	Discarded due to bruising	Rejected from the market	Past sell-by date	Past sell-by date	
Inherent factors of FLW	Premature or delayed harvest	Poor storage facilities	Lack of cold chain	Failure in demand forecasting	Over purchase
	Poor harvesting equipment	Inefficient processing	Poor transportation	Prepared improperly	Lack of cooking knowledge
	Price volatility	Mechanical error	Demand issue	Too large portions	Overcooking

2010; Reardon et al., 2018). In Table 1, we list various possible causes and factors of FLW by stages of a food supply chain, including primary production, storage, processing and packaging, distribution and wholesale market, retail, and household consumption.

FLW definitional framework, index, and databases

Lack of a standardized definition for FLW has led to several interpretations. Table 2 summarizes the definitions, starting with the first definition in 1977 and ending with the most recent definition from 2020.

Of the varying definitions mentioned in Table 2, the definition developed from the Food Use for Social Innovation by Optimising Waste Prevention Strategies (FUSIONS) and the Resource Efficient Food and Drink for the Entire Supply Chain (REFRESH) project is commonly implemented within the EU framework for FLW. The FUSIONS definitional framework includes both edible and inedible fractions of food being

Table 2 Various food loss and waste definitions, terms, and their contexts

Year	*Summary of definition*	*Context*	*Terms*	*Reference*
1981	**Food lost or wasted** was considered to mean when a product edible for human consumption (dry weight basis), and hence known as food, was avoided by consumers due to varying parameters, e.g. quality or availability in market.	Food (all)	Food loss and waste	Bourne (1977) FAO (1981)
1994	**Post-harvest loss** (i.e. FLW) is the **quantitative and qualitative loss** of product, including losses at the stage of harvest, in turn leading it to being feed for animals.	Food (all)	PHL post-harvest loss), loss	De Lucia and Assennato (1994)
2002	**Food loss** includes any modification that leads to both **quantitative and qualitative losses.** Damage during harvest, such as rodent infestation, is not considered within this framework.	Food (all)	Food loss	Grolleaud 2002)
2011	**Food loss** is a subset of post-harvest losses and represents the part of the edible share of food that is available for consumption at either the retail or consumer level but which is not consumed for any reason.	Food (all)	Post-harvest	Hodges (2011) Fusions (2014)
2012	**Food that is unsuitable for sale** at the full price but is required to be sent to various kinds of waste management.	Food (all)	Food loss	Møller (2012)
2013	**Post-harvest losses** start when the food in focus has reached its maturity in the field. This also includes the series of activities conducted starting from the field all the way up to the consumer.	Cereal grains	PHL, weight losses	African Postharvest Losses Information System (APHLIS) (2013)
2014	According to this definition, **food loss is loss in quantity and quality of food** and is further expanded to encompass the term 'food waste' by considering it as food lost due to consumer or supply chain actor choice or being overall unfit for consumption.	Food (all edible products)	Food loss, food waste	Parfitt et al. (2010); Foresight (2011); Parfitt (2011); FAO (2014)
2014	The quantity of **food lost at post-harvest that is available for human consumption but not consumed** due to reasons such as lack of proper storage, supply system, or food-handling practices, which have been interpreted as food loss.	Food (all edible products)	Food loss	Buzby et al. (2014); FAO (2017)

(Continued)

Table 2 Continued

Year	*Summary of definition*	*Context*	*Terms*	*Reference*
	Food waste is a part of food loss and occurs when an item fit for consumption goes unconsumed, due to changes in colour or overall appearance, or neglect by consumers.			
2016	In this framework, food waste is defined as the **waste of any food matter including both edible and inedible parts** of food that is removed from the food supply chain to either be recovered or disposed of.	Food (edible and inedible)	Food waste	Fusions (2016)
2017	**Food waste is defined as all the food that goes into landfill** across each stage of the supply chain.	Food (all)	Food waste	Bellemare et al. (2017)
2019	**The food loss index (FLI) is defined as the food lost starting from the production stage** all the way up to the retail stage, but not including losses in the retail stage.	Food (in general)	Food loss index	FAO (2019)
2020	The food waste index (FWI) is defined as the food, including all the inedible parts, being removed across various stages of the food supply chain (manufacturing, retail, wholesale, and consumers).	Food (in general)	Food waste index	UN Environment (2021)

separated into food waste categories. This is mainly done to encompass the quantification of waste and resource efficiency in the food supply chain, including adding all waste categories. However, the FUSIONS project also recommends measuring edible and inedible parts separately to identify interventions better.

