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Missing Food, Missing Data? A Critical Review of Global Food Losses and Food Waste Data

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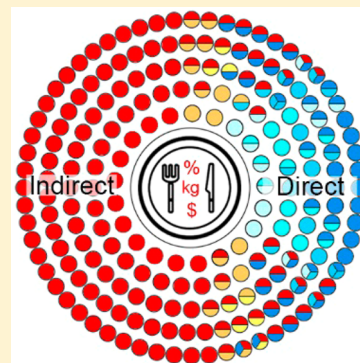
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Supporting Information

ABSTRACT: Food losses and food waste (FLW) have become a global concern in recent years and emerge as a priority in the global and national political agenda (e.g., with Target 12.3 in the new United Nations Sustainable Development Goals). A good understanding of the availability and quality of global FLW data is a prerequisite for tracking progress on reduction targets, analyzing environmental impacts, and exploring mitigation strategies for FLW. There has been a growing body of literature on FLW quantification in the past years; however, significant challenges remain, such as data inconsistency and a narrow temporal, geographical, and food supply chain coverage. In this paper, we examined 202 publications which reported FLW data for 84 countries and 52 individual years from 1933 to 2014. We found that most existing publications are conducted for a few industrialized countries (e.g., the United Kingdom and the United States), and over half of them are based only on secondary data, which signals high uncertainties in the existing global FLW database. Despite these uncertainties, existing data indicate that per-capita food waste in the household increases with an increase of per-capita GDP. We believe that more consistent, in-depth, and primary-data-based studies, especially for emerging economies, are badly needed to better inform relevant policy on FLW reduction and environmental impacts mitigation.



1. INTRODUCTION

Food losses and food waste (FLW) occur throughout the food chain from farm to fork. FLW has become a worldwide concern in recent years and is widely identified as a key barrier to global sustainability due to its adverse impacts on food security,¹ natural resources² (e.g., land, water, and energy), environment³ (e.g., greenhouse gas emissions), and human health⁴ (e.g., toxic emissions from incineration). Consequently, reduction of FLW emerges as a priority on the global and national political agenda. For example, the United Nations have adopted a specific target in the recently released Sustainable Development Goals (SDG) to halve per-capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains by 2030 (Target 12.3).⁵ The European Union⁶ and the United States⁷ have consequently adopted this target, and the African Union's 2014 Malabo Declaration also includes a commitment "to halve the current levels of post-harvest losses by the year 2025."⁸

In response to the increasing public concerns and political attention on FLW, the past decades have seen a growing body of literature on the quantification of FLW across the food supply chains at global, regional, and national levels. For example, the Food and Agriculture Organization (FAO) of the United Nations estimated that roughly one-third of food produced for human consumption (or 1.3 billion tons) was lost or wasted globally.⁹ The carbon and water footprint of this significant amount of FLW were estimated to be 4.4 gigatons (or 8% of the world's total) of CO₂ equivalent¹⁰ and 250 km³ of blue water,² respectively. It would also mean 1.4 billion hectares (or 28% of the world's total) of agriculture land use and an economic cost of about 750 million U.S. dollars (USD),

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which equals the GDP of Turkey.² Many other studies at the regional or individual country levels have also highlighted a similar large scale of FLW (though not always directly comparable) and its profound impacts on food security, environment, and economic development. For example, the EU-28 generate approximately 100 million tons of FLW annually in which households contribute the most (45%).¹¹ As to its member states, the U.K. households alone wasted about 7.2 million tons of food in 2012, over 60% of which was identified as avoidable.¹² The amount of food thrown away from households in Finland, Denmark, Norway, and Sweden account for 30%, 23%, 20%, and 10–20% of food bought, respectively.¹³ Roughly $\frac{1}{3}$ of the edible calories produced in Switzerland is wasted, and the household is the largest contributor.¹⁴ Other industrialized countries show a similar trend too. For example, the per-capita FLW in the United States increased by about 50% from 1979 to 2003.¹⁵ Over 4.2 million tons of FLW is disposed to landfill in Australia every year, costing over 10.5 billion USD only in waste-disposal charges.¹⁶ About 27 billion USD of food is wasted throughout the food supply chains in Canada annually, equivalent to 40% of all food produced and 2% of Canada's GDP.¹⁷

A few national agencies and intergovernmental organizations have been working on FLW quantification continuously over the past decades. In particular, the FAO has released several influential reports on FLW quantification on a global level.^{2,9,18} The United States Department of Agriculture Economic Research Service (USDA-ERS) has created the Loss-Adjusted Food Availability Data Series since 1997, reporting over 200 commodities by three stages (farm to retail, retail, and consumer) of losses in terms of quantities, values, and calories.^{19–23} The Waste and Resources Action Programme (WRAP) has issued a range of reports on FLW in the supply chain, household, and food service in the United Kingdom since 2007.^{12,24–30}

More recently, stakeholders from academia, industry, and governmental and nongovernmental organizations have started to join efforts in research projects and working groups for FLW quantification and method standardization. For example, the European Commission funded projects “Food Use for Social Innovation by Optimising Waste Prevention Strategies (FUSIONS)” (2012–2016) and “Resource Efficient Food and dRink for the Entire Supply cHain (REFRESH)” (2015–2019) have issued a series of publications, covering various aspects of FLW definition, quantification, and mitigation and valorization strategies.^{12,31–34} In June 2016, a partnership of leading international organizations (e.g., World Resources Institute, FAO, WRAP, United Nations Environment Programme, and World Business Council for Sustainable Development) launched a first-ever global standard to measure FLW.³⁵

Despite these growing efforts on the quantification of FLW and standardization of methodologies, several researchers have also raised concerns on the data deficiency and inconsistency and called for better and more measurements on FLW.^{36–38} In summary, we argue that the existing global FLW data suffer from the following major gaps.

- Their spatial coverage is narrow. Most existing studies on FLW are conducted in industrialized countries. For example, there are numerous publications quantifying FLW in the United States^{39–61} and Sweden;^{62–76} on the contrary, only a handful of studies illustrate FLW in low-income countries, such as Nepal,⁷⁷ the Philippines,⁷⁸

Egypt,^{79,80} and countries undergoing rapid dietary transition, such as China, Brazil, and India.⁸¹

- There is an unbalanced focus on the different stages along the food supply chain. There are a large number of studies on food waste at the retailing and consumer levels^{23,39,44,48,49,58,82–85} (mainly in industrialized countries, e.g., the United States), while there are fewer studies addressing the immediate postharvest losses (mainly in a few developing countries, e.g., India^{86,87} and Vietnam⁸⁸).
- Some available data are outdated but are still used. Due to lack of more recent data, researchers have to fall back on older data. For example, data of the 1980s and 1990s from the same reference were used in two publications (published in 2005 and 2010, respectively) as the current postharvest FLW of fresh fruits and vegetables in Egypt and Venezuela.^{78,79}
- There is inadequate first-hand data and a number of studies have to rely on data derived from literature. For example, many studies have frequently quoted data reported in the 2011 FAO report,^{53,89–93} which may not be representative or accurate for some countries and commodities³⁷ (e.g., household food waste data in Asia and Africa do not have a single measured data point in this report). Data in the African Postharvest Losses Information System (APHLIS) have also been widely used for postharvest FLW analyses elsewhere.^{49,94–96}
- The system boundary and methods as well as definition of FLW used vary in different studies, which make systematic comparison and verification of FLW data between countries, stages, and commodities often difficult. Thus, any extrapolation based on the existing data and discussion on relationship between FLW and related socioeconomic, environmental, and technological aspects would also be uncertain.

