



Global nutrient content embedded in food losses and waste: Identifying the sources and magnitude along the food supply chain

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ABSTRACT

Reducing food losses and waste (FLW) can contribute to improving nutrient availability to meet the nutritional needs of the global population. Identifying foods that contribute most to nutrient content in FLW is crucial for developing effective strategies to reduce FLW. Here, we assessed the current literature for quality and consistency of FLW data, and then evaluated the quantity of nutrients that are wasted as a consequence of FLW, identifying the primary food sources contributing to this on a global scale. Several FLW definitions and quantification methods were identified in the literature, making it difficult to compare FLW data and estimates of nutrient content in FLW between existing studies. The nutrient content in global FLW was determined for 29 nutrients from 99 food commodities with the DELTA Model®, after which the contribution of each food group to the nutrient content of FLW was calculated. An indicator was developed to assess the potential impact of resolving FLW on global nutrient availability. Nutrient content in FLW was highest for phosphorus (69 % of global requirement), tryptophan (62 %), thiamine (61 %), methionine (58 %) and histidine (54 %). For 17 out of 29 nutrients, >40 % of the global requirement was embedded in FLW. Cereals contributed most to nutrient losses, followed by fruits and vegetables. According to the indicator, rice, wheat, vegetables, maize, and milk provided the greatest opportunity for increasing nutrient supply via reduction of FLW, due to the combination of waste rates and nutrient density. Our findings highlight the importance of broadening FLW research beyond food mass to incorporate nutritional aspects as important indicators, and to identify key food items to reduce FLW for the improvement of nutrient availability.

1. Introduction

Food losses and waste (FLW) are gaining increasing attention worldwide due to their environmental, economic and nutritional impacts (Kummu et al., 2012; Spang et al., 2019; Conrad and Blackstone, 2020). For example, it was estimated that 23–24 % of total freshwater resources, cropland area, and fertiliser used in food crop production was used for lost or wasted crops (Kummu et al., 2012).

In 2011, the Food and Agricultural Organisation (FAO) of the United Nations (UN) estimated that one-third of all global food production is lost or wasted (FAO, 2011). A decade later, new global estimates on FLW have been published, estimating that 8 % of all food produced in the world is lost on the farm, 14 % between farm gate and retail/consumption stage and 17 % is wasted at the retail, food service and household stages of the food supply chain (FSC) (Lipinski, 2021; United Nations Environment Programme, 2021; WWF-UK, 2021). International

attention is reflected in target 12.3 of the Sustainable Development Goals (SDGs), a global aspiration to halve per capita food waste at retail and consumption level and reduce food losses along the FSC by 2030 (Lipinski, 2021).

However, quantifying FLW solely in terms of mass overlooks the loss of macro- and micronutrients, which are essential for healthy functioning of the body and the core value of food. Substantial amounts of nutrients are embedded in FLW (Conrad et al., 2018; Chen et al., 2020; WWF-UK, 2021). Some of these nutrients are considered a public health concern because intake and supply are suboptimal and associated with adverse health outcomes (Conrad and Blackstone, 2020; Smith et al., 2021). The DELTA Model®, a tool for investigating the nutrient availability supplied by the global food system, showed that even with equitable distribution of food, the global food system does not provide sufficient calcium and vitamin E (Smith et al., 2021). Similar findings exist elsewhere, with concerns additionally raised for several other micronutrients, including vitamins A and B12, iron and zinc (Beal et al.,

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Abbreviations

FAO	Food and Agricultural Organisation of the United Nations
FBS	Food Balance Sheets
FLW	Food Losses and Waste
FLW Standard	Food Loss & Waste Protocol Accounting and Reporting Standard
FSC	Food Supply Chain
FWI Report	Food Waste Index Report
HIC	High-Income Country
SDG	Sustainable Development Goal
UN	United Nations
UNEP	United Nations Environment Programme

2017; Lividini and Masters, 2022; Passarelli et al., 2024). Reducing FLW could make more of these nutrients available for consumption, or reduce the demand to produce food in current quantities. The amount and composition of FLW, as well as drivers, vary across regions, FSC stages and food groups (FAO, 2011). Identifying foods that contribute most to nutrient content in FLW is crucial for developing effective strategies to reduce FLW and enhance nutrient availability and food security, but remains understudied and poorly quantified at a global level in the academic literature (Chen et al., 2020).

In order to evaluate which foods contribute most to nutritional losses through FLW, a clear understanding of the availability and quality of global FLW data is essential. Most studies on global food losses along the supply chain utilise the FAO Food Balance Sheets (FBS). This provides national level estimates of losses between the farm gate and retail for 99 food commodities, is updated annually, and is publicly available. However, for on-farm losses and food waste post-retail, data sources are more diverse and generally of lower quality and currency, with inconsistent definitions and system boundaries between studies.

The aims of this study were: a) to review the different definitions and methodologies that have been employed to quantify FLW from farm gate to consumer, and discuss patterns and implications, b) to identify the best FLW data sources available at a global level and understand their limitations, and c) to evaluate the quantity of nutrients that are wasted as a consequence of FLW, and d) identify, through the use of a novel indicator, the primary food sources on a global scale with the greatest potential to impact global nutrient availability if their FLW were resolved. For the last aspect, we leveraged the DELTA Model®, a global food system mass balance able to capture loss and waste from farm gate to consumer (Smith et al., 2021). The results will provide insight on the challenges in methodological variation in FLW quantification, identify FLW data gaps and weaknesses to be addressed by future research, and highlight the foods which should be targeted for urgent waste reduction from a global nutrient supply perspective.

2. Literature review

A literature review was conducted to compare FLW definitions and methodologies to measure FLW, to search for the most recent FLW estimates in terms of mass and estimates of nutrient content embedded in FLW. The literature search incorporated peer-reviewed literature as well as relevant “grey literature”, including reports from United Nations agencies, the World Wildlife Fund, and internationally accepted FLW standards and protocols. We approached grey literature by carefully evaluating each source for credibility of publishing institute, methodology, review process, and relevance to our research objectives. As the DELTA Model® only considers FLW starting at the farm gate, this study focused on losses along the supply chain and food waste in retail, food services and households rather than on-farm losses. Therefore,

publications with a focus on on-farm losses were excluded. Publications with a focus on other qualitative aspects of FLW, such as policies to prevent FLW, drivers and causes of FLW were also excluded, as these topics were outside the scope of this study.

2.1. Influence of definition and methodology on FLW estimates

2.1.1. Definition food losses and waste

There is no universal definition of FLW, and the terms ‘food loss’, ‘food waste’ and ‘food losses and waste’ are often used interchangeably (Delgado et al., 2021; Boiteau and Pingali, 2023). While there is consensus that ‘food’ refers to ‘products intended for human consumption’ (Chaboud and Daviron, 2017; Spang et al., 2019), differences emerge across several other aspects of FLW definitions. These differences include the distinction between ‘food loss’ and ‘food waste’, the inclusion of different stages in the FSC, the destination of FLW, the inclusion of inedible parts, the perspective of the study and the type of data considered (quantitative or qualitative) (Chaboud and Daviron, 2017; FAO, 2019; Chauhan et al., 2021).

Firstly, distinctions are commonly made between the terms ‘food loss’ and ‘food waste’. In some definitions, the distinction is based on the stage of the FSC where losses occur. As such, ‘food losses’ usually refers to stages early in the supply chain (during production, post-harvest, processing of foods), and ‘food waste’ to retail and consumption stages (FAO, 2011; Spang et al., 2019; O’Connor et al., 2023). In other definitions, the distinction depends on the cause of the food losses (Delgado et al., 2021). ‘Food losses’ can refer to unintended reductions in quantity or quality of food, while ‘food waste’ is a subset of food losses that “has been left to spoil or expire due to economic behaviour, poor stock management or neglect” (FAO, 2014; Xue et al., 2017; Spang et al., 2019). Additionally, some definitions do not differentiate between food losses and waste (Xue et al., 2017).

