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Food Losses in Agrifood Systems: What We Know

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Abstract

In 2015, the United Nations and the G20 put food loss and food waste on the global agenda. While progress has been made since then, the scale of the problem persists because food loss and food waste are measured together, not separately. The paucity of data also poses a challenge. This article reviews the measurements, causes, and determinants of food loss as well as the interventions to reduce it. The review finds that food loss is considered in isolation, even though it is one of the causes and results of how agrifood systems function. The review calls for improved microdata collection and standardized measurements to separate food loss from food waste. Such efforts would help integrate feedback loops and cascading effects across the value chain with agrifood systems to identify intervention hot spots, trade-offs, and synergies of interventions as well as the effects of food loss reduction on socioeconomic, environmental, and food security goals.

1. INTRODUCTION

Since the United Nations made halving food loss (FL) and food waste (FW) Target 12.3 of the Sustainable Development Goals (SDGs), the topic of food loss and waste (FLW) has captured the public's attention, and its significance to the development community has grown. This review focuses on FL, given its importance in developing countries and for smallholder farmers (FAO 2019).

FL is both the result and the cause of how our agrifood systems function. Detecting losses along the value chain (VC) can highlight structural failures in agrifood systems. In turn, addressing FL can improve agrifood systems' sustainability. Thus, finding solutions to reduce FL has broader implications for the SDGs related to agrifood systems. Yet, an agrifood systems approach to achieving social, nutritional, or environmental targets remains largely absent.

The goal of policies to address food insecurity or the increasing pressure on the world's land is to boost agricultural productivity. These efforts are often cost and time intensive and do not consider FL reduction as a tool to meet the growing food demand; nor do they consider reducing FL to ease pressure on the environment and reduce inequalities. For instance, although as many as 96% of the Nationally Determined Contributions under the Paris Agreement on climate change address the land sector (Crumpler et al. 2019), measures related to FL or food consumption are generally absent. Also, reducing FL can increase the availability of nutrients and cut hunger and malnutrition. Models estimate that reducing FLW by 50% by 2030 would increase calorie availability from insufficient to sufficient amounts in low-income countries and decrease vitamin A, folate, calcium, and other nutrient deficiencies by as much as 50% (Chen et al. 2020, FAO 2019). Finally, since the loss of marketable food can reduce producers' income and increase consumers' expenses, cutting FL can help disadvantaged populations (FAO 2019).

The multidimensionality and persistence of FL for developing countries demand that we consider it an integral part of agrifood systems. FL can be reduced through an agrifood systems approach via direct and indirect drivers and the feedback mechanisms between the drivers. **Figure 1** depicts the linkages between FL and agricultural production, environmental pressure, food safety, and the income of producers and consumers as direct links. Climate hazards such as flooding or drought, innovations in science and technology, geopolitical events, and the actions of civic groups, together with global health risks, can significantly affect the magnitude of FL and are represented as indirect links. **Figure 2** shows the prevalence of studies addressing FL in agrifood systems. While FL has been extensively studied at the production level, its connection to other direct thematic links, such as environmental pressure or income effects, has been neglected. Yet, policy interventions need to understand FL's role in food systems to anticipate multiplier or rebound effects. Doing so calls for an integrated food systems approach, from preproduction to consumption, as well as particular attention to the direct and indirect links between FL and its origins and causes so that the latter can be assessed and solutions can be found.

In this review, we assess the existing knowledge about FL in the context of agrifood systems, specifically with regard to all direct and indirect links. Understanding the definitions and differences in measurement is the first step. It is equally important to know how much food is lost, where in the VC the losses occur, and why they occur. We need to understand the effectiveness of interventions to reduce FL and how much of it can be recycled into food systems. Finally, we need to know whether current efforts to reduce FL can help bring about agrifood systems–based interventions and incentives.

This review is organized into seven sections. Although the review focuses primarily on FL, it is sometimes impossible to disentangle FL and FW across all sections because of the definitions and methodologies used in the literature. Section 2 identifies different definitions of FLW,

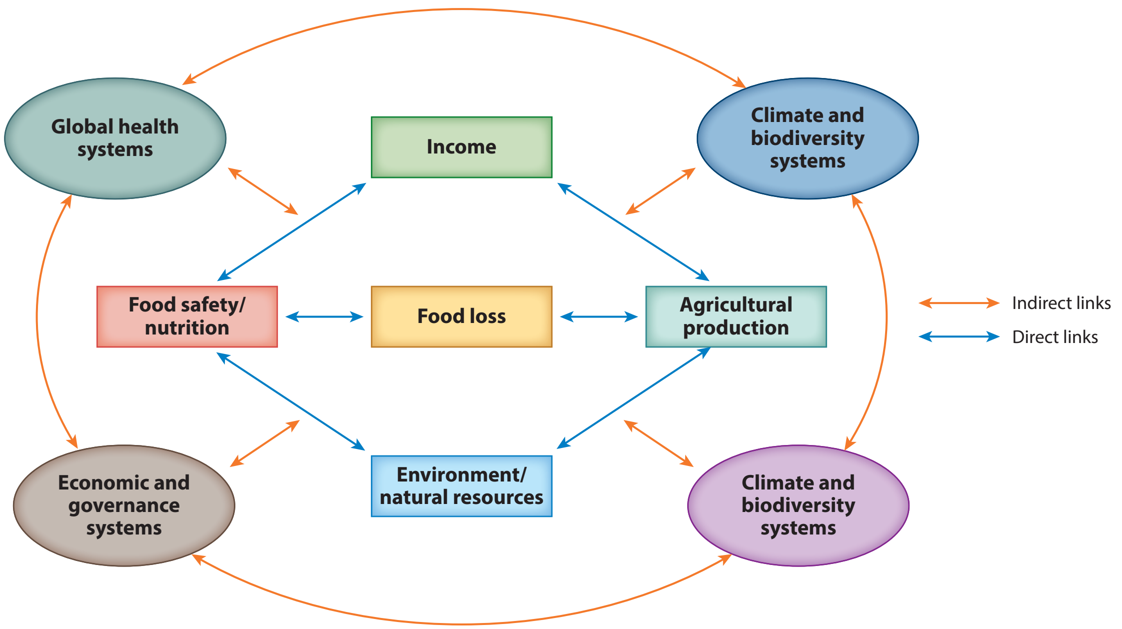

Figure 1

Food loss in agrifood systems.

highlighting why it is important to differentiate losses from waste (contrary to Gustavsson et al. 2011). Section 3 reviews the literature on measuring FL, which is essential for interpreting different figures of FL in the literature. Section 4 presents a review of the varying magnitude of FL and FLW; the latter is presented only the case in which, in the literature, the difference is not specified. Section 5 presents the known causes of FL. Section 6 reviews interventions for FL reduction and their socioeconomic, environmental, and nutritional impacts. Section 7 concludes.