A good and clear understanding of the availability and quality of global FLW data is of particular importance. First, it is a prerequisite of benchmark progress toward the global SDG Target 12.3 and national FLW reduction targets and of assessing the effectiveness of interventions. Second, it would help to raise awareness, explore mitigation strategies, and prioritize efforts on FLW prevention and reduction. Third, better data would enable verification and comparison between countries, food supply chains, and commodities and thus help identify patterns and driving factors of FLW generation. Fourth, it provides a necessary basis for further analysis of the social, economic, and environmental impacts of FLW.

In this paper, we aim to provide a critical overview of all the existing FLW data in the current literature. We will assess their availability, quality, methods of measurement, and discuss their patterns and implications for future work. A spreadsheet database containing all the collected FLW data is supplemented in the [Supporting Information](#), which we believe provides a fundamental physical database for further analyses on environmental impacts and appropriate mitigation strategies of FLW. We aim to answer the following questions in this review:

- What are the bibliometric characteristics of existing literature on FLW quantification?
- What are the methods used for FLW measurement, and what are their advantages and disadvantages?

- What are the patterns of FLW generation among countries, food supply chains, and commodities and over time?
- What are the implications for further research in the future?

2. MATERIALS AND METHODS

2.1. System Definition. Food Losses and Food Waste.

FLW occurs at each stage throughout the food supply chain. Distinctions between the terms food losses and food waste, edible and inedible food waste, and avoidable and unavoidable food waste are sometimes made in the literature. These distinctions were not quantitatively considered in our comparison due to lack of consistencies and transparencies in the reviewed literature. For example, many studies differentiate food loss and food waste according to the FAO,⁹⁷ which defines food loss as “the decrease in quantity or quality of food” and food waste as part of food loss that “has been left to spoil or expire as a result of negligence by the actor (predominantly, but not exclusively, the final consumer)”. Food waste is usually connected to deliberate discarding or alternative (nonfood) use of food (e.g., animal feed) that is safe and nutritious for human consumption. The reviewed data do not allow us to distinguish between food loss and waste; thus, in this paper, we use FLW to refer to the combined amount of food loss and waste.

Food Supply Chain. FLW can be related to six main processes as shown in Figure 1 (note that not all stages are

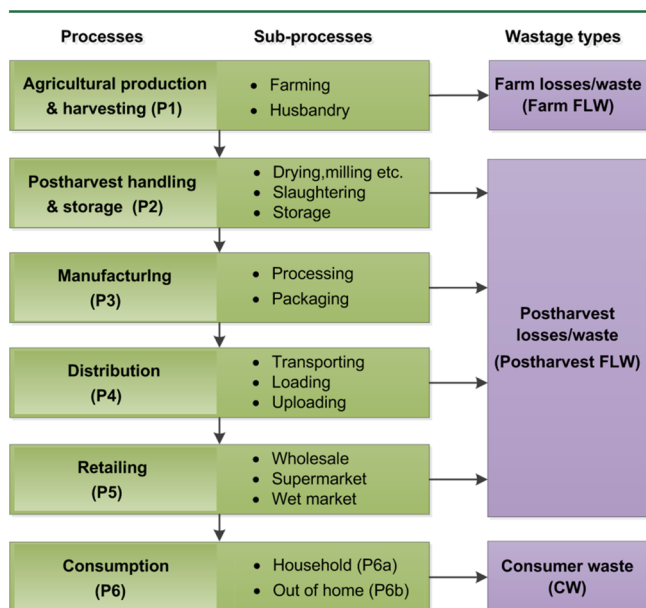


Figure 1. Food supply chain for FLW used in this review. Note that we put “waste” alongside “losses” for the farm and postharvest stages because some of the losses in these stages are arguably “wasteful” and avoidable, which makes it difficult to distinguish between loss and waste.

relevant to all products; for example, fresh vegetables may be supplied directly to market). We further categorized FLW as three types: farm losses and waste (during agricultural production and harvesting), postharvest losses and waste (during postharvest handling and storage, manufacturing, distribution, and retailing), and consumer waste (both in-household and out-of-home).

Food Commodity Groups. A total of 10 groups of food commodities were defined according to the classification used by the FAO and characteristics of the data in the literature: (1) cereal and cereal products (e.g., wheat, maize, and rice); (2) roots and tubers (e.g., potatoes, sweet potatoes, and cassava); (3) oilseeds and pulses (e.g., peanuts, soybeans, and olives); (4) fruits; (5) vegetables; (6) meat; (7) fish and seafood; (8) dairy products; (9) eggs; and (10) others or not specified.

Geographical and Temporal Boundary. We included all of the reported FLW data at the global, regional, and national levels and from as early as possible until December 2015 in the literature. The countries were grouped as medium/high-income countries and low-income countries (see Table S2) based on per-capita GDP and the grouping principle of FAO.⁹

2.2. Literature Selection. To ensure a broad coverage of literature containing FLW data, both Web of Science and Google Scholar were used in the literature search. In addition, we also explored the “grey literature”, i.e., reports prepared by academic institutions, industrial associations, and governmental and nongovernmental organizations, considering their significant amount in recent years. “Food waste” or “food losses” were used as keywords in the search of titles of publications, and only articles published in English by December 2015 were filtered (more details in section 1 of the Supporting Information).

To further ensure the relevance of the selected publications, we reviewed the abstracts, keywords, and method details of all the publications to screen out articles that contained data (e.g., weight and monetary values) on FLW for at least one food commodity, one food supply stage, and one region or country. Finally, 202 publications form the body of literature that we reviewed and examined in depth in this analysis.

2.3. Data Extraction and Treatment. The compiled FLW data were measured by different metrics, e.g., by physical weight, calorific value, or by monetary value. They were also reported in several ways: (i) single values, (ii) values in a range, or (iii) mean value or mean values with a variation. These values were either in absolute terms or as percentages. All of these differences were considered in our extraction of data from the literature (details are shown in the Supporting Information).

Whenever possible, comparison and trend analysis of data by physical weight (in terms of both percentage and absolute values) were conducted across countries and over time and by food commodity. To facilitate the comparison, original data were further processed as follows:

- If the original data points were reported in a range, the arithmetic averages were first determined based on the minimum and maximum values. Furthermore, global median values were generated and used in the comparison of per-capita farm FLW and postharvest FLW among different food commodities because median values are not strongly affected by extreme values (compared to average values) and thus might be more-representative in the comparison. Consumer waste was usually reported as the weight of cooked food, which was kept in the database and comparison.
- The values reported as the total amount of FLW in a region or country were divided by their corresponding population in the same year, for the convenience of comparison on a per-capita level. When the year of estimation was not specified, 2 years before the year of

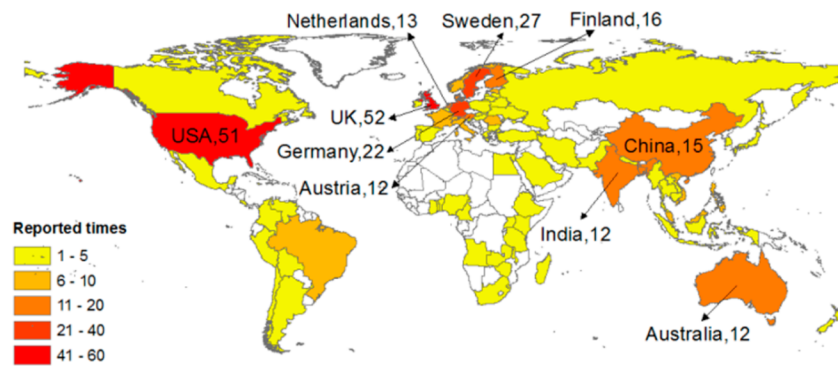


Figure 2. Geographical distribution of case countries (with the name of top 10 countries) reported in the reviewed literature. The numbers are the times that individual countries are reported.