Secondly, the supply chain stages that are considered in the definition of either food losses or waste can differ. For instance, food losses may include on-farm waste, or commence at the farm gate (Spang et al., 2019). Regarding food waste at the consumption level, the stages of the supply chain included can also differ. Some definitions include retail stages in food waste, whereas others only include households and food services (FAO, 2011; United Nations Environment Programme, 2021).

Thirdly, differences exist in the destination of FLW. Some definitions describe FLW as all products initially intended for human consumption but not consumed (FAO, 2011; Chaboud and Daviron, 2017), while others exclude food that is repurposed for economically productive non-food uses from FLW (such as animal feed or bioenergy) (FAO, 2019). This differentiation often depends on the perspective or objective of the study, whether it adopts a food security or an environmental perspective (Chaboud and Daviron, 2017).

A fourth difference is the inclusion or exclusion of inedible parts (e.g., bones, egg shell or banana peel) (Chaboud and Daviron, 2017). However, what comprises the edible parts of food can vary between cultures and contexts and is not a fixed concept (Spang et al., 2019). Therefore, some studies choose to include the inedible parts in the definition of food and thus FLW (United Nations Environment Programme, 2021). Considering inedible parts as FLW has become more common in recent years and is also present in policies, for example in the development of a law on FLW prevention in Spain and the EU food waste measurement methodology (European Commission, 2019; Hoehn et al., 2023).

Lastly, food losses and waste definitions can consider both the quantity and/or quality of the food. Quantity loss/waste relates to reductions in mass or volume, whereas quality relates to various attributes of a food item, such as food safety, sensory aspects, and economic or nutritional value (Boiteau and Pingali, 2023). As such, a decrease in the nutritional value of food products, or non-optimal use of food products in relation to their potential can be considered as FLW (Chaboud and Daviron, 2017).

The variation in definitions often reflects the different problems or objectives that organisations focus on or associate with FLW. Perspectives can encompass environmental aspects, health and nutrition, food safety, and food security. Consequently, the definition of food losses and waste often depends on the perception of the problem by the definer (Chaboud and Daviron, 2017; FAO, 2019).

The lack of a universal and comprehensive FLW definition is the first difficulty in any comparison of FLW estimations. This challenge has been widely recognised and sparked efforts at standardization (see subsequent section). For this paper, our use of the term FLW largely aligns with the widely cited FAO, 2011 report (FAO, 2011). Food losses refer to the reduction in mass of edible food occurring at post-harvest and processing stages in the FSC, but not including the retail or on-farm level; while food waste refers to the reduction in edible food mass at the retail, food service and household level. Given our focus on nutrient supply to meet human nutritional requirements, FLW are measured for products that are directed to human consumption, excluding inedible parts.

2.1.2. Quantification methods

In addition to the lack of general agreement on the definition and concept of FLW, quantification methods are not universal, further complicating the process of making comparisons (Hoehn et al., 2023). Quantification methods can be split into direct methods based on primary data collection, and indirect methods with data derived from other publications or datasets (Hanson et al., 2016; Xue et al., 2017; O'Connor et al., 2023).

Direct methods are most often used in a specific FSC stage and on a small scale, resulting in a lack of representativeness at larger scales (Xue et al., 2017). Weighing, counting, assessing volume and waste composition analysis are time-consuming and expensive, but often provide accurate and objective data (Xue et al., 2017; Baquero et al., 2023). Surveys, diaries, and records are relatively less time-consuming and expensive, but depend on personal perceptions and subjectivity of observers, reducing accuracy (Xue et al., 2017).

Indirect methods are often used to estimate regional or national food waste (Xue et al., 2017). The costs of indirect methods are lower than direct methods and take less time. However, the accuracy of results using indirect measurements is highly dependent on the quality and accuracy of the source data (Xue et al., 2017).

Studies can use these methods alone or in combination in one or several stages of the FSC (Baquero et al., 2023). Indirect methods are used more often than direct methods, with modelling and the use of existing data being the most commonly used, especially to estimate global, regional, or national food waste (Baquero et al., 2023).

The choice of quantification method has a large and unpredictable impact on the estimation of FLW (Baquero et al., 2023). For example, a study in Switzerland showed that the estimation of household food waste per capita with self-reported surveys was 10 times lower than estimations based on extrapolations of a national waste composition analysis report (Delley and Brunner, 2018). The study highlighted the extent of underreporting in self-assessment methods and argued that the extrapolation was more objective. Baquero et al. (2023) found that direct methods give more accurate results, while indirect methods overestimate FLW generation. The choice of direct method is highly important: because surveys, diaries and records depend on personal perceptions and subjectivity of observers, the accuracy of these methods is reduced compared to other direct methods (Xue et al., 2017; Hoehn et al., 2023).

The indirect estimation of FLW is also influenced by the input data used for the calculations. The FAO FBS are a widely used resource for calculating food losses along the supply chain. The FBS provide national level estimates of losses between the farm gate and retail for 99 food commodities. The FBS calculate losses using national statistics on population, supply and utilization, acquired from surveys with industries (FAO, 2001). Despite their extensive use, concerns have been raised about the documentation and transparency of FBS (Hoehn et al., 2023).

The accuracy of FBS depends on the reliability of underlying data, which can vary in terms of coverage and accuracy (FAO, 2001). There are many data gaps, often filled by expert opinion and assumptions, leading to high uncertainty in the quality of the data. The quantity of food loss is often estimated as a fixed percentage of availability, however it is not well documented how these percentages are estimated, or the extent to which loss linearly scales with availability (Bovay and Zhang, 2020). Furthermore, it underestimates food availability in developing countries, particularly in rural areas where homegrown food is not accounted for (Lopez Barrera and Hertel, 2021). FLW is not comprehensively reported in the FBS, and even in countries with well-documented FLW data some components are still predicted or not covered in the FBS (Thar et al., 2020), resulting in data quality issues. Still, the FBS is currently the best available data source for analysis of the FSC, including food losses. As the FAO acknowledges the uncertainties of the data quality, it notes that FBS provides an approximate picture of the overall situation in a country or region and can be used to provide an indication of the situation at present (FAO, 2001). A review study that examined the uses of FAO FBS in international studies of health and nutrition indicated that FBS are reliable when averaged over several years and when results are reported as nutrient densities, trends and percentage of energy or ratios, rather than absolute value (Thar et al., 2020).

Most global or international studies use FLW ratios from a 2011 FAO report, relying on the same raw data with only regional, broad food group resolution (FAO, 2011). These studies therefore do not provide independent estimates of the extent of FLW. Furthermore, it is emphasized that these 2011 estimates were based on numerous assumptions due to a lack of data availability and therefore results must be interpreted with caution. FLW estimations derived from these sources carry high levels of uncertainty (Spang et al., 2019; Hoehn et al., 2023). Still, the report and its estimates on FLW remain widely used in making new estimates in recent studies (van Zanten et al., 2023).

Recognizing the need for standardized quantification methods, the Global Food Loss and Waste Accounting and Reporting Standard (FLW Standard) was established in 2016, providing guidelines for organisations (including governments, non-governmental organisations, and businesses) to measure FLW (Hanson et al., 2016). Adherence to the FLW Standard should ensure international consistency in FLW assessments and facilitate transparency of the reported data, allowing for comparison of FLW inventories both within and between organisations. This will facilitate accurate insights in key FLW points and enables the implementation of targeted interventions (Jia and Qiao, 2022). As such, guidelines for member states of the European Union were developed in collaboration with the authors of the FLW Standard (FUSIONS, 2016). Table 1 presents a comparison of the scope and quantification methods of the FAO, 2011 report and the Food Waste Index Report 2021 (FWI Report), based on the FLW Standard framework.

2.2. Current estimates of global food losses and waste

Various global studies have investigated the issue of food waste. One of the first global estimates of FLW was presented by the FAO in 2011 (FAO, 2011). This widely cited report estimated that approximately one-third of food intended for human consumption is lost or wasted, which equals 1.3 billion tonnes annually. This is equivalent to 280–300 kg/capita/year in Europe and North America, and 120–170 kg/capita/year in Sub-Saharan Africa and South/Southeast Asia (FAO, 2011; HLPE, 2014).

