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Food Loss and Waste: Measurement, Drivers, and Solutions

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Abstract

It has been estimated that one-third of global food is lost or wasted, entailing significant environmental, economic, and social costs. The scale and impact of food loss and waste (FLW) has attracted significant interest across sectors, leading to a relatively recent proliferation of publications. This article synthesizes existing knowledge in the literature with a focus on FLW measurement, drivers, and solutions. We apply the widely adopted DPSIR (Driver-Pressure-State-Impact-Response) framework to structure the review. Key takeaways include the following: Existing definitions of FLW are inconsistent and incomplete, significant data gaps remain (by food type, stage of supply chain, and region, especially for developing countries), FLW solutions focus more on proximate causes rather than larger systemic drivers, and effective responses to FLW will require complementary approaches and robust evaluation.

Contents

1. MOTIVATION AND ORGANIZATION OF THE REVIEW

According to one frequently cited estimate, one-third of food produced worldwide is lost or wasted (1). The economic costs of global food loss and waste (FLW) have been estimated to exceed $1 trillion annually (2). Although the concepts, methods, and data supporting these estimates remain contested (3), these figures suggest massive inefficiencies in the global food system, entailing huge environmental, economic, and social costs. Supplying food is resource intensive, involving 20% of global land, 70% of global water withdrawals, 32% of worldwide energy consumption, as well as other inputs, while generating solid waste, greenhouse gas (GHG) emissions, and other pollutants (4–7). Thus, reducing FLW promises significant benefits. Ongoing challenges to global food security (8), exacerbated by increasing demand for food and potential food supply shocks from climate change (9, 10), also have attracted intense interest in FLW. Most notably, United Nations Sustainable Development Goal (SDG) 12.3 aims to halve per

Food loss and waste (FLW): any food intended for human consumption that ultimately is never eaten by humans capita global retail and consumer food waste and reduce food losses in the early stages of the food supply chain (FSC) by 2030 (11). Businesses also have responded: The majority (60% by revenue) of the world's 50 largest food companies aligned their corporate FLW goals with SDG 12.3 (12).

This growing interest in FLW has produced a recent explosion in publications (13). However, FLW is a complex topic, spanning multiple scales and with dynamics driven by interacting combinations of individual activities as well as larger economic, policy, and sociocultural factors. To organize a review of this emerging research field, our team adopted the well-established DPSIR (Driver-Pressure-State-Impact-Response) framework. The European Environmental Agency introduced DPSIR in 1999 to enable better understanding of causal linkages in coupled human-environment systems (14). As applied to a systems perspective on FLW, drivers are macroeconomic, sociocultural, technological, and policy factors that shape human activities related to the entire food system (e.g., labor markets, population and income growth, technological innovation, cultural change, and shifting social norms). Pressures are the individual and institutional aspects endogenous to the system (e.g., farmers' choices about land, fertilizer, and water; households' choices about food acquisition, consumption, and disposal). The state of the food system is defined by current conditions in parameters of interest (e.g., number of food-insecure households, quantity of food materials discarded, regional FLW patterns). Impacts in the context of this review are economic, social, and environmental side-effects and costs of FLW. Responses are changes in behavior, practices, institutions, and policies induced by FLW impacts; responses can address any of the preceding components individually or in combination.

Food supply chain (FSC): the entirety of the food life-cycle from production through harvesting, processing, transport, storage, retail, consumption, and disposal

DPSIR: the Driver-Pressure-State-Impact-Response framework, an approach for conceptualizing complex human-environment interactions

DPSIR has proven useful in the assessment of various coupled human-environment systems and related complex problems, including its adaptation by the Millennium Ecosystem Assessment (15), despite some shortcomings (16). Our team found DPSIR especially useful for framing the complex issue of FLW. Its application to the vast and emerging FLW literature enabled a comprehensive, systems-based understanding of FLW that can inform interventions and policies to achieve global goals to reduce FLW, while pursuing the linked agenda of increasing food security and reducing the overall environmental, economic, and social costs of our food systems.

Our review is structured to match the DPSIR framework as follows. Section 2, Defining Food Loss and Waste, discusses various definitions of FLW. Section 3, Drivers and Pressures: Causes of Food Loss and Waste Across the Food Supply Chain, describes the many causes of FLW. Section 4, The State of Food Loss and Waste, details how much, where, and what type of food is lost and wasted. Section 5, Food Loss and Waste Impacts: Economic, Environmental, and Social Costs, outlines the economic, environmental, and social costs of FLW. Section 6, Responses: Existing and Emerging Solutions to Reduce, Recover, and Recycle Food Loss and Waste, asks how we can reduce and manage FLW. We conclude with Summary Points, as per the existing literature, and Future Issues, our suggestions for emerging research priorities.

2. DEFINING FOOD LOSS AND WASTE

There is a remarkable diversity of definitions for FLW, and related terms (e.g., spoilage, shrink, and discards), in the literature—a result of the complexity inherent to the topic. Most definitions specify "food" as food materials "intended or reasonably expected to be consumed by a human," making the definition a core underlying construct (17–20). Food materials not included in the human FSC, such as food materials intended for animal feed or biofuel feedstock, are generally excluded from the definition of FLW. As **Figure 1** depicts, commonly used definitions of FLW differ primarily in terms of stage of the FSC, edibility/inclusion of inedible parts, and end-of-life treatment or destination (3, 21, 22).

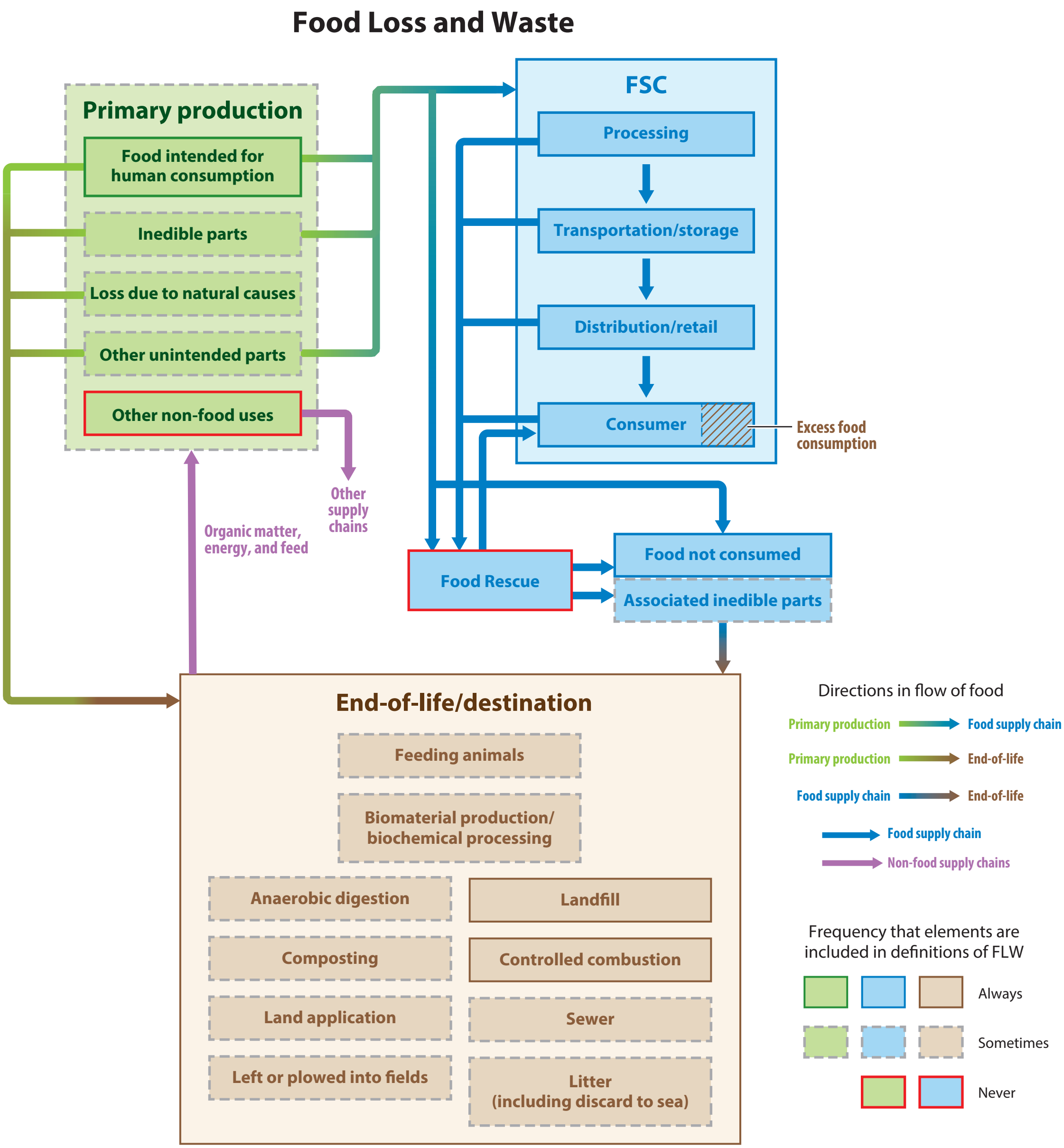

Figure 1

Capturing the multiplicity of food loss and waste (FLW) definitions. Defining FLW requires understanding and identifying flows of food material in and out of the food supply chain (FSC). The three main differences characterizing definitions of FLW include stages of the FSC included, end-of-life/discard options included, and inclusion or exclusion of inedible parts. "Productive uses" of discarded food materials, such as anaerobic digestion and composting, are sometimes excluded from the definition of food waste [e.g., Bellemare et al. (3)]. Food rescue is considered a part of the FSC, and thus not considered a loss or waste. Other distinctions between specific definitions of FLW are the inclusion of excess food consumption (i.e., consumption that exceeds metabolic needs) as food waste (26) and the inclusion of losses of quality (e.g., nutritional value) in addition to the oft-used losses of quantity (e.g., mass) (17, 18, 21).

The first main difference characterizing FLW definitions concerns stages of the FSC included. Most definitions include postharvest transportation and storage, processing, distribution, and consumer stages. However, losses at primary production, such as crops left unharvested, are sometimes excluded (19, 21). This distinction affects the baseline measure of food available for human consumption. For definitions starting at the farm gate, food available for human consumption equals food harvested. However, for definitions including losses in on-farm production, the baseline is quantity of food grown.

Stages in the supply chain can also differentiate between definitions of food loss and food waste. In these definitions, food losses occur earlier in the FSC (production, transportation and storage, processing, and some distribution), whereas food waste occurs further down the FSC, i.e., retail and consumer levels (18, 21). Others define food waste as a subset of food loss (19) or distinguish whether it is voluntary (waste) or involuntary (loss). These distinctions recognize differing causes and potential solutions (18). However, not all definitions distinguish between food loss and food waste (22).

