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A framework to quantify mass flow and assess food loss and waste in the US food supply chain

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Reducing food loss and waste can improve the efficiency of food supply chains and provide food security. Here we estimate mass flow as well as food loss and waste along the US food supply chain for 10 commodity groups and nine management pathways to provide a baseline for designing efficient strategies to reduce, recycle, and recover food loss and waste. We estimate a total food loss and waste of 335.4 million metric tonnes from the U.S. food supply chain in 2016. Water evaporation (19%), recycling (55%), and landfill, incineration, or wastewater treatment (23%) accounted for most of the loss and waste. The consumption stage accounted for 57% of the food loss and waste disposed of through landfill, incineration, or wastewater treatment. Manufacturing was the largest contributor to food loss and waste (61%) but had a high recycling rate. High demand, perishable products accounted for 67% of food waste. We suggest that funding for infrastructure and incentives for earlier food donation can promote efficiency and sustainability of the supply chain, promote FLW collection and recycling along the U.S. FSC, and improve consumer education in order to move towards a circular economy.

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Human food-related activities are resource-intensive and contribute significantly to environmental problems[1–7]. It is estimated that to meet its human food needs, the U.S. uses 25.5% of its total land area, consumes 28% of its freshwater withdrawals, allocates 11.5% of its annual fossil fuel budget, and produces 18.1% of its annual greenhouse gas (GHG) emissions, without counting the resources required for food loss and waste (FLW) management[2]. In addition, over one-third of the food produced in the U.S. is never eaten, accounting for 31% of land use, 34% of blue water use, 35% energy use, and 34% of GHG emissions of the whole U.S. food supply chain (FSC)[8]. It has been shown that the U.S. generates more FLW per capita than most other countries in the world[9–11]. It is essential to improve the efficiency of the U.S. FSC to meet the anticipated growth of food demand without further compromising ecosystem quality[12–14]. Reducing FLW can avoid the unnecessary consumption of resources, alleviate environmental problems associated with FSC, and improve food security[14–18]. Efforts and initiatives have been developed and implemented to address FLW. For example, the U.S. Department of Agriculture (USDA) and the U.S. Environmental Protection Agency (EPA) launched a joint national goal in 2015 to reduce FLW sent to landfills and incinerators by 50% by 2030[19].

Quantifying FLW along the U.S. FSC to identify the primary contributor of FLW generation and understand the components and characteristics of FLW is an essential first step for designing efficient strategies to reduce, recycle, and recover FLW. Unfortunately, according to our best understanding, a complete and comprehensive accounting of the U.S. FLW has not been done, which is unsurprising given the size and complexity of the U.S. FSC. Several attempts have been made to quantify U.S. FLW, but they have significant discrepancies in the definition of FLW, data sources, and scope (e.g., year and region of analysis), supply chain coverage, and accounting method[7,11]. Table 1 lists those major studies, indicating the scope, boundaries (FSC stages analyzed), major data sources, methods, and limitations of each study. It illustrates that most of these studies only focused on the warehouse and retail (W&R) and consumption stages (i.e., food services and households), excluded the inedible parts of food from their analysis and did not quantify the management of FLW[8–10,20,21]. While many studies exclude it, managing inedible FLW still requires resource inputs (e.g., energy consumed for logistics) and represents great opportunities for FLW recovery and recycling (e.g., animal feed, composting). A few studies included the on-farm production, manufacturing, and distribution stages, quantified FLW in these stages by applying waste factors to mass data or business data[11,22–26], and failed to explicitly define the scope of the waste factors (e.g., whether the by-products from food manufacturing are considered FLW). Moreover, most of these waste factor-based studies did not compare their results to the actual mass flow along the U.S. FSC and rarely measured their uncertainties. After providing a clear FLW definition, this study describes a consolidated framework for U.S. FLW quantification with a life cycle approach and breaking down mass flows by FSC stages and major food commodity groups. Furthermore, this study quantifies the FLW distribution across different FLW management pathways, which can aid in the development of better practices of FLW recycling and recovery (R/R).

This study quantifies the mass flow and FLW generation along five U.S. FSC stages: on-farm production, manufacturing, distribution, W&R, and consumption (i.e., food services and households). The definitions and boundaries of each stage can be found in section "Methods" and Supplementary Note 1. For this study, food is defined as any food product intended for human consumption, excluding soda and alcoholic products. For simplicity, this study focuses on the flow of agricultural materials and excludes other inputs (e.g., water added during manufacturing and packaging materials). This study follows the definitions of the EPA[22] and FLW protocol standard[27] on wasted food FLW is food intended for human consumption that leaves the FSC (including both edible and inedible parts), regardless of its end destination. Stage-based food losses that are donated to people with low food security or recycled for animal feed or other industrial uses are included in this definition of FLW at a specific stage, as that food is still lost to the stage. For example—donated food in the manufacturing stage is a lost product to the manufacturer, as their intention is to produce food to sell to their customers, not to donate it. This literature-based definition aligns with this work's mathematical definition from the mass flow analysis: the FLW at an FSC stage is determined by the mass difference between the output streams and the inputs streams of that stage (see section "Methods") and therefore, includes any by-products and recoverable food materials (e.g., food donation). While the donated food from each FSC stage is considered stage-level FLW, the donated food is eventually consumed and does not actually leave the FSC. Therefore, the donated and consumed food are not considered FLW for the entire U.S. FSC, and the summation of stage-level FLW is not equal to overall FLW from the U.S. FSC. In other words, FLW is defined for a specific system boundary, a stage or total FSC. The mathematical definition of FLW also aligns with the inclusion of the edible and inedible mass in the FLW, as the two are not always distinguishable due to data limitations. A distinction between edible food and inedible food is useful in determining whether the FLW is avoidable or donatable, so further disaggregation should be considered in future studies. The food products are categorized into 10 commodity groups: grain (including corn sweeteners), fruits, vegetables (including vegetable oil), sugar, oil, dairy (including dairy fats), meat, and poultry (M&P; including animal fat), seafood, eggs, and nuts. A detailed list of what is included in each of the covered food commodities can be found in Supplementary Note 2.

This study focuses on the nine pathways that are applied for FLW management in practice: food donation, animal feed, composting, anaerobic digestion (AD), land application, biochemical processing (e.g., bioplastics), landfills, incineration, and wastewater treatment. For simplicity, this study further aggregates these FLW management pathways into four groups adapted from the EPA's Food Recovery Hierarchy[28]. The Food Recovery Hierarchy illustrates the preference for different FLW management pathways and emphasizes reduction at the source (i.e., prevention). After source reduction, food donation is the most preferred pathway to R/R FLW. The third level includes animal feed, industrial uses (i.e., AD and biochemical processing), and composting. Land application, one of the FLW management pathways discussed in this work, is not covered by the EPA's Hierarchy. However, this study groups it with composting due to the similarity of the processing procedures and the application of the end product of the pathway. Landfill and incineration are at the bottom of the Hierarchy as the fourth group and are the least preferred FLW management methods. Although wastewater treatment is not considered in the EPA's Food Recovery Hierarchy, this study combines it with landfill and incineration. While wastewater treatment may have energy recovery opportunities, they are not as substantial as AD. More detailed descriptions of the FLW management pathways can be found in Supplementary Note 3. This study considers food donation as the only food recovery pathway and includes animal feed, composting, AD, land application, and biochemical processing as food recycling (R).

