



Food Loss and Waste: Farm to Table: A Review

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10.18805/ag.RF-386

ABSTRACT

Food loss and waste occur between production and distribution and is common in low-income countries, while food waste occurs mostly at the consumer level, in the retail and food service sectors and particularly in developed countries. The environmental impact of food loss and waste in terms of volume and cost is tremendous and represents a huge cost to society, in terms of greenhouse gas emission, water footprint, wastage of agricultural land and biodiversity loss. Approaches/solutions to reduce the global food loss and waste through the food supply chain are discussed, both at the post-harvest, handling, storage and processing levels (close to the farm) and at the retail and consumption level (close to the fork). Knowing where food loss and waste occur in the food chain, in which foods and in which countries is crucial for deciding where and how to direct efforts most effectively. This article aims to provide an overview of the formation and prevention of food loss and waste (FLW). The main focus here is to determine the reasons for the emergence of FLW throughout the food supply chain. A framework has been established for the emergence of FLW at every stage of the food supply chain. Based on this framework, feasible solutions are presented. There is growing recognition among scientists, institutions, businesses, policymakers and citizens of the unsustainability of the present food system. Therefore, developing appropriate strategies to reduce FLW is one of the most important issues related to sustainable development. This review has enhanced the comprehension of the subject matter, emphasised the multifaceted nature of the problem of FLW and underscoring the involvement of various actors along the food supply chain. For various reasons, FLW is still remaining in each chain. It is therefore imperative that well-planned policies and programmes are created with a view to reducing FLW at various points in the food supply chain. The issue of FLW requires a greater degree of consistent attention, study, research, action and awareness, particularly with regard to its prevention.

Key words: Farm to table, Food loss, Food safety, Food security, Food waste.

Food; all kinds of processed, partially processed or unprocessed substances or products, liquor, chewing gum and water or any substance used during the production, preparation or treatment of food, except for live animals, feed, unharvested plants, medicinal products used for therapeutic purposes, cosmetics, tobacco and tobacco products, narcotic or psychotropic substances and residues and contaminants that are not offered for direct human consumption (FAO, 2024).

Food losses are the reduction in the amount of edible food available for human consumption at various stages of the food supply chain. In addition to numerical losses in food products, there may be deterioration in terms of quality, which may result in economic and nutritional losses (FAO, 2019; Tuncel, 2019; Anonymous, 2024). Losses throughout the food supply chain are often due to socioeconomic, biological and/or microbiological, chemical, mechanical and/or environmental factors. Food waste is the excessive or unconscious use of food produced and waste without being consumed. Food waste occurs when the food produced from the farm to our tables is wasted, destroyed or cannot be consumed. The causes of food loss and waste (FLW) generation are related to technologies, methods, techniques and practices such as mechanization, agricultural practices, farm management practices carried out by various actors in the food chain (FAO, 2019).

Worldwide, 30% of food waste consists of cereals (half of the world's annual cereal production), 40-50% of root

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How to cite this article: Yaralı, E. (2026). Food Loss and Waste: Farm to Table: A Review. *Agricultural Reviews*. **47(5)**: 796-805. doi: 10.18805/ag.RF-386.

Submitted: 14-04-2025 **Accepted:** 25-04-2026 **Online:** 09-06-2026

crops, fruits and vegetables and 20% of oilseeds, meat and dairy products and fish. While it is reported that approximately 40% of food waste in developing countries occurs before harvest, during harvest and during processing, it is reported that in developed countries, food waste occurs in retail supply chains and during consumption (Akgül, 2019). Food chain losses vary by country. For instance, 5-6% is wasted or lost in Australia and New Zealand, 20-21% in Central and Southeast Asia and 16% in Europe and North America. The quantity of comestibles discarded by domestic households is estimated to be 40 million tons in the US, 47 million tons in the EU, 4.5 million tons in the UK, 7.3 million tons in Australia and 18 million tons in China (IFCO, 2020).

