# Global food loss and waste estimates show increasing nutritional and environmental pressures

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# Global food loss and waste estimates show increasing nutritional and environmental pressures

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Accurate global food losses and waste (FLW) quantification remains challenging owing to limited harmonized global estimates, a lack of comprehensive quantification approaches and an absence of frameworks for addressing FLW challenges. Here we compile a country-level database that assesses FLW across global value chains and quantifies the nutritional and environmental impact of FLW for 121 countries and 20 composite regions. Between 2004 and 2014, FLW increased by a quarter, especially in sub-Saharan Africa and Southeast Asia, where increasing nutritional losses of ~550 cal per capita per day impact food security. Growing food imports in high-income countries and fast-growing economies worsened FLW and related environmental footprints in exporting low-income regions. Reducing overconsumption and FLW in high-income countries may have positive effects in middle- and low-income countries, where food exports largely drive farm-level losses. Policies should focus on promoting the profitable reuse of unavoidable FLW while enhancing agricultural production efficiency to improve water use and nutritional security.

Reducing global food losses and waste (FLW) lies at the core of the transition to a more secure and sustainable food system[1]. FLW generated along global food supply chains (FSCs) contribute to climate change[2] and natural resource depletion[3], threatening economic stability[4] and endangering humanity's path toward global food security[5]. Tackling global FLW in line with United Nations' Sustainable Development Goal (UN-SDG) 12.3 requires quantifying the magnitude, composition and geographical location of lost and discarded foods, outlining where policy interventions may provide the highest socio-economic and environmental benefits. Today, three major barriers hinder the development of consistent policies for tackling FLW.

The first barrier is the lack of harmonized global FLW estimates[6]. The Food and Agriculture Organization (FAO) FLW database, created over a decade ago[7], continues to be a key data source despite criticisms of internal inconsistency[8,9]. Recent attempts to improve global FLW quantification have had limited success, with databases from FAO[10] and Organization for Economic Co-operation and Development (OECD)[11] providing limited regional or commodity coverage. Other global databases[9,12–14] use different definitions and supply chain coverage approaches, rendering estimates largely incomparable[15].

The second barrier is the absence of comprehensive approaches to quantifying FLW. Technical studies[7,13,16,17] often rely on detailed physical mass flows but overlook socio-economic drivers[18], while economic studies[19,20] focus on monetary analyses, neglecting key physical flow information. The globalization of the food system further complicates FLW quantification, as a consistent representation of international trade is currently lacking but remains crucial for understanding food flows from farm to fork. Analysing global food trade can help identify the geographical location of lost or wasted foods and address food security challenges by matching surplus and deficits between regions, reducing FLW.

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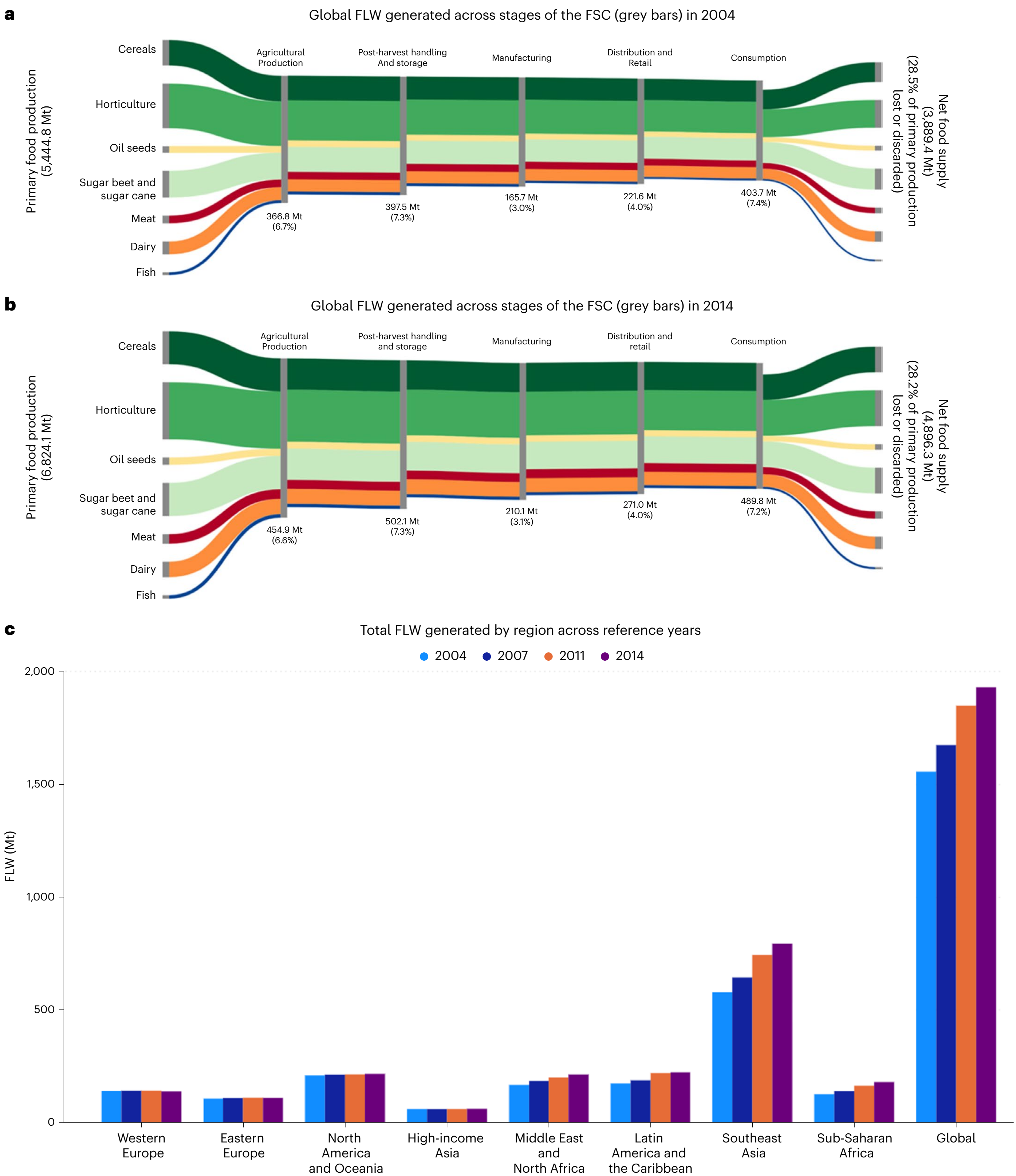


**Fig. 1 | Flows of FLW by primary food product generated along different stages of global FSC (by reference year).** Estimates report million tonnes of generated FLW from primary production to final consumption. **a**, Global FLW generation by FSC stage in 2004. **b**, Global FLW generation by FSC stage in 2014. **c**, Total FLW generated by region and globally across analysed reference years. Additional FLW trends are reported in Supplementary Figs. 2–4.