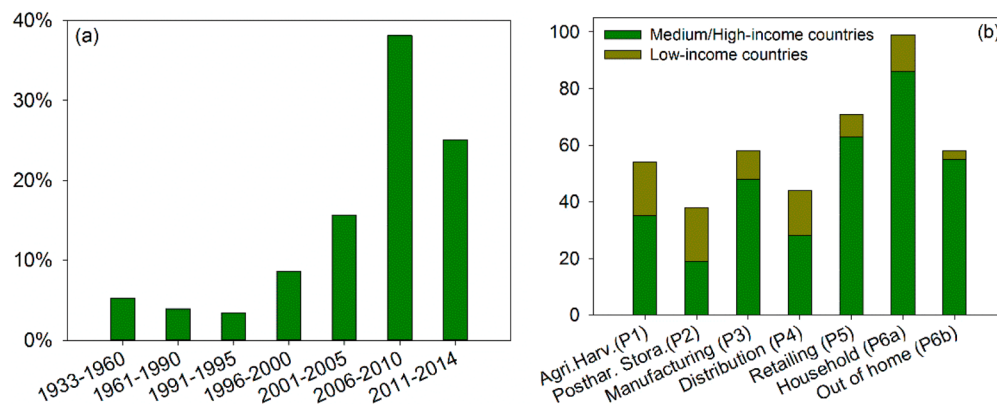


Figure 3. (a) Temporal trend of reported FLW data in terms of year of estimation; (b) the number of publications covering different food-supply stages and different development levels of countries.

publication was assumed as a reference for population and per-capita GDP. Population statistics and GDP data (in current USD) were obtained from the World Bank.

- We introduced a food losses and food waste rate (FLWR) for each food supply stage, which was defined as the proportion of FLW at each stage of the food supply chain to the amount of total food initially produced (reference flow, corresponding to a fictive output of 100% of the amount produced). FLWR was calculated by considering the proportion of FLW across each single stage (see Figure 1), as shown below:

$$FLWR_i = r_i \prod_{i=1}^{j-1} (1 - r_j) \quad (i \geq 2)$$

where r_i represents the proportion of FLW at the stage to be calculated (between 0 and 1), and r_j represents the proportion of FLW at the previous stages of the food supply chain. Note that the FLWRs are additive, while the proportion of FLW at each stage (r) are not additive because the mass flow is successively decreasing. For the reference stage ($i = 2$) the $r_{(i-1)}$ is set to 0. The proportion of FLW at individual stages, r , was derived from the reviewed literature (either directly or by dividing the quantity of FLW reported in the literature by total production reported in the FAOSTAT).

3. RESULTS AND DISCUSSION

3.1. Bibliometric Analysis of Literature on FLW Quantification. *Type of Publications.* The 202 reviewed publications were composed of 5 types: peer-reviewed journal

articles (53.5%), reports (35.6%), PhD and master theses (5.9%), conference proceedings (3.0%), and book chapters (2.0%). The 108 journal articles were published in 69 different journals, covering a wide range of disciplines, and about 45% of them were published in 10 journals (in descending order in terms of number of published articles), i.e., Waste Management (15.7%), Waste Management & Research (7.4%), Resources, Conservation and Recycling (5.6%), Food Policy (4.6%), Journal of Cleaner Production (2.8%), Environmental Science & Technology (1.9%), Journal of Industrial Ecology (1.9%), Journal of Environmental Management (1.9%), Environmental Science & Policy (1.9%), and Sustainability (1.9%).

Distribution of Countries and Year of Estimation. The compiled FLW data covered 84 countries (reported 498 times in total) and 52 individual years (reported 383 times in total) from 1933 to 2014. This adds up to 2933 rows and 5898 data points of FLW physical data in the compiled database (one row represents the entire food supply chain of one food community in one country or region; see the [supplementary spreadsheet](#)). Figure 2 illustrates the geographical distribution of case countries and the top 10 countries that have been studied. It can be seen that most of the existing data were found for the United Kingdom^{24–28,51,60,85,98–118} and the United States,^{39–61} both of which accounted for over 10% in terms of reported times, respectively. Then countries in Northern and Western Europe, i.e., Sweden,^{62–76} Germany,^{56,70,74,76,117,119–125} and Finland^{13,70,74,84,126–129} followed with a share of 5.4%, 4.4%, and 3.2%, respectively. Figure 3a shows the temporal trend of the year of estimation (see Figure S1 for the trend in terms of year of publication). Reported FLW data were found as early as

Table 1. Description of Advantages, Disadvantages, and Examples of Different Methods Used for FLW Quantification

| | method | symbol | time | cost | accuracy | objectivity | reliability | example of case countries and regions | food supply chain | reference |
|---|------------------------|--------|------|------|----------|-------------|-------------|---------------------------------------|--------------------------------|-----------------------------------|
| direct measurement or approximation based on first-hand data | weighing | W | ●●● | ●●● | ●●● | ●●● | ●●● | Portugal | P6b | Ferreira et al. ¹⁴⁸ |
| | | | | | | | | Italy | P6b | Falascioni et al. ¹⁵⁷ |
| | garbage collection | G | ●●● | ●●● | ●●● | ●●● | ●●● | Austria | P6a | Lebersorger et al. ¹⁵⁰ |
| | | | | | | | | | Sweden | P6a |
| | surveys | S | ●● | ●● | ●● | ●● | ●● | Sweden | P5 | Gustavsson et al. ⁶⁵ |
| | | | | | | | | | U.K. | P1, P2, P3, P5 |
| | diaries | D | ●●● | ●● | ●● | ●● | ●● | U.K. | P6a | Langley et al. ¹⁰⁸ |
| | | | | | | | | | Sweden | P6a |
| | records | R | ● | ● | ●● | ●● | ●● | Sweden | P5 | Eriksson et al. ⁷³ |
| | | | | | | | | | Sweden | P5 |
| observation | O | ● | ● | ● | ● | ● | U.K. | P6b | Sonnino et al. ¹¹⁰ | |
| | | | | | | | | Italy | P6b | Saccareo et al. ¹⁵⁹ |
| indirect measurement or calculation derived from secondary data | modeling | M | ●● | ● | ● | ●● | ● | United States | P6 | Hall et al. ¹⁵ |
| | | | | | | | | EU-27 | P1, P2, P3, P4, P5, P6 | Khan et al. ¹³⁵ |
| | food balance | F | ● | ● | ●● | ●●● | ●● | United States | P6 | Buzby et al. ²³ |
| | | | | | | | | global | P1, P2, P3, P4, P5, P6 | Gustavsson et al. ⁹ |
| | use of proxy data | P | ● | ● | ●● | ●●● | ●● | Austria | P5 | Lebersorger et al. ⁵⁶ |
| | | | | | | | | Singapore | P6a | Grandhi et al. ¹⁶⁰ |
| | use of literature data | L | ● | ● | ●● | ●●● | ● | global | P1, P2, P3, P4, P5, P6 | Lipinski et al. ⁹⁰ |
| Denmark | | | | | | | | P1, P3, P4, P6 | Halloran et al. ¹⁶¹ | |

^aNote: ●●●, high; ●●, medium; ●, low. Cost includes both economic cost and labor cost of conducting the research. P1: agricultural production and harvesting; P2: postharvest handling and storage; P3: manufacturing; P4: distribution; P5: retailing; and P6: consumption (including P6a: household and P6b: out of home).