2. HOW FOOD LOSSES HAVE BEEN DEFINED

One difficulty in grasping the enormity of the problem is that there is still no agreement on the definition of FL. Most of the literature uses terms postharvest loss, food loss (FL), food waste (FW), and food loss and waste (FLW) interchangeably, but these terms hardly ever refer consistently to the same concept. For some authors, the distinction is linked to the stages at which the loss occurs. For others, it is based on the causes of the loss and whether it was intentional. Different studies have tried to clarify these terms by defining FL as an unintentional reduction in food quantity or quality before consumption (FAO 2014, 2019; HLPE 2014; Lipinski et al. 2013). Such losses usually occur at the earlier stages of the food VC, between production and distribution and before wholesale. Postharvest loss is an element of FL and excludes losses at the production level, although losses during harvest are sometimes misleadingly included in the concept (Affognon et al. 2014). FW refers to food that is fit for human consumption but is deliberately discarded. It is most common toward the end of the VC at the retail and household levels. The FLW concept encompasses the totality of losses and waste along the VC with respect to total harvested production (FAO 2014). The definitions of FL and FW align with the distinction implicit in SDG Target 12.3, which refers to "food losses along production and supply chains" and "food waste at the retail and consumer levels" (**Figure 3**). Target 12.3.1 defines such losses as those happening at

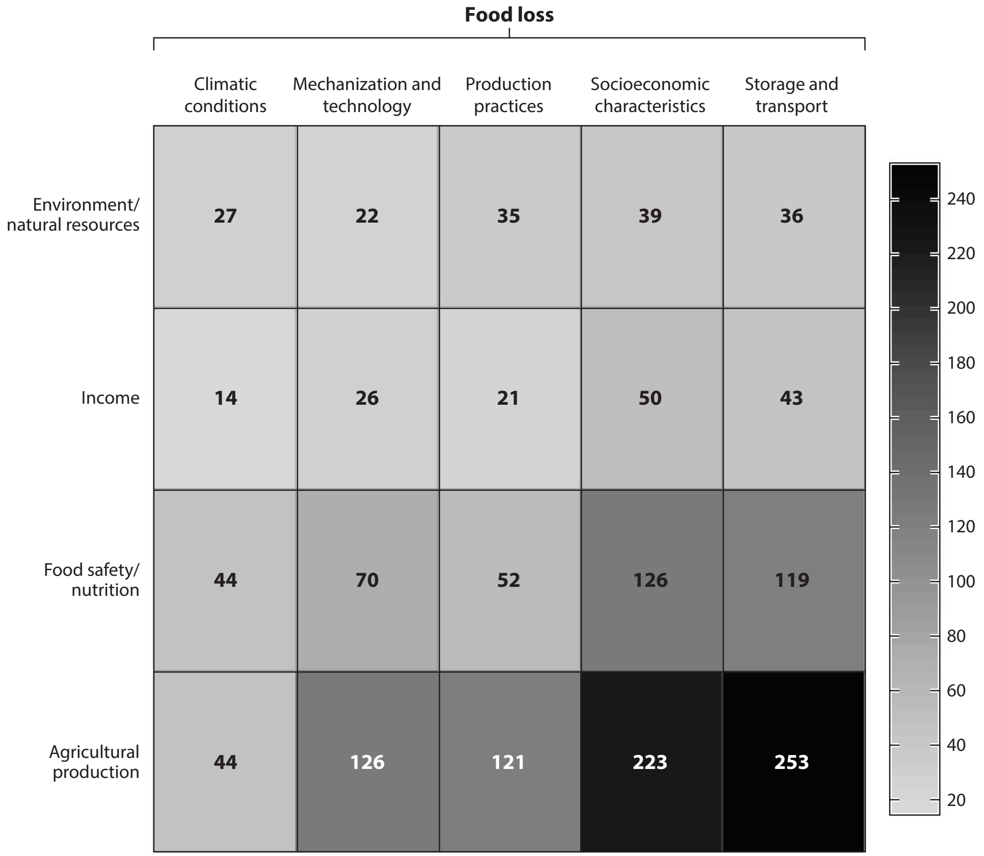

Figure 2

Prevalence of studies addressing food loss in food systems. Figure based on topical filtration of the literature from the Food and Agriculture Organization Food Loss and Waste database. Topical filters for the data were created for two categories: the main themes (Agricultural Production, Income, Environment/Natural Resources, Food Safety/Nutrition) and their respective subthemes (Production Practices: Soil, Pests, and Inputs; Socioeconomic Characteristics of the Farmer; Storage and Transport; Mechanization and Technology; Climatic Conditions; Marketing and Infrastructure Overstocking; Behavioral and Social Practices). A total of 530 articles were relevant to this review. The authors conducted a separate search in external websites to harvest more articles starting from 2010, yielding a total of 832 relevant articles, with some overlaps between topics.

the on-farm postharvest stage up to processing and packaging, including wholesale. FW happens at the retail and household levels. Losses that occur preharvest are not considered part of the FLW concept; they are also not part of the SDG definition, even though they should be (FAO 2019). Schuster & Torero (2016) proposed a more expansive definition using a new term, potential food loss and waste (PFLW). This definition incorporates preharvest loss into FL,[1] emphasizing the opportunity cost of not using natural resources to their maximum potential.

[1]Preharvest losses generally comprise crops lost due to pests and diseases, crops left in the field, crops lost due to poor harvesting techniques or sharp price drops, or food that was not produced because of a lack of adequate agricultural inputs, including the availability of labor and fertilizer (Delgado et al. 2021a).

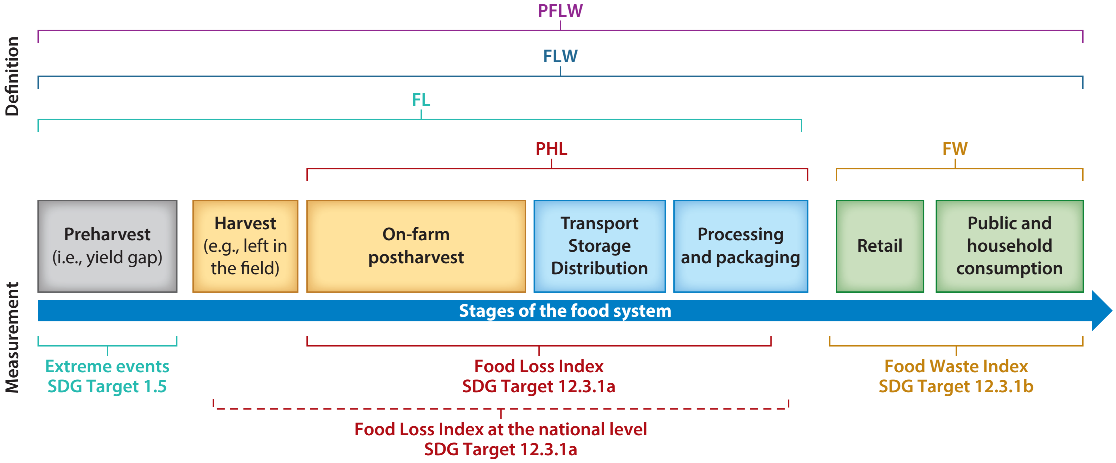

Figure 3

Definition and scope of the Food Loss Index across the food supply chain. Figure based on FAO (2019). Abbreviations: FL, food loss; FLW, food loss and waste; FW, food waste; PFLW, potential food loss and waste; PHL, postharvest loss; SDG, Sustainable Development Goal.