Reports pertaining to food waste have indicated that the economic cost of food waste in agricultural products is

approximately US\$650 billion (FAO, 2013a). Moreover, it has been documented that the quantity of food that is discarded in developed countries (222 million tons) is nearly equivalent to the aggregate food production in Sub-Saharan Africa (230 million tons) (Lipinski *et al.* 2013). According to the available data concerning food waste produced in the European Union, most of the losses occur at household and processing sector level (47 million and 17 million tons respectively), which account for 72% of total food waste in the EU. The remainder (11 million tons of waste, or 12% of the total) is generated by the food services, production, retail and wholesale phases (9 and 5 million tons, respectively). Research has revealed that 24% of global FLW occurs at the production stage, 24% after harvest and 35% at consumption and these stages account for more than 80% of global loss and waste (FAO, 2013a; Lipinski *et al.*, 2013). In Europe and North America, food waste per consumer is reported to be 95-115 kg per year, while in Africa and South/Southeast Asia it is reported to be 6-11 kg per year (FAO, 2019). Food “loss” (from production to retail) and food “waste” (at the point of sale and consumption) are concentrated at different points (Table 1) (FAO, 2024).

FLW are complex issues that seriously affect natural resources, economy, agriculture, soil productivity, environment and natural balance, health, global warming and climate, international relations and policies, social equality and income distribution and many other areas (Turkish Court of Accounts, 2018). The UN 2015 Sustainable Development Goals’ (SDG) include Target 12.3, halving food waste and cutting supply-chain losses by 2030 making FLW reduction critical for sustainability, food security and resource efficiency worldwide (United Nations, 2025). The food production chain includes a series of activities

starting from raw materials to processing, production, distribution and consumption. At each stage of this chain, various processes, both agricultural and industrial, are applied and different types of losses and wastes occur. The areas where global food losses and waste occur are indicated in Fig 1 (FAO, 2020a).

Factors effecting FLW

Pre-harvest/pre-slaughter applications

A plethora of factors have been identified as contributing to losses during the harvest phase, including temporal inaccuracies, methodologies employed, equipment utilised and harvesting conditions. While the conditions and actions taken in the farm before harvest are not part of the FLW, unfavorable weather patterns and damages from multiple causes prior to harvest (such as weeds, insect and diseases, *etc.*), as well as transport conditions and storage processes, can indirectly effect the losses experienced in the subsequent phases of the supply chain (HLPE, 2014). In developed countries, it has been reported that losses have increased due to reasons such as not harvesting products due to prices and costs, product losses and damages due to mechanization during harvest and overproduction (HLPE, 2014; FAO, 2020b). In developing countries, it has been reported that losses have increased due to poor agricultural practices, adverse weather conditions, early harvest due to food supply and urgent need for cash and poor care-feeding and milking conditions in livestock. In this regard, additional reasons for food waste include overlooking meteorological predictions, lacking soil assessment, incorrect pesticide application, failing to schedule harvest periods, employing improper harvesting methods, as well as biological and biotic influences such as like unwanted plants, pest invasions and diseases (HLPE, 2014; Johnson *et al.*, 2019; FAO, 2020b).

According to 2025 reports, climate change has led to increased pre-harvest aflatoxin (fungal toxin) contamination in corn and grain fields across Europe. In some regions, up to 20% of the crop is considered “lost” because it exceeds food safety limits while still in the field. In Africa and South Asia, pre-harvest losses are 2-3 times higher than in developed countries due to inadequate infrastructure and poor pest management (Bereziartua *et al.*, 2025). According to data from the Indian Council of Agricultural Research (ICAR), approximately 15-25% of the grain and pulses produced in the country are lost due to pests and diseases before harvest. For instance, the issue of rice

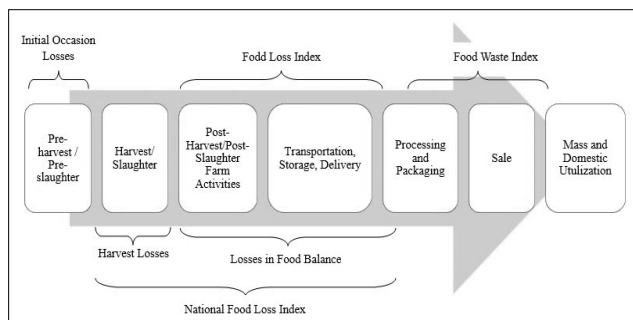


Fig 1: The functional framework of national FLW.