1933, and then the number stayed steady and low until 1995. After 1995, the number went up considerably and over 60% was seen in the past decade (38.1% from 2006 to 2010 and 25.1% from 2011 to 2014).

Data Coverage along the Food Supply Chain and across Countries. Figure 3b illustrates the number of publications covering different food supply stages and development levels of countries (medium- and high-income countries versus low-income countries). It can be seen that most of the studies have included the retailing and consumption stages. Household was covered in almost half (49%) of all the publications, followed by the retailing stage (35%). However, only a small share (18%–30%) of publications covered the stages between agricultural production and distribution (agricultural production: 26.7%; postharvest handling and storage: 18.8%; manufacturing: 28.7%; and distribution: 21.8%).

The number of publications on FLW amount of medium- and high-income countries was substantially higher than that of low-income countries throughout the food supply chain except for the postharvest handling and storage stage, for which the number of publications was the same for both. Publications covering the retailing and consumption stages were mostly

found for the medium- and high-income countries, with very few data sources in developing and emerging countries. Low-income countries showed a clear focus in the early and middle food-supply stages (especially agricultural production and postharvest handling and storage).

3.2. Overview, Advantages, and Disadvantages of Different Methods Used for FLW Quantification. Table 1 summarizes methods that were used to quantify FLW in the reviewed publications. They can be categorized as two groups: (i) direct measurement or approximation based on first-hand data and (ii) indirect measurement or calculation derived from secondary data.

Direct measurement involves several ways to directly quantify or estimate the actual amount of FLW:

- Weighing: Using weighing scales to measure the total weight of FLW; usually used in restaurants, hospitals, and schools; may or may not include compositional analysis of FLW with each fraction being weighed.
- Garbage collection: Separating FLW from other categories of residual waste containers to determine the weight and proportion of FLW and from weight data derived from separate FLW collections; may or may not

include compositional analysis of FLW. It can be collected from the curb¹³⁰ or collected by households at home and handed over to researchers.^{99,131}

- **Surveys:** Collecting information regarding people's perceptions or behaviors on FLW through questionnaires that are answered by a large number of individuals and face-to-face interview of key stakeholders in this field. In these surveys, people can be asked to directly estimate the amount of food waste in their household, e.g., in number of portions,¹⁰⁷ or to estimate the percentage of food items bought into the household that goes to waste.¹³² Visual tools have sometimes been used to help people indicate the amount of food waste.¹³³
- **Diaries:** Gathering data via keeping a daily record on the amount and types of FLW for a period of time; commonly used for households and commercial kitchens. Households are sometimes provided with weighing scales to measure the weight of food waste.^{128,134}
- **Records:** Determining the amount of FLW via the routinely collected information that is not initially used for FLW record (e.g., warehouse record books, point of sales data, data from food manufacture regulatory sources); usually used for the retailing stage and food manufacture (especially supermarkets and larger food businesses).
- **Observation:** Using scales with several points to evaluate food leftover by visual method or by counting the number of items to assess the volume of FLW.

Indirect measurement includes methods derived from existing data of various secondary sources:

- **Modeling:** Using mathematical models based on factors that affect the generation of FLW to calculate the amount of FLW.
- **Food balance:** Calculating FLW by using a food balance sheet (e.g., from FAOSTAT) or human metabolism (e.g., relating body weight to the amount of food eaten) based on inputs, outputs, and stocks along the food supply chain.
- **Use of proxy data:** Inferring quantities of FLW by using data from companies or statistical agencies (mostly used for scaling data to produce aggregated FLW estimates).
- **Use of literature data:** Directly using data from literature or calculating the amount of FLW based on the data reported in other publications.

Figure 4 illustrates how these methods were used in each of the 202 publications. The result shows that only a small share (around 20%; blue colors in Figure 4) of the reviewed publications has relied on direct measurement or approximation based on first-hand data. The remaining majority relied on indirect measurement or calculation derived from secondary data (red-yellow colors in Figure 4); over 40% of them were based only on literature data, and about 1/3 used a combination of literature data with one or two other types of methods in the quantification, for example, with modeling^{15,135,136} or proxy data^{59,94,137–139} (indirect measurement) or with weighing or surveys^{115,119,140–146} (direct measurement). For the 138 publications that used literature data (Figure 5), their estimates often relied on each other and pointed to a handful of publications; over a quarter of them cited data from the top 10 cited publications, and the number of citations has increased greatly since 2008. Such a high share of use of secondary data may signal high uncertainties in the available global FLW

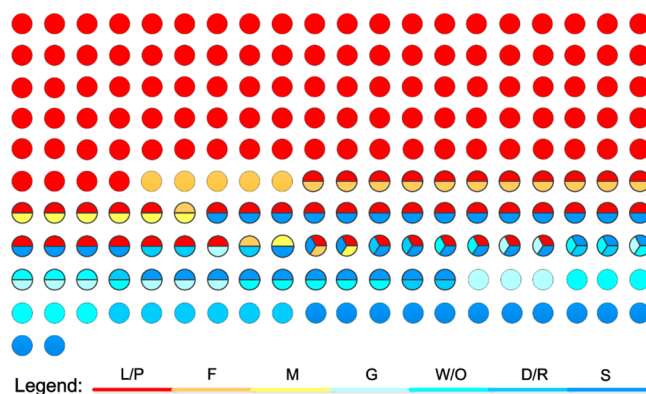


Figure 4. Overview of the methods used in the 202 reviewed publications. Each dot represents one publication, and the colors indicate different methods used. L: use of literature data; P: use of proxy data; F: food balance; M: modeling; G: garbage collection; W: weighing; O: observation; D: diaries; R: records; and S: surveys. For the convenience of visualization, we have aggregated similar methods, i.e., L/P, W/O, and D/R, in groups (see Figure S2 for a more-disaggregated version).

database, especially when the literature data are not representative but used for a different country or a different year than it was collected for originally.

The advantages and disadvantages of different methods were evaluated based on different criteria (e.g., time, cost, and accuracy) listed in Table 1.

- Weighing and garbage collection result in relatively objective and accurate information on FLW. The two methods may result in a total quantification of FLW (i.e., operational data), or they can yield far more granular data at food product category level. However, these two methods are more time-consuming and expensive than other methods and usually can only be conducted when space is available for sorting food. For example, to characterize the plate waste in Portuguese hospitals each year, Ferreira et al. weighed plate waste in almost 8000 meals during 8 weeks by individual items (soup, main dish, fruit, and bread) in a case hospital.¹⁴⁸ Of course, the accuracy of a waste composition analysis depends on methodological decisions, and various sources of error have been identified.^{149,150} In particular, in-home food waste that is disposed of by other means than curb side collection (e.g., sink garbage disposals, home composting, and animal feed) is usually not observed.¹⁵¹
- Surveys, diaries, records, and observation are other ways of direct measurement and approximation of FLW data and are relatively less time-consuming and expensive comparing to direct weighing. However, they largely depend on personal perceptions, the manner that raw data was collected, and the subjectivity of observers, which may reduce the accuracy of the data. For surveys, for instance, potential biases in FLW estimates can occur because this method relies on people's memory, and people may provide socially desirable answers. Keeping a food waste diary can be a considerable task for participants, and this is reflected in a tapering of enthusiasm of participants¹⁰⁸ as well as difficulties in recruitment and high dropout rates.¹⁵² Moreover, the accuracy of diaries has been questioned, as keeping a diary can by itself lead to increased awareness and