The third barrier involves the lack of a multidisciplinary framework able to comprehensively address the FLW challenges. While some studies link FLW estimates with nutritional losses[21–23], information on how FLW affects food and nutritional intakes along the FSC is often missing. In addition, single-country assessments of the environmental footprints embedded in FLW are currently missing but remain urgently

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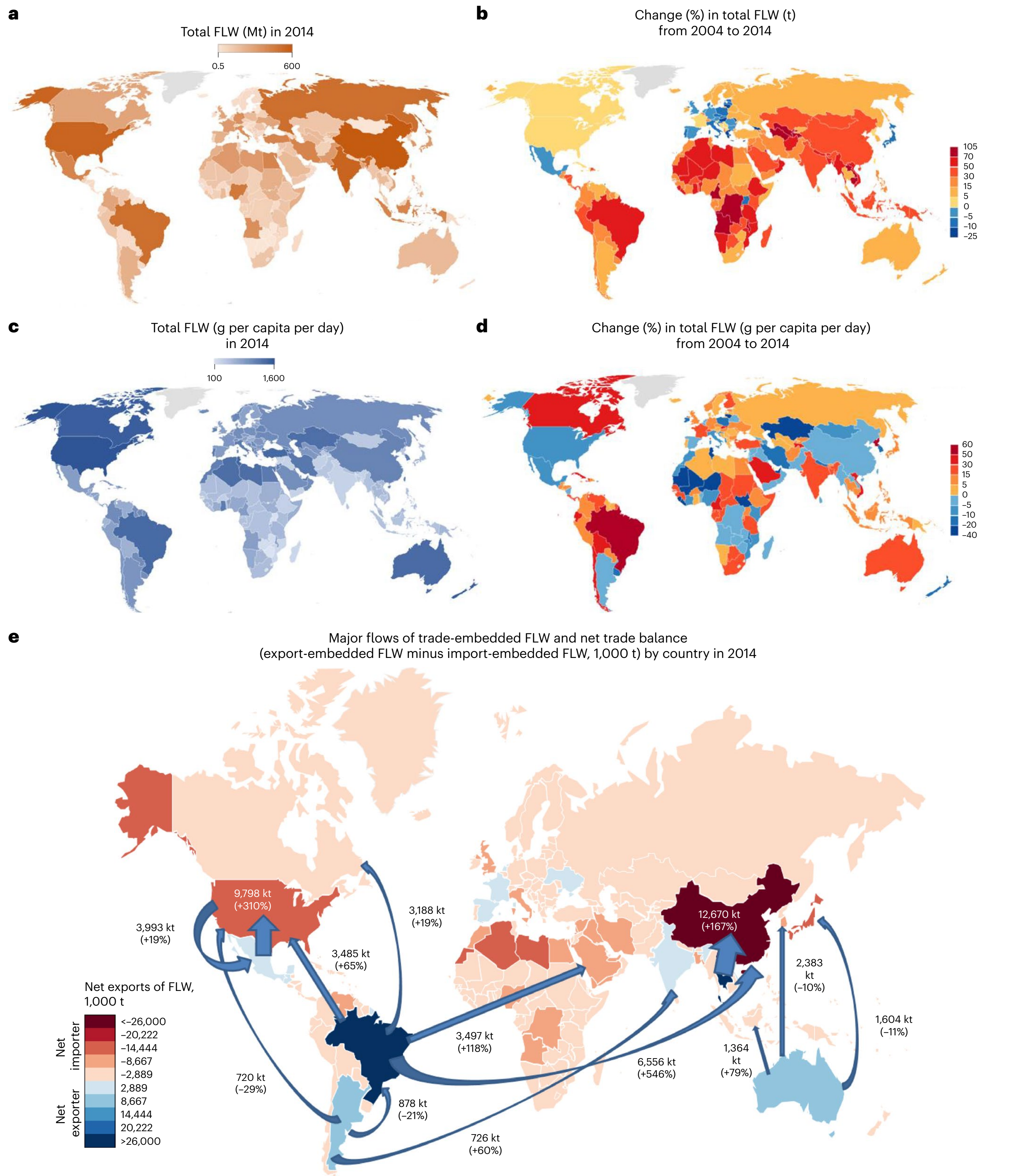


**Fig. 2 | Total FLW generation, per capita FLW generation and trade-embedded FLW by country.** Estimates reported in the figure refer to FLW generation and are specified in different metrics according to the panel. **a**, Total FLW generation (million tonnes) by country in 2014. **b**, Changes (%) in total FLW generation by country in the time period between 2004 and 2014. **c**, FLW generation (grams per capita per day) by country in 2014. **d**, Changes (%) in grams per capita per day FLW generation between 2004 and 2014 by country. **e**, Major global flows of trade-embedded FLW across global regions (1,000 t and change (%) with respect to 2004), also indicating FLW-related trade balances (exports of FLW minus imports of FLW) across regions. The arrows illustrate the direction of the net FLW flows linked to the food trade in 2014. An arrow from country A to country B indicates that country A is a net exporter of food, hence FLW, to country B. For illustrative purposes, the size of the arrows does not necessarily reflect the magnitude of FLW flows. For this, please note that magnitudes (1,000 t) and percentage changes (between 2004 and 2014) are reported next to each arrow. Basemaps from www.datawrapper.de.

needed to contextualize FLW within the multidisciplinary framework of the SDGs.

In this Article, we address these challenges by developing a global database to provide insights into the magnitude, composition, location and environmental footprints of the FLW. First, we collect the best available estimates on shares of lost and discarded foods across commodity groups, food supply stages and geographical regions, defining FLW as 'food (including inedible parts) lost or discarded along the food supply chain, comprising pre-harvest losses and excluding food diverted to animal feed, seed or to other non-food material uses such as bio-based products', in line with the UN[1]. Second, building on recent developments that incorporate physical and nutritional flows in a global economic framework[24], we trace food and nutritional supply across FSC stages within a global multiregion input–output framework. Finally, using the constructed database, we explore country-level FLW developments across a 10 year period (2004–2014), quantifying the magnitude, composition, geographical location and nutritional contents of FLW while considering the role of international trade. In addition, we integrate data on land use, water use and greenhouse gas (GHG) emissions to quantify the environmental footprints embedded in FLW generation along the global FSC.

Our analysis aims to bridge knowledge gaps on global FLW, providing a link to nutritional security and environmental impacts within the multidisciplinary framework of the SDGs. This information can assist in shaping future policies toward FLW reduction and circularity.

## Results

### Quantifying FLW along FSCs

In 2014, global FLW amounted to 1.92 Gt, reflecting a 24.0% increase since 2004. The most substantial relative rise occurred in the manufacturing stage (+26.8%; Fig. 1a,b), driven by increased consumption of processed foods. Despite this, agricultural production and post-harvest handling and storage remained the primary global hotspots, generating 956 Mt of FLW, constituting 49.6% of the global share. Notably, plant-based FLW, particularly in horticulture and sugar beet and sugar cane, saw the largest increase, emphasizing opportunities for circular practices in the food system. The regions with the highest absolute FLW were North America (mainly the United States), China and India, collectively contributing 42.6% of global FLW.