Building on the FUSIONS definition, REFRESH defined consumer food waste as food and drink fractions edible from products/meals intended for consumption but unconsumed and discarded. This definition is based on research on the specific behaviours of consumers. It further adds that, as consumers are often not in control of the destination of the discarded food that leaves their home (or their out-of-home site), food waste is scoped here to involve the stages from acquisition through discarding within the household or out-of-home boundary.

One of the most recent definitional frameworks (Van Greffen et al., 2016) considers food loss to be losses up to the market stage, and food waste to be everything starting from the market, including the consumer stage, thus considering both definitional frameworks built from the FUSIONS and REFRESH projects. However, it is essential to successfully implement and provide accountability to these terms, quantifying the losses across the value chain. For this research purpose, the focus is on the edible food fractions within consumer food discards. It will be referred to as 'food waste' in the remainder of the study. Other scientific studies within the consumer behaviour body of literature also follow this scope (Stefan et al., 2013; Katajajuuri et al., 2014; Stancu et al., 2016).

FLW measurement methods and their advantages and disadvantages

With significantly large numbers of FLW globally, measurement methods allow the losses to be quantified, and help assess their impact at economic, environmental, and social levels. The choice of measurement method largely depends on a study's objective, the commodity selected, the stages of a food supply chain, and the resources available for the assessment. The selection of the units (farm, household, firm, location) and appropriate sampling design are also crucial before applying an FLW measurement method. Table 3 describes the various available measurement methods, their applications, advantages, and disadvantages. The methods described in Table 3 align with the FLW Standard (WRI, 2016a,b).

Over the years, several platforms have been established to quantify FLW that implement the measurement techniques mentioned above. These include platforms such as the African Postharvest Losses Information System (APHLIS), Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), and the International Food Policy Research Institute (IFPRI). The APHLIS measurement model allows practitioners in the field to assess the estimated loss in a specific region or area in focus. This model mainly focuses on evidence-based data that is obtained through observation (usually direct). This information is further combined with evidence from scientific research. As the model is based on a combination of scientific research and observation-based data, the potential for missing or incomplete data is to be considered. The GIZ methodology allows for the assessment of losses across a rapid value chain. In this tool, quantification is based on participatory approaches previously tried and tested in the field. Improvements to the tool are through outcomes from a participatory approach. The IFPRI methodology takes an all-round approach to the measurement of losses both in a quantitative and qualitative manner by using surveys as a measurement tool. The survey includes stakeholders at each processing stage of the food supply chain. These platforms are being used for specific commodities or countries and are sometimes adapted for quantifying losses of a new product.

To assess these methods, Table 4 ranks the methods and their application in the food supply chain. Since the choice of appropriate methodology depends on the commodity, supply chain stages, and resources available, etc., the FLW Standard developed a decision tool to help organizations select appropriate methods (WRI, 2016b). Examples of direct measurement include weighing unharvested produce in fields (Johnson et al., 2018), weighing hospital food (Dias-Ferreira et al., 2015), measuring food waste in school catering (Buzby and Guthrie, 2002; Falasconi et al., 2015), and scanning items discarded or donated from supermarkets (Tesco, 2018).

Examples of waste-composition analysis include sorting and weighing FLW in mixed waste streams (Lebersorger and Schneider, 2011; Waste Reduction Action Programme (WRAP), 2012) and household-level food waste-composition studies