3. HOW FOOD LOSSES HAVE BEEN MEASURED

Losses occur at different stages of the VC but cannot be observed in isolation. The causes of FL can often be traced back to the early stages of the VC, all the way to harvest or even preharvest, highlighting the need to consider the food VC as a system of interdependent stages when measuring losses.

Two main estimation methodologies have been used to study FL across the VC: a macro approach, using aggregated data from national or local authorities and large companies, and a micro approach, using data specific to actors in the different VC stages. The macro approach relies on mass or energy balances, in which raw material inputs, either by weight or in caloric terms, are compared with produce outputs. This is a low-cost method to obtain an indication of overall losses along the entire VC and has been estimated by the Food and Agriculture Organization (FAO) (Gustavsson et al. 2011), but it does not allow for disentangling FL from FW. The study by Gustavsson et al. (2011) is arguably the most-quoted source on the subject and is still widely used as a reference for global FLW estimates. By highlighting the extent of the problem, these measurements can make a robust financial, environmental, and social case for reducing FLW. However, they provide little information on the stages of the VC where losses occur, making it difficult to determine where interventions will have the greatest impact. Also, the method demands (representative and high-quality) data on production, loss, and waste. Data gaps are severe in certain regions, such as low- and middle-income countries, and in specific stages of the VC, such as primary production, processing, and retail (Stuart 2009). This method is also not representative of smaller regional units. Finally, the aggregate data used for mass balances often cannot differentiate between natural loss like moisture loss, unnatural weight loss due to spoilage, and edible and inedible loss.

The micro approach uses sample survey data for specific VC actors. Data are obtained through structured questionnaires and interviews, FL diaries, or direct measurements by the researcher. These methods are highly region and context specific, providing information on the origin of loss along the VC and insights into the causes and how they can be prevented. They are cost and time intensive. Results can be hard to compare because studies focus on specific stages of the VC and use different methodologies. Several authors have reviewed loss estimates from studies that followed a micro approach to obtain more general loss figures for certain regions and countries. For example, Kader (2009) reviews loss estimates for fruits and vegetables in both developing and developed countries. Monier et al. (2010) quantify losses for different stages of the food VC in 27 EU member states. Affognon et al. (2014) conduct a comprehensive review of 213 papers on FLW in sub-Saharan Africa (SSA). The Joint Research Centre of the EU Commission has developed a tool that uses country-specific microdata submitted by agriculturalists to estimate postharvest cereal weight loss in SSA (see **https://www.aphlis.net/en**). Delgado et al. (2021a) have developed measurement methodologies to be applied at the micro level to different VC actors; they test the tool in six developing countries. Overall, all of these studies identify large differences in estimates attributable to the definition chosen, as well as the estimation methodology and factors, such as agroecological conditions, technology, and socioeconomic contexts.

FAO (2019) and the UN Environment Programme (UNEP 2021) have prepared two indices to estimate how much food is lost in production or in the VC before it reaches the retail level [through the Food Loss Index (FLI)] and how much is subsequently wasted by consumers or retailers [through the Food Waste Index (FWI)] (**Figure 3**). The indices monitor progress toward SDG Target 12.3. The FLI measures losses in physical quantities for a basket of 10 main commodities per country and then calculates weights to aggregate them. The primary data source for the index is loss quantities in the FAO Food Balance Sheets. Other sources are nationally representative survey data or modeled information from case studies. The FLI is based on the weight of production of the harvested crops, so the estimates exclude qualitative loss as well as losses at the preharvest stage (e.g., yield gap) and the harvest stage (e.g., crops left in the field).

In contrast to the FLI, the FWI measures total FW (rather than loss or waste of specific commodities) from primary country data. While the FLI follows a macro approach, the FWI is constructed from insights from both macro and micro studies. Both FAO and UNEP advocate for survey-based and nationally representative data collection to improve the quality of estimates.

Delgado et al. (2021a) have described the advantages and drawbacks of the macro and micro approaches to FLW estimation. While the model-based macro approach can provide loss estimates on a large scale, it may not perform as well as other micro modeling approaches in breaking down loss by VC stage. The macro approach also may not capture economic and nutritional losses,[2] which are highly relevant when looking at nutrition and inequality outcomes within a food systems approach. Efforts to include the qualitative component of FL in measurements are currently underway. For instance, Delgado et al. (2021a) propose four methods that have the potential to account for a decrease in quality (e.g., in nutrition, appearance, or other quality attributes) in addition to a decrease in dry matter. All four methodologies can measure losses at different stages of the VC and can be applied across crops and regions. In a recent review on postharvest loss reduction interventions in SSA and South Asia, Stathers et al. (2020) evaluate damage—discolored grain and decay—in addition to weight loss. Others have investigated the reduction in prices that results from quality losses (Hoffmann et al. 2020, Kadjo et al. 2016). Ricker-Gilbert et al. (2022) recently developed a conceptual framework for identifying physical quantity losses along with observable and unobservable quality losses.

Standardizing estimation methods is desirable. Standardization efforts should include areas currently suffering from a lack of attention (**Figure 2**). As noted by Sheahan & Barrett (2017), there is still a paucity of research on measuring quality losses due to reduced nutritional value

[2] For instance, in the FLI, high-value commodities carry greater weight in loss estimation than do low-value commodities. While this approach assigns an economic value to FL, the index cannot capture economic or nutritional losses associated with quality deterioration.

or food safety. Preharvest losses remain neglected, even though preharvest has been identified as a key VC stage where losses occur (Delgado et al. 2021a, WWF 2021). The concept of profit frontiers can be used to capture PFLW (Aigner et al. 1977; Charnes et al. 1978, 1981).

Finally, units and their suitability for measuring a specific objective, such as social, economic, or environmental objectives, are important measurement aspects. Most studies have analyzed the quantity of FL in weight reduction due to estimation difficulties, product seasonality, and market sensitivity to food quality (HLPE 2014, Hodges et al. 2014). The FLI is based on the economic value as reflected by farmgate prices of commodities, which may be relevant when devising FL interventions because they account for the costs and benefits of loss reductions. Some studies translate quantity losses into caloric terms (Abbade 2020, Kummu et al. 2012, Lipinski et al. 2013). Caloric units may be more relevant in nutritional terms, in which case energy-dense foods will have a greater weight in calculations of FL. However, calories do not account for the entire nutritional value of the food that is lost. If the policy focuses on environmental sustainability, it makes sense to look at purely physical quantities and multiply them by an environmental impact factor.

4. THE MAGNITUDE OF FOOD LOSS: WHAT WE KNOW

In 2011, FAO estimated that 32% of the world's food is lost or wasted yearly (Gustavsson et al. 2011).[3] This estimate is still widely cited even though it was very rough (Bellemare et al. 2017, Xue et al. 2017) and does not separate FL from FW. According to FAO's new FLI, around 14% of the world's food is lost after harvesting and before the retail stage (FAO 2019). UNEP's new FWI estimates that 17% of global food production is wasted at the retail and consumer levels (UNEP 2021). The estimates of the FLI and FWI cannot simply be combined into one total FLW figure because of the differences in definition and in scope—the FLI focuses on all agricultural production, whereas the FWI focuses only on food. Still, they give an idea of the scale of the problem.