Table 1: Food loss and waste rate in different stage.

Stage	Ratio/amount	Explanation
Food loss (Post-harvest to pre-retail)	13.2%	According to FAO data, food is lost in the field, in storage or during transport before it even reaches the table.
Food waste (Retail and consumption)	19.0%	Approximately one-fifth of food available for consumption is wasted in retail outlets, restaurants and households.
Household waste	60.0%	The largest share of total waste (631 million tons) comes from homes.

harvest losses is a matter of grave concern, particularly in countries where rice is a staple food and also serves as the primary source of livelihood for millions of people. The aforementioned phenomenon has been demonstrated to engender a diminution in food availability, a disruption in economic activity and an impact on human health. Additionally, according to 2024 data, approximately 12% of Brazil's total agricultural production is lost due to biotic stress (pests) before harvest machines even enter the field (ICAR, 2024; FAO, 2024; Aruna *et al.*, 2026). Other factors that contribute to FLW along the chain include improper harvest planning and careless handling of produce. For example, over-ripening and delayed harvesting of cereal have been reported to cause aflatoxin formation. Mechanical damage that occurs during harvesting of products such as fruits and vegetables can also cause FLW. Wounded spots and tissues in products create a suitable environment for contamination by pathogens. At the same time, these damages increase water loss and ethylene formation, causing the problem to worsen (FAO, 2013b).

In animal production, based on pre-slaughter conditions, poor herd care and feeding management, pre-slaughter stress and adverse transportation conditions significantly affect meat and carcass quality and may cause losses. Studies report that losses due to injury and bruising in animals range from 15-25% in cattle, 10-12% in pigs and 5-10% in poultry (Viator *et al.*, 2017; Williams *et al.*, 2020; Gagaua *et al.*, 2022). For milk production, large losses are most often due to the inability to maintain hygienic conditions in milking and the lack of proper milking equipment. This situation contaminates all raw materials and can lead to large losses. In dairy farming, especially among small farmers, it has been reported that among the causes of losses are mastitis or water forgery leading to rejection in milk collection centers or factory. A study demonstrated that the findings of the present research indicated that inadequate milk processing, spoilage, lack of access to milk marketing, lack of cooling facilities, lack of transportation and lack of infrastructure were the main causes of post-harvest milk losses and spoilage. (Fekata *et al.*, 2023; FAO, 2014). According to FAO (2024), 5 to 10 per cent of milk in developing countries is lost before reaching processing facilities. Approximately 45-50 million tons of global raw milk production, which is approximately 930-940 million tons per year (2024-2025), is lost during collection and transportation.

Storage conditions

Food storage conditions vary depending on many factors. With the storage of the products, time management can be done better and it is possible to save time in marketing and consumption. This is an accurate statement when the storage process is carried out under appropriate conditions; conversely, in the absence of such appropriate conditions, the possibility of serious product loss cannot be discounted. However, it should not be forgotten that

even if they are stored in the best conditions, the shelf life of the products varies according to the practices such as whether they are properly collected in the early stages of the supply chain, how long they are kept under the sun and their storage suitability (FAO, 2020b). For example, in Sub-Saharan Africa and South Asia, fruit and vegetable losses exceed 50% due to lack of access to cold chains. Reports from 2024 show that in India alone, \$10-15 billion worth of fresh produce is wasted annually due to inadequate cold storage. Research conducted in the EU and the US has shown that, although infrastructure is strong in these regions, losses are mainly due to "quality defects" and "overstocking." For example, in Europe, approximately 7-10% of cold storage stocks that cannot be circulated are destroyed as their expiration date approaches (FAO, 2024).

In general, adequate storage facilities with appropriate conditions in terms of temperature, relative humidity and gas composition are needed for perishable and sensitive products. The inadequate infrastructure for storage has a detrimental effect on the quality and longevity of sensitive items. In the absence of adequate storage facilities, growers and producers risk losses by selling their produce regardless of the market price or leaving the produce in the field without harvesting, or delayed harvesting by shippers, wholesale or retail stores. Failure to provide optimum storage conditions in products often leads to undesirable changes in color, flavor, texture and nutritional value, which in turn encourages chemical and biochemical reactions (Rolle, 2006).