Subsequently, an increasing number of studies and reports addressing FLW have been published, predominantly focusing on regional, national, or subnational level, and mostly in high-income countries (HICs) (Gustavsson et al., 2013; Hoehn et al., 2023). Although there has been a rise in small-scale studies using direct measurement methods, primary data is still limited globally (Xue et al., 2017; Hoehn et al., 2023). Consequently, most studies on FLW are conducted in HICs and rely on secondary data, resulting in outdated measurements and large

Table 1
Comparison of quantification methods used in the reports of [FAO \(2011\)](#) and [UNEP \(2021\)](#). Framework adapted from [Hanson et al. \(2016\)](#), incorporated additional components for food groups, quantification methods and unit of FLW.

	FAO, 2011	Food waste index report
Timeframe	12 months	12 months
Material type	Only edible parts	Edible and inedible parts
Destination	All non-food destinations: animal feed, biomaterials/ biochemical processing, co/ anaerobic digestion, compost/ aerobic, controlled combustion, land application, landfill, refuse/discard, sewer	Co/anaerobic digestion, compost/aerobic, controlled combustion, land application, landfill, refuse/ discards, sewer
Boundaries		
Food category	All food and beverages	All food and beverages
Food supply chain stage	Entire food supply chain: agricultural production, postharvest handling & storage, processing and packaging, distribution (including retail), consumption	Retail, food service and household
Geography	World regions	Countries – extrapolated to world regions
Food groups	Cereals, roots & tubers, oilseeds & pulses, fruit & vegetables, meat, fish & seafood, milk & egg	Total food waste
Quantification method	Mass balance, modelling	Use of existing data, modelling
Unit of FLW	Mass (million tonnes), mass per capita (kg/capita/year), percentage	Mass per capita (kg/capita/ year)

[FAO \(2011\)](#) and [\(United Nations Environment Programme, 2021\)](#). Abbreviations: FAO, Food and Agriculture Organisation of the United Nations; FLW, Food Losses and Waste; UNEP, United Nations Environment Programme.

gaps in national estimates ([Xue et al., 2017](#); [United Nations Environment Programme, 2021](#)). Many recent studies ultimately rely on a small number of older estimates for their base data ([Xue et al., 2017](#)). Most research has focused on retail and consumer waste, neglecting earlier stages of the supply chain, as it was generally believed that the later stages were the more significant and addressable contributors to total food waste ([Hoehn et al., 2023](#); [O'Connor et al., 2023](#)). A detailed quantification at each stage would help to better understand FLW drivers ([Xue et al., 2017](#)).

In 2021, the United Nations Environment Programme (UNEP) published the global FWI Report, developed to monitor progress towards SDG 12.3 ([United Nations Environment Programme, 2021](#)). The report estimated that 17 % of the total global food production is wasted in the consumption stage, which is equivalent to 931 million tonnes (121 kg/capita/year). The report stated that the [FAO, 2011](#) estimates of food waste at consumer level underestimated its scale, indicating that food waste at the consumer level appears to be more than double the previous FAO estimate ([FAO, 2011](#)). However, differences in methodologies between the FWI Report and the [FAO, 2011](#) report ([Table 1](#); most importantly the inclusion of inedible parts in the FWI Report), make comparisons difficult.

Several additional studies have been conducted to gain a better understanding of food waste on a global scale. A review by [Dou and Toth \(2021\)](#) looked at 151 studies for food waste rates, of which 79 studies used direct measurement methods ([Dou and Toth, 2021](#)). The majority of included studies reported on total food waste, whereas <5 % of the datapoints were for edible waste only. As expected, studies reporting total food waste were significantly different from studies reporting only edible food waste. Including inedible parts, the average total food waste was 73.73 kg/capita/year. In contrast, studies on edible food waste reported 17.52 kg/cap/year.

Additionally, a scoping review including nine studies on FLW

indicated food waste ranged from 65 to 110 kg/capita/year ([Brennan and Browne, 2021](#)). Variations in estimates could be due to location, dietary and waste practices, sample size of the study and methods used to measure food waste.

A study by [Chen et al. \(2020\)](#) found that globally 412.5 million tonnes/year of edible food were wasted, equivalent to 65 kg/capita/year ([Chen et al., 2020](#)). The wasted amount varied per country and world region. On average, 23 % of food supply in a household was wasted in North America, in contrast to <5 % in South Asia and Africa. The commodities contributing most to food waste were vegetables (25 %), cereals (24 %) and fruit (12 %). Differences in the contribution of food groups to food waste were evident across world regions: North America had high dairy waste but low cereals and roots & tubers waste, while the opposite was true for South Asia and Sub-Saharan Africa. It should be noted that this study used the food waste percentages of the [FAO, 2011](#) report to calculate food waste, and results should therefore be interpreted with caution.

Alternatively, [Gatto and Chepeliev \(2024\)](#) conducted a study with a different approach ([Gatto and Chepeliev, 2024](#)). Leveraging the Global Trade Analysis Project Database, they compiled a FLW database including 121 countries across a ten-year timeframe (2004–2014). Global hotspots of FLW were found in agricultural and post-harvest handling and storage stages of the FSC, together generating about half of all FLW. Estimates of FLW were higher compared to the other studies reviewed here ([Table 2](#)), ranging from 21 kg/capita/year in Zimbabwe to 565 kg/capita/year in the USA, due to inclusion of all FSC stages and inedible parts.

Altogether, global FLW estimates range from 6 to 531 kg/capita/year depending on methodology, included data, and global region. Each study used a different definition and methodology, which influenced the estimation of FLW, making comparison of the estimates difficult. Moreover, most studies only considered total FLW, while from a nutritional or food security perspective, it could be argued that FLW per commodity would provide more detailed insights for targeted reductions. An overview of the estimates can be found in [Table 2](#).

2.3. Nutritional losses in food waste

The increase in FLW around the world results in an increase of nutritional losses along global FSCs ([Gatto and Chepeliev, 2024](#)). One of the first studies looking at nutritional aspects of FLW estimated that the global FLW of one-third of food lost or wasted, as reported by the FAO, results in calorie losses of 24 % (614 kcal/capita/day) ([Kummu et al., 2012](#)). However, focusing on the caloric value of wasted food may

Table 2
Global food waste estimates for different supply chain stages and material types.

Study	FSC stage	Material type	Food waste (kg/capita/year)
Global Food losses and food waste - extent, causes and prevention (FAO, 2011) Food Waste Index Report 2021 (UNEP, 2021)	Entire FSC	Edible only	120–300
	Households	Edible only	6–115
	Households, retail, food service	Edible and inedible parts	121
	Households	Edible and inedible parts	76–91
Chen et al., 2020 Dou and Toth, 2021	Households	Edible only	65
	Households	Edible only	18
		Edible and inedible parts	74
Brennan and Browne, 2021	Households	Different per study included	65–110
Gatto and Chepeliev, 2024	Entire FSC	Edible and inedible parts	21–565

FSC, Food Supply Chain.

overrepresent calorie-dense foods and underrepresent the loss of micronutrients (Spiker et al., 2017). Micronutrients are essential for the functioning of the body, and quantifying food waste in terms of calories does not fully represent the nutrition that is lost (Chen et al., 2020).

Several studies have examined nutrient losses associated with food waste in the past five years, primarily at a national level in HICs and predominantly at the end of the FSC. Food composition tables are used to translate FLW mass to nutritional losses. Three studies have investigated nutrient waste on a global scale (Ritchie et al., 2018; Chen et al., 2020; Gatto and Chepeliev, 2024). Estimates of nutrient losses differ substantially between studies as well as between countries. The studies used different methodologies, most importantly the inclusion of inedible parts and the FSC stages that were included, limit comparability of the results. A global overview of nutrients embedded in FLW is provided in Table 3 (a complete overview of nutrient losses of all studies can be found in Supplementary information S1).