A second main difference concerns end-of-life options, or "destinations" (see **Figure 1**). Many define FLW in terms of removal of the food from the FSC. Redistribution of safe, edible food to humans is not considered FLW, given the food remains in the FSC. While diverting surplus food to feeding animals and/or to biomaterial processing/production is considered removal from the FSC, these end-of-life destinations are sometimes considered separately from FLW because they result in the valorization, or "upcycling" of the food materials (22). Some definitions only consider as waste food sent to "unproductive uses" such as landfills or incinerators, excluding food that is composted or diverted to any other "productive use" (3, 21). Landfilling and incinerating food generally are considered the main nonproductive destinations, whereas drain disposal and litter are included by some but omitted by others (21, 22).

The third main difference is the inclusion or exclusion of inedible parts (**Figure 2**). Here, edibility is not defined as whether the item was safe to eat at the time of disposal (e.g., spoiled food). Rather, it indicates whether the part is expected to be eaten (e.g., bones, banana peel). However, the edibility of food items is a sociocultural concept rather than a fixed property. Some items are widely considered inedible, undigestible, or toxic for human consumption (e.g., egg shells), whereas others may differ between contexts and cultures (e.g., potato peels) (23, 24). Instead of a strict dichotomy between edible and inedible parts, "avoidability" is an alternate concept that recognizes a spectrum of edibility, with a third (middle) category to capture the concept of "potential avoidability" (24, 25). In sum, inclusion or exclusion of inedible parts as well as the definition of edibility vary, making comparisons difficult.

Other FLW definitions are distinguished by inclusion of overnutrition (i.e., consumption that exceeds human metabolic needs) as food waste (26) and the inclusion of losses of quantity and quality across the FSC (17, 18, 21).

Garrone et al. (27) identify three broader purpose-driven perspectives for understanding and defining food waste: (*a*) social, (*b*) zootechnical, and (*c*) environmental. The social perspective has the broadest view, identifying food waste as any food that is not used to feed people. The zootechnical perspective narrows the definition of food waste as food that is not consumed by either people or animals. The environmental perspective goes beyond whether food was consumed and defines food waste in terms of whether its environmental impact was mitigated. In this case, food waste is food that is not diverted from disposal (generally, landfill or incinerator) or recovered in any way (27). These perspectives shape how FLW is defined, and thus, how it is understood, quantified, and measured. However, these conceptual differences do not necessarily inhibit comparability if assumptions are clear and data are disaggregated by supply chain stage, edibility, and destination.

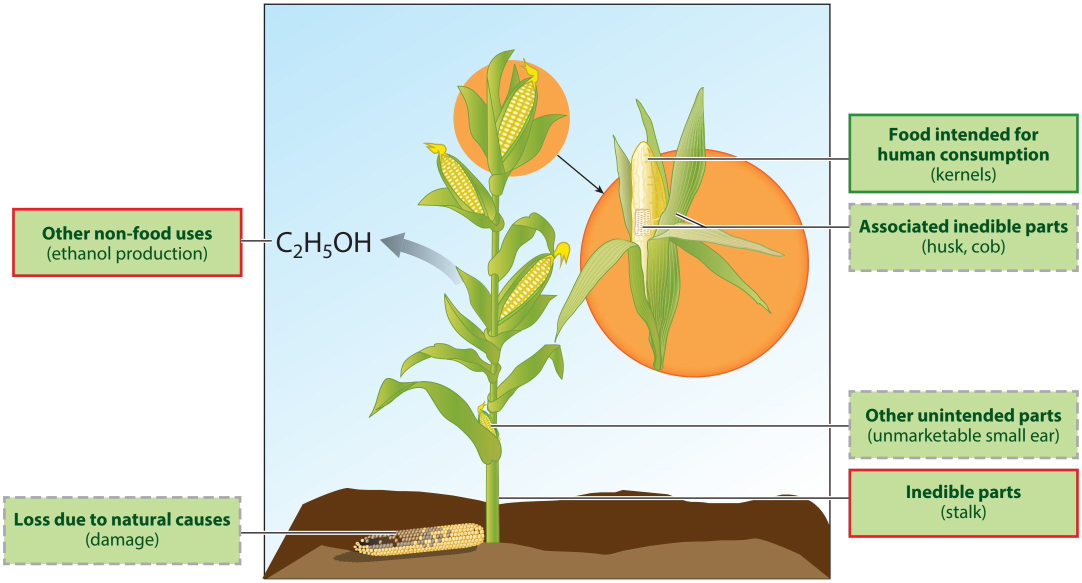

Figure 2

Classifying food material at primary production. An almost universal component of definitions of food loss and waste is identifying food "intended for human consumption," and thus excluding non-food uses of food materials and other unintended parts. Some definitions also exclude associated inedible parts (e.g., USDA, FAO); however, the categorization of edibility can vary widely.

3. DRIVERS AND PRESSURES: CAUSES OF FOOD LOSS AND WASTE ACROSS THE FOOD SUPPLY CHAIN

Causes of FLW are myriad and vary by activity along the FSC. As noted above, the DPSIR framework distinguishes between higher-level drivers (e.g., macroeconomic conditions, policies, sociocultural norms) and proximate pressures (choices, actions, practices) that directly lead to FLW. Globally, regionally, and locally, FSCs have changed dramatically over the past 25 years, especially in developing countries (28). These changes influence FLW at every stage of the FSC. The drivers behind these system-wide changes include urbanization, infrastructure investments, globalization, consolidation in the food industry, and prosperity, all of which shift food access and preferences (20, 28, 29). These large-scale trends shape the economics of the food industry, which in turn influence sectoral drivers, such as the selection of crops for cultivation, food availability, consumer purchasing, and farm policy (29). Although these drivers operate across the FSC, other FLW drivers and most pressures vary by FSC stage. As such, the following sections present this discussion organized by "upstream" FSC (including primary production, processing, transport, storage, and wholesale) and "downstream" FSC (including retail, restaurants, institutions, and households). **Table 1** provides a consolidated summary of a wide range of drivers and pressures of FLW (though not intended to be exhaustive) and includes an assessment of the level of evidence and agreement on these drivers/pressures as evidenced in the literature.

3.1. Upstream: Production and Distribution Food Loss and Waste

Plausible—yet potentially overwrought—stereotypes underpin conventional storylines distinguishing agriculture and food systems in "developed" and "developing" countries, where developed countries suffer mostly from high levels of food waste with the consumer and developing countries experience disproportionate food losses in production (1). In so-called developed

Table 1 Consolidation and assessment of existing evidence for multiple (but not exhaustive) drivers and pressures of food loss and waste covered in the literature

FSC stages		Driver/ pressure	Factor	Description	Evidence and agreement[a]	Citation[b]
Upstream	**Primary production**	Drivers	Environmental factors	Weather, pests, disease	Well established	34, 35
			Market conditions	Prices, marketing standards, labor availability, adequate supply chain capacity, and food safety	Established but incomplete	34, 35, 36, 82
		Pressures	In-field culls	Leaving produce in the field because it does not meet quality specifications (e.g., size, shape, color, maturity)	Well established	34–36, 82
			Fields not harvested	Not harvesting an entire field as a result of significant environmental damage, unfavorable market conditions (e.g., price of product is too low to justify harvesting costs), or food safety concerns	Established but incomplete	34, 35, 82
			Harvesting techniques	Harvesting by hand predominates for fresh fruits and vegetables in both “developed” and “developing countries. This approach is both labor-intensive and time-consuming, and relates to higher losses for these crops relative to crops (e.g., grains, roots, nuts, and processing perishables) where mechanized harvesting has been implemented.	Well established	13, 37
			Harvest timing	Harvest delays increase exposure to inclement weather, temperature and relative humidity variations, spoilage, and pests.	Well established	37
	Postharvest: processing, transport, storage, and packaging	Driver	Lack of investment capital	Food losses occur when there is insufficient investment in postharvest infrastructure, technologies, and human capital.	Well established	1, 13, 32, 37
		Pressures	Packing/processing culls	Removing product from the packing/processing operation because it fails to meet quality specifications	Well established	
			Improper drying operations	Industrial drying systems (e.g., heated air dryers) often not compatible with energy and financial constraints, mainly in “developing” countries, lead to significant loss of grain crops.	Established but incomplete	32, 39, 40
			Inadequate transport infrastructure	Lack of refrigerated units for food transportation (e.g., trucks and train containers), especially in “developing” countries increases spoilage and damage of food during transit.	Well established	20, 43
			Insufficient access to storage capacity	Lack of proper refrigerated storage leads to significant spoilage of highly perishable food products.	Well established	32, 39, 40
				Lack of access to small-scale (plastic and jute sacks, steel/plastic drums) and larger scale (silos, warehouses) leads to spoilage from pests, moisture, and physical damage.	Well established	32, 39, 40
			Insufficient packaging materials	Appropriate packaging is essential to preserve and protect food, as well as to maintain food safety.	Established but incomplete	41, 42

(*Continued*)

Table 1 (*Continued*)

FSC stages		Driver/ pressure	Factor	Description	Evidence and agreement[a]	Citation[b]
Downstream	**Overall**	Drivers	Overall economic conditions	Including labor force participation; wealth distribution; markets; and economic development	Established but incomplete	
			Infrastructure	Energy and transportation sectors; built environment/land use and planning sectors, including food access	Established but incomplete	20, 45, 46
			Consolidation in food systems	Length of the FSCs; type of markets; corporate mergers and acquisitions concentrating control in the food system	Established but incomplete	20, 21, 46
			Food costs	Includes availability of cheap food; prioritizing “value”; politics of food prices	Established but incomplete	20, 21, 45
			Sociocultural identity	Includes abundance; perceptions of edibility; experience growing and harvesting food; perceived social norms related to food	Established but incomplete	21, 44–46
			Health and nutrition	Includes nutritionalization of the food system; provisioning healthy food; special diets	Established but incomplete	21, 44, 45
			Regulatory standards	Developing countries may lack hygienic and specialized facilities with cooling and drying capabilities; product labeling; public health regulations	Established but incomplete	19, 20, 21, 46, 48–51, 58, 59
			Everyday life	Includes food practices; maximizing convenience; thriftiness; cooking skills; eating habits; busy lifestyles	Established but incomplete	21, 44, 45, 63, 66
			Waste management services	Access to trash, recycling, and/or compost collection	Established but incomplete	20, 21, 45, 58, 63
	Wholesale and retail	Drivers	Market standards	Includes demand for consistently high-quality items; appearance of food items; appropriateness for different portions of the FSC	Established but incomplete	19, 20, 48–51
			Sociocultural standards	Includes appearance of food items, including attractive presentation and culling; food quality; discounts and offers; expectations of food portions/serving sizes	Established but incomplete	19, 21 48–51
		Pressures	Forecasting uncertainty	Poor demand forecasting may lead to FLW	Established but incomplete	19, 20, 48–51
			Logistical inefficiencies	Includes losses due to lack of cold storage—developing countries may lack hygienic and specialized facilities with cooling and drying capabilities	Established but incomplete	19, 20, 48–51
			Technical malfunctions	Includes damaged products; spillage	Established but incomplete	19, 20, 46, 48–51
	Restaurants and institutions	Drivers	Market standards	Includes demand for consistently high-quality food; abundance; biological aging (e.g., sprouting of tubers); food standards in schools	Established but incomplete	19, 21, 46, 58, 59