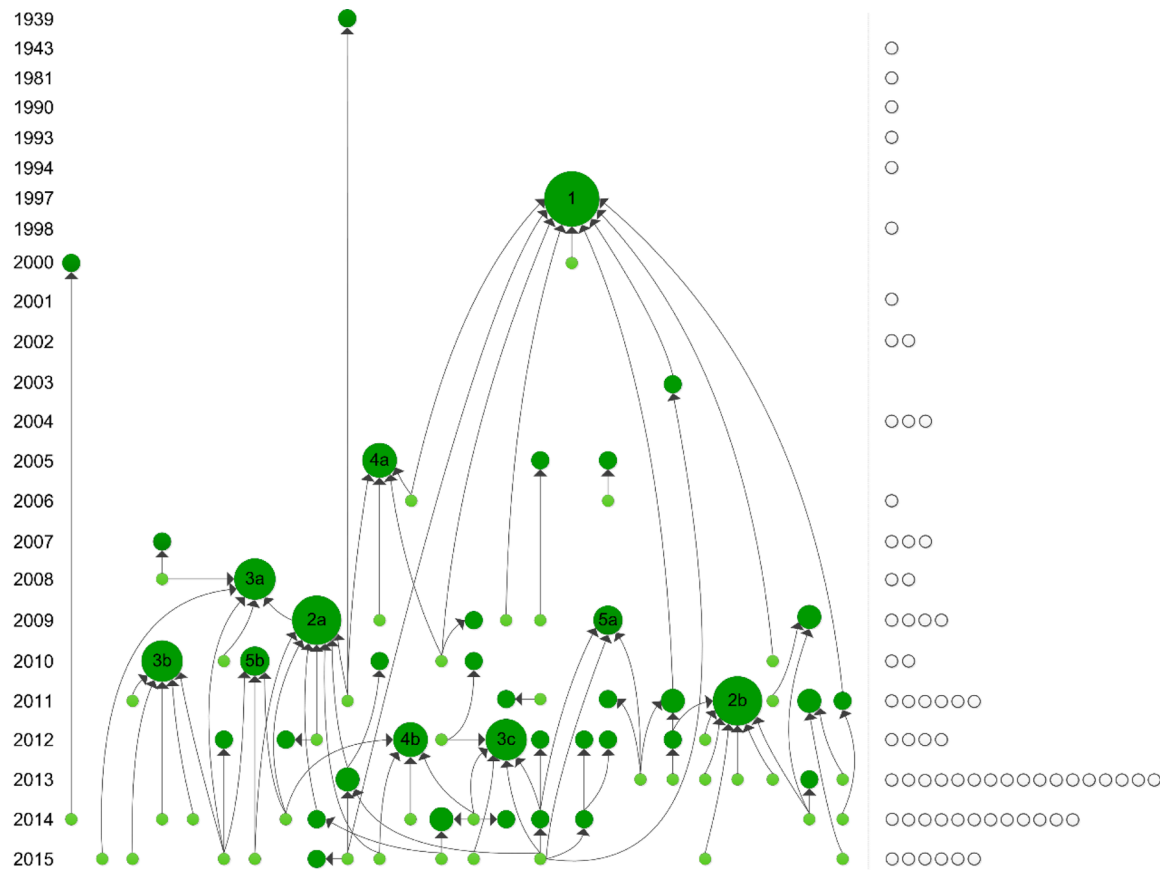


Figure 5. Citation network of the 138 publications that used literature data. Each dot represents a publication. The size of the dot indicates the number of citations, and the arrow represents the direction of citation. The dots in white on the right denote publications outside the citation network. The top 10 cited publications are 1, Kantor et al., 1997;⁴¹ 2a, WRAP, 2009;²⁶ 2b, Gustavsson et al., 2011;⁹ 3a, WRAP, 2008;²⁵ 3b, Monier et al., 2010;¹⁴⁷ 3c, Buzby and Hyman, 2012;⁵² 4a, Kader, 2005;⁷⁹ 4b, Kranert et al., 2012;¹²¹ 5a, Buzby et al., 2009;²⁰ and 5b, Langley et al., 2010.¹⁰⁸

behavioral change.^{108,134,152} For observation, it requires less time than weighing but varies in accuracy and reliability. For example, Hanks and colleagues compared three types of observation measurements (quarter-waste, half-waste, and photograph) in a school cafeteria setting, and they found that on-site visual methods outperformed photographs in inter-rater and intermethod reliability.¹⁵³

- Indirect measurement or calculation derived from secondary data is more widely used due to their low cost and high feasibility. However, these methods usually bear higher uncertainty. For example, results from modeling are heavily affected by the choice of model parameters and their relationship with the quantities of FLW. The accuracy of the food balance method depends primarily on the quality and comprehensiveness of the food balance sheet data. The use of proxy data and literature data is the easiest among all methods, but its accuracy depends ultimately on the quality and representativeness of the source data that is used.

Arguably, no direct or indirect measurements can be all-satisfactory by themselves. The direct measurements, despite the advantage, are commonly performed in a certain community or city and a certain stage of the food supply chains involving limited number of participants, resulting in an inevitable issue of lack of representativeness (especially problematic for big countries like China and the United States). The indirect measurements, on the contrary, can provide an overall picture for the whole country or region and

for different stages. One way to go forward could be an integrated approach of coupling direct with indirect measurements: statistics-based estimation of FLW at the national and regional levels to determine the magnitude of the problem (more for policy-making and strategy-setting) and first-hand measurements at the ground level plus in-depth examination of FLW drivers and affecting factors so as to design effective intervention steps.

The choice of method has critical influences on the determined amount of FLW, which sometimes leads to data discrepancy in the reviewed publications. For example, EUROSTAT reported that about 5.7 million tons of FLW were generated from the manufacturing sector in Italy in 2006,¹⁴⁷ while another model-based study estimated 1.9 million tons for the sector.⁷⁴ The reason for such a significant difference is that the two publications were based on different data sources and assumptions. The former included both FLW and byproducts that were reused and recycled, while the latter one depended on the loss share of the manufacturing stage and methodologies reported by FAO.^{9,154} As another example, Zhou reported that the wasted amount of wheat, maize, and vegetables were 4.2, 4.9 and, 4.3 million tons in the early 1980s in China, respectively,¹⁵⁵ whereas Smil estimated the wasted quantity of these three food types as 1.9, 2.0, and 10.9 million tons, respectively.¹⁵⁶ This discrepancy can be explained by the fact that the data source of the former publication was the FAOSTAT food balance sheet, whereas the latter was based on

various literature data and assumed cereal waste at 4% and vegetable waste at 10%.

3.3. Statistical Analysis of FLW Data. Farm Losses and Waste. In general, farm FLW in agricultural production in low-income countries is higher than that in medium- and high-income countries because the former countries usually have less advanced technology and infrastructure in harvest processing. For example, it was estimated that FLW during agricultural production accounts for 13% of the total FLW along the whole supply chain in Canada,⁹³ whereas this stage made up the largest share (26%) of the overall FLW in South Africa.¹⁶²

There is not much information about FLW by commodity groups in agricultural production and harvesting (Figure 6).