Table 3 FLW measurement methods and their advantages and disadvantages

FLW measurement methods	*Key advantages*	*Key disadvantages*
Weighing	• Directly counted or weighed • Often most accurate measurement of FLW • Allows tracking	• Direct measurement can be expensive and time-intensive • Access to farm facilities is required • May lead to behavioural change (e.g. stimulate FLW-prevention activities), thus making baseline measurements less accurate
Waste-composition analysis	• Measured by physical separation, weighing, and categorizing food waste • Provides relatively accurate data on FLW	• Relatively expensive and requires a large sample size • May not be useful to track the cause of FLW • Cannot be applied to all stages of the FSC • Estimation can be affected by moisture losses in hot weather conditions
Counting	• A low cost yet efficient method • Requires consistency and appropriate assumptions to deliver accurate measurements	• Inconsistent calculations or assumptions can lead to an inaccurate dataset • This method can be used for measuring only one kind of FLW • Multiple FLW (varying in size, product) could enhance the discrepancies
Surveys (interviews)	• A cost-effective way to collect and quantitatively estimate FLW • Provides information about their causes • Provides FLW data including information on various characteristics of participants • Interviews can be conducted in-person, via telephone, or through electronic questionnaires	• Information is the perception of the participant • Risk of recall bias, leading to inaccurate data • Needs to be considered as a rough estimate of FLW • Participants may underestimate waste due to aspirational bias
Records	• Records such as waste transfer receipts, warehouse receipts, donation receipts, etc., can be used to quantify FLW for a few stages of the FSC • A useful method in food distribution and retail sectors where food inventory and waste management data are tracked	• Can only be used for a few stages of the supply chain where useful records are available • Accuracy depends on the quality of the collected records

(Continued)

Table 3 Continued

FLW measurement methods	*Key advantages*	*Key disadvantages*
	• Can be used to supplement other methods of measuring FLW	• Not useful to track the type of food wasted
Diaries	• Diaries provide a log of the amount and type of food that is lost or wasted along with how and why the FLW was discarded • Could be printed, electronic, or a smartphone app • Can gather information on food waste going into sewers or compost	• Can be relatively expensive, especially when the participants are provided with some incentives • May underestimate the amount of waste due to aspirational biases • Participants may underreport due to 'diary fatigue'
Mass balance	• Measures FLW by comparing inputs (e.g. product entering a facility) and outputs (e.g. product going out) • Cost-effective when input and output data exist	• Potential high inaccuracy depending on the input and output data • Difficult to track the causes of FLW
Proxy data/ literature data	• Used to estimate FLW for a unit when there are no other resources available for conducting other methods • A low-cost method for a rough estimation of FLW	• Data is usually unreliable • Should only be a starting point

Table 4 Ranking of FLW measurement methods and their application in the food supply chain

FLW measurement methods	*Commonly used for FSC stage*	*Accuracy*	*Cost*	*Time required*	*Meaningful (track causes)*
Weighing	1,2,4,5	High	High	High	**Yes**
Waste-composition analysis	2,3,4,5	High	High	High	**No**
Counting	1,4,5	High	Low	Low–medium	**Yes**
Surveys (interviews)	1,5	Low–medium	Medium–high	Low–medium	**Yes**
Records	1,2,3,4,5	Low–high	Low	Low	**No**
Diaries	5	Low–medium	Medium	Low	**Yes**
Mass balance	2,3,4	Medium	Low	Low	**No**
Proxy data	**1,3,4,5**	**Low**	**Low**	**Low**	**No**

Notes: FSC stages are as follows: 1 = production; 2 = storage, processing, and packaging; 3 = distribution and wholesale; 4 = retail; 5 = household consumption.

(Dahlén and Lagerkvist, 2008; Bernstad et al., 2015). Among the abundant use of the survey-based method, Kaminski and Christiaensen (2014) and Shee et al. (2019) used respondents' self-reported perceptions of the post-harvest losses occurring at each post-harvest stage, and van Herpen et al. (2016) assessed in-home food waste measurement using consumers' self-reported information. Examples of using records include using the wasted mass of products in supermarkets (Eriksson et al., 2014; Scholz et al., 2015). Regarding diaries, Langley et al. (2010) implemented individual household-level diaries to compositionally analyse domestic food waste. The mass balance method is widely used to estimate FLW by comparing production and consumption of food volumes (Hall et al., 2009; Gustavsson et al., 2011; Buzby et al., 2014). The use of proxy data in the literature includes loss assessment in food retail (Lebersorger et al., 2014), food wastage at the household (Grandhi et al., 2016), and integrating data from multiple sources (WWF-WRAP, 2020).