(*Continued*)

Table 1 (*Continued*)

FSC stages		Driver/ pressure	Factor	Description	Evidence and agreement[a]	Citation[b]
			Sociocultural standards	Includes demand for consistently high quality/culturally appropriate food; discounts and offers; expectations of food portions/serving sizes; limited resources in institutional settings to satisfy consumers' quality demands	Established but incomplete	19, 21, 46, 58, 59
		Pressures	Unplanned inefficiencies	Includes technical malfunctions, including inventory management; spillages	Established but incomplete	19, 46, 58, 59
			Maintaining brand identity	Includes corporate social responsibility; product choices	Speculative	58, 59
			Menu choices and portion sizes	Includes food choices, quantities, garnishes, presentation, and packaging	Established but incomplete	59–61
			Consumer behavior	Includes food preferences; appetite; taking home leftovers, and other consumer choices	Established but incomplete	59–61
	Households	Drivers	Market standards	Includes demand for consistently high-quality food; abundance; biological aging (e.g., sprouting of tubers); food standards in schools	Established but incomplete	19, 21, 46, 58, 59
			Sociocultural standards	Includes demand for consistently high-quality/culturally appropriate food; discounts and offers; expectations of food portions/serving sizes; limited resources in institutional settings to satisfy consumers' quality demands	Established but incomplete	19, 21, 46, 58, 59
		Pressures	Household food management	Planning, shopping, storing, cooking, eating, and disposing; includes participation in specific behaviors like meal planning	Established but incomplete	21, 44, 45, 63, 64, 66
			Perception of "good" food	Determining whether food is fresh, what parts are edible, including managing leftovers and navigating food safety concerns	Established but incomplete	21, 44, 45, 63, 65
			Date labels	Can prompt consumers to discard safe and edible food; need for consistency	Established but incomplete	21, 44, 45, 58, 63, 65
			Packaging	Properties of packaging can both increase and decrease FLW: can lengthen shelf life of food; inadequate labeling and packages prompting overpurchasing	Established but incomplete	21, 44, 45, 63, 65

Abbreviations: FLW, food loss and waste; FSC, food supply chain.

[a]Following Moss & Schneider (2000) (125), our team aimed to treat descriptions of qualitative uncertainty consistently by referring to a matrix of two columns for amount of evidence (low, high) and two rows for level of agreement in the literature (low, high), generating four reserved phrases, including "speculative" (low evidence, low agreement), "established but incomplete" (low evidence, high agreement), "competing explanations" (high evidence, low agreement), and "well established" (high evidence, high agreement). Existing research does not have any clear cases of competing explanations, which is a finding in itself.

[b]See Section 3, where these works are discussed.

countries (e.g., United States, Canada, most European nations, and Japan), the typical attributes are (*a*) high yields, high input intensity (including energy inputs), high financial capital investment, and abundant skilled human resources, engaged across highly integrated food production, processing, and distribution enterprises (28) and supported by physical infrastructure and public institutions that boost productivity and innovation. Specific features include mechanized production, sophisticated irrigation and nutrient management, concentrated animal feeding operations, advanced processing operations, and (increasingly) highly integrated distribution systems (cold storage, warehousing, packaging, and transportation) (30). However, by some estimates, up to 20% of food losses occur at production, postharvest, and processing stages within these highly developed food systems (31). And although there is abundant research on postharvest losses in these systems (Section 4.2), there is less information regarding on-farm losses.

In contrast to this "developed" stereotype of agriculture and food systems, the storyline for so-called "developing" countries emphasizes overall lack of capital and investment in agriculture and food systems, and this underpins the core drivers of FLW in these countries, specifically, scarce capital and inadequate physical infrastructure and technology; scarce technical and managerial skills in food production and postharvest processing and distribution; and limited means to reduce spoilage and postharvest losses throughout the FSC, leading to expectations of relatively higher upstream FLW in the developing country stereotype (32, 33). Therefore, it has been estimated that up to 30% of food losses occur at the production, postharvest, and processing levels within less developed food systems (31). Although these broad distinctions between the "developed" and "developing" stereotypes offer useful insights on plausible high-level drivers of upstream FLW, food systems are globalizing rapidly and thus many drivers and pressures of FLW in the upstream FSC are increasingly similar across regions.

3.1.1. Primary food production. Ideally, agricultural (and animal protein) production systems maximize yield, minimize loss and damage, and promptly deliver a safe and high-quality product to the market. However, production and profitability depend heavily on drivers beyond the control of the producer, most notably environmental factors (e.g., weather, pests, and disease) and market conditions (e.g., prices, labor availability, food safety scares, and marketing standards) (34, 35). For example, in agriculture, a significant portion of fruit and vegetable crops are culled during harvest when the product does not meet market-based quality specifications, including purely cosmetic components (e.g., color, shape, size) as well as qualities needed for successful transport through the supply chain (e.g., level of ripeness) (36).

Harvesting techniques and timing are both pressures that can lead to FLW; harvest delays increase exposure to inclement weather, spoilage, and pests (37). Depending on the type of commodity, crops can be hand-picked, mechanically harvested, and/or aided by machines (e.g., conveyors, platforms) (37). Mechanical harvesting predominates in developed countries for grains, roots, tubers, pulses, nuts, and processed perishables; this is not as much the case for fresh fruits and vegetables (37). Meanwhile, harvesting by hand is a labor-intensive and time-consuming process that generally results in higher losses than mechanized operations (13, 37).

3.1.2. Postharvest: processing, storage, packaging, and transport. Once harvested, fresh produce in particular requires proper handling, processing, storage, and packaging to reduce risks of postharvest losses. Notable pressures that affect postharvest FLW include improper drying operations, insufficient cold storage capacity, poor packaging materials, and inadequate transport infrastructure. On the positive side, some processors find value in by-products and coproducts that otherwise become waste (38); energy generation and animal feed are important examples in both developed and developing countries. Refrigerated storage and industrial drying systems (e.g., heated air dryers) are often not compatible with the energy and financial constraints in developing countries, leading to significant spoilage of fresh produce (32, 39, 40). Appropriate packaging is also essential for preserving food and ensuring safety to consumers (41). Producers around the world use a variety of conventional (e.g., plastic and jute sacks and steel/plastic drums) and mechanical (e.g., refrigerating facilities and silos) means to store produce. Although developed countries typically have greater access to these storage solutions than developing countries, the literature lacks definitive estimates of FLW from lack of appropriate packaging (32, 41, 42). Finally, inadequate roads and transport (e.g., lack of refrigerated trucks) increases spoilage and damage of food in transit (20, 43).

3.2. Downstream: Retail and Consumer Food Loss and Waste

Food reaches consumers through retail and wholesale food distribution channels, including supermarkets, and also through other consumer-facing establishments such as restaurants and institutions. FLW may occur at any of these locations, as well as in households, and together these comprise downstream FLW. A variety of drivers at this FSC stage are described in the literature, including infrastructure (energy and transportation sectors); waste management services; cultural identity; health; and everyday life, including family, friends, and community (20, 21, 44, 45). Other potential drivers, such as labor force participation, wealth distribution, food costs, and consolidation in food systems, have not been explored at length. Some studies aiming to comprehensively identify drivers of FLW actually focus on proximate pressures (in the DPSIR sense) with limited attention to powerful drivers such as culture and infrastructure (45, 46). Additionally, information on how drivers influence pressures is limited. One recent review concluded that research on consumer-level food waste suffers from limited evidence of causal connections (21).

3.2.1. Wholesale and retail. Retail FLW refers to foods that go uneaten from supermarkets, convenience stores, and other retail outlets, but does not include loss in restaurants and other food-service outlets (47). Wholesale and informal markets can be treated as a subset of retail (13) or combined with retailers. Structure and physical characteristics of wholesale markets vary by country, with developing countries more likely to lack hygienic and specialized facilities with cooling and drying capabilities (1). More generally, wholesale and informal markets' roles decrease as retail markets contract directly with producers (20).

Market, regulatory, and sociocultural standards for food quality, aesthetic, safety, and abundance all represent key drivers of retail and wholesale FLW, and pressures include forecasting uncertainty, logistical inefficiencies, and technical malfunctions (e.g., damaged product). For example, shelf life of food products is mentioned frequently as a pressure of FLW, likely a result of forecasting challenges and retailers' desires to present fully stocked shelves (19, 20, 48–51).

Retailers are also important "gatekeepers" in the FSC, linking producers, processors, and/or distributors with individual consumers (50). Thus, retail practices influence not only waste in the retail sector, but also the generation of waste upstream (e.g., contract quality standards that lead to on-farm losses) and downstream in the FSC (e.g., preset portion sizes and promotions driving consumer overpurchasing) (44).

3.2.2. Consumer Food Loss and Waste. Wasting food is not a single behavior; rather, it is the outcome of multiple behaviors (44). Although research on consumer food waste is increasing, it remains scarce and fragmented. The complexity and diversity of food waste behavior contributes to lack of focus on mechanisms underlying how and why food is wasted (21). Additionally, these behaviors are mediated by and interact with other everyday routines, including work and caring for loved ones (52). Despite this diversity, one finding is consistent across national boundaries: Most people express aversion to or guilt about wasting food (53–55).

There is a dearth of evidence on consumer FLW in developing countries, especially for Africa and Asia (13). It has been suggested but remains unproven that there is less waste at the consumer level in developing countries than higher-income countries (1). However, a food waste case study in Bogor, Indonesia, contests this dominant narrative that upstream FLW should be the focus in the Global South (56). Similarly, a study of households in Brazil found that lower-middle-income households also waste food (57). This suggests that FLW at the consumer level in developing countries should be further explored, although its contribution to FLW globally remains relatively unknown.

3.2.2.1. Restaurants and institutional foodservices. FLW is created in restaurants and institutional foodservices in schools, universities, correctional facilities, hospitals, and workplaces as well as other establishments such as sports venues, airlines, and catering. Pressures influencing preconsumer food waste in foodservice are similar to those identified for retail: standards for food quality, quantity, and safety; unplanned inefficiencies and technical malfunctions such as inventory management; and maintaining brand identity (58, 59). On the consumer side, pressures influencing foodservice FLW include menu choices, portion sizes, and consumer behavior (59–61).