Per capita estimates revealed a nuanced picture, highlighting the influence of income and consumption patterns. While North America exhibited both high absolute and per capita FLW losses (United States, 1,549 g per capita per day, and Canada, 1,442 g per capita per day), this is not the case for China and India. Even though both China's and India's population is almost four times larger than that of the United States and Canada combined[25], a lower per capita gross domestic product (GDP; income) and gross per capita food supply in these two middle-income countries result in a substantially lower FLW generation per person (Fig. 3a,b). The highest per capita FLW occurred in high-income countries such as Australia, New Zealand, Singapore and Hong Kong (average 1,340 g per capita per day) where GDP and gross food supply surpassed global averages.

Divergent FLW patterns were observed between low- and high-income countries. In low-income countries, losses predominantly occurred in the early supply chain stages, while high-income countries generated more FLW in the final stages. This distribution resulted from varying marginal benefits of food across income levels and limited technological solutions in developing countries. Agricultural production and post-harvest handling and storage losses were substantial in Latin America and the Caribbean, Southeast Asia and sub-Saharan Africa, while consumption-stage waste occurred primarily in North America and Oceania, Europe and high-income Asia.

Over the analysed time frame, Southeast Asia and sub-Saharan Africa experienced notable FLW increases of 37.2% and 43.2%, respectively, particularly during the 2007–2011 period (an average global increase of +10.4%; Fig. 1c). The largest relative increases were seen in South–Central Africa (average +104.7%), Central Asia (average +86.5%) and Southeast Asia (mainly Lao People's Democratic Republic, +90.5%) (Figs. 2b and 3c). Factors such as increased per capita GDP, population growth and changing food intensity influenced FLW dynamics. The sharp decrease in 'food intensity', measured by changes in gross food consumption per unit of GDP, in Southeast Asia, China and India, played a key role in limiting the increase in FLW across years in these countries. A lower 'food intensity' has led to a decrease in FLW in Europe (an average of −1.5%) and in high-income Asian countries such as Japan and South Korea (an average of −7.3%).

To understand the drivers behind changes in FLW over time, the study used the logarithmic mean Divisia index I additive decomposition method[26] (see Section 3 of Supplementary Information). Consistent with the Kaya[27] decomposition results (Fig. 3c), we find that the activity level (increasing food demand) is the key driver of rising FLW, explaining 96% of the overall increase over the analysed time period at the global level (Supplementary Information). Countries achieving substantial FLW reductions, such as Japan, Italy and Greece, experienced the most remarkable declines from the activity channel. Conversely, in Mexico and Germany, changing composition of food consumption (structure channel) contributed to FLW reductions, while in Spain and the United Kingdom, reduced food intensity of FLW was the key driver.

Approximately 15.7% of global FLW in 2014 was associated with traded food. Export-embedded FLW (Fig. 2e) was prominent in Brazil (54.8 Mt, 53.0% of total FLW), the United States (20.9 Mt, 11.1% of total FLW) and Mexico (12.1 Mt, 31.5% of total FLW), driven by large volumes of exports of horticulture and cereals. Import-embedded FLW was notable in China (35.2 Mt, 6.6% of total FLW), Japan (12.1 Mt, 49.2% of total FLW), North Africa (Libya, Algeria, Morocco and West Sahara, 10.0 Mt, 46.6% of total FLW) and the United States (29.8 Mt, 16.1% of total FLW). Major flows of imported FLW in China derive from Thailand (12.6 Mt) and Brazil (6.5 Mt), while high-income Asian countries such as Japan and South Korea largely import FLW from Australia (total 3.9 Mt). Food imports by Canada and the United States directly drive FLW generation in Argentina and particularly in Brazil, where export-embedded FLW towards North America increased by an

**Fig. 3 | Relation between FLW, gross food supply and GDP by country in 2014 and changes in FLW based on KAYA identity from 2004 to 2014.** **a**, Relation between FLW generation (grams per capita per day) and gross food supply (grams per capita per day) by country in 2014. **b**, Relation between FLW generation (grams per capita per day) and per capita GDP by country in 2014. In **a**, estimates of gross food supply match the estimates reported in the FAO FBS. In **b**, per capita GDP estimates are derived from Aguiar et al.[40]. From **a** and **b**, it is possible to observe that higher availability of food (gross food supply) and an averagely higher income per capita (GDP per capita) are direct drivers of FLW generation in 2014. In **b**, the relatively lower $R^2$ value is influenced by small high-income countries (Luxembourg, Switzerland, Qatar, Norway) in which FLW generation appears to be lower owing to differences in the composition of food consumption and varying FLW shares across commodities. For **a** and **b**, see Supplementary Table 12 for a full list of country abbreviations. **c**, KAYA identity[27] illustrating percentage changes in FLW from 2004 to 2014 by region based on changes in the main drivers of FLW generation. The choice of variables in the KAYA identity is based on a direct comparison with the variables often used in the literature to perform KAYA decompositions of changes in energy-related emissions[46–48]. While 'changes in population' and 'changes in per capita GDP' are kept the same, variables such as 'carbon intensity' and 'energy intensity' have been readapted to our specific study case in the form of 'FLW intensity', that is, FLW generated per unit of food consumed, and 'food intensity', that is, changes in gross food consumption per unit of GDP.

average of 38.7% (or 1.8 Mt) since 2004. Additional details regarding magnitudes of trade-embedded FLW flows by country are reported in Supplementary Table 17.

Changing patterns of bilateral trade over the analysed period have been driving changes in trade-related FLW across countries. In China, a sharp increase in food imports since 2004 (154.1%) has contributed