Table 1 Summary of several U.S. FLW estimation studies.

Study	FLW (MMT) (Year)	FSC stages					Methods/data	Limitations
Chen et al.[9]	57 (2011)					C	• Waste factors from FAO • Edible food Amount from GENus	• Only for edible FLW • No FLW management
Conrad et al.[20]	48 (2014)						• Food Availability data from USDA	• Food waste factors for North America/Oceania instead of the U.S
Cuéllar et al.[21] Buzby et al.[10] Birney et al.[8]	44 (2007) 60.37 (2010) 71 (2010)				W	C	• Food Availability data from USDA • Updated waste generation factors	• Only for edible FLW • No FLW management
Venkat[58]	55 (2009)			D	W	C	• Food Availability data from USDA	• Only 134 food commodities • Only for edible FLW • No FLW management
EPA[22]	93.4 (2018)		M		W	C	• Waste generation factors to business data • Estimated FLW management with factors and known management through specific pathways	• Less representative Conversion factors • Underestimated FLW for several pathways • No validation with real mass flows • No explicitly defined scope of waste generation factors
Dou et al.[15]	150 (2016)						• Authors' own estimation of manufacturing FLW • Same estimation as Buzby et al. (2014) for the other stages	• Missing manufacturing FLW for some food commodities • Unknown methodology for manufacturing FLW estimation • No FLW management
FAO[24]	93.4 (2010)	F	M		W	C	• Applications of waste generation factors to mass flow (FAO Food Balance Sheets or multiple datasets maintained by USDA) at each stage	• Food waste factors for North America/Oceania instead of the U.S. • Only for edible FLW • No FLW management
Pagani et al.[25] and Vittuari et al.[26]	77 (2015)							• Only for edible FLW • No international trade • No FLW management
CEC[11]	113.4 (2007)							Similar to FAO's study but partially inclusion of inedible FLW
ReFED[23]	56.69 (2016)						• Application of waste generation factors to business data	• Only FLW of vegetables and fruits at the on-farm production stage • Waste generation factors only for landfilled FLW
This work	335.4 (2016)	F	M	D	W	C	• Mass flow analysis mainly based on Food Availability data and Agriculture Statistics from USDA • Other factors from multiple sources • FLW management based on EPA's method	• Limited data sources for on-farm FLW, distribution FLW, and separating flows between food services and households • Possibly underestimated weight reduction from manufacturing water evaporation. • See Supplementary Note 11 for details

[a]On-farm production [F], food manufacturing [M], distribution [D], wholesale & retail [W], consumption [C].
[b]U.S. Department of Agriculture [USDA], Food and Agriculture Organization the United Nations [FAO], U.S. Environmental Protection Agency [EPA].

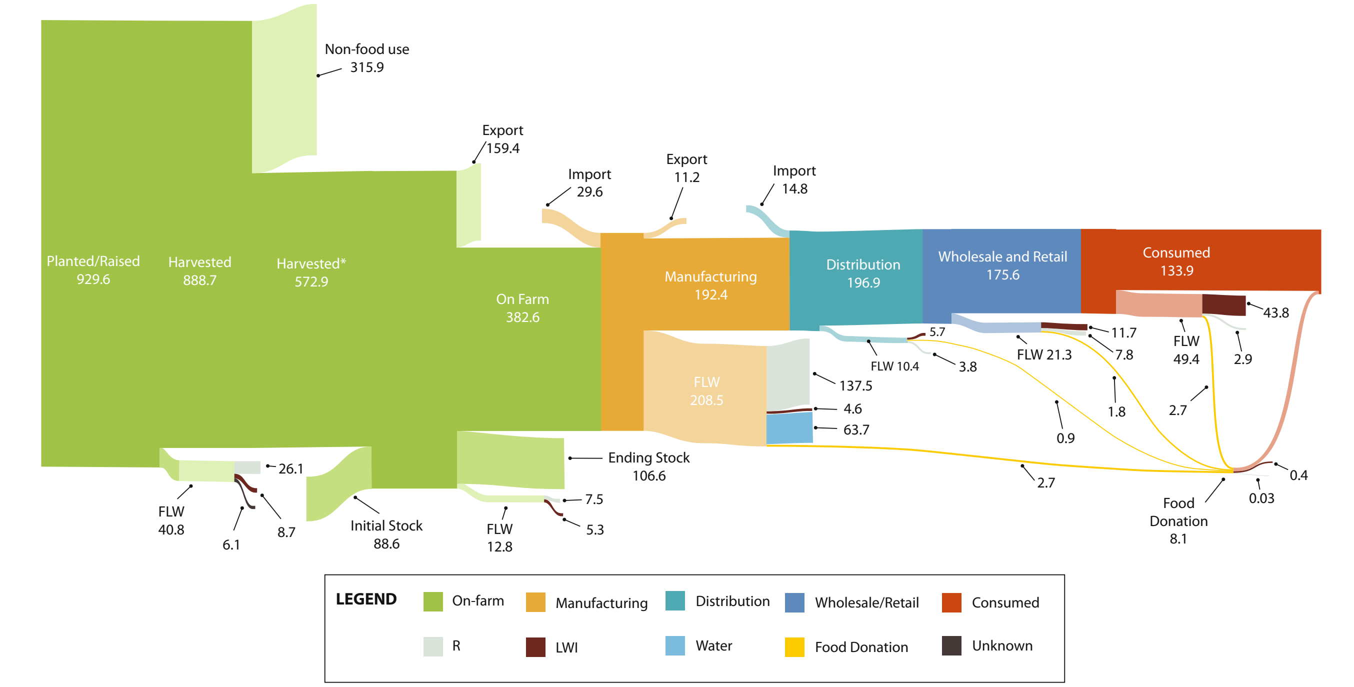

Fig. 1 Sankey diagram of the mass flows of the 2016 U.S. FSC (in MMT). Mass flow of food across the 2016 U.S. FSC in MMT. The different stages are labeled and in different colors, and lighter shades represent inlet and outlet flows directly from the main mass flow. On-farm activities, in light green, consist of Planted/Raised (e.g., crops planted, or animals raised), Harvested (total agricultural materials harvested), Harvested* (where the asterisk represents that it is food intended for human consumption), and finally On-farm (representing the mass flow out of the on-farm stage). On-farm also includes several inlet and outlet flows (all in a lighter shade of green): non-food use (agricultural materials harvested specifically for non-human food uses —e.g., biofuel production, animal feed), exports, initial and ending stock, and two FLW streams (unharvested and unsold food). All other stages only have one substage within them and only Manufacturing (human food manufacturing; in orange) and Distribution (in teal) have inlet and outlet flows beyond FLW (imports and exports and imports only, respectively). Wholesale and Retail (W&R; dark blue) and Consumed (food consumed at the Consumption stage; red) only have FLW flows leaving the main FSC. All FLW flows have several potential outlets: FLW managed through animal feed, composting, AD, land application, biochemical processing (R, gray green); FLW disposed of through landfill, wastewater treatment, and incineration (LWI, dark red), unharvested animal product waste with unknown disposal (unknown, dark gray), mass removed via evaporation (or other similar processes) in manufacturing (water, light blue), and food donation (yellow).