As populations become wealthier and more urban, and as employment patterns shift, food consumption away from home increases; thus addressing waste in restaurants and institutions is of growing importance worldwide (62) because the shift to food consumption away from home also shifts consumer FLW from households to restaurants and other locations (46). Thus, additional research exploring food waste drivers, pressures, and responses in restaurants and institutional foodservices is a priority.

3.2.2.2. Households. A growing body of literature aims to understand the drivers and pressures of household FLW. A recent review synthesized four overarching drivers and pressures of consumer food waste: (*a*) household food management (e.g., provisioning, storage, and cooking), (*b*) personal factors (e.g., demographics, knowledge, skills, attitudes, and lifestyles), (*c*) material factors (e.g., properties of food and packaging), and (*d*) societal factors (e.g., technology, retail availability, regulation, and culture) (21). Unfortunately, there is limited understanding of the causal mechanisms behind drivers, pressures, and states of household FLW (21), with the exception of a few notable studies. One study concluded that some demographic factors, such as gender and race, do not appear to have much power in predicting food waste (63). Another study found that how food is packaged and sold (e.g., size) seems to be an important pressure that results in smaller households wasting more food, even though they are equally likely to engage in practices that reduce food waste (64).

Most research does not explore precursor behaviors and the multiple routes of influence that may exist between drivers, pressures, and states (45). Food waste behaviors and precursor behaviors have been categorized into seven activities: planning, shopping, storing, preparing, cooking, eating, and discarding. These activities do not necessarily follow a linear path (e.g., storing food happens before and after eating), and discarding food happens at any time across activities. Additionally, how and whether participation in these behaviors results in FLW is influenced by contextual, personal, and sociocultural factors such as time availability or access to a food store. Understanding these precursor behaviors, their contexts, their interactions, and their relations to discarding food is fundamental to understanding consumer food waste (44).

Some research at the household level does focus on specific consumer food waste pressures, including ways in which (*a*) date labels prompt consumers to discard edible food; (*b*) packaging contributes to (or mitigates) food waste; (*c*) consumers determine whether foods are fresh or edible, including managing leftovers and navigating food safety concerns; and (*d*) specific behaviors, such as meal planning or checking cupboards before shopping, affect food waste (45, 63, 65).

Much of the literature focuses on actions by individual consumers, including overpurchasing, instead of social, cultural, and structural drivers and pressures shaping the larger social phenomenon of food waste (45, 52, 53). In his seminal work, Evans (53, p. 42) concluded that "food waste is a more or less mundane consequence of the ways in which domestic practices are socially and materially organized." Consumers negotiate between wanting to avoid food waste and other competing priorities (66), such as food safety, convenience, and time demands (67). Framing food waste within a broader structural and systems framework provides a more comprehensive view of why food is wasted and of strategies to reduce it.

3.2.3. Linkages across the food supply chain. Some drivers and pressures influence FLW across the supply chain. Upstream policies and decisions related to food production, manufacturing, distribution, packaging, and marketing structure consumers' environments and shape their food consumption and waste-related behaviors (44). Thus, it is important to consider the FSC holistically to understand how actors and actions at each stage affect waste at other stages (68). Meanwhile, perceptions of consumer desires affect processing, packaging, and presentation (e.g., retail esthetic standards, date labeling) (65) as well as culling of cosmetically imperfect product, even when flavor, safety, or nutritional value have not been compromised (31). Furthermore, these preferences often are codified and enforced by regulators (30, 32, 33). Moreover, consumers' preferences for superficial aspects of food can translate across borders through trade (34).

Finally, emerging research has suggested that waste management may drive FLW in perverse ways if, for example, the availability of food recycling services affects people's level of concern about food waste. One retail FLW study in the United Kingdom suggests that despite corporate policies identifying food waste as a major issue, most store managers do not see it as a priority, attributing some of the lack of concern to stores' waste mitigation efforts, such as recycling (48). This phenomenon was also identified in a study of consumer waste, in which individuals were more likely to waste food when they were informed that waste would be composted (69).

4. THE STATE OF FOOD LOSS AND WASTE

4.1. Food Loss and Waste Quantification and Assessment

Research efforts quantifying FLW increased significantly in recent years (13), potentially spurred by the seminal 2011 United Nations Food and Agricultural Organization (FAO) report on FLW at the global scale (1) and the adoption of SDG 12.3 in 2015 (11). Quantifying FLW is necessary to decide whether action is required; understanding so-called hotspots, so that action can be prioritized; evaluating a solution or initiative; and monitoring targets (e.g., for SDG 12.3). These varied purposes require differing levels of precision and granularity in FLW estimation. For example, understanding hotspots in a manufacturing business may require fine-scale data on types of food waste and where in the process this occurs. In contrast, a country monitoring progress toward a policy target may only need to estimate aggregate FLW generated.

Data usually are collected by weight, volume, or value. Normalizing these data by FSC stage (e.g., for a retailer, calculating their FLW as a percentage of the food they purchase) can clarify the scale of the issue and enable comparisons across organizations. The choice of metric influences the analyses that can be made; units used should reflect the drivers and purposes that matter to the organization (70).

Beyond knowing how much is wasted, individuals and decision makers usually require more information to guide action, including the types of food wasted, why food gets wasted, where it is generated, and where it goes. This information requires additional effort and entails real costs. However, in some cases, these measurement costs can be recouped through actions to reduce FLW (71). Individual organizations also must decide on the timeframe, frequency, types of material, destinations, and stages in the supply chain for measurement (see **Figure 1**) (70). The most appropriate measurement method depends on the nature of the waste itself (e.g., whether solid or liquid, separated from non-food), its destination, whether the organization wishing to quantify it has access to it, the purpose of the measurement (e.g., diversion to composting or prevention), and the resources and capabilities available.

Decision tools exist to help organizations select appropriate methods among the wide range available (72), including options such as the following:

- Direct measurement: e.g., weighing unharvested produce in fields (36), use of smart bins in kitchens, weighing FLW from plates in schools (73), scanning items discarded or donated from supermarkets (74).
- Sorting and weighing FLW in mixed waste streams (e.g., waste composition analysis) (75–77).
- Self-reported measures (e.g., surveys and diaries) (78).
- Indirect calculations, such as mass balance (e.g., comparing production to consumption) (19, 79, 80), applying percentage FLW to food or waste flows (1), and synthesis approaches that integrate data from multiple sources (81).
- Qualitative interviews and site visits to understand why food gets wasted (82).

4.2. Quality and Coverage of Food Loss and Waste Estimates

In terms of global FLW data coverage, the above-mentioned 2011 FAO report (1) stands out as one of the most frequently cited reports (13). The report estimated 1.3 gigatonnes (Gt), or one-third, of edible food intended for human consumption is lost or wasted at the global scale (based on 2007 global food production data), and it also provided disaggregated FLW estimates by region (and by income class), by food type, and by FSC stage (1). However, the data from this report should be utilized with caution, as there is significant uncertainty embedded in these estimates, driven by a substantial heterogeneity of data quality across the multiple dimensions presented (83). **Table 2** summarizes the quantitative results of the FAO 2011 study, but also assesses data quality across three quality categories: high (region-specific primary or secondary data), medium (secondary data translated across regions), and low (no data). For example, although relatively high-quality data are available for postharvest crop losses in both developed and developing countries, data on fish, meat, and dairy are not available at the same standard (83). Furthermore, data on processing, distribution, and consumer FLW of all food types are of relatively poor quality for developing countries (83).

A vast and growing number of FLW publications take a more focused look at specific regions, supply chain stage, and food type (13, 63). A recent review of global FLW data identified 202 publications from 84 countries between 1933 and 2014 (13). The study concluded that coverage is biased toward high-income countries (especially the United States and United Kingdom); secondary data are highly propagated through the literature (with few independent estimates based on primary data); and consumer FLW tends to increase with income (although more research is needed). They suggest future studies focus on primary data collection using consistent and rigorous methods prioritizing low-income countries.

Despite an abundance of publications, comparability between FLW estimates remains limited. A pair of studies (84, 85) found that data for many European countries were either missing or inconsistent, making comparisons problematic, and the above-mentioned review of global data arrived at similar conclusions (13). Identified shortcomings include inconsistent FLW definitions and measurement methods (with varying levels of accuracy), and thus a need to standardize quantification methods (or at least have increased transparency on methods applied) (86). This heterogeneity in quantification approaches leads to a lack of consensus on FLW estimates across the full

Table 2 Consolidated estimates of global food loss and waste by food type, stage of food supply chain, and region (mid-/high-income versus low-income) with indication of data quality for each estimate. Table adapted from References 1 and 83

Stage (per 1,000,000 tonnes)		Region[a]	Commodity type: Grains		Roots and tubers		Oil crops and beans		Fruits and vegetables		Meat		Fish		Dairy	
Initial production quantity		Mid-/high-income	635		319		63		729		198		29		469	
		Low-income	653		369		149		586		102		23		347	
Losses and waste	Agriculture	Mid-/high-income	12.7	2%	63.7	20%	6.1[b]	9%	96.1[c]	17%	6.2	3%	3.9	12%	16.4	4%
		Low-income	39.2	6%	41.7	10%	11.8	10%	94	16%	6.8	8%	1.6	7%	12.7	4%
	Postharvest	Mid-/high-income	35.7	5%	20.6	9%	0.7	1%	43.4	6%	1.4	1%	0.5	1%	2.2[d]	1%
		Low-income	49.6	7%	56.9	15%	13.2	7%	47.2	10%	0.7	1%	1.7	6%	18.6	7%
	Processing	Mid-/high-income	37.2	0.5%, 10%	12.4	15%	2	5%	3.1	2%	9	5%	2	6%	3.8	1%
		Low-income	35.8	4%	10.6	12%	3.2	8%	18.6	23%	4.2	5%	0.8	9%	4.8	2%
	Distribution	Mid-/high-income	6.3	2%	8.3	8%	0.6	1%	41.6	10%	8.4	5%	1.7	10%	2.8	1%
		Low-income	8.6	3%	9.9	6%	2	2%	40	14%	4.5	6%	2.3	13%	23.6	9%
	Consumption	Mid-/high-income	69.2	24%	16.5	19%	2.2	4%	86.3	21%	15.8	10%	2.5	17%	29.7	9%
		Low-income	22.6	7%	3.9	4%	1.2	2%	21.7	9%	3.8	5%	0.3	3%	4.7	2%
	Total	Mid-/high-income	161.1	25%	121.5	38%	11.6	18%	270.5	37%	40.8	21%	10.6	36%	54.9	12%
		Low-income	155.8	24%	123	33%	31.4	21%	221.5	38%	20	20%	6.7	29%	64.4	19%

[a]Mid-/high-income regions include Europe, North America and Oceania, and Industrialized Asia; low-income regions include sub-Saharan Africa, North Africa, Western and Central Asia, South and Southeast Asia, and Latin America.

[b]Cells in white indicate high data quality, with region-specific primary or secondary data.

[c]Cells in light gray indicate medium data quality, with secondary data translated across regions.