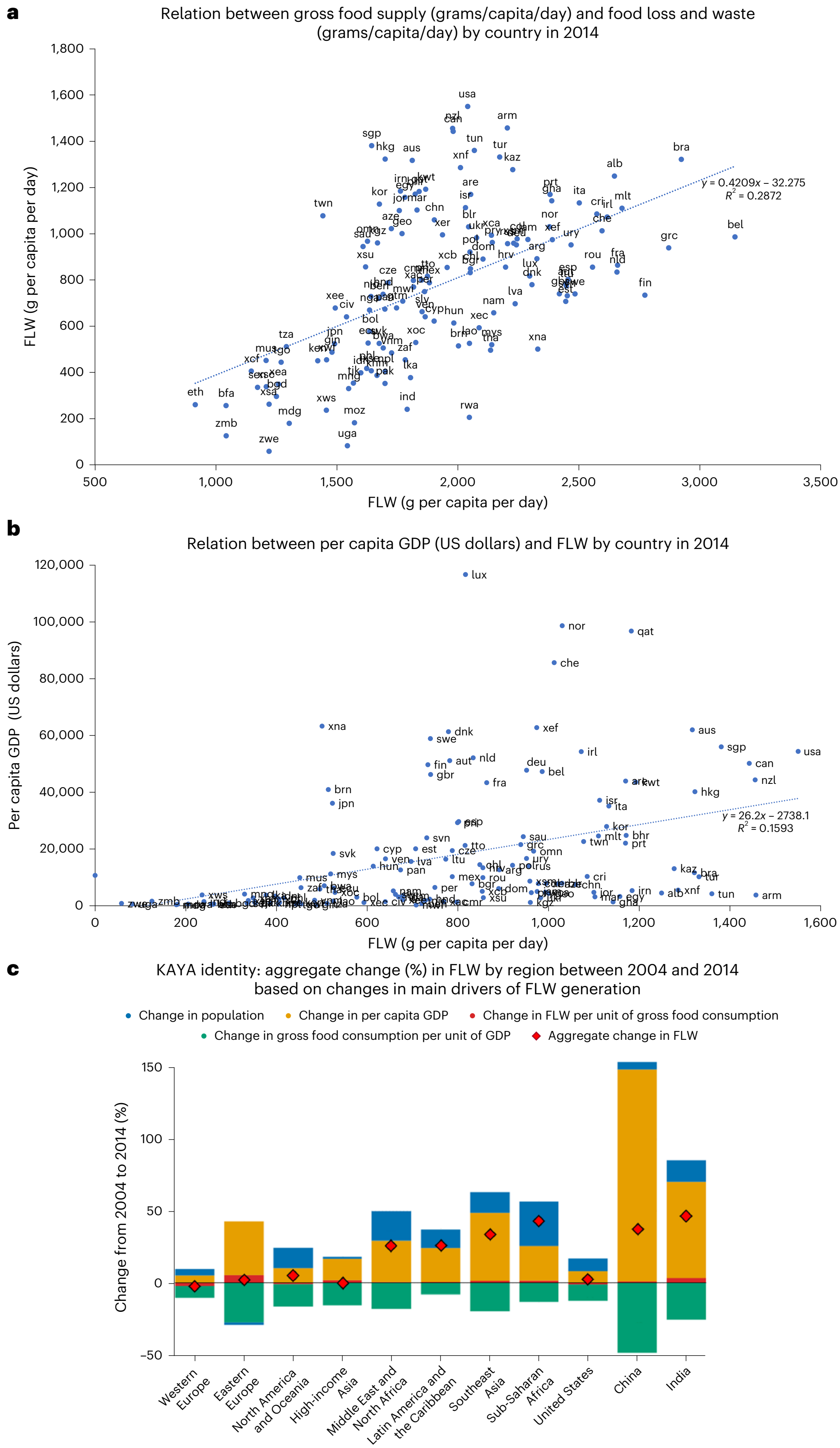

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**Table 1 | Nutritional and environmental pressures of global FLW by region in 2014**

| | Gross energy supply[a] (kcal per capita per day) | Loss of calories embedded in FLW (kcal per capita per day) | Total land use (1,000 ha) | Land use embedded in FLW (1,000 ha) | Total water use (billion $m^3$) | Water use embedded in FLW (billion $m^3$) | Total GHG emissions ($MtCO_2eq$) | GHG emissions embedded in FLW ($MtCO_2eq$) |
|---|---|---|---|---|---|---|---|---|
| EU-27 | 3,652 | 1,018 (27.9%) | 208,219 | 38,170 (18.3%) | 139.9 | 27.1 (19.4%) | 4,392 | 189.3 (4.3%) |
| North America and Oceania | 3,815 | 1,457 (38.2%) | 581,889 | 158,352 (27.2%) | 263.1 | 66.7 (25.4%) | 7,451 | 290.8 (3.9%) |
| High-income Asia | 3,029 | 985 (32.5%) | 112,856 | 18,554 (16.4%) | 134.0 | 38.8 (29.0%) | 2,585 | 76.9 (3.0%) |
| Rest of Europe and Central Asia | 3,387 | 1,025 (30.3%) | 504,407 | 99,582 (19.7%) | 192.6 | 37.7 (19.6%) | 3,624 | 168.8 (4.7%) |
| Middle East and North Africa | 3,475 | 1,035 (29.8%) | 564,967 | 108,630 (19.2%) | 427.3 | 116.9 (27.4%) | 3,478 | 151.3 (4.4%) |
| Latin America and the Caribbean | 3,418 | 954 (27.9%) | 604,908 | 100,665 (16.6%) | 208.6 | 47.4 (22.8%) | 3,283 | 205.1 (6.2%) |
| Southeast Asia[b] | 2,953 | 621 (21.0%) | 1,159,065 | 179,150 (15.5%) | 1,866.7 | 308.1 (16.5%) | 15,681 | 595.8 (3.8%) |
| Sub-Saharan Africa | 2,749 | 591 (21.5%) | 905,088 | 212,557 (23.5%) | 126.0 | 19.8 (15.8%) | 1,941 | 208.3 (10.7%) |
| **Global** | **3,116** | **775 (24.9%)** | **4,641,401** | **915,662 (19.7%)** | **3,358.3** | **662.9 (19.8%)** | **42,438** | **1,886.7 (4.4%)** |

[a]Regional average weighted on country population and matching FAO FBS gross energy supply estimates. [b]Including China and India. $MtCO_2eq$, million tonnes of $CO_2$ equivalent.

to export-embedded FLW in Thailand (+167.4% or 7.9 Mt) and Brazil (+545.9% or 5.5 Mt). Growth in the Brazilian export-embedded FLW was further driven by expanding food demand in the Middle East, particularly by food imports from Saudi Arabia (+117.9% or 1.8 Mt). Similarly, an expansion in the food trade between the United States and Mexico has resulted in higher amounts of export-embedded FLW in Mexico (+310.2% or 7.4 Mt), as well as in the United States (+18.9% or 0.6 Mt). Finally, while food imports by Japan and South Korea have contributed to large export-embedded FLW in Australia, such amounts have been decreasing (an average of 18.1% reduction in the aggregate export-embedded FLW in Australia).

## Nutritional and environmental losses in FLW

The increasing magnitude of global FLW correlates with growing nutritional losses along supply chains. On average, 775 cal per capita per day is lost or wasted globally (Table 1). High-income regions, notably North America, Australia and New Zealand, experience the highest calorie losses (average 1,560 cal per capita per day), driven by elevated consumption of animal-sourced foods (ASF), processed foods and sugars (Fig. 4a). Latin America (mainly Brazil—an average of 1,500 cal per capita per day) and North Africa (an average of 1,600 cal per capita per day) also show substantial calorie losses owing to the production of calorie-rich foods such as oils, oilseeds, and sugar beet and sugar cane. Conversely, sub-Saharan Africa (527 cal per capita per day) and Southeast Asia (571 cal per capita per day) exhibit lower nutritional losses, reflecting food insecurity and higher consumption of calorie-poor foods. Between 2004 and 2014, calorie losses increased in North Africa (14.6%) and South–Central Africa (16.7%) owing to rising food consumption and/or increased food exports. Similar trends occurred in Brazil (23.2%) and Southeast Asia (including China and India, 30.1%), while North America (−2.4%) and Europe (−1.8%) witnessed declines, mainly owing to a substantial decrease from calorie-rich oilseeds within total FLW.