Sampling design for accurate quantification of FLW

The FLW measurement methods described previously are categorized either as an objective measurement of physical loss or a subjective assessment by respondents. Many of the previously mentioned studies estimating an FLW level did not follow suitable statistical methods, for example. Hence, they may not reflect the accurate and representative loss level at the regional or national level (Ahmad et al., 2016). Before any data collection and measurement, the observation units (food samples, bags, farmer, field, consumer) should be selected using an appropriate statistical sampling design for rigour and validity. The recommended sampling design is probability sampling, where a unit is selected based on a random process, ensuring that every unit of the sampling frame has a known probability of selection. Probability sampling can be performed using a random number generator or a table. Random sampling can be conducted when a list of the members of a population or sample frame is available (Jha et al., 2015; Ahmad et al., 2016; GSARS, 2017; FAO, 2018). The rationale for using probability sampling is that it ensures statistically representative measures for different locations, groups, regions, and countries. The estimates generated by probability sampling methods can be considered representative of the targeted population, such as at regional and national levels.

It is essential to highlight the difference between probability sampling and purposive sampling. While a random selection is ensured in probability sampling, in purposive sampling, researchers choose sample units for practical reasons, such as proximity and participants' self-selection. Purposive or non-probabilistic sampling has two main disadvantages:

- Since the selection is not random, it is impossible to attribute a selection probability (sample weights) to each unit, thus precluding the researcher from extrapolating the results representative of the entire target population.
- Non-probabilistic selection may generate bias in the estimates. For example, if farmers in the selected sample are in the process of implementing loss-mitigation measures and are interested to know if their strategies are effective,

purposive selection of such farmers will result in biased FLW measurements for the region.

Overall, the sampling design is defined by the number of selection stages (one or more stages), the stratification (by agroecological zone, farm size, etc.), and the sample-selection procedure. Units can be selected at each stage based on the probability sampling described earlier. Typically, agricultural survey-based FLW measurements in developing countries are based on several stages of random selection (Fabi et al., 2021).

Apart from probability sampling, selecting an appropriate number of units (sample size) is important for precision and statistical representativeness. The targeted sample size is usually a compromise between the available budget and the properties that the analyst or policymaker requires for the final estimate of FLW. The optimal sample size can be calculated through a formula relating to sample size, the targeted standard deviation, and the budget allocated to the study. Moreover, it is crucial to determine how the FLW data will be used and what the main objectives are for collecting such data before the measurement study is initiated.

Translating food loss and waste into financial, environmental, and nutritional indicators

Translating FLW physical amounts (mainly represented in tonnes per annum) into more relatable indicators, such as financial (economic), environmental (GHG emissions), and nutritional (daily calorie requirements per person per annum), is common practice to convey the message to different disciples of research and policymakers (Sheahan and Barrett, 2017; APHLIS, 2018). As per the latest report (2021) of the World Economic Forum, the annual cost of FLW to the global economy was $936 billion. Moreover, food system costs were $12 trillion in terms of health, economic, and environmental costs. There are tools available online that can quantify the economic loss of food waste at each step of the value chain. APHLIS is one such initiative, which translates FLW into economic and nutritional value. This is particularly important for businesses in the current scenario where sustainability and net zero are actual targets for everyone. One such example is a recent case study from Olam Agri. Olam Agri has pledged to reduce FLW in their direct supply chains by 50 per cent by 2030 (APHLIS, 2022). Looking at the environmental costs, current estimates suggest that FLW emits close to 4.4 Giga tonnes of CO_2 eq per year, accounting for approximately 8–10 per cent of global GHG emissions. According to the FAO, 1.3 billion tonnes of food are either lost or wasted worldwide, roughly one-third of the total food production. These levels of FLW account for 30 per cent of the world's agricultural land and 38 per cent of the total energy consumption of worldwide food systems. Reducing these vast amounts of FLW and enhancing the energy efficiencies of our food systems provides an excellent opportunity to augment sustainability, meet the growing demand for food, and mitigate climate change. The UN SDG 12.3 sets a clear target of halving food waste by 2030, and highlights the interdependence of reducing FLW on climate change mitigation. The Paris Agreement (2015) on climate change action also recognizes the linkages between climate change, food production systems, and food security.