[d]Cells in dark gray indicate low data quality, or no data.

FSC, with annual per capita estimates ranging from 194–389 kg across global studies and 158–298 kg across studies just focused on the EU region (87).

In response to this issue, the international Food Loss and Waste Accounting and Reporting Standard (70) was established in 2016 to outline a consistent process for organizations (including governments, businesses, and NGOs) to measure FLW. Subsequent regional FLW quantification initiatives that comply with the FLW Standard include the EU FUSIONS project manual (88) for European nations; the Commission for Environmental Cooperation for businesses in Canada, Mexico, and the United States (89); the UK Food Waste Reduction Roadmap and Toolkit (90); and the National Zero Waste Council of Canada's household food waste guide (91).

Although the convergence of FLW quantification methods bodes well for future research, the current estimates of FLW in the literature remain disaggregated and of varying quality. In the following sections, we aim to highlight some notable quantitative estimates from the literature for FLW in the upstream and downstream portions of the FSC, although these numbers should be interpreted in the context of the data limitations and challenges described above. We also identify notable data gaps in the literature as areas to direct potential future research.

4.2.1. Upstream food loss and waste. Estimates of FLW in the upstream FSC suffer from inconsistent FLW definitions, system boundaries, and methodologies (87). Many assumptions are made due to lack of data, direct or indirect, and existing data are often outdated (13, 20, 87, 92). Estimating uncertainty is challenging given the complexity and variability of FSC, especially in rapidly developing countries (87, 93). FLW data gaps and deficiencies are most significant for countries and regions experiencing rapid diet shifts away from starchy staples (China and India), and many studies overstate losses with respect to traditional agricultural systems in developing countries (13, 20).

Quantification of FLW in the upstream FSC is most often estimated indirectly, relying on statistics and secondary data, and often leads to overestimates, compared to direct measurement methods (13, 20, 87, 92, 93). Many estimates are based on outdated data derived from poorly specified methods; nonetheless, these unreliable source data are still used to derive new estimates along the supply chain (92). Agricultural production has the least number of publications, followed by postharvest handling and storage as compared to other FSC stages. Additionally, upstream stages have less publications compared to the downstream stages (13, 92). Processing and packaging have the highest number of publications of the upstream FSC stages, but data are still limited (92).

Existing reviews of the available data suggest that there is not a clear consensus on estimates of FLW quantities for primary production, postharvest handling, and processing/manufacturing (87). The estimates of FLW for each of these stages vary significantly by food type and region studied, but even where studies align along these dimensions, significant variation is evident in the published estimates (13), and the values exhibit a high level of uncertainty (87). The comprehensive review conducted by Xue et al. (13) provides the robust consolidation of FLW estimates by food type and supply chain stage, although the resultant dataset should be interpreted with caution, as the large pool of source studies vary by year, location, and measurement approach.

Despite its shortcomings, the FAO 2011 report remains the baseline reference for considering estimation of relative losses along the supply chain by region (1, 87). The study suggests that 20% of total food production in Europe and North America is lost in the upstream FSC, yielding 280 to 300 kg per capita losses per year (1). In contrast, approximately 40% of food losses are estimated to occur in the upstream FSC in developing countries, resulting in per capita losses of approximately 120 to 170 kg of food per year in sub-Saharan Africa and Southeast Asia (1). A separate review study estimates that processing and packaging losses in developed countries range from 1.2 to 61.7 kg per capita per year (92).

4.2.2. Downstream food supply chain.

Direct measurement of consumer-level FLW, including waste composition analyses and kitchen diaries, can be expensive (13) and limited by biases and access to materials. For instance, self-reporting in household kitchen diaries, which track waste as it is discarded, understates waste by approximately 40% compared to direct waste composition analyses (77, 94). There is relatively little data, much of which is rather uncertain, on consumer-level food waste, although a recent literature review found that household food waste has more total publications compared to other FSC stages (13). However, the majority of these studies are for higher-income regions (13). Out-of-home consumption and retailing have the fewest number of publications containing quantitative data on FLW for low-income countries compared to the other stages of the FSC (13). In the context of these limitations, we provide a composite view of existing estimates of FLW for the retail sector, foodservices, and households.

The retail sector generated an estimated 19.5 million tonnes (Mt) of edible wasted food in the United States in 2010 (19) and 5 Mt in the EU in 2012 (including both food and associated inedible parts), accounting for 5% of total EU FLW (85). Specifically, wholesale FLW estimates for Italy, Germany, and the United Kingdom are 118, 60, and 17 thousand tonnes (kt), respectively (95). In developing countries, minimal to no comprehensive data describe the wholesale FLW (96). Estimates of retail's contribution to FLW vary greatly by region and food type, and it is estimated to be the smallest contributor for fruits and vegetables, but the second-largest contributor (excluding households) for cereals (13). Generally, food distribution, which includes retail, represents the smallest fraction of FLW in Europe, North America, and Oceania, whereas it is higher in developing countries (17, 43).

The 2011 FAO global study estimates that a substantial portion of FLW—ranging from approximately 40% of all FLW in North America and Oceania to less than 5% in sub-Saharan Africa—occurs at the consumer level (1). In terms of weight, consumer-level FLW estimates range from approximately 100 kg per person per year in North America/Oceania and Europe (1) to 16 kg in China (97) and 10 kg in sub-Saharan Africa and South/Southeast Asia (1). Generally, estimates of consumer FLW are greater in high-income countries and among more affluent populations (1, 30), although other studies find waste prevalent among lower-income populations (57). Nearly all of the research on consumer FLW has been conducted in North America, Europe, China, Australia, and New Zealand (13, 98); the consumer-level FLW estimates for developing countries in the oft-cited FAO 2011 were derived from limited to no primary data from these regions (13).

Households are estimated to generate more than half of consumer FLW in the United States, followed by restaurants, institutions, and foodservice establishments (58). The same trend has been identified in Europe, with households contributing 53% of total food waste for the 28 member countries of the European Union (EU) and foodservice contributing 12% (85). In the United States, estimates suggest that full-service restaurants generate the most waste in the foodservice sector, followed by institutional and other foodservice establishments, and limited-service restaurants[1] (58). A pilot study in China found per capita restaurant food waste to be similar to that of Western nations (99).

In addition to quantifying the problem of consumer-level FLW in terms of value or weight, other studies identify patterns or hotspots. In the United Kingdom, the Waste and Resources Action Programme (WRAP) found that the most wasted food types in households (including edible and inedible parts) by weight are fresh vegetables and salads, beverages, and fresh fruit (24). Meanwhile, a study of households in three US cities found that the most wasted edible food categories

[1]Full-service restaurants generally provide full wait service and take payment after a customer has eaten. At limited-service restaurants, customers generally pay before eating and can dine in (without full wait service), take food out, or have food delivered.

were fruits and vegetables and prepared foods, including leftovers (77). However, as with so many aspects of FLW, estimates in this sector are limited by the quality and quantity of data (85).

5. FOOD LOSS AND WASTE IMPACTS: ECONOMIC, ENVIRONMENTAL, AND SOCIAL COSTS

Estimates of mass quantities of FLW often are used to estimate economic, environmental, and social impacts (2) to assess policy objectives, set abatement targets, and prioritize FLW reduction interventions, as well as broader communication purposes. As with measurement of FLW flows, and in part because of those uncertainties in flows, estimates of impacts vary significantly by method, food type, region and scale, and FSC stage.

In 2014, the FAO produced a comprehensive report on the linkages between FLW and economic, environmental, and social impacts at the global scale (2), estimating total economic costs at $1,055 billion, total environmental costs at $696 billion, and total social costs at $882 billion (all in 2012 US dollars). In interpreting these results, consider the high level of uncertainty embedded in the calculations that relied on global FLW data from the original FAO 2011 report (which has its own data challenges; see **Table 2**) as well as the range of assumptions required to estimate the monetary value of the associated economic, social, and environmental costs by region.

However, this report remains the most comprehensive assessment of its kind (to date)—and the most useful for considering the potential magnitude of the combined global costs of FLW (which, on the basis of conservative assumptions, are an underestimation) (2). The report highlights the uneven distribution of the estimated costs by region. For example, Industrialized Asia and South/Southeastern Asia had the highest costs from GHG emissions (more than twice Europe and North America/Oceania). North Africa and West/Central Asia had the greatest costs related to water scarcity (more than six times the next highest region, South/Southeastern Asia). The greatest contributors to GHG costs were meat, milk, and grains.

Although this FAO report (2) is unique in estimating global costs across a range of indicators, several other studies have sought to estimate economic, environmental, or social impacts for a particular region and/or food type.

5.1. Economic

The economic costs of FLW are manifold and differ by actor in the FSC. For example, FLW can result in lost profits to producers from unsold food or consumer expenditures on food items that are never eaten. (Producers do still profit in this scenario.) Given this complexity, the value of FLW is often reported as either the combined costs incurred to produce, deliver, and dispose of food that is not consumed (58) or as the retail value of the food product that is lost or wasted (19). Of course, it is necessary to consider the site-specific value of the food product based on its stage in the supply chain (e.g., the application of retail value to a lost product in the upstream FSC will overstate the estimate of the economic value) (3). Assessing the value of FLW can be further complicated by fluctuating market prices.

A 2010 study estimated the total value of FLW in the United States from retail through consumers as $161.6 billion ($522 per capita), based on retail prices (19). Meat, poultry, and fish ($48 billion, or 30% of total value); vegetables ($30 billion, 19%); and dairy ($27 billion, 17%) comprised the majority of this total. Expanding the scope to the entire food life-cycle, a 2016 report estimated the total value of FLW in the United States at $218 billion, with $15 billion occurring on-farm, $2 billion in food processing and manufacturing, $57 billion at consumer-facing businesses, and $144 billion in households (58). For comparison, a 2016 study in the EU estimated that the 88 Mt of FLW across the FSC had a value of approximately 143 billion euros ($152 billion)

(85). Two-thirds of this was attributed to losses in the household, reflecting the large role of households in FLW and the higher value of food as it moves through the supply chain (85).

Few studies have integrated FLW directly into economic models to determine the cost of FLW economy-wide. One notable exception is a recent study (2017; see 100) that used linear multiplier general equilibrium models based on social accounting matrices to estimate the impact of avoidable FLW reductions in wholesale/retail, foodservice/catering, and households in Spain, Germany, and Poland. The results suggested that reduction in FLW can lead to overall reduction in economic output with system-wide reductions of total output (GDP) ranging from −1.21% to −2.15% (100). Given the complexity of the links between FLW and the broader economy, further studies of this type could be useful to guide policy makers in developing FLW reduction strategies.