Results

The Sankey diagram in Fig. 1 illustrates the mass flows of all food commodities, in millions of metric tonnes (MMT), along the U.S. FSC in 2016. The detailed calculation procedure used to generate it can be found in Supplementary Notes 4–9 and the results can be found in Supplementary Data 1. The total FLW from the five FSC stages is 343.2 MMT, though due to 7.8 MMT FLW reentering the FSC and consumed via food donation, the total FSC FLW is 335.4 MMT. among the 335.4 MMT of FLW, 19% (63.7 MMT) of FLW is the mass lost via evaporation or other processes for the manufacturing of dried products (e.g., powdered milk and dried fruit). While it is mass lost in the manufacturing stage, and therefore FLW, it was considered a distinct FLW mass flow and kept separate from the remaining manufacturing FLW for the analyses. As this is specifically water removed via drying techniques that do not require wastewater disposal (e.g., evaporation, boiling) it was not included in the analysis to allocate FLW to different management pathways. The mass remains part of the mass flow before the manufacturing stage, as it still consumes energy for growth and transport to and within the manufacturing facilities. The management of on-farm animal-related FLW (8.9 MMT; 2.7%) is described as unknown due to data limitations. In addition, most of the rest of the FLW is either recovered or recycled (185.5 MMT, 55.3%). The remainder of the FLW (77.3 MMT, 23.1%) is disposed by landfilling, incineration, or wastewater treatment. In the following descriptions of FLW composition and management, we will be discussing FLW on a per stage basis, (i.e., a total of 343.2 MMT from all stages), and thus food donation is still considered FLW and as one of the management pathways.

Mass flows and FLW generation by FSC stage. As demonstrated by Fig. 1, a total of 888.7 MMT of agriculture materials were harvested in the U.S. in 2016 (including materials not intended for human consumption), while 40.8 MMT were planted but left unharvested and considered FLW. Among all harvested, 315.9 MMT was used for non-food purposes (e.g., seeding, animal feed manufacturing, or biofuel and alcohol production). That left 572.9 MMT of agricultural materials available for manufacturing, but 12.8 MMT failed to enter the food market (i.e., became unsold FLW) caused by poor quality, damage during harvesting operation, and on-farm storage. In addition, 159.4 MMT of agricultural products left the U.S. as international trade, and a net 18.1 MMT was added to the agricultural stock (difference between the 2016 initial stock and ending stock). Supplementary Note 4 provides more details on the data and calculations for this stage.

While 382.6 MMT of U.S. and 29.5 MMT of imported agricultural materials entered the manufacturing stage in 2016 (for a total of 412.1 MMT), only 203.6 MMT of food products were produced by U.S. food manufacturers (Supplementary Note 5), including 11.2 MMT exported. At the same time, 14.8 MMT of manufactured food products were imported, leading to a total of 207.2 MMT of food entering the distribution stage. With a total of 208.5 MMT of manufacturing FLW (Fig. 1),

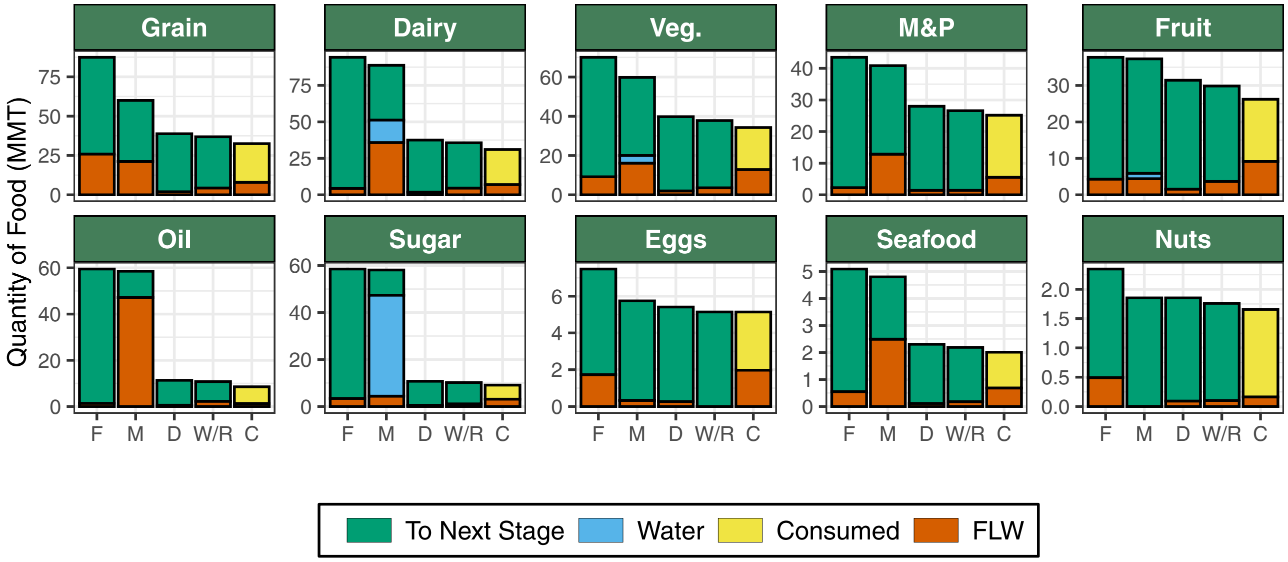

Fig. 2 Food commodities' contribution to FLW in different stages of the FSC. Detailing the food products/agricultural materials' flow to the next stage (green) or water evaporated during food manufacturing process (Water, blue), consumed (yellow), or as FLW (vermillion). The 10 commodities are represented with their own labeled panel (M&P represents meat and poultry, and Veg. represents vegetables) and each stage is a different column (on-farm production [F], food manufacturing [M], distribution [D], wholesale & retail [W/R], consumption [C]). The *y*-axes labels vary between panels so mass flow details are more visible.