Results from country-specific studies using mass balance data are of similar magnitude. The US Department of Agriculture's mass balance data series shows a 28.7% loss of harvested product between postproduction and consumption in the USA (Venkat 2011) and that 31% of the available food supply in the country is lost during distribution and consumption (Buzby et al. 2014). Some studies express the loss in calories. For example, Lipinski et al. (2013) translate the weight volumes of FL reported by FAO in 2011 into calories, concluding that approximately 23% of calories are lost globally. Beretta et al. (2013) find that in Switzerland 48% of the total calories produced are lost across the whole food VC. Finally, Abbade (2020) goes beyond calorie conversion to estimate the nutritional loss based on FLW worldwide. He calculates that the energy loss globally in 2017 was 685,596 billion kilocalories, equivalent to 17,551 billion grams of protein.

Studies following a micro approach tend to show greater variability in the estimated loss figures. The African Postharvest Losses Information System (see **https://www.aphlis.net/en**) estimates that the primary production and postharvest weight loss for cereal crops in SSA is between 11.7% and 20.6% of total production. Kader (2009) finds an average of 32% loss for fruits and vegetables across different developed and developing countries. Delgado et al. (2021a) quantify FL for five VCs in six developing countries. Results suggest that losses are highest at the producer level (between 6% and 19% depending on the country and commodity) and smallest at the middleman level (between 0.5 and 2% depending on the country and commodity), that is, between 6.5% and 21% across the VC.

[3]Kummu et al. (2012) and Lipinski et al. (2013) show that this amount translates into a 24% decrease in caloric terms.

In order to address FL, it is important to understand where and at what stage in the VC it occurs. **Figure 4** provides an overview of the VC stages during which losses occur for different commodities and regions. They are the results of FAO's meta-analysis of FL studies, which support estimations of the FLI and FWI (FAO 2019). The mean and median levels of loss and waste of cereals and pulses (around 4.3% and 3.7%; **Figure 4*a***) are almost always higher than those of meat and animal products (around 3% and 2.5%; **Figure 4*b***) and lower than those of fruits and vegetables (10% and 7.5%; **Figure 4*c***), which are highly perishable. However, the losses remain high, indicating the need for intervention. The spread percentages in SSA and East and Southeast Asia highlight the potential for reduction in these regions. In contrast, in Central and South Asia, the reported loss percentages for cereals and pulses are very low for all stages of the VC, indicating that countries in this region should focus their interventions on food products other than cereals and pulses. The loss values for meat and animal products (**Figure 4*b***) show great heterogeneity, especially in SSA. Most of the losses happen on the farm or during storage, the early stages of the VC.

Loss figures for fruits and vegetables (**Figure 4*c***) vary significantly across all VC stages and regions, indicating significant potential for FL reduction, especially in SSA and East and Southeast Asia. The median levels of loss or waste in Central and South Asia are lower than in other regions, but the spread around the median remains high, particularly at the transport and retail stages, highlighting the potential for reduction. The causes of FW at the retail stage are likely linked to the limited shelf life of food products; the need for products to meet aesthetic standards; and the variability of demand, particularly for fresh products.

Figure 4*d* presents loss and waste levels for fruits and vegetables and cereals and pulses in developed regions (North America and Europe) and in less developed regions. Fruits and vegetables and other highly perishable food products, such as animal products or baked and cooked foods, generally suffer higher FLW at the retail stage than cereals and pulses. Up to 15% of fruits and vegetables are lost at the retail level in all regions, except for SSA, where FLW levels are as high as 35%, suggesting significant reduction potential in the region. The median FLW percentage for fruits and vegetables at the retail level is lowest in North America and Europe, although still significant at 3.75%. This supports the finding that retail FLW levels can be high even in high-income countries.

In summary, the literature shows that FL can occur at all stages of the food VC and that specific commodity groups are systematically more affected. FL is highest in commodity groups like fruits and vegetables and animal products, where nutrient content is highest. The wide range of FLW percentages for the same commodities and VC stages, both within and across countries, suggests a considerable potential to reduce FLW when percentage losses are above average. It is essential to measure losses and waste at each stage of the food VC to identify critical control points.

According to Fabi et al. (2021), the only option to improve estimates of FLW in the short term is to make the best use of existing information from repositories of international organizations or national survey data.[4] Another way forward is to increase the number of evidence-based studies following a micro approach, collecting sample survey data for specific VC actors. The micro approach enables measurement of FL in quality and nutritional value, an area that remains unexplored. The micro evidence thus generated can be extrapolated to other crops in each crop group. Field-level studies should be conducted to confirm the validity of such an approach.

[4]For example, to produce the first estimates for the FLI, FAO gathered more than 500 studies on FLW and performed a detailed meta-analysis (Fabi et al. 2021).

