Unequal Environmental Burdens of Food Loss and Waste in global food supply chain

ZiyanYang[1], Prof.Yan Xia[1], Prof.Xiang Gao[2]

1. Institutes of Science and development, Chinese Academy of Sciences, Beijing, China
2. Academy of Mathematics and Systems Sciences, Chinese Academy of Sciences, Beijing, China

Abstract

Global food trade drives economic growth but also intensifies food loss and waste (FLW), creating unequal environmental burdens. Existing studies focus on total FLW volumes, overlooking disparities across income groups. This study constructs a global agri-food trade matrix covering 98 products across 49 countries/regions to estimate FLW and its environmental impact. Using FAOSTAT, Exiobase, and the FAO FLW Database, we quantify direct and indirect environmental burdens. Applying structural decomposition analysis (SDA), we identify key drivers and trade-related effects. An inequality index highlights the uneven distribution of FLW, with low-income countries facing higher production losses and high-income nations contributing more post-consumer waste. Our findings offer insights for sustainable and equitable food policies.

1 Main

Global food trade, through agricultural intensification and redistribution, has enhanced food supply diversity and economic globalization[1-2]. However, this process has also exacerbated the uneven distribution of food loss and waste (FLW) and its environmental footprint among countries with different income levels[3]. According to the latest Food Waste Index Report 2024[4] released by the United Nations Environment Programme (UNEP), an estimated 1.05 billion tonnes of food waste (including inedible parts) were generated globally in 2022. This equates to an average of 132 kilograms of food wasted per person, accounting for nearly one-fifth of all food available to consumers. Such figures run counter to Sustainable Development Goal (SDG) 12.3, which aims to halve global per capita food waste at the retail and consumer levels and reduce food losses along production and supply chains by 2030.

Moreover, food loss and waste (FLW) not only lead to a significant waste of food resources but also contribute to substantial greenhouse gas emissions, excessive land use, and water waste[5-8]. As food moves along the food supply chain (FSC), various resources are consumed for transportation, processing, storage, and preservation—each of which imposes an environmental burden in different ways[9]. Early studies indicate that FLW accounts for approximately 8% of global greenhouse gas emissions—equivalent to the total emissions from all sectors in the European Union[10]. Additionally, FLW is responsible for 24% of global agricultural water use and 20% of agricultural land use[5].

However, this environmental burden is unequally distributed across income groups, further exacerbating social inequality. The emissions embedded in food loss are dispersed across food-producing regions, which are often far from the final consumption sites. High-income countries, which generate greater amounts of food waste at the consumer level[11], effectively shift the environmental costs of food production losses onto developing nations that serve as primary food suppliers. Meanwhile, due to technological limitations and poor management, developing countries experience significant food losses during production, processing, transportation, and storage[12]. Wealthier populations tend to enjoy a more diverse and higher-quality diet, while lower-income groups disproportionately bear the environmental consequences of food production and consumption patterns, including excessive water consumption and soil degradation. This unequal distribution of environmental burdens contradicts Sustainable Development Goal (SDG) 10, which aims to reduce inequality within and among countries, as well as SDG 13, which calls for urgent climate action and a reduction in greenhouse gas emissions.

Most studies on food loss and waste (FLW) focus on estimating the total amount of food loss and its environmental impact[13-15], with relatively limited attention given to its unequal distribution across income groups. In light of this gap, our study explores disparities in FLW within the global food supply chain, examines its associated environmental burdens, and proposes policy recommendations that balance equity and sustainability. Specifically, we construct a global agricultural trade matrix based on FAOSTAT food balance sheets and Exiobase input-output data. This matrix covers 98 agricultural products and five utilization categories across 49 countries and regions, allowing us to estimate FLW along the global food supply chain. By integrating satellite accounts with our constructed matrix, we quantify both the direct and indirect environmental impacts of FLW. Building on this, we introduce the Environmental Burden Inequality Index (EEI) to assess the unequal distribution of environmental burdens—such as pollution and resource depletion—among different social groups, regions, or nations. This index aims to highlight whether environmental costs are equitably shared across various sectors of society.

The structure of this paper is as follows: Section 2 details the research methodology, including the construction of the agricultural trade matrix. Section 3 presents the main findings of our study. Section 4 contains supplementary results and additional information.

2 Methods

We developed a comprehensive modeling framework to estimate global food loss embedded in national trade and assess the inequality of its associated environmental burden.

The framework consists of several key steps. First, we constructed an agri-food matrix using FAOSTAT food balance sheet data and Exiobase input-output data, covering 98 agricultural and food products across 49 countries and regions, classified by different utilization purposes (seeds, feed, processing, other uses, and food consumption). Next, we mapped regional FLW shares from the FAO Food Loss and Waste Database and existing literature on loss rates to individual countries available in Exiobase, ultimately creating the FSC-FLW database for 49 countries/regions.

We then matched the inflows at various stages of the food supply chain with the loss rates from the FSC-FLW database. Specifically, the agricultural production and post-harvest handling & storage stages were linked to primary production, while the manufacturing and consumption stages were associated with intermediate food production and final consumption, respectively. Additionally, to accurately quantify the physical flows related to food distribution and retail, we allocated the distribution and retail stages from the FLW database to food flows from primary and intermediate production to final consumption, accounting for both raw and processed food distribution and retail volumes. This process allowed us to estimate food loss across different stages (Primary Production, Post-harvest Handling & Storage, Processing & Manufacturing, Retail & Distribution, and Consumption) for 49 countries and regions.