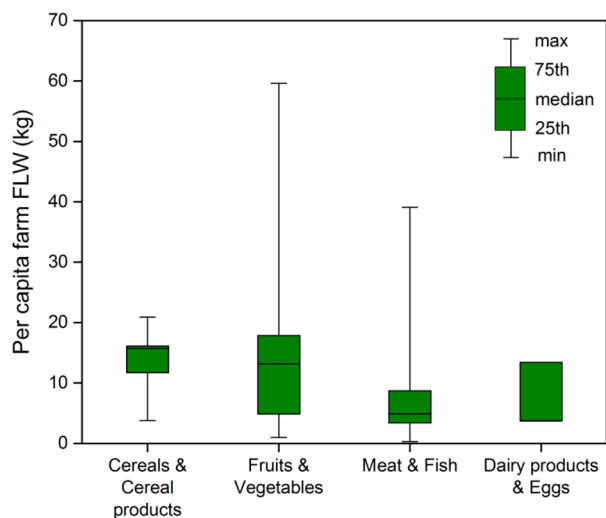


Figure 6. Per-capita farm FLW of different food commodities. Detailed data are available in Table S3.

According to the compiled data (note that the data are from a global panel for different countries and years, and the same goes for the statistical analysis in the *Postharvest Loss and Waste* and *Farm Losses and Waste* sections below), the median of cereal farm FLW is the largest among all food categories, at a level of approximately 16 kg/cap. It was estimated that approximately 5–9% of grain was lost in China at this stage, which is similar to that of Ghana,⁹⁵ Armenia, and Turkey.¹⁶³ Fruits and vegetables are the second largest in farm FLW, with a median of 13 kg/cap. However, the magnitude of fruits and vegetables losses and waste varies significantly between developing and developed countries. For example, it was estimated that 20–30% of total fruits and vegetables production was lost at the agricultural stage in China,³⁷ while this share was only 6–15% in Italy.⁹⁶ This big difference can be explained by the use of more advanced and new technologies and innovations in more developed countries (where farm FLW is mainly in the form of outgrades). The farm FLW rates of meat and fish and dairy products and eggs are relatively small.

Postharvest Losses and Waste. Figure 7 presents postharvest FLW (during postharvest handling and storage, manufacturing, distribution, and retailing) of the four most-relevant food commodities in the literature along the supply chain.

- The postharvest FLW of cereals and cereal products vary greatly at different stages. The major FLW are found at the postharvest handling and storage stage (over 18 kg/

cap) and in developing countries. For example, it was reported that cereals had the highest postharvest FLW out of all food commodities in South and Southeast Asia. In particular, rice as the staple food in the Philippines had a postharvest FLW rate of 10%.¹⁸ The retailing stage seconds this with a median value of over 10 kg/cap, followed by the manufacturing and distribution stages (approximately 5 kg/cap).

- Fruits and vegetables dominate postharvest FLW among all food commodities. For example, it was estimated that the manufacturing FLW of fruits and vegetables was over 33 kg/cap in South Africa,⁹³ which was much higher than that of all other food groups or stages. FLW at manufacturing stage in developed countries are relatively low, e.g., only about 5 kg/cap in Denmark.¹⁶¹ The distribution stage shows a high FLW of approximate 17 kg/cap, which is about 4 and 6 kg/cap, respectively, higher than the postharvest handling and storage and manufacturing stages. The FLW at retailing stage is the smallest, about 3 kg/cap.
- Meat and fish products contribute the least to postharvest FLW. Their FLW at postharvest handling and storage stage is very small, at about 0.3 kg/cap. The FLW at manufacturing and retailing stages are similar, both with a median value of about 1.3 kg/cap. One study reported that the FLW rates of meat at postharvest handling and storage, manufacturing, and distribution in Turkey were 0.2%, 5%, and 0.5%, respectively.¹⁶⁴
- The median FLW of dairy products and eggs is observed at approximately 6, 3, 0.2, and 3.4 kg per capita for the four substages, respectively. A study found that the FLW rates of milk at manufacturing and distribution stages in Ukraine were 3–15% and 8–11%, respectively, due mainly to poor cooling systems.¹⁶⁴

FLW at the retailing stage in the United States is a particular focus in the literature. It was estimated that about 2.4 million tons of food (excluding inedible parts) was lost at the retailing stage in 1995,⁴¹ but it has gone up to 19.5 million (including part of inedible food) tons in 2010, representing 10% of the available food supply in the United States.²³ Cereal products, vegetables, and fruits contribute the most to the retailing FLW, roughly about 10.5, 8, and 6 kg per capita, respectively, while meat and fish products contributes the least (details in Figure S3 and Table S8). For example, some studies reported that the retailing FLW of cereal products equaled to 12% of the U.S. food supply.^{48,49,52} It should be noted that retailing FLW in industrialized countries, including the United States, is likely to be dominated by supermarkets but not street markets and nonsupermarkets (often found in less-developed countries). In 2005 and 2006, for example, the U.S. supermarket FLW for fresh fruits, vegetables, and meat and seafood were, on average, 11.4%, 9.7%, and 4.5%, respectively.²⁰ These data are consistent with estimates from other industrialized countries, indicating that fresh products and bakery make up the largest share of retailing FLW due to factors such as expired sell-by dates, product damage and quality issues, and improper stock rotation.⁴¹

Consumer Food Waste. Household Food Waste. In medium- and high-income countries, household food waste makes up the largest share in the total FLW, mainly because of poor purchase planning, cooking or serving too much, overstocking, and misinterpretation of “best before” and “use

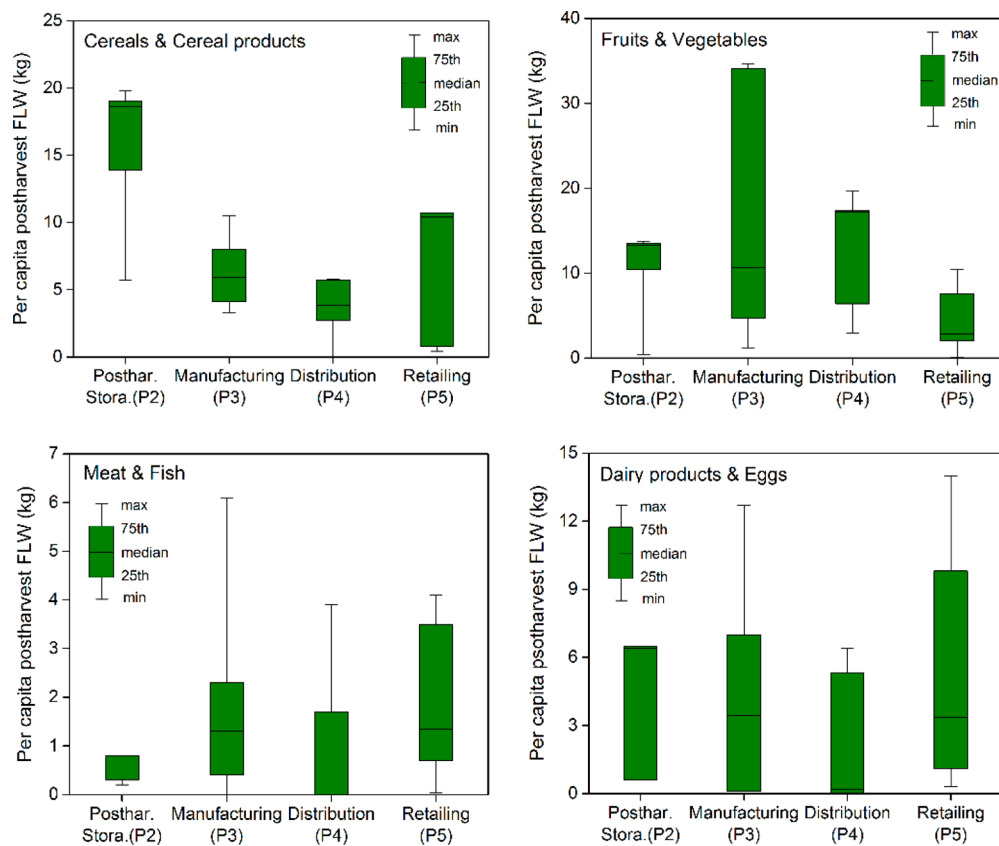


Figure 7. Per-capita postharvest FLW of cereals and cereal products, fruits and vegetables, meat and fish, and dairy products and eggs at different stages. Detailed data are shown in Tables S4–S7.