Protein losses follow a similar pattern, with higher consumption of protein-rich ASF in high-income countries resulting in higher concentrations of protein losses along supply chains (Fig. 4c). North America, high-income Oceania and Europe show the most substantial volumes of lost proteins (average of 57.2 g of proteins per capita per day). By contrast, sub-Saharan Africa exhibits lower losses (6.0 grams of proteins per capita per day). Over the analysed time frame, protein losses increased in East and Southeast Asia (16.4%) but declined in North America (−3.2%) and Europe (−2.1%), owing to an increase in shares of protein-poor plant-based FLW within total FLW. Losses of fats (Fig. 4e) mirror the trends observed for calorie losses, concentrated in high-income regions such as North America (an average of 72.3 g of fats per capita per day), high-income Oceania (an average of 61.0 g of fats per capita per day), Europe (an average of 39.4 g of fats per capita per day) and Middle East (an average of 33.1 g of fats per capita per day). Conversely, sub-Saharan Africa shows lower losses of fats (3.4 g of fats per capita per day). Severe increases in per capita fat losses were experienced by Brazil (104.2%) and South–Central Africa (70.6%), driven by growing oilseed production and relatively high sugar intake.

While losses of carbohydrates exhibit similar geographical distribution (Fig. 4g), global trends over time reveal a decrease in most regions (Figs. 4h and 5). This shift, attributed to changing global diets, favouring ASF over cereals, is particularly evident in sub-Saharan Africa, where carbohydrate losses decreased by an average of 22.2% since 2004. Eastern Europe and western Asia, driven by large exports of carbohydrate-rich foods, experienced upward trends (average of 4.2%). In 2014, carbohydrate losses were highest in North America (an average of 261.5 g of carbohydrates per capita per day) and the Middle East (an average of 274.3 g of carbohydrates per capita per day). Low-income regions such as sub-Saharan Africa (an average of 80.5 g of carbohydrates per capita per day) and Southeast Asia (an average of 105.6 g of carbohydrates per capita per day) are associated with the lowest amounts of carbohydrate losses, which is primarily driven by the low levels of per capita food consumption.

In what follows, we briefly summarize the environmental footprints embedded in global FLW. Additional country-specific information, figures and data are available in Supplementary Information (Sections 2 and 3). In 2014, around 19.7% of global agricultural land was used to produce food that was lost or wasted along the FSC (Table 1). Areas of the land use embedded in FLW are large in major agrifood-producing regions such as Latin America and the Caribbean and Southeast Asia. In the case of sub-Saharan Africa, the area of land use embedded in FLW is relatively high owing to the relatively low efficiency of agricultural production practices in the region. Between 2004 and 2014, global land use embedded in FLW increased by 4.4% (Supplementary Fig. 8b) with the largest increases observed in Latin America and the Caribbean (25.2%), Central Asia (12.5%) and Southeast Asia (14.4%).

Around 19.8% of the global water used for food crops is embedded in lost or discarded food along the supply chains (Table 1). Similar to land use, the largest amounts of water use embedded in FLW are observed in large agricultural-producing regions such as Southeast Asia and North America and Oceania. In Europe, a relatively high agricultural production efficiency, as well as different crop mix and geographical conditions, results in low levels of water use per tonne of food produced. Low amounts of FLW and limited water availability in sub-Saharan Africa act as key drivers for reducing water footprints of the FLW in this region. Despite the relatively low water intensity of the FLW in selected countries and regions, between 2004 and 2014, global FLW-embedded water use increased substantially—by 33.6% (Supplementary Fig. 8d). In relative terms, major growth in this environmental indicator was observed in Central and Southern African countries (an average of 77.5%) and in Central–East Asia (an average of 57.5%) further exacerbating the burden of water scarcity in these developing economies.

Finally, GHG emissions embedded into food that is lost or discarded along the FSC in 2014 amount to 1.8 $GtCO_2eq$ accounting for around 4.4% of global GHG emissions (Table 1). The largest amounts of FLW-embedded GHG emissions were generated in Southeast Asia, North America and Oceania, and sub-Saharan Africa. Compared with 2004, GHG emissions embedded in FLW increased by 8.5%. In relative terms, the growth took place primarily in low-income regions such as sub-Saharan Africa, Southeast Asia, and Latin America and the Caribbean (Supplementary Fig. 8f). However, decreasing trends were observed in Europe (average −29.1%), North America and Oceania (−7.9%), and East Asia (excluding China; −25.3%). These patterns are associated with the changing composition of FLW, wherein the share of plant-based foods has increased compared with that of (the more GHG-intensive) animal-based products, leading to a reduction in emissions embedded into discarded or lost food.

## Discussion

Between 2004 and 2014, a larger and richer global population intensified the nutritional and environmental pressures caused by FLW. Approximately one-third to one-fourth (1.92 Gt) of food produced for human consumption was lost or wasted in 2014, surpassing the 1.3 Gt estimated by Gustavsson et al.[7], as we consider the entire food commodities and not just the edible shares of food products. Our findings highlight key hotspots of FLW generation in agricultural production and post-harvest handling and storage in low- and middle-income countries, and at the consumption stage in high-income regions. These findings align with previous studies[6,28–30] and support the need for targeted policy interventions at the farm level in low- and middle-income countries and at the consumer level in high-income countries[7,10,12].

While specific methodological features of the FAO-FLW database[10] hinder direct comparisons with our estimates, cross-check analyses with selected country- and region-level studies provide validation (see Section 3 of Supplementary Information). Our estimates for the European Union-27 (EU-27), Latin America and the Caribbean, and sub-Saharan Africa closely align with the findings of Caldeira et al.[16], FAO[31] and Lipinski et al.[3], respectively. Comparisons with the Organization for Economic Co-operation and Development (OECD) Food Waste database[11] further validate our estimates, closely matching several country-specific figures (for example, for Mexico, Turkey and Japan). With respect to global nutritional losses, we find an average loss of 277 cal per capita per day embedded in food waste, consistent with the findings of Chen et al.[22]. Protein, carbohydrate and fat losses due to food waste align with ranges reported in various studies[32–34], reinforcing the reliability of our estimates.

Examining trends over time, our analysis reveals a concerning increase in FLW, particularly for horticulture, cereals, and sugar beet and sugar cane at the early stages of the FSC. This underscores a growing share of unprocessed plant-based biomass within total FLW, presenting both a challenge and an opportunity for implementing circularity practices within the food system. Plant-based FLW offers a broader range of reuse possibilities compared with animal-based sources[14], creating opportunities for using lost and discarded food as feed for livestock or as fertilizer for crop production[35,36].

The expansion of domestic and international markets has increased the share of food losses associated with traded food, contributing to a leakage effect. While farm-level losses are mainly located in low- and middle-income countries, a substantial portion of these losses is linked to food consumed in high-income regions. This exacerbates social and environmental pressures in low- and middle-income regions and highlights the need for improved infrastructure and technologies to facilitate FLW reuse[12]. However, high-income countries, with better FLW reuse infrastructure, may have fewer opportunities to benefit from this as they increase reliance on food imports from developing countries, effectively 'outsourcing' FLW. Despite the potential for FLW reuse in high-income economies, current food safety laws may limit the usability of substantial amounts of available food waste[37].