Transport and logistics

One of the main causes of FLW is the activities resulting from transportation and logistics between production and consumption. During this period, there are losses that may arise from physical, chemical and biological hazards. Inappropriate vehicle loading and unloading systems, poor packaging, long transportation processes, inadequate cooling, uncontrolled movement in the vehicle, transportation of products that cannot be carried together and vehicle driver errors are effective in the occurrence of these errors (FAO, 2020b). In developing countries, the inadequacy of transportation vehicles, poor road conditions, transportation of food at inappropriate temperatures, use of inappropriate packaging in transportation and inadequate market conditions are more prominent (Rolle, 2006; HLPE, 2014; FAO, 2020b). The substandard quality of rural road infrastructure has been demonstrated to have a detrimental effect on the efficiency of transportation processes, which in turn can lead to a rapid deterioration of perishable goods (IMEchE, 2013). An illustration of inefficiency within the food chain can be observed in India, which, despite producing sufficient food to satisfy its entire population, is ranked as the second largest producer of fruit globally. However, the country nevertheless occupies 119th position in the Global Hunger Index (GHI). This mismatch is due to an estimated food loss of around 25-30% from inadequate transport

logistics and a lack of controlled temperature and atmosphere facilities, which have high energetic costs (Shiraishi *et al.*, 2025).

Animal transportation can create stressful and harmful situations, which can lead to deterioration of animal welfare and loss of production. In the USA, it has been reported that approximately 80,000 pigs die in transit each year. According to 2024 data, the average mortality rate for poultry during transport in the USA is 0.23%. While this rate may seem low, considering that 9 billion chickens are slaughtered annually, it means that approximately 20 million chickens die en route before reaching the factory. In the 2024 inspections conducted at large slaughterhouses in Germany, approximately 12% of pigs were found to have PSE (pale, soft, exudative) meat defects due to transport and pre-slaughter stress. Academic studies conducted in Turkey show that the rate of physical injury in transports from local markets to slaughterhouses, particularly in cattle, is between 18% and 22% due to inappropriate ramp and tethering methods. Similarly, logistics losses in dairy products are important in developing countries. One of the reasons for losses in dairy products is the inability to market their products due to seasonal conditions and inadequate transportation and lack of cold chain during the hot season (EC, 2024).

Another problem encountered during the distribution phase is rejected products. In some cases, products are not accepted due to failure to meet the requirements or market standards set by the target markets. In such cases, if an alternative buyer or solution cannot be found in a timely manner, the entire shipment is discarded/destroyed. Furthermore, imported products are subjected to rigorous scrutiny at customs to ensure adherence to food safety regulations. These testing processes often delay shipments and significantly reduce the shelf life of perishable products (HLPE, 2014).

Processing and packaging

Errors made during the food production process can lead to problems in the size, weight, shape and appearance of the final product or to damaged packaging. The absence of adequate food safety and quality standards can lead to some products being unsafe and nutritionally poor. The common sustainable packaging trends are like downsizing the weight of packing material, improved recycling and recovery of waste and increasing the use of recycled content (HLPE, 2014; Ojha *et al.*, 2015; FAO, 2020b). It has been reported that the applications made to provide the desired shape and size in the final product, the incorrect processes in production and the activities carried out to ensure the high standard come to the fore in the losses that occur in developed countries. In the context of developing countries, the inadequacy of dairy, meat products, fruit and vegetable production facilities, contamination during production, inadequate cooling activities and packaging errors are effective in the losses

(HLPE, 2014; FAO, 2020b). The fact that the production of some products depends on the season makes things worse. For instance, although there is a seasonal increase in the production of certain fruits and vegetables, the products are not processed with insufficient capacity and they are discarded. The same is true for milk and during periods of abundant rainfall and animal feed, a high volume of raw materials is produced, but the milk produced cannot be processed due to inadequate conditions (HLPE, 2014).