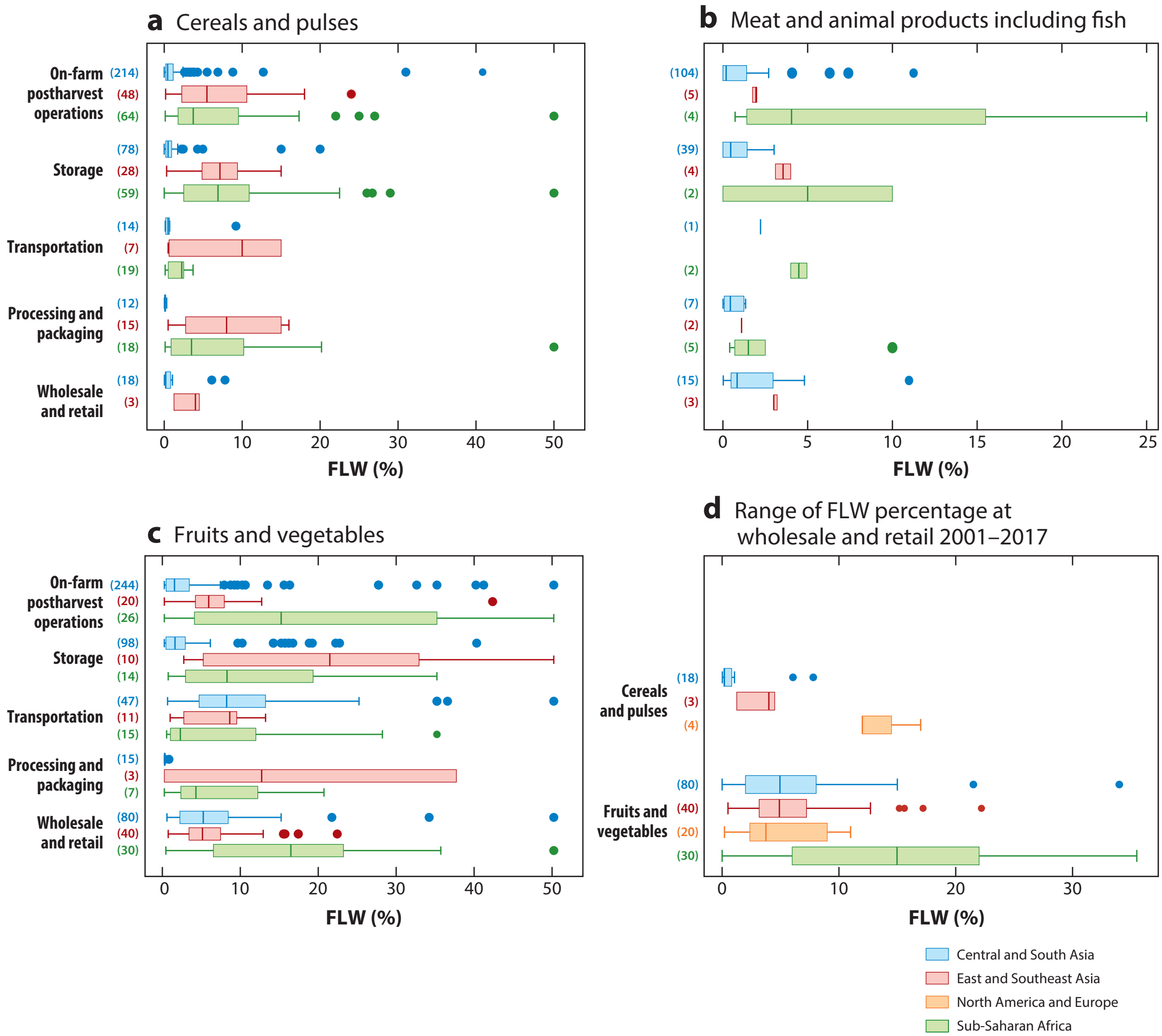

Figure 4

Range of reported food loss waste (FLW) percentages by value chain stage (2000–2017). Each box contains the middle half of all data points (observations) from the twenty-fifth to the seventy-fifth percentile of observations. The vertical line inside each box represents the median. The upper and lower whiskers contain the values up to and above the middle 50% (up to the twenty-fifth and above the seventy-fifth percentile, respectively), and the ends of the whiskers show the maximum (greatest value) and the minimum (least value), excluding outliers. Dots represent outliers. (*a*) A total of 599 observations for cereals and pulses, of which 56% refer to Central and South Asia, 27% to sub-Saharan Africa, and 17% to East and Southeast Asia. Most observations concern the on-farm stage (55% of all observations) and storage (28%). (*b*) A total of 219 observations, of which 71% refer to Central and South Asia, 23% to sub-Saharan Africa, and 6% to East and Southeast Asia. (*c*) A total of 661 observations, of which 73% refer to Central and South Asia, 14% to sub-Saharan Africa, and 13% to East and Southeast Asia. Of the observations, 44% concern the on-farm stage, followed by retail (23%) and storage (19%). (*d*) Most observations (170 of 195) refer to fruits and vegetables, with much less application in cereals and pulses (25 observations). Half of the collected data points cover Central and Southern Asia, followed by East and Southeast Asia (22%), sub-Saharan Africa (15%), and finally North America and Europe (12%). Panels *a*, *c*, and *d* based on data from FAO (2019).

5. THE CAUSES AND DETERMINANTS: WHAT WE KNOW

Identifying the causes of FL is key to identifying solutions to reduce them. It calls for an integrated VC approach, in which the different stages of the VC are considered not in isolation but rather as part of a system. This is because the VC stages where losses occur may not be where the interventions should be targeted if the causes of the losses happen upstream in the VC. Identifying quality losses along the VC is particularly important in a system-based approach because the loss of quality may translate into a loss of quantity at a later stage of the VC and a loss of nutritional and economic value.

One study has investigated the origins of FL. Delgado et al. (2021b) suggest a wide range of possible causes of FL, from farmers' production practices and socioeconomic characteristics to markets, technology, and climatic conditions. Below, we summarize the most commonly identified causes of FL.

5.1. Production Practices: Soil, Pests, and Inputs

Soil is essential for producing crops. At the most basic level, it anchors the plant by providing physical support for roots and supplies it with essential nutrients and water (Afzaal et al. 2021, Weiland 2012). However, soil properties and conditions also constitute the environment in which plant roots interact with soilborne insects and pathogens, influencing the occurrence and severity of plant diseases that inhibit plant growth, and thus influence loss at the production level (Ghorbani et al. 2008, Huber et al. 2012).

Pest attacks and weeds are major factors in preharvest and postharvest losses. Savary et al. (2012) report that the combined yield losses caused by pathogens, animals, and weeds account for reductions ranging between 20% and 40% of global agricultural productivity (Oerke 2006, Oerke et al. 1994, Teng 1987, Teng & Krupa 1980). Oerke et al. (1994) report that global losses due to animal pests, pathogens, and weeds are 15.6%, 13.3%, and 13.2%, respectively. Chegere (2018) and John (2014) find that rodents are a major factor in the postharvest loss of rice in Southeast Asia. Abdoulaye et al. (2016) report that more than 75% of farmers in Ghana, Tanzania, and Benin identified insects as the major cause of postharvest loss, while most farmers in Ethiopia, Uganda, and Nigeria complained about rodents and moisture as the main causes of postharvest loss. Baoua et al. (2014) and Compton et al. (1997) show that each percentage point of insect infestation results in between 0.6% and 1% depreciation in the value of maize. Finally, Delgado et al. (2021b) identify pests and disease as the major reasons for preharvest losses in five of the six crops studied; they are also mentioned as an important cause of postharvest losses.

The main fungus that frequently contaminates crops is *Aspergillus flavus*, which produces the carcinogen aflatoxin. Aflatoxin-producing fungi can contaminate crops in the field, at harvest, and during storage. Aflatoxin contamination is commonly caused by high temperatures and drought. Frequent rains in autumn can also delay cereal harvests, reducing grain quality due to sprouting and increasing mycotoxin contamination. Grain either is lost entirely or is of lower quality, so it moves from food grade to feed grade, resulting in lower prices (Savary et al. 2012). Exposure to aflatoxins by eating contaminated food or inhaling dust (by agricultural workers) is associated with an increased risk of cancer.

Finally, plant production interventions aim to maintain and improve soil fertility and productivity through the targeted use of resources, including organic and inorganic fertilizers (Benjamin et al. 2003, Rengel 2020). An inadequate supply of the 16 essential macro- and micronutrients in the soil reduces yields and compromises crop quality, which will lead to a decrease in the quantity and quality of food (Alloway 2008, Karthika et al. 2018, Reddy 2017, Rengel 2020).

5.2. Climatic and Environmental Conditions

Blakeney (2019) finds that climatic and environmental factors have an obvious effect on yield, with climate change inflicting a series of agricultural stresses through increases in heat, salinity, and pest infestation. High temperatures have been reported to cause physiological disorders in crops and affect cellular structure. Light intensity, types of light, and light length affect the quality and phytonutrient content of fruit (Afzaal et al. 2021). Delgado et al. (2021b) find that unfavorable climatic conditions in Honduras, Guatemala, Mozambique, and Ethiopia, such as lack of rain, are positively correlated with the occurrence of losses. Studies also support the idea that excessive heat and humidity, pests, or environmental host stressors can influence crop colonization, crop growth, and toxin production of *Aspergillus* (Abbas et al. 2009, Bauchet & Prieto 2021).