Our results also indicate that global losses of macronutrients have increased over time, posing a major challenge to food security. The only exception includes carbohydrates, whose losses have decreased owing to a shift in global dietary patterns away from cereals and starchy vegetables (rich in carbohydrates) and towards ASF. Calorie and protein losses have particularly increased in low-income regions, such as Southeast Asia, North Africa and sub-Saharan Africa, emphasizing the importance of addressing nutritional security in these economies. Agricultural production emerges as the single largest hotspot for losses of calories across regions, suggesting that interventions to improve agricultural production efficiency, especially in low-income countries, can significantly aid food security.

The need for interventions in agricultural production to decrease food losses is also supported by the assessed environmental impact of FLW. We find that nearly 20% of global agricultural land and water used for growing crops dedicated to producing food that is ultimately lost or discarded. The trend of increasing land use for agricultural production embedded in FLW is particularly substantial in low-income regions, such as sub-Saharan Africa. To address this issue, technological improvements and conservation practices at the post-harvest handling & storage stage may increase land productivity, contributing to improved food security and economic prosperity in these regions. Similarly, the increasing water use embedded in FLW, particularly in Central and Southern African countries and Central Asia, calls for policy interventions aimed at reducing the water footprint of FLW.

**Fig. 4 | Nutritional composition of FLW (grams per capita per day) generated along global FSC.** Estimates reported in the figure refer to the amount of macronutrients (capita per day—calories and grams of macronutrients) embedded in lost or discarded food (grams per capita per day). **a**, Total amount of calories (capita per day) embedded in FLW generated by country in 2014. **b**, Change in the total amount of calories (capita per day) embedded in FLW generated by country from 2004 to 2014. **c**,**e**,**g**, Total amount of proteins (grams per capita per day) (**a**), fats (grams per capita per day) (**b**) and carbohydrates (grams per capita per day) (**c**) embedded in FLW generated by country in 2014. **d**,**f**,**h**, Change in the total amount of macronutrients, proteins (**d**), fats (**f**) and carbohydrates (**h**) (grams per capita per day), embedded in the FLW generated by country from 2004 to 2014. The magnitude and composition of lost and discarded food are two key drivers of nutritional losses along the global FSC. On average, as higher-income regions have relatively higher food consumption rates, with large shares of ASF and sugars, losses of nutrients result more severe. However, changing dietary composition and higher food intakes across our analysed time frame result in increasing nutrient losses for lower-income regions, especially in calories, proteins and fats in sub-Saharan Africa. Basemaps from www.datawrapper.de.

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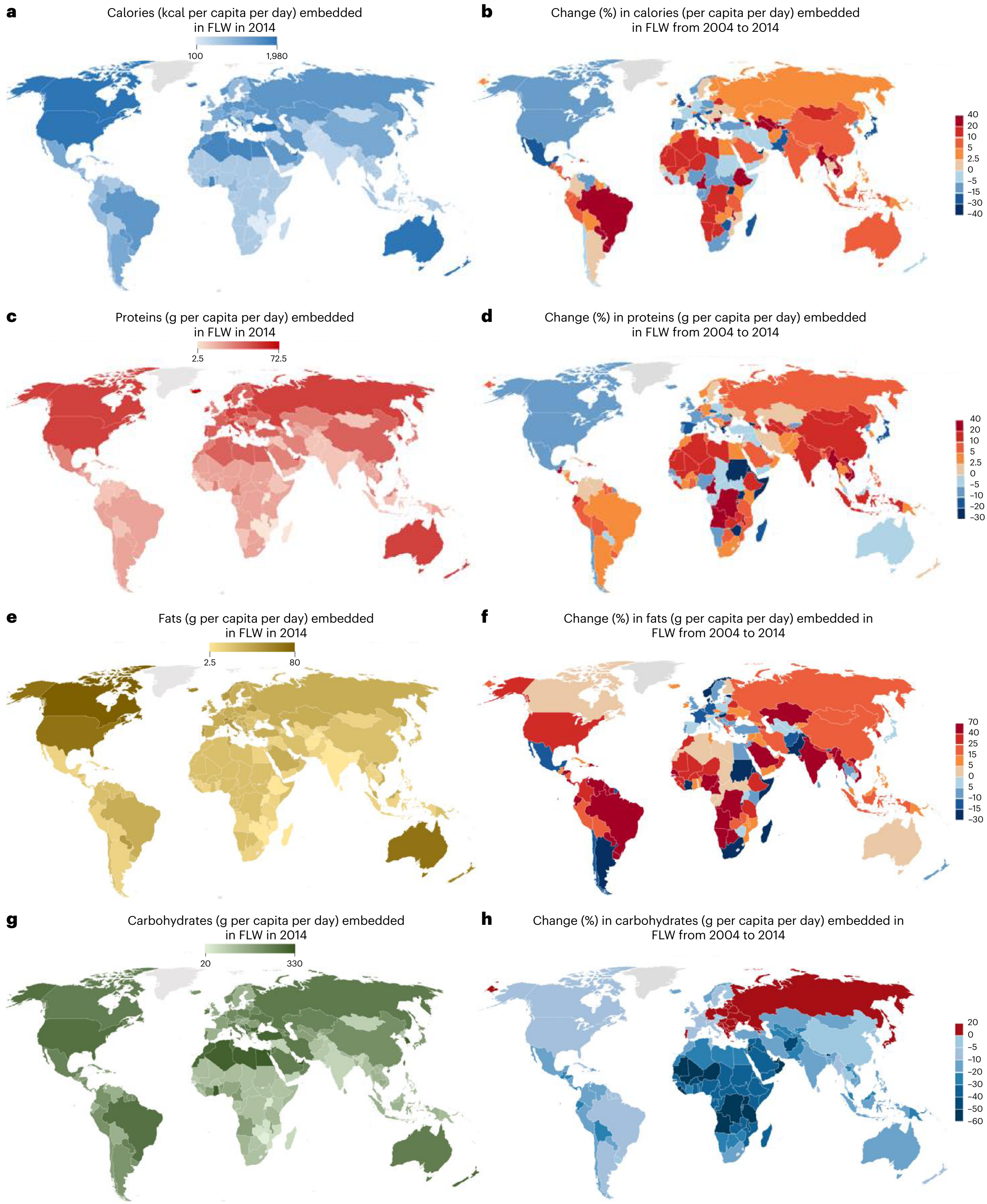
Measures such as improving water use efficiency in agriculture, reducing food waste at the producer level and incentivizing the recovery and reuse of food waste can contribute to mitigating this environmental impact. Sustainable agricultural practices, including agroforestry and conservation agriculture, can serve as efficient adaptation strategies, reducing water demand while promoting resilience to climate change.