2.3.1. Contribution of food groups to nutrient losses

Multiple studies expand on the food groups or items that contribute most to the lost or wasted nutrients. Despite certain food products contributing little to food waste in terms of mass, they can significantly contribute to nutrient waste (Cooper et al., 2018; Chen et al., 2020). Examples are meat and dairy products (Chen et al., 2020). Moreover, nutrient-dense foods such as cereals, vegetables, fruits, and animal-sourced foods are wasted at higher rates globally than legumes, roots and tubers, making them primary contributors to nutrient waste (Spiker et al., 2017; Ritchie et al., 2018; Chen et al., 2020). For instance, previous studies have identified that meat, poultry, and fish account for a substantial proportion to losses of vitamin B12 (50 %), zinc (47 %), protein (46 %), niacin (42 %) and vitamin B6 (42%) (Spiker et al., 2017; Chen et al., 2020). Similarly, major sources of wasted iron are cereals (49 %), vegetables (22 %) and meat (9 %), while nearly all vitamin C and K is wasted through fruits and vegetables (Chen et al., 2020). Loss of calcium is primarily due to dairy, cereals, and vegetables (Spiker et al., 2017; Cooper et al., 2018).

Table 3

Nutrient waste embedded in food losses and waste per capita per day, recorded by studies examining nutrient waste associated with food waste.

Nutrient	Range lost/wasted per capita per day across studies
Energy, kcal	54.4–1216.5
Protein, g	2.61–32.8
Carbohydrates, g	10.58–146.4
Fat, g	0.9–57.2
Fiber, g	0.75–7.4
Vitamin A, ug	88–368.4
Vitamin B6, mg	0.3–0.9
Vitamin B12, ug	0.3–1.8
Folate, ug	34.7–199
Niacin, mg	0.68–9.2
Vitamin B5, mg	0.6
Riboflavin, mg	0.03–0.8
Thiamine, mg	0.04–0.9
Vitamin C, ug	7.59–74.6
Vitamin E, mg	0.5–5.1
Calcium, mg	22.49–324
Iron, mg	1.0–8.0
Zinc, mg	0.51–4.6
Copper, mg	0.2–1.0
Potassium, mg	323–1099.1
Phosphorus, mg	37.11–547
Magnesium, mg	40.1–129
Selenium, ug	14.7–38

Studies included in this table are Chen et al. (2020), Cooper et al. (2018), Spiker et al. (2017), Conrad and Blackstone (2020), Wang et al. (2023), Gatto and Chepeliev (2024), and Khalid et al. (2019). Not all nutrients were assessed in each study; range is reported for nutrients across selected studies that did report on the nutrient.

Adapted from Brennan and Browne (2021).

Significant variation exists in the definitions and methodologies used to quantify food loss and waste. The result is an inability to easily compare estimates between studies, and wide variation in the estimation of total FLW or the mass of the wasted nutrients. While efforts at standardization have been made, reporting FLW at as high a resolution as possible must be encouraged, as, depending on the goals of future research, the inclusion or exclusion of inedible parts, or a focus on absolute or relative FLW, or the targeting of specific food items at specific FSC stages may be desirable. For example, any study on nutrient supply for human consumption must exclude inedible parts, or risk greatly overestimating the additional nutrient available for consumption under a scenario of reduced waste.

Where there is greater consensus is on the food groups that contribute most to nutrient waste. However, differences between results from different studies show the importance of a comprehensive approach to assess nutrient losses associated with FLW. It is also challenging to understand which foods would contribute most to overall nutrient supply if their FLW were resolved, as opposed to their contribution to specific nutrients.

It appears that the most up-to-date, highest resolution, and globally representative FLW estimates at a commodity level are contained in the FAO FBS and the FAO, 2011 report. As such, we now use the DELTA Model®, with these data sources underpinning FLW calculations, to assess global nutrient waste and develop an indicator that identifies target foods for increasing overall nutrient supply by reducing FLW.

3. Methods

The DELTA Model® was used to analyse the amount of nutrients embedded in FLW, and which foods contribute most to that nutrient content. A detailed description of the DELTA Model® can be found in Smith et al. (2021). A brief description of the model and the data used as input is provided below, and illustrated graphically in Fig. 1.

The DELTA Model® was developed in R, using data from publicly available data sources and the scientific literature. The data in this study was generated using version 2.1 of the model. The DELTA Model® uses the FAO FBS as its primary data source (FAO, 2024). The FBS provide data on global production quantities, feed and food use, supply chain losses and processing chains for 99 food commodities. This data is used to estimate the global availability of food for human consumption in 2020 by taking a linear interpolation of the most recent 20 years of this data. Inedible parts of food (e.g., animal bones) and the proportion of in-home food waste are deducted. In-home food waste proportions are based on 2011 FAO estimates for each food group in different global regions (FAO, 2011). This provides the total quantity of each food item available for consumption globally on an annual basis, which is translated into a per capita allocation, assuming equal distribution across all individuals. The FBS data on supply chain losses, and the DELTA Model® estimates of in-home food waste were the primary data sources for this study.

The quantity of each food item is converted to quantities of 29 essential nutrients, using food composition data from the United States Department of Agriculture (USDA, 2020). Bioavailability coefficients are applied for protein and the indispensable amino acids to calculate bioavailable nutrient quantities in food available for consumption, using digestibility values from the literature (Gilani et al., 2012).

By combining demographic data for the global population from the UN (FAO, 2020) with nutrient reference values from the European Food Safety Authority (European Food Safety Authority, 2017) and FAO (FAO, 2013) for 29 essential nutrients, the DELTA Model® calculates global nutrient requirements, hereafter referred to as the target intake for each nutrient.

The output of the DELTA Model® was used to determine the amount of FLW and associated nutrient content, using R (version 4.3.1). All calculations were done for total FLW, and losses and waste separately. The total mass of FLW and contribution of each food group to FLW were

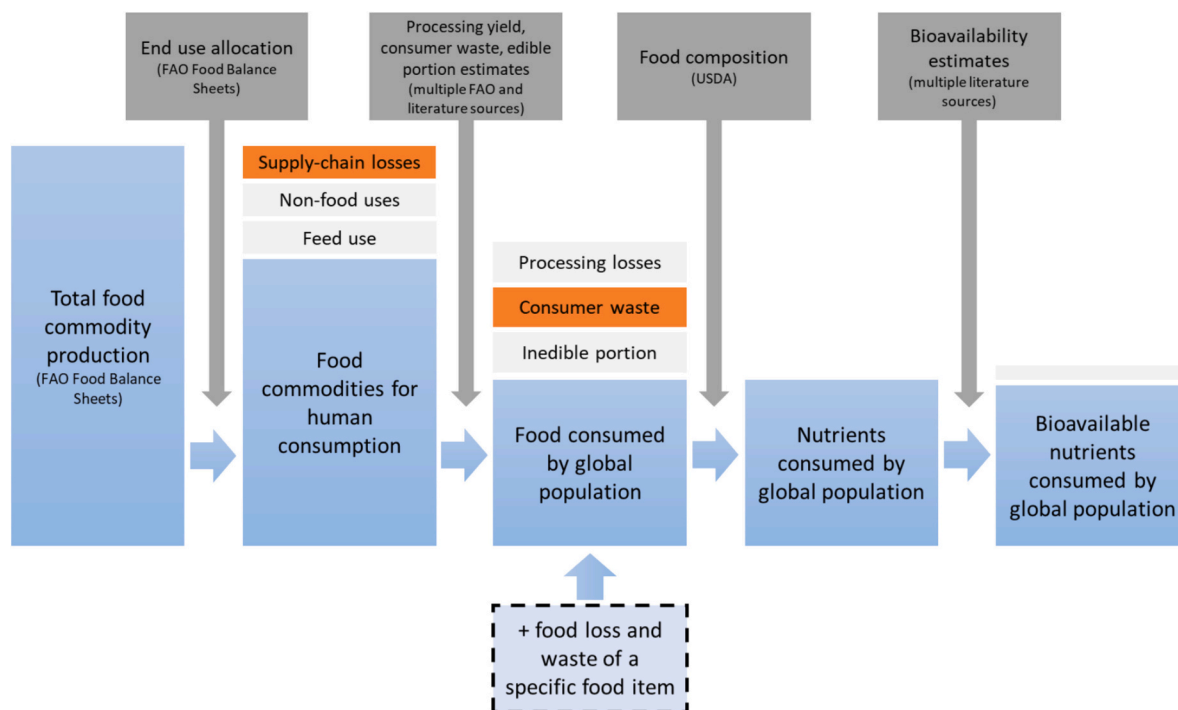


Fig. 1. Illustration of the DELTA Model® calculation process, as described in the Methods. Total food commodity mass is gradually converted to total nutrients available for consumption, as shown by the blue boxes. The points at which losses and waste are deducted from total food mass are highlighted. Shown in the dashed box, the quantity of a food item lost or wasted can be re-added into the model calculation to view scenarios where this loss and waste is resolved, for use in calculation of the indicator. Note that bioavailability coefficients are applied to protein and the indispensable amino acids only. Adapted from (Smith et al., 2022).