Integrative approach and recommendations

A significant problem with using a survey-based method is that the responses are subjective because they are based on the opinion of respondents, and therefore may not be accurate. Estimates coming from subjective methods may be affected by a declarative bias because the farmer may lack knowledge of their losses. Moreover, such methods require people to try to recall or remember what happened in the past – sometimes weeks, months, or even a season before collecting the information. Hence, survey-based FLW measurements are generally less accurate than direct measurements of FLW. Only a few studies have compared the objective and subjective measurements of FLW. As part of their research activities on post-harvest loss, Global Strategy conducted a pilot survey in Ghana to compare the objective and subjective methods for loss measurement (GSARS, 2017). They found that objective measurements generally lead to higher loss estimates than subjective measurements. The main advantage of a survey-based measurement is that it is more cost-effective and less time-consuming than direct measurement and waste-composition analysis. A survey-based method can be a vital measurement method when combined with other measurement methods. Information collected by both survey methods and direct measurement can be combined by using sophisticated estimation approaches. For example, improved FLW estimates can be obtained from the regression of losses from direct measurement of losses from the survey, and a range of farm characteristics. Such estimated parameters could also provide quick and reliable loss projections (WRI, 2016a).

Because FLW measurement methods vary by stages in a food value chain, a proper agricultural value chain analysis should be conducted before any FLW measurement, to fully characterize and decompose the chain (actors, cost structures, etc.) and identify the FLW hotspot stages (FAO, 2018; Parmar, 2018). It is also essential to choose the relevant value chain actors according to their role in the supply chain: grain producers, processors, transporters, or sellers. The already available data from value chain analysis could be used in assessing FLW at specific stages of a value chain. For a value chain analysis, the most important principle is to map the actors participating in a crop's production, distribution, sales, and retail. The mapping characterizes the actors and quantifies the flow of crops along the chain, which could be efficiently used in FLW quantification. Such details can be gathered from a combination of primary survey work, focus groups, participatory rural appraisals, informal interviews, and secondary agricultural data. For each targeted hotspot stage, different loss measurement methods can be used.

The FAO's recently published *State of Food and Agriculture* (FAO, 2019) provides an order-of-magnitude understanding of the scale of global FLW. However, the data is skewed towards a few developed countries (e.g. the United States and the United Kingdom) and a few stages in the food supply chain (e.g. household consumption), while the extent of FLW in developing countries and other stages of the food supply chain remains largely unexplored. There has been a significant data gap and inconsistency among data sources, as most FLW data are based on secondary sources. To minimize this data gap, the literature calls for a standardizing of methodologies for FLW quantification that future studies should uniformly follow. The standardization should include the definition of FLW, stages of the food supply chain, and the destination of FLW. As only about 20 per cent of the existing literature on FLW quantification is based on primary data, there is an urgent need to collect primary data, especially data collected based on direct measurement methods.

References

Affognon, H., Mutungi, C., Sanginga, P. and Borgemeister, C. (2015) 'Unpacking post-harvest losses in Sub-Saharan Africa: a meta-analysis', *World Development* 66: 49–68.

African Postharvest Losses Information System (APHLIS) (2018) The African Postharvest Losses Information System [website], <www.aphlis.net>. [accessed 1 July 2022]

African Postharvest Losses Information System (APHLIS) (2022) 'Global agribusiness Olam Agri works with smallholders to measure and reduce losses at and after harvest in agri-supply chains' <https://www.aphlis.net/en/news/52/global-agribusiness-olam-agri-works-with-smallholders-to-measure-and-reduce-losses-at-and-after-harvest-in-agri-supply-chains>.[accessed 1 July 2022]

Ahmad, T., Sud, U.C., Rai, A., Sahoo, P.M., Jha, S.N. and Vishwakarma, R.K. (2016) 'Sampling methodology for estimation of harvest and post-harvest losses of major crops and commodities', paper presented during the *Global Strategy Outreach Workshop on Agricultural Statistics*, 24–25 October, FAO Headquarters, Rome.

Bellemare, M.F., Çakir, M., Peterson, H.H., Novak, L. and Rudi, J. (2017)', On the measurement of food waste, *American Journal of Agricultural Economics*, 99(5): 1148–58 <https://ssrn.com/abstract=3577886 or http://dx.doi.org/10.1093/ajae/aax034>.

Bernstad Saraiva Schott, A. and Andersson, T. (2015) 'Food waste minimisation from a life-cycle perspective', *Journal of Environmental Management* 147: 219–26.