The biggest cause of losses during processing in the US is the strict "appearance" standards set by retailers. Approximately 13 million tons of food are lost annually during processing in food production facilities. For example, in fried potato production, 10-15% of peeled and sliced potatoes are discarded as animal feed or waste simply because they do not meet "size and color" standards (ReFED, 2025). For example, in yogurt and cheese factories, the amount of product remaining in pipes during production line changes and discharged with cleaning water (CIP systems) accounts for 1.5 to 2 per cent of total production. In Germany alone, thousands of tons of dairy products are discharged into the sewage system each year using this method (FSO, 2024).

In animal production, contamination in the production chain is a major cause of losses. Contamination can be attributed to two primary factors. Firstly, inadequate cleaning and disinfection of the processing unit following prior operations can lead to the dissemination of contaminants. Secondly, the presence of a contaminant within a product can have a detrimental effect on the entire production chain. Following slaughter processing, carcasses should be cooled immediately to prevent bacterial growth and processing facilities should maintain strict temperature controls to prevent contamination (Williams *et al.*, 2020; Gagaoua *et al.*, 2022). Additionally, when properly implemented, good manufacturing practices (GMPs), HACCP (Hazard analysis critical control points) and good hygiene practices (GHPs) are able to protect food from contamination, pests, insects or pests in the primary stages of production (HLPE, 2014).

Sale

Conditions at the sales level (temperature, humidity, lighting, ventilation, etc.) and activities affect the quality of the product, its shelf life and customers' decisions. The tendency to offer a sample of products that are aesthetically pleasing to the eye, that is, suitable in color, shape and size, causes many retailers to set high standards on products. In the event that products fail to comply with the aforementioned standards, they are to be rejected on delivery and subsequently disposed of. In the United States alone, in-store food losses have been estimated to be 10% of the total food supply (Buzby *et al.*, 2014). Retail food waste in the EU is affected by confusion between the "Use by" date and the "Best before" date. Across the EU, the retail sector wastes approximately 5 million tons of food annually (about 10 kg per person).

For example, dairy products and packaged meat are removed from shelves and destroyed 1-2 days before the date expires (EUROSTAT, 2025).

Consumption

FWL has significant negative impacts, drawing increasing global attention due to their links to food security and climate change. Throughout its lifecycle-from production to consumption-food directly affects the environment. Unlike typical products, food waste is intertwined with societal issues like eating habits and cultural traditions (Manzoor *et al.*, 2024). Over the past 20 years, increasing income levels and demographic conditions have also led to changes in eating habits. Examples of these changes include increased consumption of processed foods and changing dietary preferences in per capita consumption of meat, poultry, dairy and seafood. However, as the welfare level of the household increases, the food waste of the consumer may also increase (FAO, 2020b). In developed countries, it has been reported that consumers' tendency to overeat food, poor storage conditions at home, excessive portion consumption and waste, misunderstood statements in food labeling and excessive waste are the main causes of losses. It has been noted that four factors typically influence the amount of waste produced in households within developed nations. These include household consumption and variety, financial status, population characteristics and cultural aspects. Households with smaller populations produce more waste as the products purchased and prepared are often larger than the consumption capacity (HLPE, 2014; FAO, 2020b).

Consumers generally tend to buy larger packages and in bulk to get the most bang for their buck and portioning and package size are major drivers of food waste. Consumers looking to purchase only limited amounts of a product are often required to obtain more than necessary because of the packaging dimensions. In addition, advertising campaigns that encourage purchasing, such as "buy three for two" or "economy packages" in supermarkets, product promotions and mass discounts can cause waste as the product tends to deteriorate after opening and not all of them are consumed. A study of middle school students in the United States city of Boston determined that, on average, students discarded approximately 19% of their main meals, 47% of their fruits, 25% of their milk and 73% of their vegetables, when measured in terms of calories (Cohen *et al.*, 2013). In their study, Heng and House (2022) compared food waste behaviours among consumers in the United States, Canada, the United Kingdom and France. The authors integrated portion size, shopping habits and food labeling with perceptual, behavioral, cultural and economic dimensions, emphasizing that high-income levels, product abundance and purchasing power may render consumers less sensitive to food waste.