calculated. The nutrient content in FLW was determined for each individual nutrient, after which the contribution of each food group to the nutrient content of FLW was calculated. The nutrient content embedded in FLW was compared to the global target intake, to calculate the proportion of the target intake that was made unavailable due to FLW.

To assess the potential impact of resolving FLW on global nutrient availability, a novel indicator was developed, as described in the equations below. This indicator aimed to measure the additional nutrient availability if all FLW of a specific food item were resolved. The methodology, comparing nutrient content to nutrient requirement and summing across nutrients, is analogous to techniques used elsewhere for understanding food nutrient density (Drewnowski, 2010; Beal and Ortenzi, 2022) The calculation involved evaluating the current global nutrient supply compared to nutrient requirement, represented by the ratio of nutrient supply to the target intake, summed for all nutrients (Eq. (1)). Note that the units for supply and target intake are specific to the nutrient in question (e.g. kcal for energy, mg for iron, etc.), but the outcome of each of the below equations and the indicator itself are dimensionless.

$$\sum_i (Supply_i / Target\ intake_i) \text{ for all nutrients } i. \tag{1}$$

Then, the potential nutrient supply if losses and/or waste for a specific food item were resolved was calculated. The calculation is similar to that of Eq. (1), with the addition of the nutrient content lost or wasted in food item j (Eq. (2)).

$$\sum_i ((Supply_i + nutrient\ content\ in\ FLW_{ij}) / Target\ intake_i) \text{ for all nutrients } i \text{ and any food item } j. \tag{2}$$

The resulting indicator score for each food item j was derived as the difference between the values obtained from Eqs. (1) and (2):

$$Indicator_j = Equation\ 2 - Equation\ 1$$

This indicator served as a metric to identify food items with the greatest potential to improve the current global nutrient supply situation if their FLW were resolved. The analysis excluded processed products due to the complexity and subjectivity of determining use of the FLW of their raw commodity ingredients.

4. Results

4.1. Global FLW amounts in mass

The total weight of FLW based on the DELTA Model® 2020 baseline scenario was 1.4 billion tonnes, equivalent to 181 kg/capita/year (497 g/capita/day). Of the total FLW, 46 % was caused by losses and 54 % by food waste. This breakdown translates to 648 million tonnes of food losses, accounting for 83 kg/capita/year (228 g/capita/day), and 765 million tonnes of food waste, equivalent to 98 kg/capita/year (269 g/capita/day).

All food groups contributed to FLW, but in varying degrees. The food groups contributing most to total mass of FLW were cereals (41 %), fruits and vegetables (32 %) and roots and tubers (11 %) (Fig. 2). Small

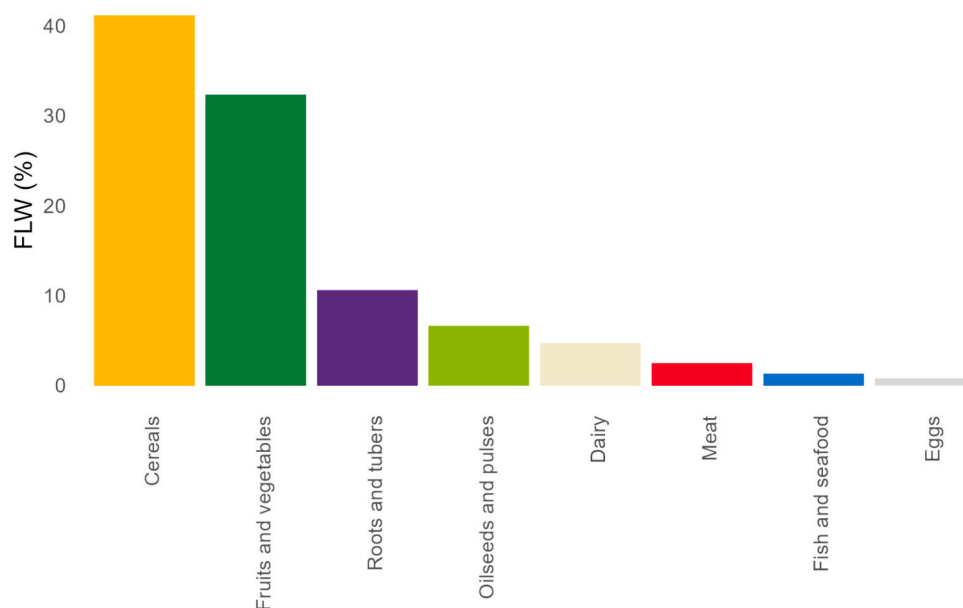


Fig. 2. Contribution of food groups to food losses and waste (FLW), as a percentage of total FLW.

differences existed between the contribution of food groups to food losses and food waste separately. For example, food losses were higher for oilseeds and pulses, whereas waste was higher for dairy and meat (Supplementary information S2).

On the food commodity level, ‘other vegetables’ (15 %), ‘rice and products’ (11 %), ‘sugar cane’ (9 %), ‘wheat and products’ (9 %) and ‘maize and products’ (7 %) were the greatest contributors to total FLW. Examining losses separately, ‘sugar cane’ contributed most (18 %), followed by ‘other vegetables’ (13 %), ‘maize and products’ (10 %), ‘oil palm fruit’ (7 %) and ‘potatoes and products’ (6 %). In the waste category, contributions were highest for ‘other vegetables’ (17 %), ‘rice and products’ (15 %), and ‘wheat and products’ (13 %), followed by lower contributions from other food items (<5 % each) (Fig. 3). Both the rankings for food groups and food items approximately followed the distribution of global food production and were therefore expected.

4.2. Nutrients embedded in FLW

Nutrient content embedded in FLW as a percentage of the target intake is presented in Fig. 4. This was highest for phosphorus (69 % of global target intake), tryptophan (62 %), thiamine (61 %), methionine (58 %) and histidine (54 %). For 17 out of 29 nutrients, >40 % of the target intake was embedded in FLW. For all nutrients, the nutrient content in FLW exceeded 10 % of the target intake. Nutrient content in food waste was consistently higher than that in food losses, which is similar to the distribution of total mass of food losses and food waste. Quantities of nutrient content in food waste and food losses separately can be found in Supplementary information S3.

Some food groups contributed more to nutrients in FLW than others. Fig. 5 represents the contribution of different food groups to the nutrient content embedded in FLW. Cereals emerged as a large contributor, accounting for >30 % of nutrient content for all nutrients except calcium, fat, and vitamins A, B12, C, and E. Fruits and vegetables, as well as oilseeds and pulses also significantly contributed to nutrient content in FLW, however the extent varied for each nutrient. Fruits and vegetables accounted for 71 % of vitamin C, 52 % of vitamin A and 34 % of vitamin E in FLW. Oilseeds and pulses contributed 40 % to vitamin E in FLW. Roots and tubers accounted for a relatively low proportion of nutrient content in FLW, <20 % for each nutrient. Animal-sourced foods (dairy, meat, fish and seafood, eggs) contributions were similarly minor, except for vitamin B12. Meat accounted for the highest proportion of vitamin

B12 (58 %) content in FLW, followed by dairy (18 %) and fish and seafood (15 %). Calcium in FLW was largely from fruits and vegetables (28 %), cereals (25 %), and dairy (23 %).