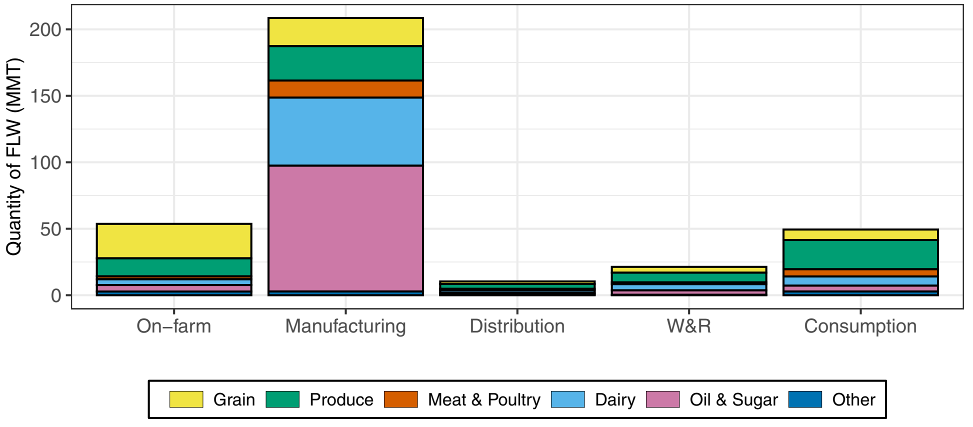

Fig. 3 FLW in the different stages of the FSC. Breakdown of FLW by commodity group for each FSC stage: on-farm (on-farm production), manufacturing (food manufacturing), distribution, wholesale and retail (W&R), and consumption. Commodities are grouped for visual clarity and remain in order from top to bottom of each column: grain (yellow), produce (fruits and vegetables, green), meat and poultry (vermillion), dairy (light blue), oil and sugar (purple-pink), other (dark blue) includes the low demand commodities—nuts, seafood, and eggs.

the U.S. food manufacturing sector appears to be extremely inefficient. However, the estimated manufacturing FLW does not indicate wastefulness, but is simply the mass difference from the beginning and end of the stage. FLW in the manufacturing stage is mostly caused by the necessary separation of edible food from the uncommonly eaten (e.g., offal, organs, cartilage, whey, oil meal), inedible parts (e.g., bones, cores, seeds, shells, germ, and bran), and water (e.g., evaporation during the manufacturing of sugar and some dairy products). Furthermore, most of the manufacturing FLW (140.2 MMT) is recycled or recovered through several pathways (such as animal feed manufacturing), which will be discussed further later.

With 207.2 MMT of food products being distributed and 196.9 MMT entering W&R in 2016 (Fig. 1), the distribution stage accounts for a relatively low amount of FLW (10.4 MMT). This efficiency is likely driven by advanced logistic practices (e.g., cold chains). From the W&R stage, 175.6 MMT arrived at the consumption stage (i.e., food services and households), leaving 21.3 MMT of W&R FLW. The consumption stage also has an input of 7.8 MMT of donated food from the FSC that gets consumed. At this stage, only 133.9 MMT food (including 126.1 MMT of the purchased food and 7.8 MMT donated food[29]) was consumed, leaving 49.4 MMT as consumption FLW (49.4 from households and food services and 0.38 MMT from food banks). More details regarding the determination of the food donation streams can be found below and in Supplementary Note 8.

Mass flows and FLW generation by food commodity. The mass flows and FLW generation at different FSC stages disaggregated by food commodity are illustrated in Figs. 2 and 3, respectively. As shown in Fig. 2, on-farm production activities of animal products (i.e., M&P, eggs, seafood, and dairy) result in relatively smaller amounts of FLW (2.3 MMT for M&P, 0.6 MMT for seafood, 1.7 MMT for eggs, and 4.3 MMT for dairy) compared to crops (e.g., 9.2 MMT for vegetables and 25.9 MMT for grains).

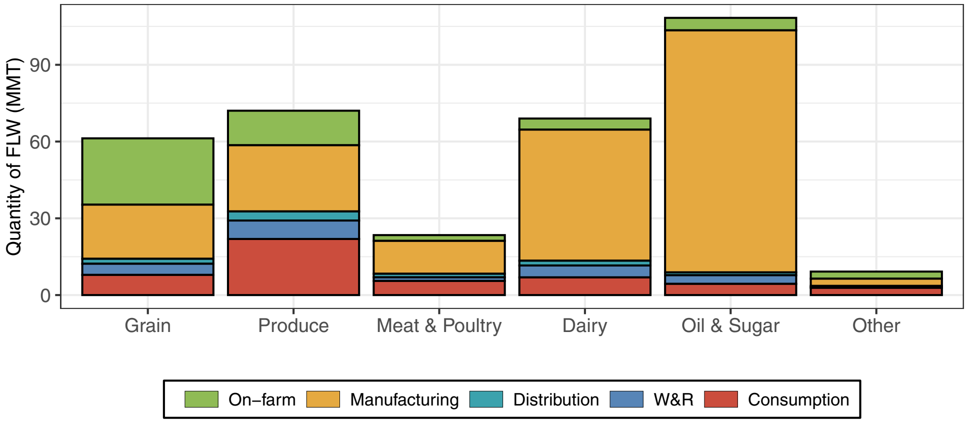

Fig. 4 Contribution to FLW for each commodity group. Breakdown of FLW by FSC stage for each commodity group: grain, produce (fruits and vegetables), meat and poultry, dairy, oil and sugar, other (nuts, seafood, and eggs). The stages remain in the same order in each column: on-farm (green), manufacturing (orange), distribution (teal), wholesale and retail (W&R, dark blue), and consumption (red).

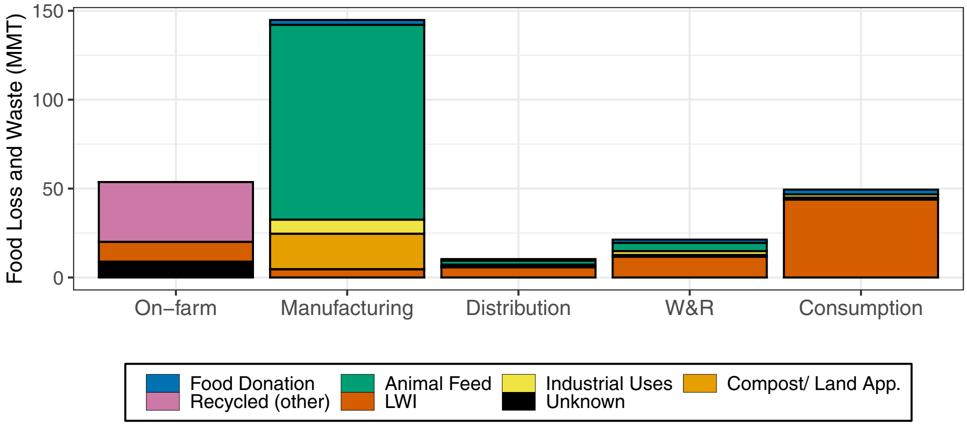

Fig. 5 FLW management pathways along the FSC. Breakdown of FLW by FLW management pathway for each FSC stage: on-farm, manufacturing, distribution, wholesale and retail (W&R), and consumption. The pathways remain in the same order in each column (if used within the stage), relating to the EPA' food recovery hierarchy: food donation (purple-pink), animal feed (green), industrial uses (yellow), compost or land application (orange), recycled (other) is specifically for crop-based on-farm FLW recycled using unknown methods, LWI (vermillion) represents disposal via landfill, wastewater treatment, and incineration, unknown (black) represents animal-based on-farm FLW disposed via unknown methods.