Food Recovery Hierarchy: a heuristic model of prioritized approaches for managing FLW, including (in order of preference) source reduction, followed by feeding hungry people, feeding animals, industrial uses, composting, and finally, landfill and incineration

5.2. Environmental

FLW–environmental linkages have been explored extensively in the literature, with a range of methodologies applied. Estimates of the environmental "footprint" of FLW generally focus on specific environmental impacts (e.g., water or nitrogen footprint) or a collection of impacts for a particular food type (101); occasionally a complete flow of FLW through a region is estimated (102). However, most studies of environmental impacts of FLW focus on GHG emissions. The FAO estimates that FLW accounts for 8% of global GHG emissions; thus, if global FLW GHG emissions were to be ranked in relation to national emissions, it would rank third behind China and the United States (103).

Environmentally Extended Input-Output (EEIO) and Life Cycle Assessment (LCA) have emerged as dominant approaches to assess the environmental impacts of food systems and FLW. An EEIO captures resource consumption in the production of goods (including food) in a regional economy (104). LCAs are used for more comprehensive environmental accounting for a process or product. However, both approaches often rely on aggregate data and estimates that can limit their use in policy analysis (34, 105).

Environmental impacts of FLW also are highly dependent on disposal destination. FLW disposal options are characterized in the Food Recovery Hierarchy adopted by the United States Environmental Protection Agency (106), discussed at length in the next section: source reduction, followed by feeding hungry people, feeding animals, industrial uses, composting, and finally, landfill and incineration. **Figure 1** includes these options and others, such as direct land application and disposal to storm drains and sewers.

Available studies suggest the vast majority (approximately 90%) of FLW is still sent to disposal routes (landfills or incineration) in both developed (e.g., for households in the United Kingdom; 81) and developing countries (93), with the remaining waste diverted to other uses (mostly animal feed and compost). However, some sectors in the FSC demonstrate better performance in diverting FLW from landfills. One 2011 survey of US food manufacturers, wholesalers, and retailers found that of the 20 Mt of food manufacturing FLW, 5% was landfilled with 93% recycled (mostly animal feed and land application) and 2% donated, and, of the 1.7 Mt of wholesale and retail FLW, 44% was landfilled with 38% recycled (mostly animal feed and composting) and 18% donated.

Finally, from an environmental perspective, packaging can be both a problem and a solution for FLW. Although packaging can add to the environmental impact of the FSC overall by increasing resource use, some packaging can directly reduce FLW by preventing damage and extending shelf life (107). The trade-offs of packaging options need further assessment, as complete environmental impacts (e.g., plastics fate and impacts to oceans) are still not accessible via current LCA tools (108), concerns exist about contamination of food from absorption of packaging materials into food products (109), and higher-value diversion options [e.g., composting or anaerobic digestion (AD)] are complicated by the mixing of inorganic material with organic waste streams (110).

5.3. Social

FLW affects individuals and communities directly and indirectly in measures of social welfare (111), human health (50, 112), and employment (113). Many of the linkages between FLW and economic, environmental, and social impacts at the global scale are considered in the aforementioned FAO 2014 report (2). Although linkages between FLW and social impacts are evident, the current literature on this topic is underdeveloped (114).

Approximately 795 million people worldwide suffered from hunger in 2017 (31). Although reducing FLW will not resolve worldwide hunger, which is primarily a problem of distribution and income, not of food supply, a significant amount of food nutrients is lost each year as FLW (115). Cereal losses alone are estimated to account for 53% of total kilocalories lost globally (116).

Studies suggest potential trade-offs between dietary quality, FLW, and social and environmental impacts. Neff et al. (117) discuss mutually beneficial solutions (such as standardizing date labeling or educating consumers) as well as inherent tensions in objectives (e.g., recommending shelf-stable processed foods, which are wasted less but tend to be less nutritious). Furthermore, fruits and vegetables provide the foundation of a healthy diet, but they also represent the greatest FLW by weight in the United States (58). Thus, nutritional and environmental aspects of diet are interconnected and must be recognized as such (112, 117). The challenge lies in determining solutions that improve dietary quality, decrease FLW, and improve overall environmental sustainability simultaneously (111, 118).

6. RESPONSES: EXISTING AND EMERGING SOLUTIONS TO REDUCE, RECOVER, AND RECYCLE FOOD LOSS AND WASTE

This section reviews a range of current and emerging options to address the challenge of FLW, organized according to the well-known Food Recovery Hierarchy (106)—reduce, recover, recycle. The section also includes a discussion of cross-cutting policy approaches. As we consider the literature of each of these classes of interventions, bear in mind that they are related as substitutes or complements in systematic efforts to address FLW. Although these linkages between responses are recognized in the literature, more research is needed to assess interventions that address multiple levels of the FLW hierarchy simultaneously (119).

The prioritization of FLW responses varies by economic, environmental, and social objectives (119–121) as well as by geographic scale (i.e., local to global approaches) (1, 2, 93, 116, 122, 123). In the United States, ReFED (Rethink Food Waste through Economics and Data) performed a cross-cutting analysis of the economic value and diversion potential of various FLW solutions, with FLW prevention efforts estimated to be the most cost-effective interventions (124). A review of FLW responses in the United States and France concluded that most studies focus on recycling, with recovery and prevention being relatively neglected (119). Although a comprehensive assessment of all potential responses to reduce, recover, and recycle FLW is beyond the scope of this review, **Table 3** provides an overview of a range of response types, consistent classification of quantity and quality of evidence in support of the listed approaches (based on an existing framework; 125), and a high-level assessment of the strengths and weaknesses.

6.1. Food Loss and Waste Reduction

FLW reduction, including both prevention and minimization, typically is seen as the highest-value FLW solution (106), as the basic intention of producing food is for it to be eaten by humans. Interventions for FLW reduction vary across the supply chain, but generally tend to focus on FLW pressures as opposed to larger systemic drivers of FLW, such as relationships of risk, value,

Table 3 Assessment of FLW reduction, recovery, and recycling responses identified in the literature

Stage		Response	Key citations[a]	Evidence and agreement (qualitative uncertainty terminology)[b]	Strengths	Weaknesses
Reduction	**Upstream FSC: agricultural production, postharvest handling and storage, and transport**	Market solutions, e.g., relaxed cosmetic marketing standards on agricultural products	34	Established but incomplete	Increases marketable produce from agricultural production	Requires policy revision as well as behavior change in retailers and consumers
		Technology (hardware), e.g., irrigation systems and machine harvesting, resilient crop strains, improved cold-chain and dry-chain systems	99, 116, 128, 176–180	Well established	Significantly improves harvest yield and shelf life; several technologies and strategies available to improve efficiency (e.g., advances in material, biological, and chemical sciences)	High cost (current); requires stable and continuous energy supply (challenging for developing countries)
		Technology (software), e.g., sensors for agricultural and logistics optimization	99, 177, 178	Established but incomplete	Improves shelf life and quality; several technologies and strategies available to improve efficiency (e.g., sensors and data science)	High cost (current); requires stable and continuous energy supply and information systems (challenging for developing countries)
		Training and education, e.g., training programs for improved production, postharvest, transport, and logistics management	30	Well established	Lower cost; accessible to developing countries	Less potential for overall efficiency improvement
		Improved packaging (biodegradable materials, portion sizes, RFID tags)	20, 181, 182	Established but incomplete	Increased protection during shipment; reduced material waste; portioned to match consumer needs; smart tracking potential (RFID tags); good for developing and developed countries	Potential increased cost of goods; increased material waste; commingled organic and inorganic waste streams
	Downstream FSC: retail and consumer	Distribution technologies, e.g., food packaging; inventory management systems, temperature control systems and tracking, development of new produce varieties with improved shelf life	1, 20, 47, 65	Established but incomplete	Increased shelf life of products expands timeline for food to be used rather than wasted; inventory controls enable retailers to optimize purchases and minimize FLW	Packaging solutions have the potential to increase environmental footprint, contaminate food, and increase costs. Other efforts require financial investments that may require supports for businesses.

(*Continued*)

Table 3 (*Continued*)

Stage	Response	Key citations[a]	Evidence and agreement (qualitative uncertainty terminology)[b]	Strengths	Weaknesses
	Retail operations, e.g., enhanced food handler training for store employees, increased frequency of food deliveries, waste tracking	1, 20, 47, 58, 65	Established but incomplete	Less resource-intensive efforts to educate store employees, track FLW, and modify delivery schedules can help stores better manage food supplies.	Large numbers of food stores globally to implement store-by-store solutions
	Marketing solutions, e.g., discount pricing for food items near expiration or eroding quality and appearance, develop marketing cooperatives and facilities in nonhighly industrialized nations	1, 20, 47, 65	Speculative	Some studies suggest consumers will purchase foods at a discounted rate to help stores move items near spoilage.	Evidence is not consistent that consumers consistently will purchase less fresh perishable items, as they worry these will be wasted at the household level.
	Incorporate suboptimal foods into menus	58	Speculative	Institutional providers and restaurants can utilize food seconds and other suboptimal foods in recipes that are not noticeable to consumers.	Systems are needed to more fully explore and develop supply chains for this.
	Consumer campaigns: awareness and information (e.g., encouraging shopping lists/storage tips)	45, 58, 86, 98, 124, 130, 131, 183	Speculative	Preliminary evidence shows short-term FLW reduction with potential for longer-term results.	Does not easily change consumer behavior; needs to address how people relate to food in their everyday life; effectiveness is context dependent
	Consumer: intensive education (e.g., support and training to households to prevent food waste)	98, 184, 185	Established but incomplete	Several studies have shown substantial reductions in levels of food waste.	Longevity of effects unknown; resource intensive, so difficult to replicate on large population
	Consumer: changes to "environment" (e.g., reduced plate/portion size; tray-less dining)	45, 58, 98	Established but incomplete	Results show considerable reduction in food waste.	Focuses on out-of-home consumption, which for most countries is a relatively small part of total consumption
	Consumer (tools): e.g., food sharing and planning apps; intelligent packaging	45, 58, 98	Speculative	Potential to influence behavior, improve food tracking in FSC and households	Not yet commercially available, unknown level of adoption

(*Continued*)

Table 3 (*Continued*)