Bourne, M.C. (1977) *Post Harvest Food Losses – The Neglected Dimension in Increasing the World Food Supply*, New York State Agricultural Experiment Station, Department of Food Science and Technology, Geneva (USA).

Buzby, J.C. and Guthrie, J.F. (2002) 'Plate waste in school nutrition programs: final report to Congress', Rep. E-FAN-02-009, Econ. Res. Serv., US Department of Agriculture <https://www.ers.usda.gov/webdocs/publications/43131/31216_efan02009.pdf?v=41423>.

Buzby, J.C., Wells, H.F. and Hyman, J. (2014) 'The estimated amount, value, and calories of postharvest food losses at the retail and consumer levels in the United States', *Economic Information Bulletin* EIB-121, United States Department of Agriculture, Washington, DC.

Commission for Environmental Cooperation (CEC) (2019) *Why and How to Measure Food Loss and Waste: A Practical Guide*, Commission for Environmental Cooperation, Montreal.

De Lucia, M. and Assennato, D. (1994). 'Agricultural engineering in development: post- harvest operations and management of foodgrains', *FAO Agricultural Services Bulletin* 93, FAO, Rome.

Dias-Ferreira, C., Santos, T. and Oliveira, V. (2015) 'Hospital food waste and environmental and economic indicators - a Portuguese case study', *Waste Management* 46: 146–54.

Eriksson, M., Strid, I. and Hansson, P.-A. (2014) 'Waste of organic and conventional meat and dairy products: A case study from Swedish retail', *Resources, Conservation & Recycling* 83(83): 44–52.

Fabi, C., Cachia, F., Conforti, P., English, A. and Rosero Moncayo, J. (2021) 'Improving data on food losses and waste: from theory to practice', *Food Policy* 98: 101934, ISSN 0306-9192, <https://doi.org/10.1016/j.foodpol.2020.101934>.

Falasconi, L., Vittuari, M., Politano, A. and Segrè, A. (2015) 'Food waste in school catering: an Italian case study', *Sustainability* 7(11): 14745–60.

Food and Agriculture Organization (FAO) (1981) 'Food loss prevention in perishable crops', *Agricultural Services Bulletin*. 43, Food and Agriculture Organization of the United Nations, Rome.

Food and Agricultural Organization (FAO) (2011) *Global Food Losses and Food Waste – Extent, Causes, and Prevention*, FAO, Rome.

Food and Agricultural Organization (FAO) (2014) *Food Wastage Footprint* <https://www.fao.org/3/i3991e/i3991e.pdf>.

Food and Agricultural Organization (FAO) (2017) *The Future of Food and Agriculture – Trends and Challenges*. Rome. <https://www.fao.org/3/i6583e/i6583e.pdf>.

Food and Agricultural Organization (FAO), IFAD, UNICEF, WFP, and WHO (2018) *The State of Food Security and Nutrition in the World 2018: Building Climate Resilience for Food Security and Nutrition*, FAO, Rome.

Food and Agricultural Organization (FAO) (2018), *Guidelines on the Measurement of Harvest and Post-Harvest Losses: Recommendations on the Design of a Harvest and Post-Harvest Loss Statistics System for Food Grains (Cereals and Pulses)*, GSARS, Rome, Italy.

Food and Agricultural Organization (FAO) (2019), *The State of Food and Agriculture 2019. Moving Forward on Food Loss and Waste Reduction*, FAO, Rome.

Foresight (2011) *Workshop Report W4. How can Waste Reduction Help to Healthily and Sustainably Feed a Future Global Population of Nine Billion People?* Expert Forum on the Reduction of Food Waste, organised by the UK Science and Innovation Network in collaboration with Foresight, 23–24 February 2010. the Rubens Hotel, London, UK Science and Innovation with Foresight

Global Strategy to Improve Agricultural and Rural Statistics (GSARS) (2017) 'Field test report on the estimation of crop yields and post-harvest losses in Ghana', *Global Strategy Technical Report* GO-29-2017, FAO, Rome.

Grandhi, B. and Appaiah Singh, J. (2016) 'What a waste! A study of food wastage behavior in Singapore', *Journal of Food Products Marketing* 22: 471–85.