However, considering the relatively high resource demand and GHG emissions from raising animals[30–32], any animal-related FLW reductions would be impactful. Grains, fruits, and vegetables, as illustrated by Fig. 3, are the highest contributors to the on-farm FLW, but grains are also the highest volume food product at this stage. The ratio between the masses of on-farm FLW and agricultural materials harvested (for both human food and other purposes; details in Supplementary Note 4) shows that grains have a lower loss factor (5.6%) compared to vegetables (16%) and fruits (20%). Seafood, eggs, and nuts (0.5 MMT) have the smallest volumes of on-farm FLW, likely caused by their lower demand.

While several commodities have little mass lost at the food manufacturing stage (e.g., fruit, nuts, and eggs with <20% of loss in their mass flows), others are dominated by FLW (e.g., oil with 81% FLW and dairy with 57% FLW) or water evaporation (e.g., 86% for sugar), as shown by Fig. 2 and Supplementary Note 5 with more details. Figure 3 shows that the largest contributors to manufacturing FLW, are dairy (24.6%), sugar (22.7%), and oil (22.6%). Besides, grain (20%), vegetable (20%), and fruit (14%) add a large amount of FLW at this stage, partially driven by the high demand for these commodities. Conversely, nuts, seafood, and eggs contribute a very small portion of FLW at the manufacturing stage and others, again, because of their relatively low demand.

Five commodities contribute over 85% of the FLW from later stages (distribution, W&R and consumption): vegetables (19%, 17% and 26%), fruit (15%, 17% and 18%), dairy (18%, 22% and 14%), grain products (19%, 21% and 16%) and M&P (14%, 6.6%, and 11.2%), as shown in Fig. 3 and Supplementary Note 6. This is understandable as fresh vegetables, fruits, meat, and poultry, as well as bakery and dairy products are both highly perishable and in high demand. The high FLW generation from perishable products at these stages reveals the need for efforts to prevent FLW by prolonging product shelf-life, which will be further discussed below.

In addition to knowing which stages have the highest FLW, knowing which commodities produce the most FLW (Figs. 2–4) can benefit FLW reduction. Again, while sugar and oil products have a high contribution to total FLW (15.4% and 16.2%), this FLW is mainly caused by the unavoidable removal of inedible (but still recyclable) portions or water during manufacturing and is not caused by spoilage or FSC inefficiency. After oil and sugar, dairy products make up the largest portion of the FLW (20%), followed by grains (17.8%), vegetables (13.8%), fruits (7.1%), all of which include products with high demand and perishability. These commodities' FLW is largely generated on-farm and during manufacturing but FLW from those stages, and as shown below, is mostly recycled or recovered, whereas the FLW generated in

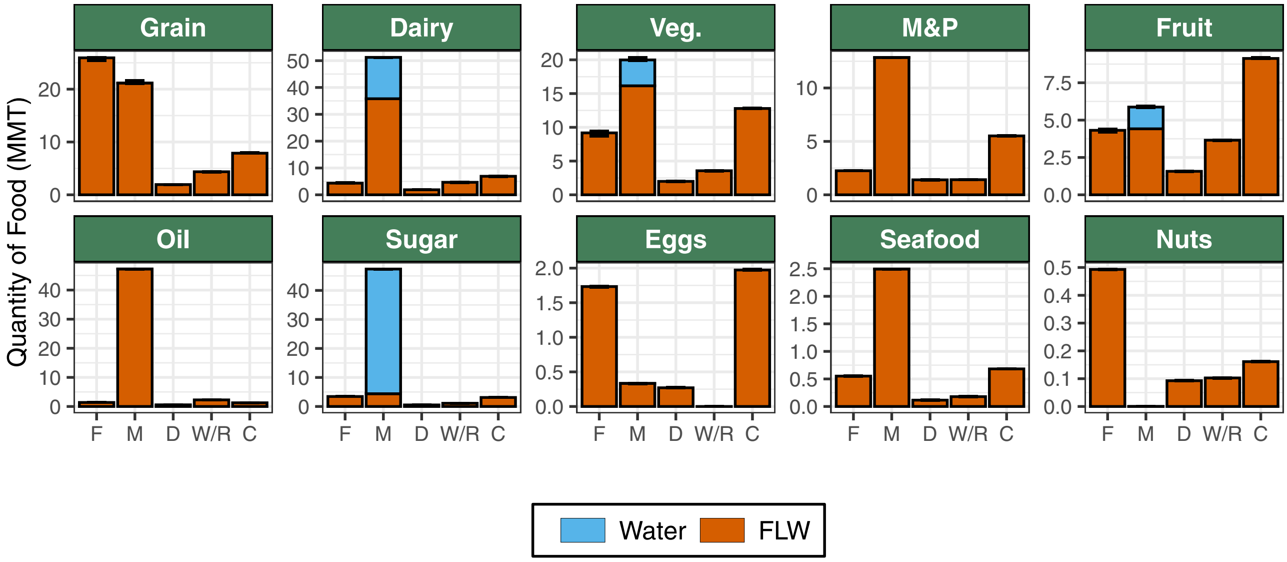

Fig. 6 Confidence interval and FLW by FSC stages and food commodities. Detailing the 95% confidence interval (black error bars) for total FLW (as either water evaporated during food manufacturing process [Water, blue] or FLW [vermillion]) for each commodity in the different stages. The 10 commodities are represented with their own labeled panel (M&P represents meat and poultry) and each stage is a different column (on-farm production [F], food manufacturing [M], distribution [D], wholesale & retail [W/R], consumption [C]). The *y*-axes labels vary between panels so mass flow details are more visible.