Stage	Response	Key citations[a]	Evidence and agreement (qualitative uncertainty terminology)[b]	Strengths	Weaknesses
Recovery	Donation (food banks/charitable organizations)	27, 48, 119, 123, 133, 134, 139, 141	Established but incomplete	Evidence shows FLW reduction.	Fluctuating food inputs, limited storage capacity, and surplus can lead to secondary diversions to animal feed or landfill; infrastructure and logistics challenges and costs; does not address root causes of hunger
	Redistribution and secondary markets (e.g., sale of "imperfect produce")	27, 133–136, 186	Speculative	Potential to redirect food that would be otherwise lost or wasted to human FSC; potential secondary market for producers and potential discount market for consumers	Still requires full logistics and infrastructure of primary market FSC, thus hard to deliver discount to consumers; potentially undercuts market for grade A product
	Shared economy (e.g., commercial food surplus recovery network built on social networks)	137, 138	Speculative	Potential of emergent networks to transact food that would otherwise be lost or wasted	Emerging concept and unproven at scale
	Upcycling/ remanufacturing	187	Established but incomplete	Value-added potential for food processing byproducts	Potentially expensive to implement byproduct capture and processing into existing operations
Recycling	Animal feed	106, 188	Well established	Economically and environmentally favorable	Cannot handle all FLW types; requires minimum quality thresholds
	Anaerobic digestion	93, 119, 146, 148, 155	Well established	Produces biogas (for energy supply) and soil nutrients in the forms of liquid fertilizer and soil amendment; low environmental burden	Subject to higher initial capital costs; management challenges; potential operational failures and low production yields/quality; could improve processing at higher solids and enhance stable conditions; well suited for treating food waste
	Composting	119, 148	Well established	Produces valuable, stable soil amendments and fertilizer; low environmental burden; low intensity technology	Less suited for high-moisture and nitrogen content in FLW; can be energy intensive due to aeration and management requirements

(*Continued*)

Table 3 (*Continued*)

Stage	Response	Key citations[a]	Evidence and agreement (qualitative uncertainty terminology)[b]	Strengths	Weaknesses
	Incineration	30, 146	Well established	Economically favorable	High environmental burden, including toxic air pollutants and energy intensive, and resource inefficient; not well suited for high-moisture content present in food waste
	Disposal	93, 146, 189	Well established	Economically favorable	High environmental burden and resource inefficient; GHG emissions; high land use
	Biorefining [e.g., produce high-value nutritional compounds (polyphenols, vitamins)]; industrial chemicals (polymers, oils, detergents, and bioplastic building blocks)	142, 143, 157, 158, 190	Established but incomplete	Potential for high-value industrial chemicals; yield products to enhance ecosystem services	Requires improvements in residue fractionation, fermentation, extraction; chemical and biological conversions needed
	Biofuel production (e.g., methane, hydrogen butanol, microbial oils, biohythane)	152–154, 191–193	Established but incomplete	Low carbon fuel production	Needs to increase yields and reduce costs for commercial feasibility

Abbreviations: FLW, food loss and waste; FSC, food supply chain; GHG, greenhouse gas; RFID, radio-frequency identification.

[a]See Section 6, where these works are discussed.

[b]Following Moss & Schneider (2000) (125), our team aimed to treat descriptions of qualitative uncertainty consistently by referring to a matrix of two columns for amount of evidence (low, high) and two rows for level of agreement in the literature (low, high), generating four reserved phrases, including "speculative" (low evidence, low agreement), "established but incomplete" (low evidence, high agreement), "competing explanations" (high evidence, low agreement), and "well established" (high evidence, high agreement). Existing research does not have any clear cases of competing explanations, which is a finding in itself.

and uncertainty across the FSC (34). In the discussion of these larger drivers, Gille (34) cautions against "conflating the location with the cause of waste" in the design of interventions. This notion is particularly salient in the context of on-farm losses, where produce with cosmetic imperfections is left in the field at harvest as a result of marketing standards that are in turn driven by retailers and consumers that demand a perfect product (34).

6.1.1. Food loss and waste reduction in food production through distribution. Most upstream FLW responses directly target FLW pressures in agricultural production and supply chain logistics, and these responses are generally well-established. Conventional agricultural technologies to reduce losses and increase yields, such as irrigation systems, mechanized harvesting, and disease- and drought-resistant crop varieties are well-established in the scientific literature (126, 127). To address the direct pressure of postharvest food spoilage, a variety of well-established technologies exist that extend product shelf life (e.g., adequate access to cold storage, drying, packaging, and storage technologies), and thereby reducing FLW and enhancing food quality and safety (128). However, as discussed previously, adoption of these approaches and technologies is limited by access to markets, capital, technology, and training in less developed regions (20). Thus, some studies suggest that developing countries may be better served by training programs to reduce FLW in production and postharvest handling through less expensive methods (30).

6.1.2. Food loss and waste reduction at the retail and consumer level. Responses to reduce food waste at the retail and consumer levels vary by sector. Retail and related preconsumer businesses and institutions employ some similar strategies to increase efficiency, improve the shelf life of foods, and create marketable products from items that might be discarded (1, 20, 47, 58, 65). The retail sector holds many technological and social options to reduce FLW, as summarized in **Table 3**. Potential responses include a mix of technology (e.g., packaging, product tracking systems), training (e.g., inventory management), and marketing approaches (e.g., reduction in volume-based discounts) (44). Similar to the upstream FSC, most of these responses address pressures, not drivers, as defined in the DPSIR framework. Further research is also needed to establish clarity about the feasibility, impact, and cost-effectiveness of existing and emerging FLW reductions solutions.

To reduce postconsumer retail and household food FLW, strategies often focus on changing the behaviors or activities of consumers through information and technology. A recent review paper (98) assessed 17 food waste prevention interventions at the consumer level. All were focused on high-income countries, the majority (12 of 17) on out-of-home consumption, and 8 of the 17 used direct measurement of the waste (as opposed to self-reporting or photo-based estimation). Most of these interventions aim to reduce pressures of consumer FLW through changes in consumer behavior and process efficiency; only a few involve policy changes. This review, as does Stöckli et al.'s (86), highlights the need for additional research on the cost-effective household food waste reduction interventions.

Information campaigns have been suggested as a cost-effective option to influence consumer food waste behavior (58), with one assessment estimating 15–33% reduction in household food waste from this approach (98). Although information and awareness campaigns are prevalent, the routinized and complex nature of everyday life is a significant barrier to long-term behavior change. Thus, further research is needed to address how people relate to food within the context of everyday life (e.g., how food is valued, convenience, health, and risk perceptions) (45), as well as to understand how food environments structure purchase, consumption, and waste behaviors (129). In the United Kingdom, WRAP's "Love Food Hate Waste" campaign offers an example of a multifaceted approach that combined consumer education with a technical program on food formulation, packaging, and marketing (130). Over the five-year program period, the United Kingdom experienced a 13% decrease in FLW, with approximately half of this reduction attributed to the WRAP campaign and the other half linked to increases in food prices and reduced wages over the same time period (131).

There are potential unintended consequences of FLW responses aimed at consumers and households, including promoting overconsumption or shifting eating patterns toward less healthy foods (98). For instance, nutrition research highlights the critical importance of higher vegetable and fruit consumption for human health. As such, household food waste reduction efforts should make clear that although reducing the purchase of fruits and vegetables could reduce waste, the goal actually is to increase consumption of fruits and vegetables while minimizing waste (113).

6.2. Food Loss and Waste Recovery

FLW recovery is defined here as the collection of safe food (that would otherwise be wasted) from any stage of the FSC that is redistributed for human consumption. Although this FLW response ranks highly on the Food Recovery Hierarchy, FLW recovery is not a comprehensive solution to lack of access to food. FLW and food insecurity are both symptoms of larger societal issues, and although they can both be used to alleviate the impacts of each other, neither issue resolves the root causes of the other (119, 132).

Several studies explore various options for FLW recovery (**Table 3**), including on-farm gleaning of produce left unharvested, development of secondary markets (e.g., for "imperfect" or "ugly" produce), and donation of surplus or near-expired food (e.g., food banks) (119, 123, 133). A major challenge to redistributing food to charitable organizations or secondary markets is that these systems require the same logistics and infrastructure (and associated costs) as regular food products in the FSC (e.g., trained labor, inventory management, and adequate storage and transport); however, the FLW recovery system is usually operated with the intent of providing discounted or donated food items (119, 134). When these infrastructure resources prove to be inadequate, food intended for recovery may face secondary diversion to animal feed or to landfill (27, 134).

In response to these challenges of recovery efficiency, several recent studies focus on new models to optimize redistribution of surpluses from various industries (27, 133–136), assessments of the availability and recoverability of edible food (27), and even the use of social networks to promote a sharing economy for surplus food recovery (137, 138). Advanced information systems can better enable robust tracking and delivery of donated food flows by monitoring and integrating key logistical parameters, such as timing of donation deliveries, rate of product expiration, and available options for redistribution (139).

Finally, not all donated food is actually wanted or needed by the target community, so there is an increasing need to consider the value (nutritional, cultural, psychosocial) of donated food from the perspective of those receiving it (48, 140). Both retailers and the associated charitable organizations incur costs in storage, logistics, and labor to donate food, so additional research to determine how resources can be best utilized to create new channels for distribution while minimizing waste is critical (141).

6.3. Food Loss and Waste Recycling

Even with extensive reduction and recovery, some FLW is unavoidable and the remaining solution is recycling. At this stage, the goals are to convert FLW to recoverable material and energy and to avoid pollution (142–145). The main options include animal feeding, AD, composting, incineration, and disposal (93). Animal feeding is generally accepted as an environmentally preferred solution, but it faces some food safety limitations (119, 146, 147). AD and composting both involve the controlled biological decomposition of organic waste, including food residues, into nutrient-rich fertilizer and soil amendments. AD additionally produces biogas, a mixture of methane and carbon dioxide, which can be converted into usable energy (148). Compared to incineration and disposal, AD and composting have relatively low environmental burdens due to minimal GHG emissions, low levels of air pollution, and the linked opportunity to produce valuable coproducts (149, 150). Strengths and weaknesses of these solutions are summarized in **Table 3**.

Incineration is a less desirable option for FLW treatment, as the composition of FLW is not optimal for combustion (low caloric value and high moisture content), but it can be more easily incorporated in land-limited areas (150). Installation of incineration technologies is increasing in middle-income countries (151). Disposal solutions, typically in the form of landfilling, are the most widely used solution for FLW globally, despite well-established evidence that it is the least desirable solution based on its considerable land-use requirements, resource inefficiency, and high GHG emissions (151).

The status of FLW as a resource for renewable energy generation in the forms of biofuels and biogas is provisionally agreed upon by most. FLW has large potential as a feedstock for bioenergy production, but its current low yields and high costs reduce its competitiveness compared to other fuels (152–155). Despite these challenges, small-scale and household-level biogas systems are emerging in low-income countries, and adoption of both composting and AD is increasing in low-, medium-, and high-income countries (151).

The emerging concept of biorefineries (142, 143, 156) may open new approaches to valorizing FLW by enabling the extraction of high-value active compounds from FLW material flows (142, 157, 158) (**Table 3**). Beyond extraction of high-value biochemical compounds, biorefining can develop products that enhance ecosystem services, especially for crop production, including conversion of FLW to alternative fertilizers and fumigants (159–161). However, biorefining techniques still require more research and are not currently a commercially viable solution for large-scale treatment of FLW (146, 156).

6.4. Food Loss and Waste Policy Options and Evaluation

Public policy is an important tool in the arsenal of responses to FLW—it has the potential to change incentives across the food system by changing the context for decision making, and thereby to shift choices of multiple actors simultaneously. Thus, policy interventions can affect fundamental underlying drivers as well as proximate pressures that determine FLW flows (states) and their economic, environmental, and social impacts.