4.3. Potential for increasing nutrient supply through addressing FLW

With the development of an indicator, an in-depth analysis was undertaken of the food items that would have the greatest impact on global availability of all nutrients if their FLW were resolved. Fig. 6 illustrates that, in case of total FLW, ‘rice and products’, ‘wheat and products’, ‘other vegetables’, ‘maize and products’, and ‘whole milk’ provided the greatest opportunity for increasing nutrient supply, with rice and wheat substantially outweighing other food items. For food losses separately, the top five items were similar. Considering food waste, animal-sourced foods (such as ‘pigmeat’, ‘poultry meat’ and ‘eggs’) ranked higher compared to their ranking for total FLW and losses. Overall, cereals, fruits and vegetables emerged as the food groups with the greatest potential to improve nutrient supply, followed by oilseeds and pulses.

When comparing the ranking based on the indicator (Fig. 6) with the ranking based on total mass of FLW (Fig. 3), similar products emerged at the top. However, notable differences were observed, such as the high contribution of ‘sugar cane’ in terms of FLW mass, but a low score for the indicator. Conversely, there was a low contribution of ‘milk’ and ‘soyabeans’ in terms of FLW mass, while these food items had high scores for the indicator. These results reflect the nutrient density of these foods: ‘sugar cane’ is a poor contributor to nutrient supply despite its high FLW mass, whereas nutrient dense foods appear higher on the ranked indicator list than would be justified from mass alone.

Observing the different scales of scores for FLW in Fig. 6, food losses and food waste, it is evident that resolving food waste rather than food losses has the greater potential to increase nutrient availability.

5. Discussion

This study aimed to evaluate FLW along global FSCs by quantifying its magnitude and composition, and by identifying which food items contribute most to nutrient content embedded in FLW.

The DELTA Model® estimated that in 2020, 181 kg per capita of food were lost or wasted, aligning with FAO's estimate of 120–300 kg/capita/year (FAO, 2011) and the estimate of 21–565 kg/capita/year of Gatto and Chepeliev (2024). When examining food waste alone, the DELTA



Fig. 3. Top 25 food items that contributed most to total food losses and waste (FLW) (A), food losses (B) and food waste (C). Values presented as a percentage of total FLW (A), total losses (B) or total waste (C), and colour coded by food group.

Model® estimated 98 kg/capita/year, slightly exceeding the estimates of other global studies on consumption level (18–91 kg/capita/year) (Chen et al., 2020; Dou and Toth, 2021; United Nations Environment Programme, 2021) and falling within the range of 60–165 kg/capita/year estimated by national-level studies (Conrad et al., 2018; Cooper

et al., 2018; Khalid et al., 2019). As described before, differences can be explained by use of different methodologies and definitions of food waste, making it difficult to compare results. As such, it is of importance to note that some of these studies included inedible parts in the estimations of FLW (Carroll et al., 2020; United Nations Environment

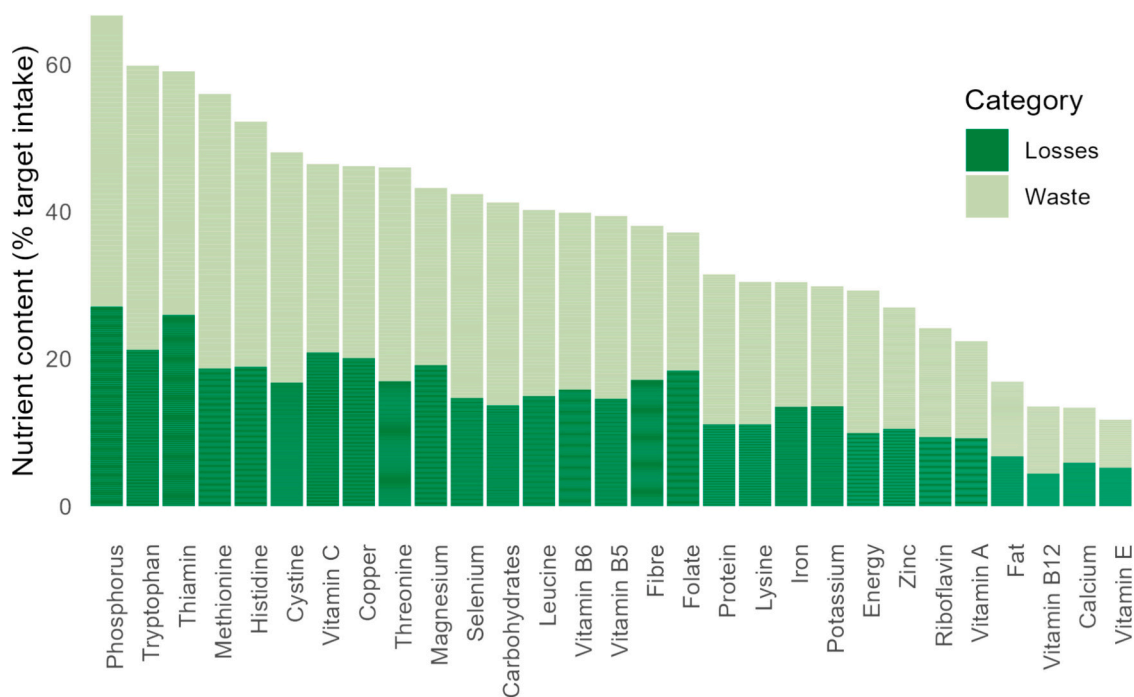


Fig. 4. Contribution of food losses and waste to wastage of each nutrient considered by the DELTA Model® for the 2020 baseline scenario. The bars show nutrient waste as a percentage of the demographically weighted global target intake.

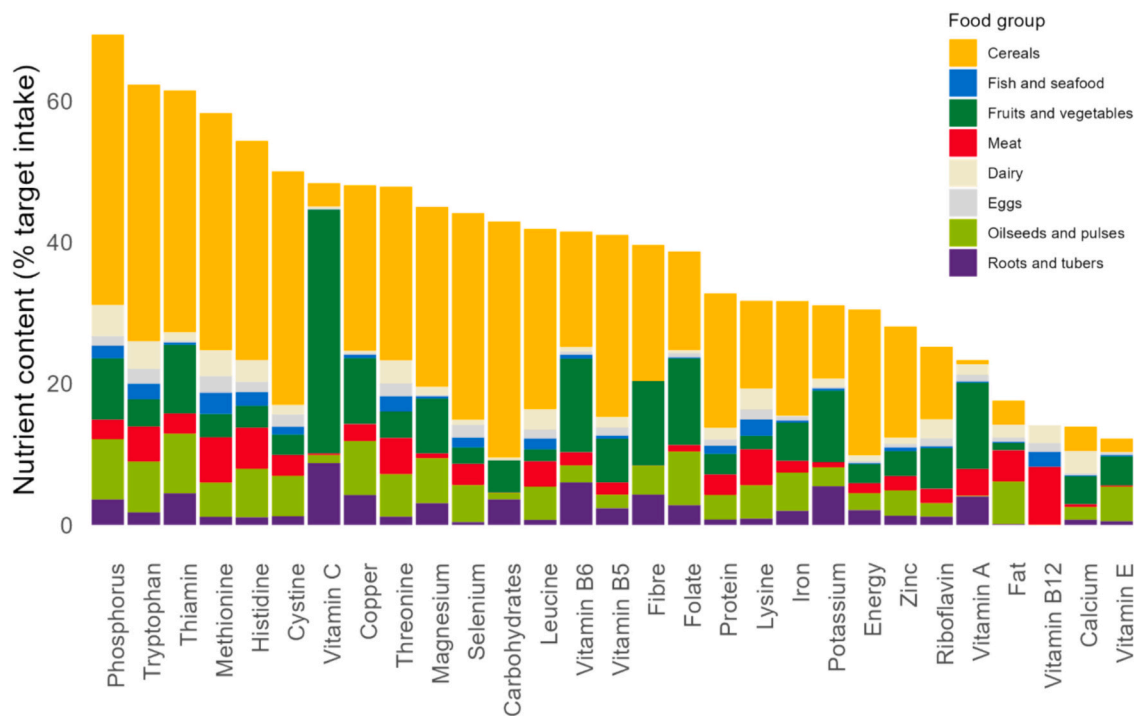


Fig. 5. Contribution of food groups to nutrients lost through FLW considered by the DELTA Model® for the 2020 baseline scenario. The bars show nutrient content in FLW as a percentage of the target intake, colour coded by food group source.