Considering future population trends[38], our analysis suggests that FLW generation may have a greater impact on food security,



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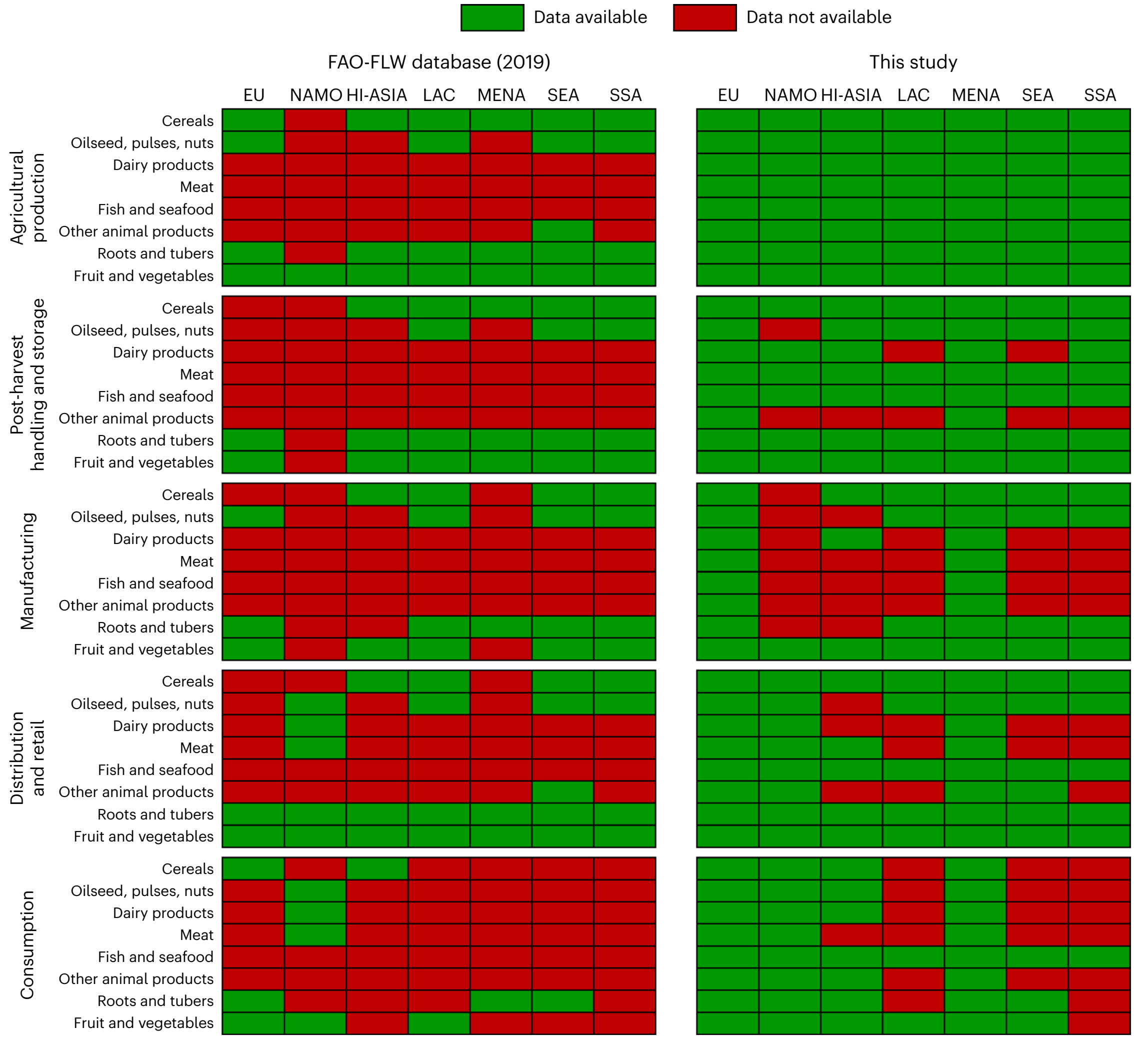


**Fig. 5 | Overview of the global data coverage (shares (%) of FLW) of the constructed database by commodity, region and supply chain stage, and data coverage comparison with the FAO-FLW database (2019).** An illustration of the outcomes of our literature review on estimates reporting shares (%) of FLW along the FSC, comparing the availability of estimates with respect to the FAO-FLW database. EU, Europe; NAMO, North America and Oceania; HI-ASIA, high-income Asia; LAC, Latin America and the Caribbean; MENA, Middle East and North Africa; SEA, Southeast Asia; SSA, sub-Saharan Africa.

particularly in lower-income regions such as sub-Saharan Africa and Southeast Asia. Policies and strategies aimed at reducing FLW need to consider the complex interplay between food production, trade, consumption patterns, and their social and environmental impacts. Sustainable consumption patterns should be encouraged through policies that prioritize targeting the production and consumption of processed foods, especially those from animal sources, which are main contributors to nutritional losses and environmental footprints embedded in FLW. To achieve SDG 12.3 targets, policies such as price mechanisms (taxation) can be considered to reduce overconsumption in high-income regions, simultaneously lowering farm-level losses in exporting low- and middle-income regions. While accepting a certain level of FLW is inevitable for global food security, policy interventions should promote the reuse of FLW as animal feed, supporting ASF production in low-income regions, which is crucial for fighting malnutrition. In addition, plant-based FLW should be promoted as a production input across food and non-food sectors, supporting more sustainable economic growth.

As usual, our findings are subject to limitations and would benefit from several future extensions. Using fixed FLW shares across years may overlook changes in FLW rates due to socio-economic and technological factors. Deriving FLW shares from existing literature reveals a lack of granular high-quality data, especially in low- and middle-income countries and final FSC stages. The application of a consistent gap-filling procedure based on FLW shares in comparable regions urges a careful utilization and interpretation of our database as data assumptions and aggregations may impact the magnitude of estimates. Our methodology, aggregating data through physical mass, does not directly assess SDG 12.3. Instead, we adopt an economic-weight-based indicator. Combining FLW estimates with per capita food intakes at the country level reveals unrealistically low net intakes in selected low- and middle-income countries, requiring downward FLW share adjustments. Future research should focus on detailed country-level surveys, expanding nutritional analysis to include lost micronutrients and understanding food quality variation across countries and uses.

In conclusion, our study provides a comprehensive analysis of FLW generation along the global FSC, addressing knowledge gaps and offering valuable insights for future policies. Despite identified limitations, our detailed global database, covering 141 countries and regions, serves as a starting point for multidisciplinary investigations into FLW, supporting strategies for a more sustainable food system. Future research avenues could involve modelling the dynamic effects of FLW reduction and reuse policies on both nutritional security

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and environmental sustainability, aiding policymakers in designing effective and holistic strategies for a sustainable global food system.