Moderate and macro causes of FLW

Key factors contributing to moderate FLW include inadequate support for R&D, absence of infrastructure, poor collaboration among stakeholders involved in the supply chain and ambiguity regarding food labeling. In general, the actors playing a role in the food sector are small-medium capacity enterprises and they face difficulties in investing. Lack of investment is often caused by a lack of access to finance and credit. In developing countries, one of the main bottlenecks to investment in adopting technologies to reduce FLW is credit constraints in rural areas (HLPE, 2013).

Macro-level causes are related to national policy and legal regulatory institutions and include systemic causes that can occur at various levels. Some legal regulations on food safety have an impact on FLW. Policies that can help or prevent the redistribution of waste food or its use as animal feed, regulations or prohibitions on fish waste, food hygiene practices, food labeling and packaging rules and waste management can be counted among these (European Union, 2014).

Legislative strategy measures are fundamental in the different stages of the food chain to promote the reduction of FLW and improve the sustainability of the food production chain through public investments and by establishing protocols with private companies. Examples of these types of collaborations were seen in Italy after the implementation of the "Gadda Law", which occurred through the cooperation of the association "Io Potentino Onlus" with the Basilisca Brewery of Potenza, which reused unsold bread to produce the beer "LA166" to combat FLW. Another example is the FUSIONS project (Food use for social innovation by optimizing waste prevention strategies), which aims at a more resource-efficient Europe, preventing FLW by stimulating innovation, funding guidelines, encouraging donations and raising awareness, among other measures (Nicastro *et al.*, 2021). The rapid globalization of food production and trade has also increased the potential for international incidents involving contaminated food. Food safety authorities around the world have stated that food safety requires policies to be implemented not only at the national level but also at the international level. The lack of international coordination of policies at the local level can be a significant cause of FLW (FAO, 2013b).

Strategies for reducing FLW

In general, there is not enough information on how much, why and where food and/or food-related inedible leave the food supply chain. This deficiency makes it difficult to develop strategies to prevent and reduce FLW and to prioritize actions in this regard. Additionally, FLW varies widely and without a consistent reporting framework, it becomes difficult to compare data within or between organizations over time and draw useful conclusions (Anonymous, 2016). It is imperative that all actors involved in the production and consumption of food take action FLW.

Consequently, various authorities and institutions have initiated awareness-raising campaigns on this issue (Fig 2) (Nicastro *et al.*, 2021).

In order to prevent FLW, food operation and cold chain management must first be strengthened and the necessary precautions must be taken. In developing countries, solutions that are both effective and applicable for small holders must be developed. Solutions should be put forward on a farm basis to facilitate producers' access to loans from financial institutions. In this sense, the existence of local governments, cooperatives and related organizations and the cooperation between them is very important. The biggest problem in developing countries is cost and energy constraints (HLPE, 2014).

It is necessary to adopt a farm-to-table food safety approach, to improve harvesting and storage conditions, to introduce modern packaging and packaging systems, to improve food processing processes, to use resources such as energy and water efficiently, to determine and measure why and where FLW occur, to improve marketing conditions and to increase practices that ensure traceability in the food chain (Kaipia *et al.*, 2013; HLPE, 2014; Vilarino *et al.*, 2017). A number of other approaches to minimising FLW through packaging include the development of novel materials and designs for packaging that are better suited to protecting food and improving both handling and usability. Furthermore, there is a necessity to advance the development of packaging machinery so as to ensure the production of packaging that is entirely free of flaws, the efficient packaging of food and the accurate printing of packaging information. The utilisation of smart packaging has the potential to serve as a means of directly reducing FLW, particularly at the consumer level. This can be achieved by utilising smart packaging, which is capable of indicating the edibility of food items, or by employing active packaging, which involves the release of specific substances that extend shelf life (Hebrok and Boks, 2017).

In developing countries, women play an important role in post-harvest procedures. Most working women in these countries do not have sufficient knowledge of good manufacturing practices and therefore women working in rural areas should be emphasized and necessary training should be provided. The utilisation of hermetic storage technology, low-toxicity insecticides and modern storage technologies has been demonstrated to be a highly effective and adaptable solution for small-scale farmers in developing countries (HLPE, 2014).