Programme, 2021), whereas the DELTA Model® only considered the edible parts in the calculations. From a nutritional perspective, the edible parts are the relevant value.

Considering the food groups that contributed most to FLW, our results align with other studies both considering all FSC stages as well as only consumption stages, although proportions vary (Table 3). The contribution of animal-sourced foods to FLW was consistently low (<10

%) in all studies, similar to our results. Not surprisingly, the distribution of FLW reflected the distribution of food production: cereals, fruits and vegetables are produced and consumed in higher quantities than animal-sourced foods, and therefore lost and wasted at a higher rate. Plant-based foods generally have higher perishability than animal-sourced foods and generally lower costs, further explaining the high contribution of fruits and vegetables and low animal-sourced foods in FLW

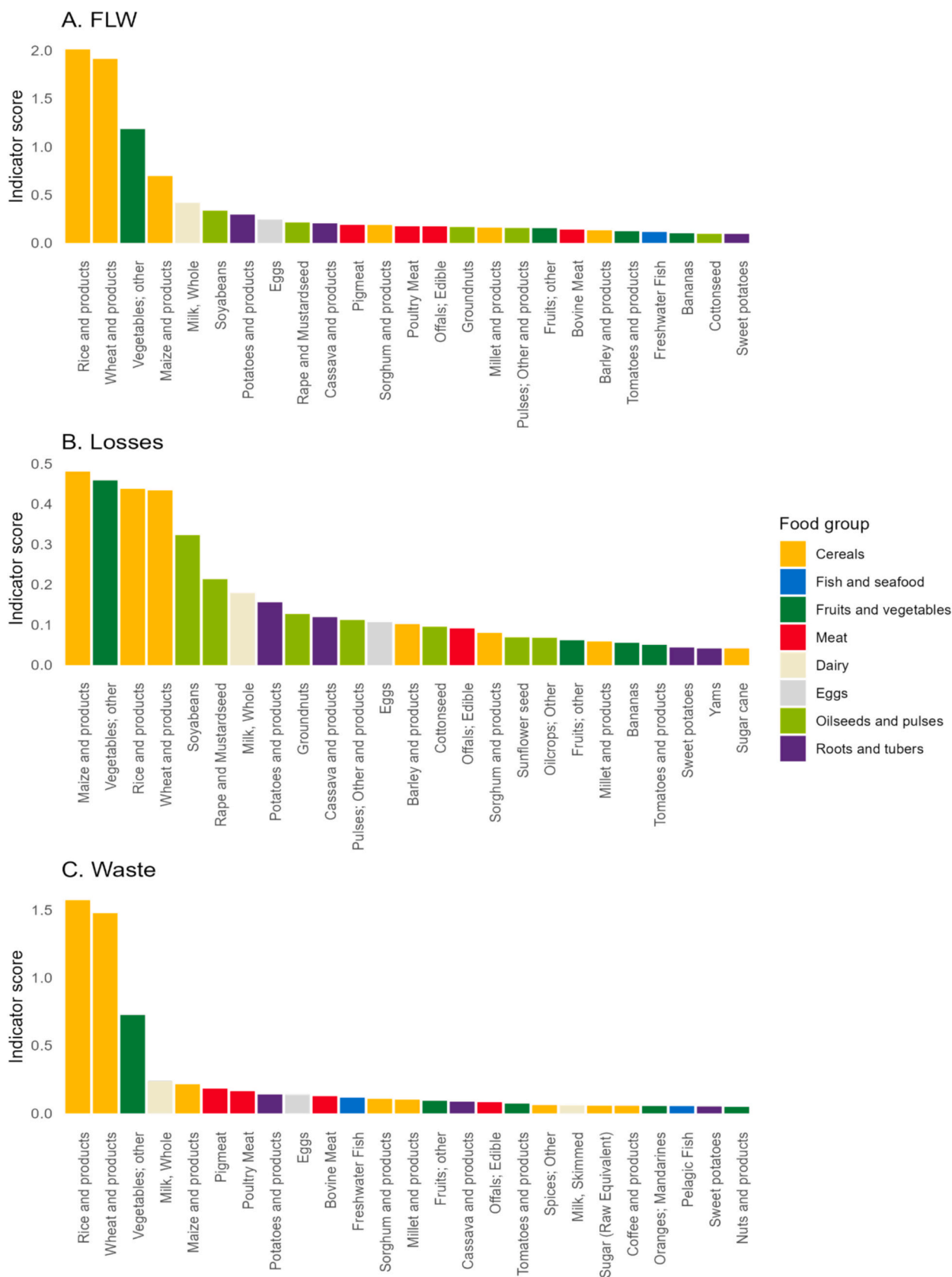


Fig. 6. Top 25 indicator scores for food items that contributed most to nutrient content embedded in total food losses and waste (FLW) (A), food losses (B) and food waste (C), colour coded by food group. Note that the scale of the y-axis is different for the three graphs.

(Spiker et al., 2017; Carroll et al., 2020; Wang et al., 2023).

Adding greater resolution to the literature, we looked at the food items contributing most to FLW. The food items that were lost or wasted the most were also among the food items with the highest production. ‘Sugar cane’ and ‘oil palm fruit’ ranked high for food losses, likely because these products have some of the highest production totals of all foods. The food item ‘other vegetables’ is a large collection of all vegetables other than onions and tomatoes, therefore contributing to a higher ranking on the list. Additionally, the cereals food group includes a high number of food items produced in large quantities, contributing to higher total production and FLW volume compared to food groups lower production, such as roots and tubers.

With the development of the indicator, we aimed to combine information to identify food items, rather than food groups, that could have the greatest potential to improve nutrient availability if their FLW would be resolved. Unlike previous studies that focused on individual nutrients, our indicator considered all nutrients collectively, providing a holistic approach. The ranking is a combination of the nutritional value and mass distribution of FLW of the food items.

While food waste and food losses contribute roughly equally to nutrient content embedded in FLW based on mass, a clear discrepancy was indicated by the indicator: food waste indicator scores were three times higher for ‘rice and products’ and ‘wheat and products’ than scores for food losses. A similar trend, although to a lesser degree, was observed for ‘other vegetables’. This can be attributed to the generally higher mass of food waste compared to food losses. The ratio of food waste to food loss in terms of mass was identical to the ratio of the indicator scores for food losses and food waste, showing the significance of mass distribution on the ranking of the indicator score. These findings underscore the higher potential of resolving food waste instead of food losses in increasing nutrient availability, if effectively addressed.

However, comparison of the mass-based ranking with the indicator score showed differences, reflecting the nutrient density of foods. ‘Sugar cane’, despite its high FLW mass, was a poor contributor to nutrient supply, whereas nutrient-dense foods, such as ‘whole milk’, appeared higher on the ranked indicator list than would be justified from mass alone. We see here that food items with a relatively higher nutrient density receive a higher score, confirming that not only mass distribution but also the nutritional value is integrated in the indicator score.

All nutrients were weighted equally in our calculations, but adjustments could be made if certain nutrients were considered as more important, such as those currently in global deficit. However, eight of the 29 nutrients included in the indicator are protein and amino acids, thus the score will favour protein-rich foods. This is reflected in the higher rankings of protein-dense foods in the indicator scores compared to mass-based rankings.

The food items with the highest indicator score contributed a substantial proportion of the FLW content for undersupplied nutrients (calcium and vitamin E). Resolving FLW for these food items could indeed potentially improve the global availability of these nutrients. However, the overall impact will be limited as the content of these nutrients in total FLW is relatively low compared to other nutrients.