5.3. Socioeconomic Characteristics of the Farmer

Most of the literature finds that farmers' demographic characteristics correlate with losses, but a clear pattern is lacking. Ambler et al. (2018) and Ansah et al. (2017) find a negative correlation between farmer age and losses. On the other hand, Ngowi & Selejio (2019) and Shee et al. (2019) analyze the maize and white-fleshed sweet potato VCs in Tanzania and Uganda to find that farmer age is positively correlated with losses.

Ahmed et al. (2015), Maziku (2020), and Paneru et al. (2018) find that more educated and experienced farmers have lower losses. Other authors confirm the negative association between education and losses (Basavaraja et al. 2007, Gebretsadik et al. 2019, Khatun & Rahman 2019, Shee et al. 2019). Yet, Ansah et al. (2017) and Doki et al. (2019) find that education positively correlates with losses in Mozambique. Kaminski & Christiaensen (2014) identify the lack of education as an important bottleneck in tackling FL in SSA.

The gender impact on losses also seems to depend on local contexts. While Delgado et al. (2021b) do not find a clear gender pattern, Chegere (2018) finds that being male correlates with reduced losses in the SSA maize VC. Folayan (2013) and Ngowi & Selejio (2019) find that being male correlates with increased losses in Nigeria and Tanzania.

5.4. Storage and Transport

Certain climatic conditions, especially heat and moisture, tend to increase the prevalence of insects, pests, and other bio-deterioration factors, especially when proper storage and transportation structures are lacking. There is evidence that a lack of postharvest storage and adequate storage techniques is an important factor behind FL (Aidoo et al. 2014, Delgado et al. 2021b, Folayan 2013, Ismail & Changalima 2019, Maziku 2020, Ngowi & Selejio 2019, Paneru et al. 2018). Losses increase significantly when food is stored for longer periods (Aidoo et al. 2014, Delgado et al. 2021b, Ismail & Changalima 2019). The lack of modern storage facilities is positively correlated with losses, while improved storage infrastructure, like silos or hermetic bags, mitigates the risks of FL (Delgado et al. 2021b, Chegere et al. 2022, Folayan 2013, Maziku 2020, Paneru et al. 2018). Bauchet & Prieto (2021), Cervini et al. (2021), and Seetha et al. (2017) also identify inadequate storage technology as one of the factors associated with high contamination by aflatoxins. Finally, Ngowi & Selejio (2019) find that applying protectants to stored crops increases losses from pests and diseases due to growing resistance to the most common protectants.

Another body of literature finds that poor roads and a lack of suitable vehicles contribute to the deterioration of perishable commodities during transport (Gebretsadik et al. 2019, Ismail & Changalima 2019, Shee et al. 2019). Minten et al. (2016) find that there is more FL of potatoes in China than in India or Bangladesh, possibly due to longer shipping distances. Hengsdijk & de Boer (2017) describe a positive and significant relationship between losses and the household's distance to the nearest market or road. Rolle (2006) considers the lack of an efficient transport system as an important cause of FL. Both Blakeney (2019) and Delgado et al. (2021b) identify the absence of adequate transportation infrastructure, particularly in developing countries, as a major cause of FLW.

5.5. Mechanization and Technology

The risk of FL is escalated by poor postharvest handling and management techniques. Which techniques constitute proper handling may vary. Tefera (2012) finds that improper postharvest crop management and harvesting techniques in Africa account for between 14% and 36% of losses in maize. Problems at the harvesting and drying stages include insufficient or excessive drying and missing grain. Improper threshing and shelling can cause grain breakage. Delgado et al. (2021b) find that mechanization and technology in production and postharvest activities negatively correlate with FL in five VCs in six developing countries. However, for three VCs, the number of machine-driven activities increased losses. Delgado et al. (2021b) also find that the use of improved seeds reduces FL. These results indicate that some postharvest interventions, such as mechanization, save farmers time and effort but may increase the quality and quantity of FL.

6. INTERVENTIONS: WHAT WE KNOW

In the past decade, policy makers, researchers, NGOs, and industry leaders have focused on efforts to reduce FL, but research on the effectiveness of interventions is still relatively new. We assess studies analyzing the effectiveness of interventions on the four direct dimensions of FL: production, income, environment, and nutrition (**Figure 1**). **Figure 5** provides a qualitative evaluation of the studies' prevalence.[5]

Interventions (and their evaluation) have focused mainly on specific VC steps and the quantitative reduction of FL along the VC. Most studies have evaluated technical measures to reduce losses during storage at the farm and at the distribution or retail level. There is a paucity of studies related to infrastructure, policy, and market interventions or training, highlighting the need to study interventions that go beyond changes in storage and technology. Also, there is a lack of measured socioeconomic, environmental, or nutritional outcomes of applying different FL reduction interventions at all VC stages. The results of interventions are expressed mainly as a percentage or weight of the loss, and nonlinear dynamics of reduction interventions are often not considered. Empirical evidence that FL reduction intervention leads to alleviation of environmental degradation or improved nutrition is limited, mainly because of inadequate monitoring of outcomes and the difficulty of measuring changes in resource use as a result of reduced FL along the VC.

Stathers et al. (2020) highlight a bias regarding the commodity type and region studied. Cereals are the most studied crop category, followed by roots and tubers, even though research from large-scale simulation models has identified the primary production stage in low-income countries and the fruits and vegetable sector as the most promising intervention points to achieve food security and environmental goals (Kuiper & Cui 2021).

There exist broader market improvements that may help reduce FL but without specifically targeting critical points of losses. Vertical coordination between VC actors can lead to substantial reductions in FL and enhance product quality (Despoudi et al. 2018, Kusumastuti et al. 2016,

[5]Note that this review is not intended to be exhaustive. This article merely points out gaps in the implementations of interventions and their evaluation.