Although much of the FLW literature considers potential policy relevance of research (45), few articles address the topic of this section: cataloging of policies that impact FLW and critical evaluation and comparison of the effectiveness of policy interventions.

Various FLW policy instruments exist, but only a handful of peer-reviewed articles have reviewed FLW policy globally, with notable underrepresentation of developing countries (58, 93, 162–164). Moreover, the academic literature lags significantly behind the gray literature in terms of cataloging and tracking FLW policy development and implementation. The EU FUSIONS database of detailed country-specific reports is a robust source on direct and indirect FLW policies and their implications (165). They categorize six types of FLW policy instruments including communication and marketing campaigns, market-based instruments, national strategic plans, regulatory instruments, voluntary agreements, and projects and other measures. **Table 4** provides examples of specific policy instruments associated with each of these categories.

Table 4 Food loss and waste (FLW) policy instrument categories as designated by EU FUSIONS with case examples of implementation

Policy instrument	Case examples
National strategy on food waste prevention	The EU's Circular Economy Package (2015) aligns the EU-wide food waste target with the UN's 12.3 Sustainable Development Goals (SDG) (to halve food waste at the retail and consumer levels by 2030 and reduce food losses along the production and supply chain) (11, 194).
Market-based instruments	A 2005 US enhanced tax deduction that was temporarily expanded to cover more businesses catalyzed a rise in food donations across the country by 137% (195).
Regulations and regulatory instruments	France and Italy have both enacted legislation that prohibits retailers from throwing away edible foods (196); several state governments in the United States have enacted organic waste bans at landfills (167).
Voluntary agreements	The Courtauld Agreement created by WRAP in the United Kingdom is a voluntary agreement that engages grocery retailers, brands, suppliers, and government entities to set collective targets with individualized solutions (49, 50).
Technical reports and main scientific arts	The US Environmental Protection Agency developed the Food Recovery Hierarchy, which ranks food waste prevention and reduction methods (106).
Communications and campaigns	WRAP's Love Food Hate Waste campaign brought together businesses, government, community organizations, and celebrity chefs to spread awareness through media campaigns and educational events, resulting in an estimated 6–7% reduction in household food waste (131).
Projects and other measures	The United States Farm Bill includes funding support for a pilot project to support state and local composting and food waste reduction plans, grants for food recovery infrastructure, and the creation of a new cross-cutting government position for a Food Loss and Waste Liaison (197).

In the United States, ReFED conducted similar work cataloging state and federal FLW policies by section of the Food Recovery Hierarchy (166). The ReFED database suggests that the majority of US food waste policies focus on recycling (the bottom of the hierarchy), such as organic waste bans implemented by multiple state governments. The emphasis of existing FLW policies on recycling appears to be a common trend worldwide (121, 163, 167). Thus, there appears to be a specific need to target research on higher-value FLW prevention and recovery policies, as these approaches appear to be less prevalent across the policy landscape.

Although the overall literature on FLW policies is limited, even less work has been done to quantify and assess the efficacy of FLW policy options. This may be explained partially by the relatively recent emergence of FLW as a widespread policy issue (spurred by SDG 12.3 in 2015), and thus a limited timeframe for policy development, implementation, and evaluation at scale. Robust evaluation is also limited by the quantification challenges outlined in Section 4.1, both for establishing a baseline and for ongoing measurement and monitoring (168).

Although various policy interventions are mentioned in the FLW literature, few are linked empirically with valid and reliable FLW reduction measurements. Chalak et al. (169) applied multivariate regression to analyze the effect of different policies (economic incentives, legislation, food redistribution programs, and awareness campaigns) on household food waste. Along with identifying a positive correlation between income and household food waste, this study found that awareness campaigns, legislation (of any kind/scale), and economic incentives were all associated with decreases in household food waste (23%, 61%, and 45%, respectively). Additionally, the impact of economic incentives dropped considerably when legislation was taken into account, indicating that well-designed regulatory frameworks can be powerful in themselves.

Cohen et al. (170) provide a uniquely rigorous study of plate waste quantities (by weight) in school lunches following changes in federal school meal standards, although this intervention was guided by child nutrition goals rather than FLW reduction goals. Contrary to hypotheses, the school nutrition interventions did not lead to any significant increase in overall food waste, and larger fruit and vegetable portion sizes led to an increase in consumption but not of waste.

In another notable study, Andersson & Stage (171) assessed weight-based pricing of household waste collection and found no impact on FLW reduction. However, the required food waste separation component of the policy did increase the amount of food waste directed to biological treatment, as well as broader increases in (non-food) material recycling.

Finally, Dai et al.'s (172) policy research on household waste management practices in Shanghai is a noteworthy example within an increasing pool of FLW policy research in China. Their review of the literature suggests that many information campaigns have failed to improve recycling behavior by consumers, and that academic theories need to be tested more rigorously in real-world, scalable solutions. Chen et al. (167) note, however, that the quality of some of these studies has been met with some skepticism, as evidenced by low citation rates.

In lieu of direct measurement (particularly at the consumer level), researchers have relied on more qualitative approaches to assess policy impact. One study surveyed content-area experts to give their opinion on the impact of various EU legislative acts on FLW (168). Among the actions perceived as most impactful were several 2014 Communications that were part of a circular economy package, considered by the commission to be a major step in "transform[ing] Europe into a more competitive resource-efficient economy and to reduce food waste" (168). Another survey-based study on consumer intentions regarding recycling concluded that recycling behavior may result from a belief in civic duty and environmental responsibility, and thus campaigns that focus on moral responsibility rather than social pressure may be more effective (173).

The lack of accurate quantification of policy impacts has enabled proliferation of policy suggestions that may have popular appeal but lack credible scientific evidence of effectiveness (45, 98). The development of the international Food Loss and Waste Accounting and Reporting Standard discussed in Section 4.2 represents a significant advancement for improved measurement and monitoring of FLW—an essential precursor to meaningful FLW policy assessment. Additionally, the EU FUSIONS Policy Evaluation Framework serves as a useful tool to assess FLW specifically, including the evaluation of prevention efforts, which tend to be more challenging to measure (174).

Additional research is also required to understand the potential trade-offs and unintended consequences of policies related to FLW. EU FUSIONS identified a breadth of policies in other sectors that may unintentionally affect FLW (positively or negatively), and suggested the majority of this spillover influence relates to policies targeting agriculture, the environment, and fisheries (168). Conversely, because FLW links to a range of economic, environmental, and social impacts (as discussed in Section 5), policies targeting FLW create unintended consequences in the opposite direction. One report explicitly identified the potential positive spillover effects of achieving SDG 12.3 on the linked SDG relating to poverty (SDG 1), hunger (SDG 2), clean water and sanitation (SDG 6), affordable and clean energy (SDG 7), climate action (SDG 13), life below water (SDG 14), and life on land (SDG 15) (175).

The potential systems influence of FLW policies, and our related lack of understanding, is perhaps best summed up in the following quote from Schanes et al. (63, p. 986): "[A] coherent and holistic policy framework that triggers appropriate action beyond the individual level and empowers actors along the supply chain is missing."

SUMMARY POINTS

1. Inconsistent concepts and definitions: Much food loss and waste (FLW) research involves collecting data and framing the problem. Inconsistent FLW definitions (and associated measurement methods) in the current literature reduce comparability of datasets and usefulness of results in building broader understanding of FLW. However, concepts and definitions are beginning to converge within the community of practice.
2. Despite the lack of consistent concepts and definitions, the research generally agrees that there are large inefficiencies along the entire food supply chain that result in food going uneaten, representing significant economic, environmental, and social costs.
3. Systemic data gaps: Significant data gaps persist regarding quantities of FLW by food types and stages in the supply chain.
4. Regional imbalances in FLW data and understanding: Most of the FLW literature focuses on the Global North. Although plausible qualitative reasoning supporting regional differences (e.g., Global South versus Global North, poor versus rich, agrarian versus postindustrial) has been reported, current data deficiencies make it difficult to generalize empirically, especially across geographic regions, regarding drivers and quantities of FLW.
5. The food system, and thus patterns of FLW, are dynamic. All the DPSIR dimensions of FLW are influenced by location, time, and the larger socioeconomic context, Further, longer-term changes in production, processing, supply chain logistics, and retail operations, as well as changes in consumer diets and habits, will resolve some issues of FLW while simultaneously introducing new challenges.
6. FLW responses must address major drivers and pressures: Understanding FLW drivers and pressures is key to designing effective responses. Much of the current research (and design of responses) focuses on pressures and does not consider underlying systemic drivers, especially how health, infrastructure, sociocultural values and norms, and structural dynamics of the larger food system contribute to FLW.
7. FLW responses are complementary: The dominant "waste hierarchy" approach needs to be viewed as a network of complementary solutions that can be combined rather than competing "silver bullet" prescriptions.

FUTURE ISSUES

1. Standardization of definitions: Standardization of definitions and measurement methods is required for convergence on understanding of food loss and waste (FLW) problems and priorities for action, but may take time to achieve. In the meantime, greater conceptual clarity and measurement transparency in the literature will help move the field toward convergence.
2. Prioritization of quantitative FLW research in—and for—developing countries: Systematic case studies in sub-Saharan Africa and South Asia are especially needed, regions that are most vulnerable to food insecurity in coming decades. Understanding FLW

challenges is at least as important in rapidly urbanizing low- and middle-income countries, which are experiencing rapid transformation of their food systems.

3. Critical assessment of FLW responses: Much of the current literature on FLW responses is limited to description and advocacy of individual interventions. There is a great need for comparative, practical research to critically assess the relative impacts, costs, and benefits of the most promising solutions advocated within the literature. Effective assessment will be challenging, given it will require multidisciplinary approaches integrating engineering, economic, environmental, and sociocultural methods to evaluate costs and benefits, both direct and indirect, of FLW interventions at policy-relevant scales (beyond pilot projects).
4. Reframing FLW concepts and responses within a broader food systems perspective: Although defining and measuring FLW and its impacts represent significant challenges, there is a larger need to understand and assess the broader trade-offs of potential FLW policy responses on the environment, human health, economic growth, and social equity, with special urgency regarding impacts on vulnerable populations and environmental justice aspects of FLW responses. This also requires inclusive engagement of multiple disciplinary and stakeholder perspectives and sufficient regional specificity and contextual detail to inform business decisions and public policy.
5. Possible food systems informatics breakthroughs for FLW monitoring and responses: Can emerging efforts to increase the traceability of food flows across the supply chain be leveraged to reduce FLW? Conversely, are there sufficient cost savings from higher-resolution FLW information to merit significant investment in food systems informatics? Where are the most effective points in the food supply chain for these monitoring investments? Will labeling and certification systems emerge to effectively curtail FLW?

DISCLOSURE STATEMENT

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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