## Methods

### An economic framework to trace global biomass flows

With post-farm-gate food value chains representing over 80% of food-related expenditures in many country cases[39], it is important to trace food flows beyond the farm gate to properly capture the environmental, social and economic dimensions of the related FLW flows. To achieve this, we rely on the approach developed by Chepeliev[24]. The method traces quantities of food, calories, fats, proteins and carbohydrates along the value chains of the global multiregion input–output Global Trade Analysis Project (GTAP) database[40]. We rely on the latest publicly available version, version 10, of the GTAP database with 2014 as the reference year, which has 141 regions and 65 sectors[40]. To provide a more consistent representation of the output of agricultural sectors, we apply a special procedure of the FAO-based agricultural production targeting following Chepeliev[41]. This approach allows better targeting of the values of agricultural output across GTAP sectors providing better harmonization between GTAP and FAO agricultural accounting (for additional details on this procedure, see Section 1 of Supplementary Information). We further rely on the FAO food balance sheet (FBS) data and nutritive factors to estimate the nutritional content of primary commodities and derived commodities represented in primary commodity equivalents within FBS. Calories, fats, proteins and carbohydrates are estimated and reported. We identify use categories that account for food, feed, seed, losses and other uses. In terms of the food supply, we identify GTAP primary commodity sectors, food processing sectors and service sectors that supply food. To trace nutritional data by GTAP sectors, we construct Leontief inverses, operating only over those sectors (and uses) that supply food. Such inverses are constructed separately for the tracing of domestic, exported and imported commodities. A constructed nutritional database (GTAP-FBS) provides food and biomass flows that are fully consistent with the FBS accounting framework of the FAO.

### Tracing FLW along global FSC

To quantify FLW along global supply chains, we compile a new global FLW database. By considering entire food commodities (that is, edible and inedible parts) and excluding non-food biomass flows (that is, feed, seed and biomass used for industrial purposes) from FLW, we overcome broadly debated methodological inconsistencies of available FLW estimates[15], providing a consistent alternative to the heavily criticized[8,9] estimates from Gustavsson et al.[7]. We define five stages of the FSC to quantify FLW at each stage of the global FSC. We collect data for eight commodity groups covering cereal crops, horticulture and ASF. The core of our database is the FAO-FLW database[10]. From the FAO-FLW database, we select estimates on physical percentage shares of lost and discarded food along different stages of global FSC. As physical (tonnes) FLW estimates often do not account for potential variations in food production related to evolving economic and environmental factors, we build our FLW database focusing on percentages of lost and discarded food, as such estimates are more consistent across years[42]. We perform a literature review on the coverage limitations of the FAO-FLW database, principally building on previous reviews[2,9,11]. First, we collect sources reporting, among other typologies of FLW data (that is, physical FLW, monetary FLW and so on), estimates on percentages of loss and waste within total food quantity. Second, we further filter gathered sources by methodology, maintaining only data computed consistently with our FLW definition. Finally, we select sources providing estimates specifically missing in the FLW-FAO database. Here we distinguish between macro and micro approaches, giving priority to estimates reported for macro commodity groups (for example, fruit and vegetables) or geographical regions (for example, Europe). An overview of the outcome of our literature review on shares of FLW and the enhanced data coverage with respect to the FAO-FLW database is provided in Fig. 5. Further details and the adopted shares of lost and discarded foods along global supply chains are provided in Supplementary Information (Section 2).

From the GTAP-FBS database, we derive gross food biomass supply in physical quantities (tonnes) along global supply chains. We trace food biomass from production to final consumption, quantifying physical flows of commodities through different food sectors before reaching final consumers. In the GTAP-FBS database, we distinguish three main stages of the FSC, that is, primary production, intermediate production and final consumption. Primary production consists of agricultural production of primary food commodities, that is, food produced at the farm level. In contrast, intermediate production represents non-primary food production, that is, food produced by processing sectors that receive primary agri-food products and process them into final products. Finally, the final consumption consists of household food consumption of both primary and processed food commodities. In the GTAP-FBS framework, primary production coincides with the outputs of primary agricultural sectors while intermediate production and final consumption are respectively quantified by intermediated food demand from food sectors and final food demand from households. To trace FLW along global FSC, we link our FLW database to food supply derived from the GTAP-FBS database. To do so, we combine the three stages of the GTAP-FBS database with the five supply chain stages available in our newly compiled global FLW database, identifying FLW amounts at each stage of global FSC. Agricultural production and post-harvest handling and storage stages are associated with primary production in the GTAP-FBS database, while manufacturing and consumption stages are linked respectively to intermediate food production and final consumption. From the GTAP-FBS database, it is not possible to explicitly quantify physical flows related to food distribution and retailing. For this, we assign our distribution and retail stage in the FLW database to food flows flowing from intermediate production to final consumption, that is, from manufacturing to consumption.

In merging FLW shares, we assume that physical amounts of food flows decrease after each supply chain stage. This entails that shares of food products are lost or discarded at different stages and food flows enter the next stage net of losses that occurred in previous stages. As final consumers demand primary and processed food, we distinguish between food flows entering the manufacturing stage (that is, consumed as processed) and foods not entering the manufacturing stage (that is, consumed as fresh). Moreover, as in the GTAP-FBS framework households consume food via food services—out-of-home food consumption (for example, restaurants, hotels and so on), we further trace food consumed via food services as fresh (not entering manufacturing) or processed (entering manufacturing) properly quantifying losses at manufacturing stages based on the consumption of final products. Finally, we attribute trade (transportation) losses to importing regions, assuming food spoiled or damaged during transportation will be physically available and possibly treated within the importing region. Additional information on merging FLW estimates into the GTAP framework is available in Supplementary Information (Section 1). With this approach, we trace and quantify FLW in physical units (tonnes), consistently accounting for global food and non-food trade, and the economic behaviour of agents along global supply chains. These results are particularly determinant for defining the geographical location of generated FLW as food consumption in one region can result in the generation of food losses in other regions. Moreover, we define processed foods and food services in primary equivalents, accounting for the region-specific heterogeneous composition of non-primary foods. Finally, as in the GTAP-FBS database nutritional data are obtained from the FAO-FBS, we account for the differences in nutritional contents of primary and processed foods across global regions, consistently quantifying the heterogenous nutritional composition of FLW.

To quantify the environmental footprint embedded in FLW flows, we use land use data from Baldos[43], which incorporates estimates from FAOSTAT and EARTHSTAT. Water use data are derived from Haqiqi et al.[44] and AQUASTAT while GHG emissions data are obtained from Aguiar[40] and Chepeliev[45]. In our approach, we assume that water, land and GHG emissions have been used and generated for the production of food products that will be successively lost or discarded. First, we quantify the amount of GHG emissions, land use and water use embedded in the primary production of food products. Next, we compute the amount of lost and discarded foods associated with food consumption and proportionally compute the amount of environmental footprint embedded in FLW flows. To trace amounts of environmental impacts associated with FLW, we adopt a full accounting based on multiregion input–output, identifying resource use and GHG emissions along global supply chains according to the geographical location of different production and consumption stages. As we account for different food production intensities in the countries around the world, FLW-embedded emissions reflect the type of food production system adopted within a specific country. The full database containing the magnitude, composition and location of global FLW, as well as nutritional and environmental losses embedded in FLW by country and region, is provided in Supplementary Information.

## Data availability
The FLW database and results data are available in Supplementary Information.

## Code availability
The code used for the analysis is described in Supplementary Information.

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## Author contributions
A.G. and M.C. conceived and designed the experiments, performed the experiments, analysed the data, contributed materials and analysis tools, and wrote the paper.

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