Grolleaud, M. (2002) *Post-Harvest Losses: Discovering the Full Story. Overview of the Phenomenon of Losses During the Post-Harvest System*. Rome (Italy). Agricultural Support Systems Div. eng.

Gustavsson, J., Cederberg, C., Sonesson, U., Otterdijk, R. and van Meybeck, A. (2011) *Global Food Losses and Food Waste: Extent, Causes and Prevention*, FAO, Rome.

Gustavsson, J., Bos-Brouwers, H., Timmermans, T., Hansen, O-J., Møller, H., et al.. (2014) *FUSIONS Definitional Framework for Food Waste - Full Report*. Project report FUSIONS. [Contract] 03072014, 2014. ffhal-02800861f

Hall, K.D., Guo, J., Dore, M. and Chow C.C. (2009) 'The progressive increase of food waste in America and its environmental impact', *PLOS ONE* 4(11):e7940.

High Level Panel of Experts on Food Security and Nutrition (HLPE) (2020) *Food Security and Nutrition: Building a Global Narrative Towards 2030*, report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome.

Hodges, R., Buzby, J. and Bennett, B. (2011) 'Post-harvest losses and waste in developed and less developed countries: opportunities to improve resource use', *The Journal of Agricultural Science* 149(S1): 37–45, <https://doi.org/10.1017/S0021859610000936>.

Jha, S.N., Vishwakarma, R.K., Ahmad, T., Rai, A. and Dixit, K. (2015) *Report on Assessmentof Quantitative Harvest and Post-Harvest Losses of Major Crops and Commodities in India*, Joint Publication of ICAR and All India Coordinated Research Project on Post-Harvest Technology, Ludhiana, India.

Johnson, L.K., Dunning, R.D., Bloom, J.D., Gunter, C.C., Boyette, M.D. and Creamer, N.G. (2018) 'Estimating on farm food loss at the field level: a methodology and applied case study on a North Carolina farm', *Resources, Conservation & Recycling*137: 243–50.

Kaminski, J. and Christiaensen, L. (2014) 'Post-harvest loss in sub-Saharan Africa – what do farmers say?', *Global Food Security* 3(3): 149–58.

Katajajuuri, j.M., Silvennoinen, K., Hartikainen, H., Heikkilä, L., Reinikainen, 'A., Food waste in the Finnish food chain', *Journal of Cleaner Production*, 73: 322–9.

Kitinoja, L., Tokala, V.Y. and Brondy, A. (2018) 'Challenges and opportunities for improved post-harvest loss measurements in plant-based food crops', *Journal of Postharvest Technology* 6(4): 16–34.

Langley, J., Yoxall, A., Heppell, G., Rodriguez, E.M., Bradbury, S., Lewis, R., Luxmoore, J., Hodzic, A. and Rowson, J. (2010) 'Food for thought? A U.K. pilot study testing a methodology for compositional domestic food waste analysis', *Waste Management and Research* 28(3): 220–7.

Lebersorger S., Schneider F., 'Food loss rates at the food retail, influencing factors and reasons as a basis for waste prevention measures'. *Waste Management* 34(11): 1911-9. <https://doi.org/10.1016/j.wasman.2014.06.013>.

Lebersorger, S. and Schneider, F. (2011) 'Discussion on the methodology for determining food waste in household waste composition studies', *Waste Management* 31(9–10): 1924–33.

Møller, H., Vold, M., Schakenda, V., Hanssen, O.J. (2012). *Mapping Method for Food Loss in the Food Processing Industry - Summary Report*. Oslo, Ostfold research.

Parfitt, J., Barthel, M. and MacNaughton, S. (2010) 'Food waste within food supply chains: quantification and potential for change to 2050', *Philosophical Transactions of the Royal Society B* 365(1554): 3065–81.

Parmar, A. (2018) *Post-Harvest Handling Practices and Associated Food Losses in Sweetpotato and Cassava Value Chains of Southern Ethiopia*, PhD Dissertation, University of Kassel, Germany <https://kobra.uni-kassel.de/bitstream/handle/123456789/2018021254576/Dissertation AdityaParmar.pdf>.

Paris Agreement (2015) United Nations Paris Agreement. The Paris Agreement | United Nations [accessed on 15 August 2022].