In developed countries, activities mainly in the retail and consumption stages are issues that need to be focused on. In this sense, a multi-framed policy should be followed in the loss and waste that occurs during the consumption phase. For example, numerous measures are recommended to raise consumer awareness, including information and education campaigns, avoiding unnecessary purchases for households, stock management at home, food preparation and information on how to use waste

(HLPE, 2014; Rohm *et al.*, 2017). Applications in information technologies also play an important role in reducing FLW. For example, weather forecasts provide farmers with accurate planning for harvest and post-harvest practices, while information containing market forecasts provides important information to suppliers and buyers (Kaipia *et al.*, 2013; HLPE, 2014).

In order to achieve this, policy actions must be based on a holistic approach that engages all parts of the food chain. This will increase cooperation and awareness among the various actors involved. Consequently, legislators have the capacity to implement a range of measures, varying in severity from simple recommendations or guidelines to more restrictive regulations and laws. It is evident that governments have the capacity to influence the sustainability of harvesting practices through various means. One method is to invest in infrastructure, thereby setting guidelines on proper harvesting and post-harvesting methods. This approach aims to ensure that harvesting activities are conducted in a sustainable manner. Additionally, governments can impose limitations on the use of chemicals by implementing sanitation protocols. Additionally, necessary practices for the evaluation of food waste should be implemented. In this sense, applications such as evaluation as animal feed, anaerobic digestion, biochemical processing, composting, controlled incineration and landfilling *etc.* should be investigated and the necessary infrastructure should be established (Anonymous, 2016; Kumar and Samadder, 2017; Sanchez *et al.*, 2017; Purmessur and Surroop, 2019).

It is paramount to reduce FLW generation rates and implement promising strategies to valorize them. The primary objective of the circular economy is to maximize the efficient and comprehensive utilization of all resources to minimize waste. Advanced technologies and innovations can support the circular economy (Herrero *et al.*, 2020) and there are many examples to support this, for instance works on digital technologies (Benyam *et al.*, 2021; Carlos *et al.*, 2024; Rusch *et al.*, 2023) and more specifically, smart sensors (Zhu *et al.*, 2022), Internet of Things (IoT) (Kumar and Prashar, 2021) and nonthermal food processing

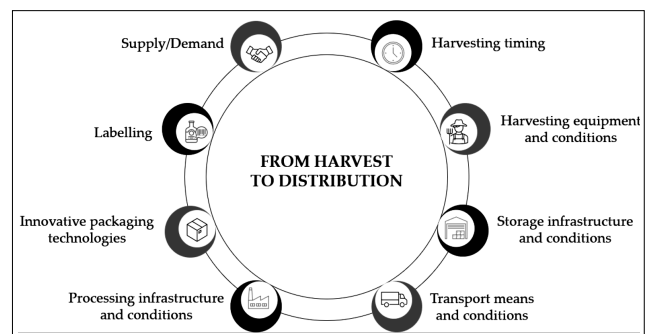


Fig 2: Measures to prevent and reduce FLW from harvest to distribution stages.

(Arshad *et al.*, 2022), among others. The fourth industrial revolution, also known as Industry 4.0, has introduced technologies that enhance production, support food traceability, improve food safety and quality, reduce FLW generation and enable complete supply chain transparency from farm to consumer (Hassoun *et al.*, 2022).

In 2000, the Millennium Development Goals (MDGs) were established during the Millennium Summit of the United Nations to combat poverty and promote sustainable development by 2015, which were then replaced by the sustainable development goals (SDGs). According to FAO (FAO, 2020c) regarding population growth, by 2050, it will be necessary to produce 50% more food, feed and biofuels to meet population demand than in 2012. Currently, one-third (1.3 billion tons) of the world's food production is wasted at the various stages of the food chain, either in production, post-harvest, processing, distribution and consumption (Vilarino *et al.*, 2017) or lost due to pests, diseases, limited harvesting techniques and price volatility. This FLW represents an overall monetary value of € 800 billion with the corresponding social and environmental impacts (Ishangulyev *et al.*, 2019). Due to their high perishability, fruits and vegetables account for 40 to 50% of global food loss (dos Santos *et al.*, 2020).