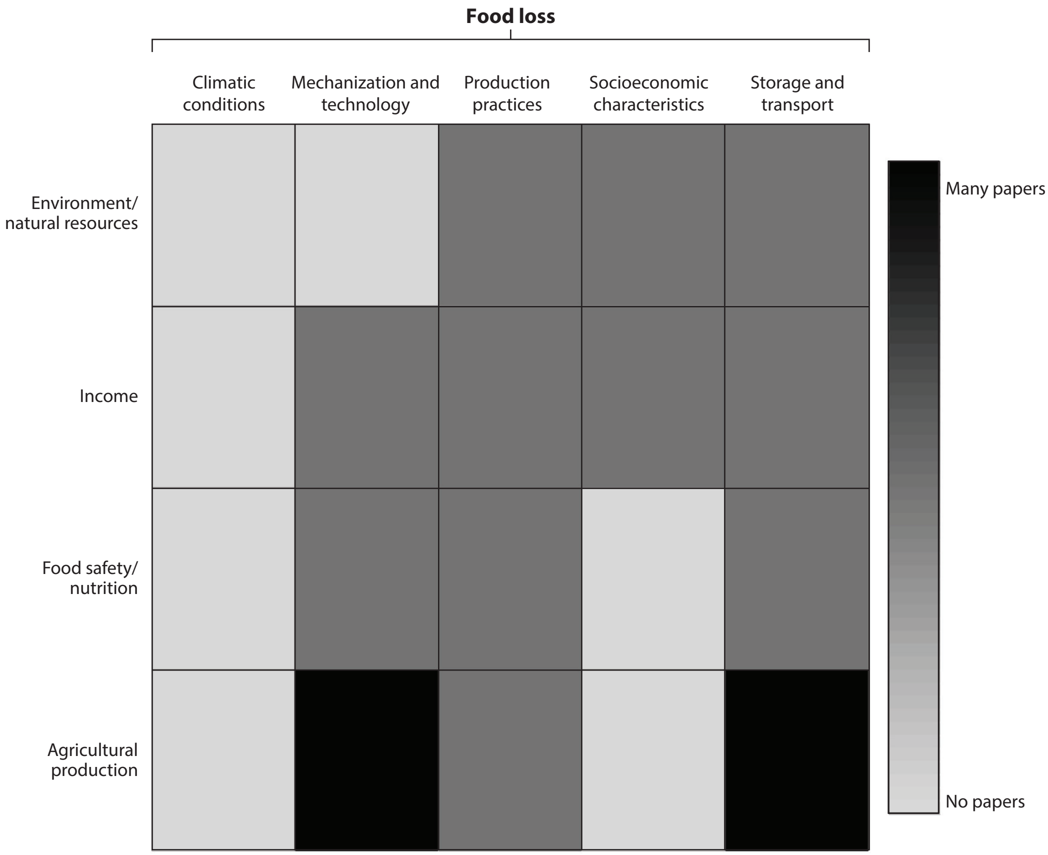

Figure 5

Prominence of food loss reduction interventions. The darkest gray cells identify the intervention and value chain stage combinations with the most evidence.

Tsolakis et al. 2014), while contract farming can reduce FL by providing farmers with a guaranteed market for their produce when a certain quality level is reached (Dsouza et al. 2021). Products' minimum quality standards maintain hygiene and traceability and reduce spoilage risks of elongated VCs (Lee et al. 2012). The goals of many product standards, such as making products available to a broader range of potential markets, can also reduce losses (Minor et al. 2020). The development of market information systems can help prevent FL by improving communication between farmers and buyers, which allows farmers to better anticipate demand and avoid overproduction (Shepherd 1997). Finally, subsidies can reduce FL by promoting investment in efficient production and distribution systems, but they may eventually lead to an increase in FL beyond a certain productivity threshold (Kang & Suh 2023).

The above policies aim to enhance the enabling environment that contributes to reductions in FL, rather than directly targeting specific points where losses occur. Although the impact of such policies is compelling, the evidence describing these dynamics remains limited. Therefore, **Figure 5** focuses on interventions that are designed to reduce FL at particular stages of the VC. We elaborate on the main findings according to the intervention stage for reducing FLW along the VC.

6.1. Preharvest and Harvest Loss Reduction Interventions

Preharvest and harvest loss reduction interventions are essential to prevent FL at the farm level. These interventions involve improving production practices, adapting to changing climatic conditions, and addressing the socioeconomic characteristics of farmers. We examine how these interventions can help reduce FL and improve food security while considering their potential environmental and economic impacts.

6.1.1. Production practices. In general, the protection of crops against plant diseases has a prominent role in meeting the growing demand for food quality and quantity (Strange & Scott 2005). Studies have shown that crop losses due to harmful organisms can be substantial and may be prevented or reduced by crop protection measures (Oerke 2006, Savary et al. 2012). Some literature shows that preharvest factors, such as cultivation practices, water supply, soil quality, and temperature, may seriously affect postharvest quality and result in the downgrading or rejection of produce at the point of sale, thus reducing farmers' income and increasing prices for consumers (Prusky 2011, Savary et al. 2012).

Traditionally, fungicides have been an effective strategy for controlling disease. However, their use affects consumer acceptance due to the presence of chemical residues in fruits, making them associated with health problems. Some recent studies discuss different interventions which represent environmentally friendly alternatives for disease control that do not affect the nutritional value of treated fruits (Afzaal et al. 2021, González-Estrada et al. 2021). Other studies evaluate the concept of integrated crop management, which includes a threshold concept for applying pest control measures and reducing the amount and frequency of pesticide application to an economically and environmentally acceptable level without incurring excessive losses (Oerke 2006).

6.1.2. Climatic conditions. Interventions focusing on climate change adaptation could reduce the likelihood of FL, especially at the farm level. Geostatistics and multiple regression analyses shed light on the influences of weather on aflatoxin contamination (Cotty & Jaime-Garcia 2007). As climate shifts, so do the complex communities of aflatoxin-producing fungi. Other studies have developed models to predict aflatoxin contamination (e.g., Chauhan et al. 2015). A mechanistic model to predict the risk of preharvest contamination could help manage this harmful mycotoxin by identifying locations and specific times when aflatoxin is more likely to be present. There are prediction models estimating the best harvest time to prevent losses, but few analyses have been carried out to assess their effectiveness in reducing aflatoxin contamination and thereby reducing FL. Also, few studies have evaluated how interventions can tackle FL resulting from climate change.

6.1.3. Socioeconomic characteristics of farmers. Many studies highlight the importance of prevention strategies to mitigate the economic and environmental impacts of FL. An important way to prevent losses is by training different VC actors (from farmers to retailers) in production and handling practices (Ali et al. 2021). Yet, only a few studies have effectively examined the impact of agricultural education (Stathers et al. 2020) and its potential to reduce FL. Overall, increased knowledge and skill as well as evaluations of training interventions at the scale required to reduce FL and enhance food security are still needed (Mvumi & Stathers 2015).

6.2. Postharvest Loss Reduction Interventions

In addition to interventions at the farm level, postharvest interventions can play an important role in reducing FL. The literature on postharvest loss reduction interventions covers various topics, from storage and transport to mechanization and technology. We review these interventions below.

6.2.1. Storage and transport.

Stathers et al. (2020) systematically reviewed postharvest loss reduction interventions for 22 crops across 57 countries in SSA and South Asia from the 1970s to 2019. Storage technology interventions targeting farmers make up 89% of the studies they reviewed. This review also finds a large variance across different types of storage interventions. Both weight loss and quality loss depend on the type of treatment during storage and the type of container. An economic analysis has shown that some interventions, like hermetic bags, are potentially profitable under basic price and loss assumptions if farmers follow certain rules for use (Ndegwa et al. 2016). Among studies focusing on quantitative losses during storage, those by Gitonga et al. (2013) and Omotilewa et al. (2018) find that improved storage is effective against pests and reduces the use of storage chemicals, improving food security.

A major limitation of most studies on storage is that they do not assess the cost-effectiveness of the interventions. Also, initial high costs are a major obstacle to smallholders' adoption of improved storage (e.g., Kumar & Kalita 2017), an area that needs further investigation. Finally, studies stop short of assessing the impact of FL on natural resource use or nutrition.