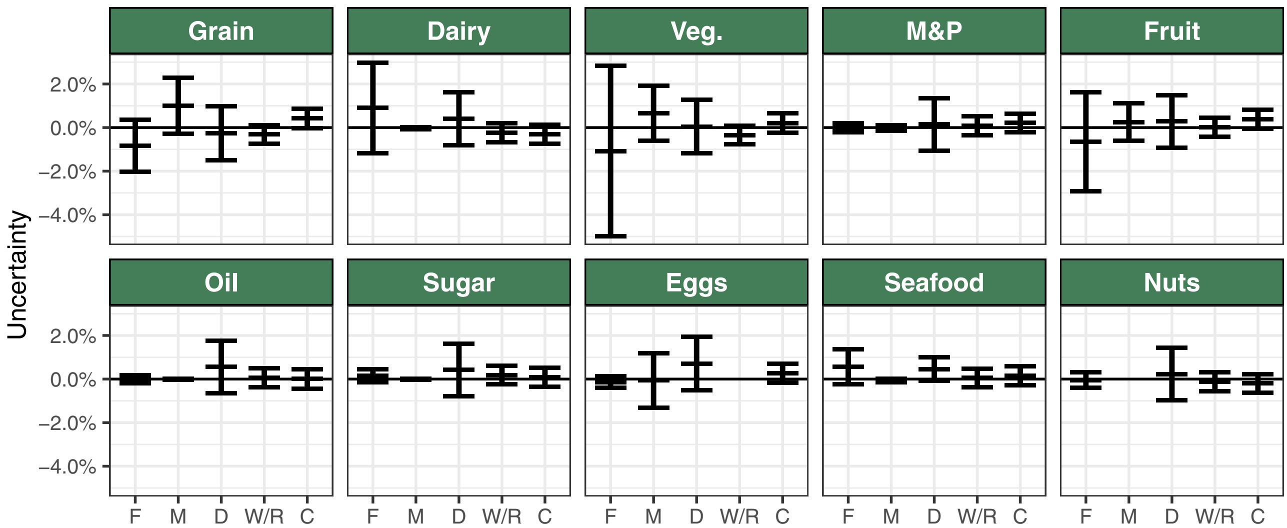

Fig. 7 Comparison between estimated FLW and the distribution of simulated amounts. The estimated result and lower bound, upper bound, and the mean value of the 95% confidence intervals for the different stages. The 10 commodities are represented with their own labeled panel (M&P represents meat and poultry) and each stage is a different set of error bars (on-farm production [F], food manufacturing [M], distribution [D], wholesale & retail [W&R], and consumption [C]).

the later FSC stages is still considerable and mostly disposed of through landfill, wastewater, or incineration (LWI). This observation once again shows the importance of technologies or actions that can prolong product shelf-life or optimize storage and transportation conditions. M&P also contributes a large amount of FLW at each FSC stage, except for on-farm production. The large amount of M&P FLW generated at the distribution, W&R, and consumption stages is, again, caused by the high demand and perishability. Conversely, the manufacturing M&P FLW is mainly unavoidable (inedible or undesirable) and can only be reduced by lower demand (e.g., diet change or reducing FLW at downstream stages). Even though on-farm production does not generate a large amount of M&P FLW, the high costs, resource demands, and GHG emissions relating to animal farming make the minimization of on-farm M&P FLW a continued priority. The other food commodities (e.g., nuts, eggs, seafood) contribute a very small portion (2.7%) of U.S FLW, due to their overall low demand.

FLW by management pathway. While Fig. 1 provides a general picture of the management of U.S. FLW from each FSC stage, Fig. 5 expands on this and provides more details on the used FLW management pathways throughout the FSC. The FLW management in the on-farm stage has not been well studied, so this study is only able to separate the crop-based on-farm FLW into three categories: LWI (11.2 MMT, i.e., landfill and incineration) and recycled (33.6 MMT) without knowing the specific channels (i.e., recycled other). Additionally, no reliable data were found for the management breakdown of animal-based on-farm FLW (8.9 MMT; Supplementary Note 8), so they were designated to have unknown management. Finally, as stated above, some of the manufacturing FLW is water removed from product processing and is not disposed of via the FLW management pathways. As the FLW management analysis uses factors to assign values of FLW to the different disposal pathways, the manufacturing FLW used in this part of the analysis (144.8 MMT) excludes the evaporated water (63.7 MMT; see Supplementary Note 5).

As illustrated by Fig. 5, manufacturing ends up being the most efficient stage when considering FLW management; only 4.1 MMT (2.8%), are diverted to landfill and 0.5 MMT (0.3%) are incinerated. Most of the manufacturing FLW (109.6 MMT; 75.7%) is used for animal feeding, followed by land application (19.3 MMT; 13.3%).

The data sources used for the FLW management analysis do not distinguish between the distribution and W&R stages. As they have similar FLW drivers, this study uses the same factors for FLW management pathways for these two stages. Distribution generates 10.4 MMT of FLW and W&R generates 21.3 MMT. Of this, 45.1% (4.7 MMT and 9.6 MMT) is diverted from waste streams to some form of recycling and 54.9% (5.7 MMT and 11.7 MMT) is sent to landfill or incinerated. Most of the 49.4 MMT of consumption FLW (43.8 MMT, 88.7 %) is washed down the drain (and sent to wastewater treatment), landfilled, or incinerated, with very little (5.6 MMT, 11.3 %) recycled.

For the whole FSC, animal feeding (116.6 MMT) is the largest FLW management pathway, and manufacturing contributes the most to this pathway (109.6 MMT, 94% of FLW managed through animal feeding). The third and fourth preferred FLW management pathways (i.e., land application/composting and other industrial uses) only received 22.7 MMT and 14.4 MMT of FLW, respectively. Moreover, in 2016, 77.3 MMT of FLW from all five stages was diverted to LWI, which are the least preferred pathways. Unfortunately, despite being the most desirable FLW management pathway, only 8.1 MMT of FLW attempted to reenter the FSC for possible human consumption through food donation, and 0.4 MMT of this reentering amount was not consumed and ended up with other pathways.

Uncertainty analysis. This study conducts uncertainty analyses by disturbing each coefficient. Since this study estimated mass flows and FLW generation following the accounting approach adopted by Calderia et al.[17], we adopted the same method for uncertainty analysis. Under the uniform distribution assumption, a Monte Carlo simulation yields the 95% confidence intervals of the amounts of FLW by FSC stages and food commodities, illustrated by Fig. 6. The figure shows that our estimations of FLW by food commodities and stages fall within the relatively small 95% confidence intervals.

To further demonstrate the impact of each coefficient, Fig. 7 shows the difference between the estimated FLW amount and the upper bound, the lower bound, and the mean value of the confidence intervals by FSC stages and food commodities. The FLW of each food commodity demonstrates a higher level of uncertainty at the distribution stage since the limited source of the waste factor at this stage. Moreover, the on-farm FLW of grains, dairy, animal products, fruits, and vegetables also demonstrate a high level of uncertainty, since the waste factors used for these food commodities are not the U.S. alone (see Supplementary Note 4). Finally, at the food manufacturing stage, grains, vegetables, fruit, and eggs also demonstrate a higher level of uncertainty since this study derived the factor for each type of food (e.g., dried vegetables), instead of using coefficient for each specific food product (e.g., dried potatoes).

Compared with several previous studies that focus on U.S. FLW quantification (listed in Table 1), this study has similar FLW estimations for later FSC stages (i.e., distribution, W&R, and consumption). However, other studies have either no or lower estimations for upstream stages. The detail is provided in Supplementary Note 9.

Discussion

Much of the mass that left the U.S. FSC was evaporated water, recycled, or recovered. However, despite food donation being the most preferred R/R way, it only comprised 2.4% (8.1 MMT) of total FLW, out of which only 7.8 MMT of the donated food finally get consumed. 77.3 MMT (22.5%) was still disposed of via wastewater treatment, landfill, or incineration (LWI). This high percentage reveals the need for continued efforts in diverting FLW from LWI to R/R and for better FLW management practice. This section discusses the opportunities and strategies for better U.S. FLW reduction and management by FSC stages, mainly from the perspective of policymakers. The discussion follows the concept of circular economy, which emphasizes the reduction, recycle, and recovery of waste.