FLW has two main effects on food security. First, reducing FLW will have a positive impact on food access by lowering food prices. However, in this particular sense, there is a need for quantitative research that defines the correlation between the quantity of food value and food waste (HLPE, 2014). Secondly, processes such as composting and anaerobic conversion will have a long-term impact on food security, making significant contributions to soil improvement and stabilization. Current studies show that landfills exhaust significant amounts of land resources, cause air and water pollution and lead to effect on human health (Sanchez *et al.*, 2017). It is evident that a reduction in FLW will facilitate a more efficient utilisation of natural resources and enhance production efficiency. Research on water, energy and food relationships shows a link between food and resource consuming (Chen *et al.*, 2020; Del Borghi *et al.*, 2020). Implementing strategies to minimize FLW represents the most ecologically sound management choice because of the resources conserved. It is estimated that preventing FLW can reduce greenhouse gas emissions, ranging from 800 to 4400 kg of CO₂ equivalent per ton of food waste (Salemdeeb *et al.*, 2017).

FLW has significant impacts, both directly through the disposal of unwanted food and indirectly through the energy inputs used to produce food that is ultimately thrown away. These effects include the formation of greenhouse gases and pollution of water resources, especially in landfills. It has been documented that the products which contribute most significantly to the carbon footprint of food waste are cereals (34%), meat (21%) and vegetables (21%). It is clear that the steps to be taken to reduce food

losses and waste are an approach to closing the gap in the expected food supply in the future (FAO, 2013b).

Additionally, one of the Sustainable Development Goals is "End hunger and achieve food security for all people by 2030", promoting and highlighting the importance and need for safety regulations, food quality, traceability and transparency in food supply chains. The main goal is to prevent food loss but also fraud, mainly involving animal disease problems, such as "Mad cow disease", "Nipah Virus" and "Avian Influenza". These examples have highlighted the importance of traceability, stimulating technological advances to decrease food safety risks, promote health and control diseases and their management (Shiraishi *et al.*, 2025).

There are three main problems required to reduce FLW. The first is that applications in this area should be concentrated in developed regions and more focused on some types of food such as milk, eggs, cereals, meat, fruits and vegetables. The second is the need for a deeper analysis of consumers' consumption behavior. Finally, the acceleration of studies on greenhouse gas emissions. A general obstacle in this regard is the difficulty of obtaining organic substances by separating them at the source. It is imperative that the necessary studies are conducted in order to facilitate the implementation of a separate collection of food waste at the source. In addition, public education on environmental awareness and consumer behavior should be conducted. To achieve all this, multidisciplinary approaches that integrate engineering, environmental and sociocultural methods are required.

In order to achieve a sustainable food system, a transition from conventional linear supply chains to circular models is imperative. These models must prioritise the reuse of co-products and the reduction of FLW throughout all phases of production. This transition is essential for advancing the United Nations Sustainable Development Goals. Public policies, consumer awareness and coordinated action among technology providers, supply chain participants and policymakers are pivotal to this transformation.

CONCLUSION

This review clearly demonstrates that food loss and waste (FLW) are influenced by complex and multifaceted factors ranging from pre-harvest processes to final consumption. Technical errors made during production and pre-processing, along with infrastructure deficiencies in storage and logistics, lead to significant losses in the early stages of the supply chain. In the processing and consumption stages, in addition to operational inefficiencies, the decisive impact of socio-economic habits on waste is particularly noteworthy. In conclusion, disciplined and coordinated strategies implemented at every stage-from farm to table-are an absolute necessity for both safeguarding global food security and ensuring environmental sustainability.

ACKNOWLEDGEMENT

The present study was not supported.

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Informed consent

All animal procedures for experiments were approved by the Committee of Experimental Animal care and handling techniques were approved by the University of Animal Care Committee.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this article. No funding or sponsorship influenced the design of the study, data collection, analysis, decision to publish, or preparation of the manuscript.

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