Reducing FLW for nutrients with high content in FLW could have benefits for population nutrition, however, these nutrients are often also abundant in supply, limiting the positive impact on deficiency rates (Smith et al., 2021). For example, cereals had a high contribution to nutrients in FLW, but the most abundant nutrients in cereal FLW are not the globally undersupplied nutrients. Undersupplied nutrients would be better resolved by increasing availability of food, rather than reducing FLW, but there is still plentiful justification for reducing FLW both for global nutrient supply and the environmental and economic benefits.

This study had some limitations related to the input data. The primary data source, the FAO FBS, is the most extensive global database on food and nutrition data. However, concerns have been raised about the data quality (Hoehn et al., 2023). Furthermore, the FBS do not provide the level of detail that is desired for this study, e.g., the food item ‘other

vegetables’ contains all vegetables except onions and tomatoes. This makes it impossible to see which vegetables are the major contributors, because they are all grouped together under one name. Other data sources with a higher resolution, such as the GENUS database, could be explored (Smith et al., 2016). The GENUS database used the FBS to increase food supply estimates from 99 to 225 food items on a country-level, combined with regional food composition data. However, the FBS remains the most extensive and widely used database for food and nutrition data, making it the best available source for analysing FLW. Moreover, the data used in the DELTA Model® is a linear interpolation from the most recent 20 years from the FBS, which will reduce some of the previously mentioned uncertainties.

Additionally, the waste percentages used in our analysis were derived from the FAO, 2011 report (FAO, 2011), which are limited to seven broad food groups, and not on a food item level, showing a mismatch in data granularity within our study. The differences in waste percentage among individual food items within a food group can be substantial. However, this is the most up-to-date publicly available dataset that aligns with the level of detail to make the calculations in this study. To improve the waste estimates, global estimates of edible food waste, by commodity, and as a proportion of food production are needed.

In addition to addressing quantification methods and the need for an increase in primary data, future studies should consider on-farm losses in FLW research. The omission of on-farm losses has large consequences on the estimation of nutrient content in FLW. WWF-UK reported in 2021 that up to 1.2 billion tonnes of food, equivalent to 15 % of total production, is lost on farms (WWF-UK, 2021). Particularly striking are the substantial losses in fruits and vegetables, accounting for a mass comparable to the total FLW calculated in the rest of the FSC and contributing 38 % to total on-farm losses. Roots, tubers and oilcrops follow with a contribution of 22 % to all on-farm losses. These losses have large implications for nutrient losses, especially concerning the undersupplied nutrients calcium and vitamin E. Future studies should include on-farm losses in FLW estimations to get a better overview of the total nutrient waste in the entire FSC.

Furthermore, in our and other studies, food that was directed for human consumption but redirected to non-food use is considered FLW, as there was no data estimating the destination of FLW once classified as lost or wasted. However, redirection of FLW to non-food purposes (e.g., animal feed, compost, bioenergy) has the potential to reduce the use of other resources (e.g., agricultural land, fertilizers) (Chaboud and Daviron, 2017). Further research is needed to investigate the effects of redirecting FLW to non-food purposes and its implications for global nutrition.

Reducing FLW is generally assumed to increase in food availability, which then automatically improves food security and nutrition and lower environmental impact by reducing the need for additional food production (FAO, 2019). However, the impact of reducing FLW is complex, depending on the stage of the FSC where reductions take place, geographical location of reductions and food-insecure or nutritionally vulnerable populations. Furthermore, a certain level of FLW serves as buffer in the food system, ensuring stable food supply and food safety (FAO, 2019).

Reducing FLW in any FSC stage can increase food supply in subsequent stages, thereby enhancing food availability and potentially reducing prices, which could improve food access (FAO, 2019; De Gorter et al., 2021). However, this does not address the current inequitable distribution and access to food: less FLW in HICs does not mean that that food is available for food insecure countries, or even food insecure populations within HICs. Lower prices might also result in higher food waste, as it would be cheaper to waste food. This so-called ‘rebound effect’ has been found to offset half to two-thirds of reduced FLW in some studies (Hegwood et al., 2023). Nevertheless, overall FLW waste in the FSC declines even with this effect (De Gorter et al., 2021).

Addressing FLW at different stages can have distinct impacts.

Reducing losses on farms and in early FSC stages tends to have the most significant impact on food security and nutrition availability, especially in countries with high levels of food insecurity (FAO, 2019). Interventions in later FSC stages can benefit those stages but may negatively affect stakeholders in earlier stages by reducing demand (FAO, 2019).

Despite variations within the system, a global reduction of FLW is expected to enhance nutrition by increasing the availability of nutritious food. Interventions are crucial in tackling FLW across various stages of the FSC and should be country- and commodity specific (de Gorter et al., 2021). The impacts of FLW reductions depend on supply and demand, international trade and the initial rates of FLW at each FSC stage, which can influence intervention outcomes (de Gorter et al., 2021). Interventions should address specific causes of FLW in each supply chain, such as insufficient infrastructure, lack of refrigerated transport and storage, inappropriate packaging, high market standards and household food management (Spang et al., 2019). Each cause or driver of FLW calls for a different solution. The results from our indicator, together with data from literature, suggests that fruits, vegetables and cereals are key targets. As mentioned above, effects of interventions can have multiple effects that cascade through the FSC. Therefore, multiple interventions should be developed simultaneously. Examples of effective strategies are plate size reductions, and information campaigns at the consumer stage (Reynolds et al., 2019), and technological solutions like better storage and cooling facilities, improving infrastructure, and packaging techniques at the farm and processing stages (Nicastro and Carillo, 2021). However, it is important that these strategies be implemented by coordinated policy actions across FSC stages to increase cooperation and awareness of actors, ranging from recommendations or guidelines to potentially restrictive regulations and laws (Nicastro and Carillo, 2021).

6. Conclusions

This study has provided an overview of the challenges around inconsistent definitions, methodologies, and reporting strategies for the understanding of FLW. This has particularly strong bearing on the quantification of nutrient losses and waste. Policies targeting reductions in food waste must be informed by a strong data foundation, and efforts to standardise FLW reporting are to be encouraged, especially the reporting of data at high resolution to allow utility for diverse future research.

The results also provided insights on the magnitude of FLW along the FSC. A more detailed quantification along the FSC, including on-farm losses and stepping down to a country level would enhance our understanding of where and to what extent FLW occur, and what strategies would fit best in a national context. This would be particularly impactful, given that FLW policy is usually set at a national level. Increasing primary data on FLW is needed across world regions and income categories, following a standardized protocol. Understanding of where most nutrients are lost and determining contributing factors can help to identify hotspots where interventions should be prioritized and what the driving factors are at different stages and geographical locations.

This study prioritized FLW reduction from a nutritional perspective. The development of an indicator, integrating content of 29 nutrients into one metric, allowed us to pinpoint individual food items with the highest potential for improving global nutrient availability if their FLW were resolved. Phosphorus, thiamine, and several amino acids were the most wasted nutrients, and cereals and vegetables ranked highest as targets for improving nutrient supply via FLW reduction using the metric. This information should be used to guide FLW and nutrition policy, with the metric able to be leveraged to identify foods best suited to the nutritional needs of specific populations.

Our findings highlight the importance of broadening FLW research beyond quantity to incorporate nutritional aspects as important indicators. Our integrated approach offers a nuanced understanding of the

potential for nutrient supply improvement by resolving FLW to improve global nutrition. In a world where malnutrition and diet-related health issues are widespread, research and action on FLW can contribute to meeting nutritional requirements as part of a sustainable food system and help ensure that the available food resources are used to meet the nutritional needs of the global population.

CRedit authorship contribution statement

Manouk Beuving: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Warren C. McNabb:** Writing – review & editing, Supervision. **Nick W. Smith:** Writing – review & editing, Supervision, Methodology, Formal analysis.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used an AI tool to improve language and readability. After using these services, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could potentially influence the work and findings in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.spc.2024.10.005>.

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