The manufacturing stage contributes the most (208.5 MMT; 61%) to U.S. FLW. However, most of the manufacturing FLW is either unavoidable or is recycled/recovered, and only 4.6 MMT (2.2%) of FLW generated from this sector is managed through landfilling or incineration. Even though U.S. food manufacturing has demonstrated a high recycle/recovery rate, it can still contribute to a more sustainable FSC by helping FLW reduction efforts at downstream stages of FSC by incorporating advanced packaging materials or using smaller, easier to seal packaging to extend shelf-life and standardize and clarify food expiration labels to reduce prematurely discarding food[30,33]. In addition, a large amount of energy is consumed to ship FLW, including water and inedible, from the farming to the manufacturing stage. Distributed manufacturing may help to improve sustainability by removing the unavoidable FLW at farms or locations near to farms to avoid additional transportation.

While extending shelf-life and clarifying information displayed on labels can theoretically contribute to FLW reduction[34–36], the practical impacts are limited by consumer behaviors and awareness. There is no guarantee that standardized date labels would have the desired effect on consumer behaviors as many consumers throw away food when they think it has spoiled. Furthermore, consumers also demonstrate hesitancy on novel packaging materials due to concerns on the safety and overall environmental impact of advanced food packaging[36–38] and are usually unwilling to pay more for products with a longer shelf-life. All of these, together with the concern on additional costs, make individual manufacturers hesitant to adopt packaging innovations[39].

To address these issues, government agencies and food manufacturers should work together to establish a comprehensive national food labeling system, with reliable, coherent, and uniform language that clearly communicates to consumers the meaning of dates as well as other safety and handling information. The federal Food and Drug Administration (FDA) and USDA have been authorized to regulate misleading labels and could develop a standardized system of date labeling that is more easily understood by consumers and less arbitrary[34]. Mandatory regulations may be issued to encourage food manufacturers to remove unnecessary or confusing dates (e.g., "sell-by") from packages; and federal aid can support the development and adoption of advanced packaging technologies. Besides, consumer education will be necessary to provide information on the new standardized labeling systems and the benefits of advanced packaging technologies.

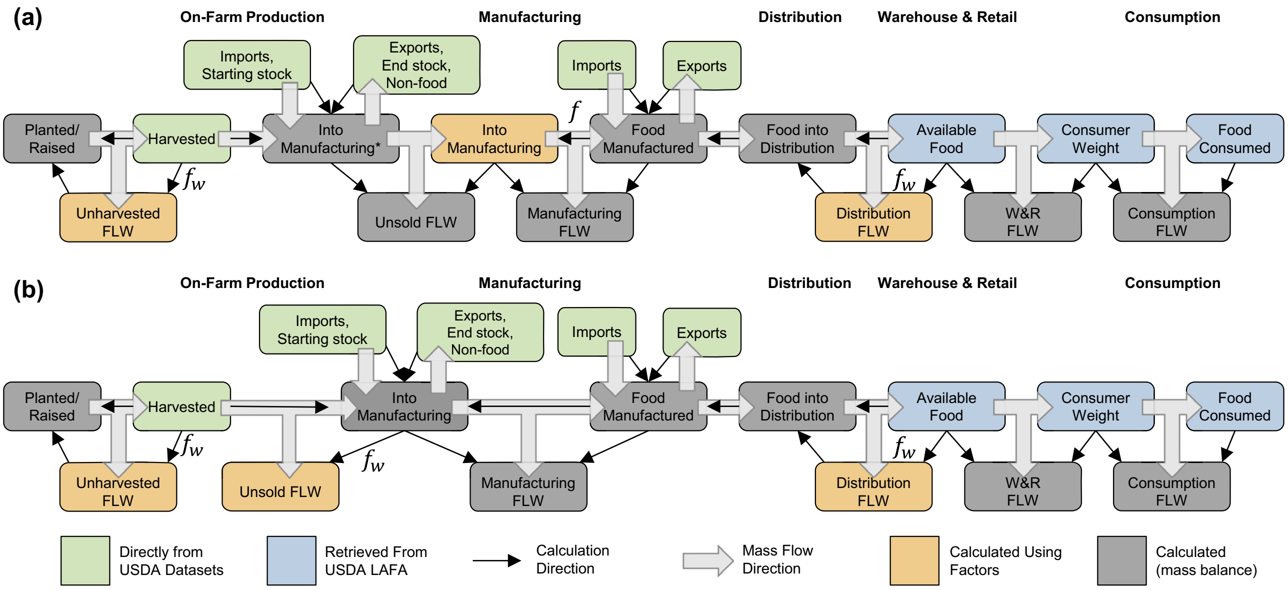

Fig. 8 Accounting approach and main source of data for estimating mass flow and food loss and waste (FLW) generation. The green and blue boxes represent the data directly taken from datasets (the US Department of Agriculture [USDA]; USDA's Loss Adjusted Food Availability Data [USDA LAFA]), the orange boxes indicate the mass flow calculation is estimated based on coefficients (shown by f and f_w, representing factors for calculating a stage output and input, respectively), and the gray boxes correspond to the mass obtained by mass balance. The thicker gray arrows represent the direct of mass flow, whereas the smaller black arrows represent the calculation flow. Grains, fruits, vegetables, seafood, and nuts products use the approach described in panel **a**. Oil, sugar, meat and poultry, dairy, and egg products use the approach described in panel **b**.

On-farm production is the second highest FLW contributor (53.6 MMT, 16%), stemming from both unharvested food and food that is not sold to later stages. This is often caused by labor shortages, a mismatch between supply and demand, and inadequate harvesting and storage capacities. Even though the on-farm FLW of some food groups cannot be donated without being processed (e.g., grain, oil, and sugar) or because of health concerns (e.g., animal-related FLW caused by death and sickness), a large portion of on-farm FLW is edible, such as fresh fruits and vegetables (25%), representing a huge opportunity for food donation. However, these items are not donated because of the associated logistic costs[30]. Therefore, the government can provide incentives (e.g., tax incentives) and provide necessary transportation and storage infrastructure for farm-level food donation.

The distribution stage contributes the least to FLW. A major driver of FLW at this stage is spoilage and physical damage, which is mitigated by increasingly better storage and cold chain transport. Other studies[34,40] have shown that most food products discarded at the W&R and consumption stages are caused by overstocking and expiration, again, showing the opportunity for manufacturers to extend shelf-life and improve consumer purchasing and consumption habits. The distribution, W&R, and consumption stages mostly landfill or incinerate their FLW (54.9%, 54.9%, and 88.5% of FLW created at these stages) and are the current focus of many efforts to reduce FLW. These stages also have a high potential for recovery and recycling of FLW, by increasing food donation, providing better access to other R/R methods (e.g., industrial use or composting), or increasing consumption before expiration, reducing the initial demand. Similar to the on-farm production stage, incentives can be adopted to promote consumers and businesses directing their FLW away from LWI to better FLW management pathways, though again, consumer education is necessary for better FLW reduction and management. The local governments could also fund the infrastructures for FLW collection, transportation, and treatment and laws can be passed requiring the collection and recycling of on-site FLW generation for businesses. In the U.S., California currently requires businesses to arrange for recycling services for organic waste over a certain size every week, and all the businesses should have containers specifically for organic waste[41,42]. Internationally, France has banned the supermarkets from discarding unsold food products, forcing them to donate unsold food to food banks or other management pathways (e.g., composting and animal feeding)[43].