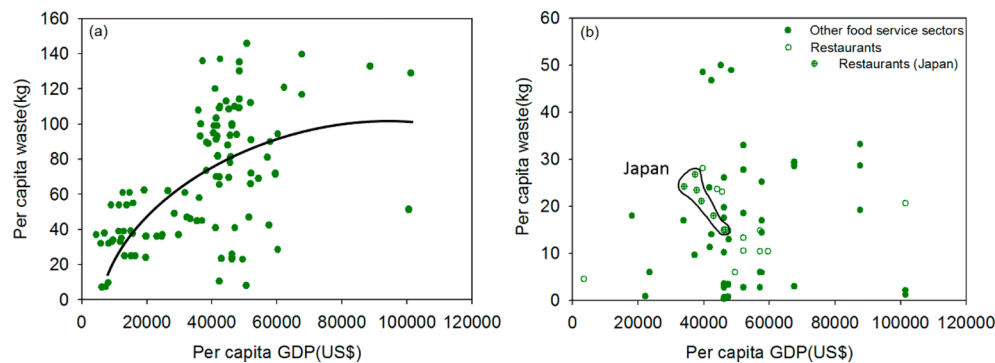


Figure 8. Correlation between per-capita GDP and per-capita consumer food waste: (a) households ($R^2 = 0.34$, $P < 0.05$); and (b) food service sector ($R^2 = 0.01$, $P > 0.05$). Data are in Tables S9 and S10. Note that an outlier in panel a is excluded for the convenience of visualization (see Figure S4 for the original version). Panel b distinguishes restaurants (empty circles) and other food service sectors (e.g., canteens; filled circles), and the circles with a cross enclosed are for restaurants in Japan.

by” dates.^{13,165} In the EU, about 45 million tons or 45% of the total FLW was found at the household level.¹¹ Food waste arising from households represented 51% of total FLW throughout the food supply chain in Canada¹⁷ and 19% of food and drink purchased by U.K. households, equivalent to 70% of U.K. postfarm-gate FLW (i.e., FLW during postharvest stages and consumption).³⁰ Similar patterns can also be observed in the households in the United States,⁵⁴ Germany,¹²¹ Sweden,⁷¹ and Australia.¹⁶⁶ Low-income countries, on the contrary, show a relatively small share of food waste in households due to limited disposable household income.^{9,165} However, upon closer inspection, we see little primary data available at household level in emerging and developing

countries, and household food waste, especially in cities, may be much larger than anticipated. Without significant primary research in these countries, generalizations should be made cautiously.

Figure 8a presents a positive relationship between per-capita GDP and household food waste per capita. When per-capita GDP rises, the amount of per-capita food waste generated in households also increases. This pattern agrees with observations in a few previous studies.^{11,134,164,166,167} For example, it was reported that in 2007, the food waste generated in households in South Africa was only 7.3 kg/cap,⁸⁹ while U.K. households generated 109.3 kg/cap,¹⁶⁹ though data robustness for the South African estimate is expected to be limited

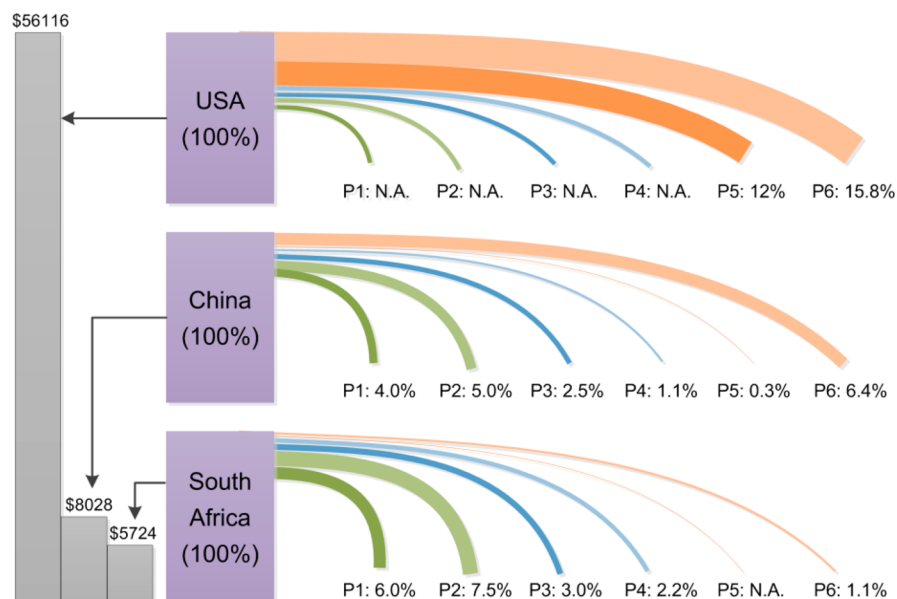


Figure 9. FLWR of cereals along the supply chain in the United States, China, and South Africa. The vertical chart on the left represents per-capita GDP in current USD in 2015 for these three countries (according to the World Bank). P1: agricultural production and harvesting; P2: postharvest handling and storage; P3: manufacturing; P4: distribution; P5: retailing; and P6: consumption. N.A. means not available. The reference flow is assumed to be a fictive output of 100% of the amount produced. Due to a lack of FLW percentage for each stage in South Africa, the average amount of waste reported between 2007 and 2009 was divided by the average quantity of production during the same period to calculate the FLWR.

(extrapolated from Sub-Saharan estimates, which are less wealthy and industrialized than South Africa).

However, it is interesting to observe that, when per-capita GDP gets higher than a certain level (roughly 50 000 USD), per-capita food waste generation tends to level off. This might reflect the increasing awareness of the public, food waste prevention campaigns, stricter regulation (e.g., clearer labeling and longer shelf life), and effect of market mechanisms (e.g., increasing cost of food purchase and food waste disposal). For example, campaigns such as “Zero Waste” and “Love Food Hate Waste” have been taken against food waste in Australia^{168,170} and the United Kingdom.^{26,171} This may also relate to higher consumption of prepared meals and less cooking from scratch (which may transfer food waste from household kitchen to food manufacturing to some extent) in more-affluent countries and the fact that waste generation data are based on the management of waste (which is generally much higher in more-affluent countries).