Another stream of literature focuses on transport and infrastructure. Enhancing the enabling environment of road infrastructure is undoubtedly critical in mitigating FL (e.g., Hodges et al. 2011). Such improvements can be optimized when coupled with interventions that target VC actors. For instance, Rosegrant et al. (2018) find that better infrastructure facilitating the transportation of products to markets reduces postharvest losses, but that the impact is even stronger if farmers have better education and adopt proper crop handling and processing techniques. Other authors highlight the potential of modifying product handling practices, such as loading and unloading procedures or the type of hooks utilized, as a means of reducing spillage during transport (e.g., Baloch 2010, Kumar & Kalita 2017).

6.2.2. Mechanization and technology.

Many studies focus on the effect of technology during farm-level storage, including hermetic bags and metal silos (Stathers et al. 2020). Technology to reduce storage losses is critical, but a better understanding of the effectiveness of new technologies at stages other than storage is also needed, especially because the effect of mechanical harvest and postharvest activities on reducing FL remains unclear (Delgado et al. 2021b). Emerging postharvest service technologies, such as minimal treatment and new packaging, enhance crops' quality and shelf life (e.g., Verghese et al. 2015) by providing environmental alternatives to disease control that preserve nutritional attributes. However, evidence—especially in developing countries—remains scant.

Chegere (2018) and de Groote et al. (2021) show that returns to technology investments must be carefully evaluated, as the costs of implementing some postharvest handling practices can outweigh the benefits. Low responses to interventions aimed at reducing postharvest losses are frequently attributed to a lack of economic incentives, credit constraints, and social/cultural factors (e.g., Kadjo et al. 2013, World Bank 2011). Additionally, profitable investments in agricultural technologies, including loss-reducing interventions, may be hindered by information asymmetry, behavioral biases, risk and loss aversion, and a failure to account for externalities (Duflo et al. 2011, Kadjo et al. 2013)

Finally, other authors have highlighted that mechanized harvest and postharvest technologies can displace labor (Alam et al. 2018, Basavarajappa et al. 2013). The trade-offs between lessening farmers' drudgery, reducing FL, and increasing welfare and nutrition must be better understood.

7. CONCLUSION AND RECOMMENDATIONS

The SDGs prioritize food security and sustainable resource use, with FL reduction playing a crucial role in achieving these goals. SDG 12 focuses on sustainable consumption and production;

Target 12.3 aims to halve global FW at the retail and consumer levels and reduce FL across the VC by 2030. In addition to these targets, the Committee on World Food Security has called for a shared understanding of FLW and an enabling environment for its "food use, not loss or waste" agenda, especially for monitoring, measurement, and reporting targets (HLPE 2014). In September 2021, the G20 agriculture ministers renewed their commitment of 2015 to address FL. In this international commitment context, identifying FL's magnitude, causes, and costs in agrifood systems is critical for setting priorities. Since 2015, progress has been made in harmonizing the definition[6] of and tracking FL, but limited data provided by countries remain a constraint. Also, FL is often considered in isolation, even though it is an integral part of agrifood systems.

Additional research and subsequent application in policy are needed to understand the effect of policy interventions on food systems' elements and actors, including environmental, socioeconomic, and nutritional outcomes. Specifically, research needs to focus on the areas discussed in the three subsections below: (*a*) quantifying and reducing uncertainty through improved microdata collection and standardized methods; (*b*) conducting systemic research, integrating feedback loops and cascading effects through the global VC to identify intervention hot spots; and (*c*) conducting integrated assessments of the effect of local FL reduction measures to balance reduction gains against the intervention costs. Such assessments are also necessary to find alternative means to reach social, environmental, and food security objectives.

7.1. Quantify and Reduce Uncertainty Through Improved Microdata Collection and Standardized Methods

Our review shows that data limitations jeopardize the quality of the FL estimates and the estimation of loss that originates at different VC stages. First, due to data constraints, the measurement of loss along the VC often differs from the more comprehensive theoretical definition. Harvest loss is rarely included in estimations, although it is widely recognized as a critical point (FAO 2019, WWF 2021). The opportunity cost of production (PFLW) has also rarely been estimated. Second, qualitative loss is often not analyzed because, compared with the complete disappearance of a product, the loss is more difficult to trace back along the VC. Omitting qualitative loss from an analysis risks confusing where specific FLW is occurring with its qualitative cause. Finally, due to data and measurement constraints, the economic and nutritional values of losses at various stages of the VC are rarely considered. Yet, losses further along the VC have higher economic and nutritional values than losses that occur earlier in the VC.

Comprehensive microdata will be necessary to improve FL reduction efforts in developing countries. These data must be gathered from representative surveys of farmers, middlemen, wholesalers, and processors, who can provide information on inputs; harvesting, storage, handling, and processing practices; and product quantities, quality, and prices along the VC. The surveys should enable the measurement of FL reduction at different stages of the VC and be applicable across crops and regions.

7.2. Conduct Systemic Research, Integrating Feedback Loops and Cascading Effects Through the Value Chain at the Global Scale to Identify Intervention Hot Spots

A food systems approach to FL recognizes that the losses affect agrifood systems' sustainability across three dimensions: economic, social, and environmental. Tracking the nutritional impact of

[6] A good step in this direction has been made by the multistakeholder Food Loss and Waste Protocol Initiative. However, this initiative excludes preharvest losses—and PFLW—from its definition.

reducing FL can make an important difference in achieving zero-hunger objectives (SDG 2). It can also address global inequalities in food access, especially in rural areas (SDG 10). Our review shows that researchers, policy makers, and practitioners rarely link SDGs 2, 10, and 12. For instance, among studies evaluating the causes of FL or impacts of interventions, deterioration of nutrients or food quality along the VC is rarely estimated. Research on food security and nutrition rarely quantifies nutrient losses.

To have a better understanding of how reduction measures address inequalities or environmental footprint, we need more-integrated global assessments that consider interactions between demand and supply, substitution effects, and how changes in prices and costs are distributed throughout the agrifood system. Recent studies that use stylized reductions in current FL rates, such as large-scale simulation models, are useful in determining where to intervene in food systems because they take into account nonlinear interactions between different segments of the economy (e.g., Barrera & Hertel 2021, Philippidis et al. 2019, Read & Muth 2021, Reutter et al. 2017). Yet, more needs to be done to allow for a weighing of FL reduction gains against the intervention costs and against alternative means to reach food security and environmental objectives.

7.3. Conduct Integrated Assessments of the Effect of Specific Local Food Loss Reduction Measures to Reach Social, Environmental, and Food Security Objectives

While it is important to have a global understanding of how FL reduction measures reduce society's environmental footprint in line with SDG Target 12.3, more localized microstudies are needed to decide which interventions are most effective. Evaluations of interventions focused on specific VC steps, mainly storage and the quantitative reduction of FL along the VC. Environmental and nutrition research has traditionally been pursued in isolation from the rest of the food system. It is hardly ever linked to research evaluating the effectiveness of interventions to reduce FL, underestimating the potential of such interventions. Further research is needed to assess the impact of interventions that improve the enabling environment but are not specifically targeted at reducing FL. Evidence for the effect of farmers' education, finance, or infrastructure interventions on postharvest loss reduction should also be augmented. Finally, FL poses multifaceted welfare, health, nutrition, and food security challenges that can only be addressed through interdisciplinary research in which all the components depicted in **Figure 1** are simultaneously considered.

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The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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