In summary, even enough a large portion of the 343.2 MMT of FLW generated along the U.S. FSC in 2016 was recovered or recycled, 77.3 MMT was disposed of via LWI and the most preferred FLW management pathway (i.e., food donation) received the smallest portion. Government support such as tax incentives and funds for infrastructures are necessary to increase food donation and provide access and drive for better FLW management pathways (e.g., AD and composting). Moreover, incentives are also necessary to promote food manufactures for adopting advanced technologies to facilitate FLW prevention. Regulations can be issued so that businesses can have a better uptake on FLW reduction and recycling. Moreover, customers' education is important for FLW reduction, recovery, and recycle along the FSC.

Methods

This study estimates the U.S. food mass flows and FLW using Mass Flow Analysis (MFA), a proven tool for mapping and quantifying the flows that need to be managed. This methodology was used by several FLW estimation studies in other regions (e.g., Europe)[44], but, to the best of our knowledge, it has never been applied for analyzing the U.S. FSC. This study follows the MFA adopted by Calderia et al.[17] with multiple modifications of calculation directions due to different data availabilities. The mass flows and stage-level FLW generation are estimated with two methods: (1) when all the inputs and outputs of a food commodity group at a stage are known, a mass balance approach is used to calculate the FLW; (2) when only parts of the inputs and/or the outputs are available, coefficients from various sources are used (e.g., estimating the food materials required to make a known quantity of product). Figure 8 provides an overview of the system boundary, mass flow directions, and the accounting approach adopted for the MFA. The green and blue boxes represent the data directly taken from datasets, the orange boxes indicate the mass flow calculation is estimated based on coefficients, and the gray boxes correspond to the mass obtained by mass balance. A more detailed description of the accounting approach by each FSC stage can be found in Supplementary Note 4–7.

This study relies on the USDA's Annual Agricultural Statistics[45] and a few supplemental reports/datasets[46–50] to obtain the harvested agricultural materials, change of stock, international trade, and non-food uses of agricultural materials (e.g., seeding, growing intentionally for animal feeding, and ethanol production) for each commodity to estimate the agricultural materials available for U.S. food manufacturing Unharvested FLW and the total agricultural materials planted or raised are estimated with additional coefficients from literature (Supplementary Note 4).

Figure 8 illustrates two calculation pathways used in the MFA, depending on data availability. The first (Fig. 8a) is used for grains, fruits, vegetables, seafood, and nuts products, for which the waste factors for unsold FLW are not available, and only agricultural materials available to the U.S. food manufacturing (Available for Manufacturing, which includes unsold FLW) can be directly obtained from the main data sources. For these food groups, coefficients are applied to the food manufactured in the U.S. (Food Manufactured, see below) to estimate the agricultural materials needed (Into Manufacturing), and the unsold FLW is considered the difference between Available for Manufacturing and Into Manufacturing. For the second group of commodities (i.e., oil, sugar, M&P, dairy, and egg products), waste factors are used to estimate unsold FLW and the agricultural materials that are sent to food manufacturers (Into Manufacturing) (Fig. 8b). For all food products, the Manufacturing FLW is the difference between Food Manufactured and Into Manufacturing, where Food Manufactured is estimated based on the mass flows at downstream stages of FSC.

The Available Food at the W&R stage, food purchased for consumption (Consumer Weight), and Food Consumed are found in USDA's Loss Adjusted Food Availability (LAFA) data[51]. FLW at W&R and the consumption stage are calculated by taking the difference of mass flows between stages. The Distribution FLW (and from there the food materials entering U.S. domestic food distribution) is estimated by assuming that 5% of the food entering W&R is lost[30]. Finally, by adding Food Into Distribution and international trade of food products, the Food Manufactured in the U.S. is calculated, allowing the calculation of Manufacutirng FLW for all commodities and Into Manufacturing for the second group of commodities.

This study includes a uncertainty analysis to evaluate the uncertainty of the results. As above mentioned, this study adopted multiple data sources and coefficients for estimating the mass flow and FLW generation along the U.S. FSC. All the datasets adopted by this study are released and maintained by U.S. federal agencies (e.g., USDA) or industry associations (e.g., the U.S. Grain Council). Therefore, this study only considers the uncertainty brought by the adopted coefficients. Following Beretta et al.[52] and Caldeira et al.[17], a semi-quantitative approach based on the use of a pedigree matrix was adopted to determine the uncertainty factor and a range associated with each coefficient. By assuming a uniform distribution, a Monte Carlo simulation is performed with 10,000 runs to obtain the 95% confidence intervals for FLW generation by food commodities and FSC stages. As shown in section "Results" and Supplementary Note 10, our estimation of FLW by food commodities and stages falls within the 95% confidence intervals. The details of the uncertainty analysis process and results can be found in Supplementary Note 10 and Supplementary Data 2 and 3.

In terms of FLW management, we first estimate the water removed or evaporated during specific food manufacturing processes (i.e., dried fruit and vegetables, sugar processing and refining, dried and condemned dairy products) and, as stated above, this is considered a separate manufacturing FLW stream. Then, the disposal of the remaining FLW is initially estimated based on the ratios derived from a recent EPA study[29] with some adjustments based on others that provide more direct estimates of the amount of FLW managed through several of the pathways studied (i.e., food donation, animal feeding, composting, AD, and wastewater treatment)[53–57]. A detailed description of data sources, methods, and step-by-step calculation of FLW management by FSC stages can be found in Supplementary Note 8.

The aggregation of the data sources and the calculations for the MFA was conducted in Microsoft Excel. R Studio was used to generate the graphs, along with necessary data manipulation, specifically the Plotly and ggPlot packages were utilized (see Supplementary Data 4). The uncertainty analysis and Monte Carlo simulation are conducted through Python (See Supplementary Data 5).

Data availability

All the datasets adopted for this study are cited and detailed in Supplementary Note 4–9. All the data sources are publicly available. The calculated results and uncertainty analysis are also available as Supplementary Data 1, 2, and 3 at GitHub, following the link of https://github.com/koay9f/Food_Loss_and_Waste.

Code availability

The R code used to generate Figs. 1–7 and the Python code used for the uncertainty analysis is provided as Supplementary Data 4 and Supplementary Data 5, which can be found at GitHub, following the link of https://github.com/koay9f/Food_Loss_and_Waste.

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Author contributions

W.D. and K.A. conceived the idea, developed the outline, collected, and analyzed the datasets, and compiled the manuscript. M.J. and S.N. supervised the whole project and helped with the idea development, data analysis, and manuscript review. W.G., J.C., and J.Z. provided critical feedback.

Competing interests

The authors declare no competing interests.

Additional information

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