Out-of-Home Food Waste. A number of studies have estimated how much food has been wasted away from home, i.e., in the food service industry, which is defined as a sector responsible for preparing or serving food outside home,^{85,129} including, for example, restaurants,^{62,126,129,145,172} canteens,^{126,161} schools,^{19,46,157,173–175} hospitals,^{45,101,110,148,159} care centers,^{42,129} military institutions,⁸² transport hubs, and in-flight catering.^{80,176}

The research on food waste in the food service sector has mostly been conducted in industrialized countries. For example, it was estimated that 0.92 million tons of food was wasted in the food service outlets each year in the United Kingdom (equivalent to 17% of all meals served), 75% of which was avoidable.⁸⁵ In Germany, the food service sector accounted for 17% (the second largest source) of total FLW along the supply chain.¹²¹ In Finland, 0.075–0.085 million tons of food was wasted in food service, which was the third largest contributor of FLW (20%) following households (35%) and food industry

(27%).¹²⁶ It should be noted that China, as the largest emerging economy in the world, was also experiencing a high level of food waste in the catering and restaurant sector, accounting for about 11–17% of all food served.³⁷

On the whole, food waste per capita at away-from-home consumption is lower than that in households (Figure 8b). It is assumed that with higher per-capita GDP and living standards, people tend to consume more food outside the home, which may consequently result in a larger amount of food waste due to various reasons (e.g., oversized dishes and taste). Yet the correlation between per-capita GDP and per-capita food waste out-of-home appears insignificant. The reason may be that the food service sector is varied and includes both the “for profit” (e.g., restaurant) and “cost” (e.g., care center) parts, leading to a mixed pattern of food waste generation. Interestingly, restaurant food waste in Japan shows a declining pattern in recent years (the circles with a cross in Figure 8b). This may be partly explained by the impact of the implementation of the Food Recycling Law (which is to reduce food waste generation by introducing specific targets for industry sectors) in Japan in May 2001, which contributed to a reduction of out-of-home food waste from 3.1 million tons in 2007 to 1.92 million tons in 2012. Accordingly, food waste per capita decreased from 24.22 to 15.05 kg in Japan.⁸⁵

In Figure 9, we take cereals and the United States, China, and South Africa as examples of industrialized, emerging, and developing countries to illustrate how the FLWR at different stages along the supply chain evolves at different development levels of an economy.

- As the United States is a highly industrialized country, there are few data on its FLWR of cereals at postharvest stages (it can also be assumed to be low). The FLWR at agricultural production, postharvest handling and storage, manufacturing, and distribution stages in South Africa are all higher than those in China. This reflects the fact that with increasing awareness and growing economy, more-

advanced harvesting technologies and more-efficient storage systems are applied in agricultural production, and improved transportation with large volumes and relatively low costs are largely used in China.¹³⁶ This also implies a huge potential of improving the technologies and infrastructure in less-developed countries as an efficient way to reduce FLW.

- The consumer cereal waste also increases as a country develops and increases its GDP. The FLWR of cereals at consumption stage in the United States is the highest (15.8%), followed by the retailing stage (12%). In China, with rapid economic development and household income increase, the FLWR of cereals at the consumption stage has increased in recent years to 6.4%, higher than that of all other stages. As a lower-income country, South Africa shows a low FLWR of cereals at consumer stage yet (1.1%). It should be noted that, because the production and consumption structure of cereals (in terms of rice, wheat, maize, other cereals, and bakery products) varies in different countries, it can be a factor behind these differences as well.

3.4. Data Gaps and Recommendations for Future Study.

Our review suggests that the quantification of FLW has become a research hotspot in recent years, with over 60% of FLW data reported for the recent decade. Whereas these growing efforts provide an order-of-magnitude understanding of the scale of global FLW and for a few countries (e.g., the United States and the United Kingdom) and stages in the food supply chain (e.g., household), the extent of FLW in many other countries and stages remains poorly understood. The existing data are also often based on secondary sources (over half of the reviewed publications) and outdated or inconsistent data sources (e.g., due to choice of method). Moreover, in line with the First Principle of Food Waste proposed by Rathje,¹³⁴ the potential for waste is expected to increase with continuing urbanization, increasing household income, and growing demand for more perishable foods. Yet the FLW data gaps and deficiencies are most-significant for those countries and regions that have undergone the most-rapid shifts away from starchy staples toward more varied and fresh diets (e.g., China and India).³⁶ Therefore, the existing global FLW data should be used and interpreted with care.

To address these data gaps, we highlight the following directions for future study:

- First, the systems and methodologies for FLW quantification should be standardized, as is already highlighted in the literature. Important aspects to be considered include: the definition of FLW (e.g., questions regarding avoidable versus unavoidable food waste),¹⁷⁷ stages of the food supply chain (e.g., different segments in distribution and consumption), destination of FLW (e.g., donation, feed, energy use, or landfill), classification of food commodities and conversion factors (e.g., factor to convert cooked food items to raw food materials), units of measurement (e.g., physical weight or calories), and the methods of measurement (cf. section 3.2 above). This would enable the comparison of existing data across countries, commodities, and food supply chains, which would further help explore patterns and driving factors of FLW generation. For example, the European FUSIONS project released a food waste quantification manual³² in 2016; the first global Food

Loss and Waste Protocol³⁵ published in 2016 provides a standard that can be used by any entity (e.g., a country, a company, a city, or an individual store or food outlet) and should be promoted more widely.

- Second, more data based on direct measurement are badly needed. Our review shows that only around 20% of the existing publications on FLW quantification are based on first-hand data, and any quotation of unrepresentative data from literature may lead to high uncertainties. Despite the higher time, labor, and economic cost, more field work and primary data collection should be encouraged and would help verify existing data, improve the accuracy and reliability of the data, and fill in the gaps in countries where data are currently not available.
- Third, more attention should be paid to countries outside the current focus area (the United States and Europe), especially to big developing and emerging economies (e.g., the BRICs: Brazil, Russia, India, China, and South Africa). There is less information regarding FLW in those countries, but the scale may be significant (e.g., a preliminary study³⁷ shows that consumer food waste in China is already higher than that of the total of EU-27). These countries are also experiencing a rapid shift in terms of dietary change, urbanization, and household income increase, and thus, their FLW is expected to grow in the coming years. The use of outdated data may have led to an overestimation of agricultural FLW and underestimation of consumer food waste in developing countries.^{37,78} Social and cultural context are also very important for FLW quantification and mitigation, which can only be addressed when more data for specific countries and cultures are available.
- Fourth, more in-depth analyses on FLW at different food supply stages should be conducted. Household food waste is a clear current focus (covered in almost half of the reviewed publications, though almost exclusively in developed countries). Research should be expanded to food supply chains with less data and poorer understanding, e.g., FLW in other segments during out-of-home consumption (e.g., canteens and restaurants) and postharvest and retailing in developing countries. A more-detailed quantification at each stage would also help a better understanding of the driving factors of FLW at different stages.
- Fifth, consistent databases (global, regional, and national) using a common reporting framework on FLW should be established, maintained, and made available to the public, with joint efforts from all stakeholders along the entire food chain. Such databases would provide a baseline for monitoring the progress of FLW reduction, which is important for tracking progress toward SDG Target 12.3, and national political targets on FLW. Governmental and nongovernmental organizations such as UN Environment and FAO and national statistical agencies should take a stronger leadership in this effort (the data series reported by WRAP and USDA-ERS are good examples). Companies should be encouraged to report their FLW regularly (e.g., in their annual corporate social responsibility report). In the long run, the “measurable, reportable, and verifiable (MRV)” principle that is widely acknowledged in greenhouse gas emissions reduction targets may be appropriate for tracking FLW reduction.

- Last but not least, quantification of FLW is only a first step; the aim of better data measurement and monitoring is to help better-understand the social, economic, and environmental impacts of FLW, identify hotspots where actions should be prioritized, develop long-term scenarios to inform relevant policy-making, understand which policies and strategies have been most-effective at achieving FLW reductions, and contribute overall to the reduction of FLW and the sustainability of the food system. Research focusing on these topics should naturally be conducted in parallel.

■ ASSOCIATED CONTENT

📄 Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.7b00401.

Additional details on the literature selection. Figures showing temporal trends, an overview of methods, per-capita FLW, and experimental relationships. Tables showing metadata used in the paper. (PDF)

A table showing compiled food losses and food waste data reported in the reviewed publications (by physical weight). (XLSX)

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Notes

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