Reardon, T., Echeverria, R., Berdegué, J., Minten, B., Liverpool-Tasie, S., Tschirley, D. and Zilberman, D. (2018) 'Rapid transformation of food systems in developing regions: highlighting the role of agricultural research & innovation', *Agricultural Systems* 172: 47–59.

Scholz, K., Eriksson, M. and Strid, I. (2015) 'Carbon footprint of supermarket food waste', *Resou rces, Conservation & Recycling* 94: 56–65.

Sheahan, M. and Barrett, C.B. (2017) 'Review: food loss and waste in Sub-Saharan Africa',*Food Policy* 70: 1–12.

Shee, A., Mayanja, S., Simba, E., Stathers, T., Bechoff, A. and Bennett, B. (2019) 'Determinants of post-harvest losses along smallholder producers maise and sweetpotato value chains: an ordered probit analysis', *Food Security* 11: 1101 <https://doi.org/10.1007/s12571-019-00949-4>.

Spang, E.S., Moreno, L.C., Pace, S.A., Achmon, Y., Donis-Gonzalez., I. and Gosliner, W.A. (2019) 'Food loss and waste: measurement, drivers and solutions', *Annual Review of Environment and Resources* 44: 117–56.

Stancu, v., Haugaard, P., Lähteenmäki L. 'Determinants of consumer food waste behaviour: two routes to food waste' *Appetite*, 96: 7–17.

Stefan, V., Van Herpen, E., Tudoran, A.A., Lähteenmäki L., (2103) 'Avoiding food waste by Romanian consumers: the importance of planning and shopping routines' *Food Qual. Prefer* 28: 375–81.

Stenmarck, A., Jensen, C., Quested, T., Moates, G., et al.(2016) FUSIONS - *Estimates of European Food Waste Levels - Full Report*. Project report FUSIONS. <https://www.eu-fusions.org/phocadownload/Publications/Estimates%20of%20European%20food%20waste%20levels.pdf>.

Tesco (2018) 'How we calculate our food waste figures (UK)', Tesco PLC, <https://www.tescoplc.com/sustainability/downloads/how-we-calculate-our-food-waste- figures-uk/>.

United Nations (2015) 'Transforming our world: the 2030 Agenda for Sustainable Development', A/RES/70/1 <https://sdgs.un.org/2030agenda>.

United Nations Environment Programme (2021), *Food Waste Index Report 2021*. Nairobi.

Van Greffen, L.E.J, van Herpen, E. and van Trijp, J.C.M. (2016) *Causes & Determinants of Consumers Food Waste: A Theoretical Framework* <https://eu-refresh.org/sites/default/files/Causes%20&%20Determinants%20of%20Consumers%20Food%20Waste_0.pdf>.

van Herpen, E., van der Lans, I., Nijenhuis-de Vries, M., Holthuysen, N., Kremer, S. and Stijnen, D. (2016) *Consumption Life Cycle Contributions: Assessment of Practical Methodologies for In-Home Food Waste Measurement*, Rep., EU Horizon 2020 REFRESH, Wageningen, NL.

Waste Reduction Action Programme (WRAP) (2012) *Methods Used for Household Food and Drink Waste in the UK*, Annex Rep. v2, 1–102, WRAP, Banbury.

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S. et al. (2019) 'Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems', *Lancet* 393(10170): 447–92.

World Resources Institute (WRI) (2016a) *Food Loss + Waste: Guidance on FLW Quantification Methods, Accounting and Reporting Standard*, Version 1.0, <https://flwprotocol.org/wp-content/uploads/2016/05/FLW_Protocol_Guidance_on_FLW_Quantification_Methods.pdf>.

World Resources Institute (WRI) (2016b) *Guidance on FLW Quantification Methods: Supplement to the Food Loss and Waste (FLW) Accounting and Reporting Standard*, Version 1.0, Rep. 1–90, WRI, Washington DC.

WWF-WRAP (2020) *Halving Food Loss and Waste in the EU by 2030: The Major Steps Needed to Accelerate Progress*, Berlin.

Xue, L., Liu, G., Parfitt, J., Liu, X., Van Herpen, E., Stenmarck, A., O'Connor, C., Östergren, K. and Cheng, S. (2017) 'Missing food, missing data? A critical review of global food losses and food waste data', *Environmental Science & Technology*, 51(12): 6618–33.