Subsequently, we applied environmentally extended input-output analysis (EEIOA) to establish a consumption-based emissions and resource use inventory, further analyzing the environmental burdens embedded in food loss across the global food supply chain. Finally, we constructed an inequality index to assess the disparities in environmental burdens caused by food loss in international trade.

2.1 System definition

Using a mass balance approach and input-output analysis, this study quantifies food loss and waste (FLW) across five stages of the food supply chain (FSC) for 98 food products in 49 countries and regions. The analysis is based on the latest EXIOBASE global multi-regional input-output (MRIO) database (version 3.8.2) and evaluates the associated energy and environmental footprints of FLW. Specifically, food loss (FL) occurs during the Agricultural Production, Post-harvest Handling & Storage, and Manufacturing stages, while food waste (FW) takes place during the Distribution & Retail and Consumption stages.

2.1.1 Definition of food loss and waste

According to the Codex Alimentarius of the FAO, food is clearly defined as any substance intended for human consumption, whether processed, semi-processed, or raw. This includes beverages, chewing gum, and any substance used in the manufacture, preparation, or treatment of "food" but excludes cosmetics, tobacco, and substances used solely as drugs.

While there is no universally accepted definition of food loss (FL) and food waste (FW), the FAO distinguishes between the two. Food loss refers to the reduction in the quantity of edible food intended for human consumption that occurs during production, post-harvest handling and storage, and processing stages, excluding non-food uses such as feed and seeds. Food waste, on the other hand, occurs at the distribution, retail, and consumption stages and is linked to the behavior of retailers and consumers, which may include food discarded at distribution points[16-17]. In most cases, FLW involves the removal or rejection of edible food from the supply chain before it reaches human consumption[18-19]. Additionally, FLW may include unavoidable inedible by-products generated during food production[20-21]. However, this study does not consider the inedible portion of FLW. Instead, it focuses solely on the loss or waste of food intended for human consumption and excludes non-food uses such as feed, seeds, and industrial applications at the production stage.

2.1.2 Food categories and food supply chain

This study is based on the FAO's food classification and considers the maximum availability of data to examine FLW across 98 food categories. For further analysis, these 98 categories were grouped into 16 broader groups (Table S1). Ultimately, these 16 groups include: (1) paddy rice; (2) wheat; (3) grains (e.g., barley and products, maize and products, rye and products); (4) fruits & vegetables (e.g., cassava and products, potatoes and products, sweet potatoes); (5) oil seeds (e.g., sunflower seed, rapeseed and mustard seed, sesame seed); (6) sugar cane/beet (e.g., sugar cane, sugar beet, non-centrifugal sugar); (7) other crops (e.g., coffee and products, cocoa beans and products, tea including mate); (8) cattle meat (e.g., bovine meat, pig meat, poultry meat); (9) other animal products (e.g., honey, animal fats, raw animal products); (10) raw milk; (11) fish (e.g., freshwater fish, demersal fish, pelagic fish); (12) vegetable oils and fats (e.g., soybean oil, groundnut oil, sunflower seed oil); (13) dairy (e.g., butter, ghee, cream); (14) food products (e.g., infant food, miscellaneous food items); (15) beverages (e.g., wine, beer, fermented beverages); (16) fish products (e.g., fish body oil, fish liver oil).

The food supply chain refers to the sequence of stages and operations involved in food production and consumption, including agricultural production, livestock farming, food processing, packaging, storage, transportation, and retail. It is characterized by complexity, dynamism, and interconnectivity. This study examines FLW flows across five key stages of the global food supply chain: agricultural production, post-harvest handling and storage, manufacturing, distribution and retail, and consumption.

Agricultural production represents the starting point of the food supply chain, encompassing crop cultivation and livestock farming. The post-harvest handling and storage stage covers transportation, storage, and preliminary processing from farms to storage facilities. The manufacturing stage involves further processing of food products. The distribution and retail stage refers to the transfer of food from processing plants or warehouses to retailers. The consumption stage includes food waste generated by households and the food service sector.

2.2 Literature review

Despite progress in FLW quantification research, inconsistencies in data, as well as limitations in temporal, geographical, and food supply chain coverage, remain major challenges in estimating global FLW[24]. Specifically, regional disparities and the varying loss characteristics of different food categories add complexity to FLW measurement. For example, in developed countries, losses are primarily concentrated in the consumption and retail stages, whereas in developing countries, food losses occur more frequently at the production and post-harvest storage stages[25]. These regional and sectoral differences make it difficult to standardize global FLW data and affect the comparability of measurement results.

In addition to data inconsistencies, FLW quantification also faces methodological challenges. Current FLW estimation methods can be broadly categorized into three approaches: direct measurement[24], indirect estimation[26], and model-based analysis[27]. Each method has its own strengths and weaknesses, leading to significant variations in measurement results, making it difficult to rely solely on a single approach to accurately reflect the global FLW situation.

Existing studies have employed different methods to quantify food losses, including both bottom-up approaches (e.g., Life Cycle Assessment (LCA)[27]) and top-down approaches (e.g., mass balance methods[23] and input-output analysis[24]). While LCA benefits from detailed product-specific data, its limitations include the subjective selection of system boundaries, leading to system truncation and associated errors. In contrast, Multi-Regional Input-Output (MRIO) models offer comprehensive global economic coverage, addressing the limitations of LCA by tracking food losses in a given country while distinguishing between domestic and foreign environmental pressures resulting from local consumption. MRIO also accounts for trade flows, country-specific production technologies, and the environmental intensity of different goods and services.

An increasing number of studies have adopted multi-regional input-output tables[26] to quantify food losses and assess the environmental footprint of food systems at national[23], regional[22], and global scales[24-25]. With globalization and the expansion of international food trade, the global food supply chain (FSC) has become a key focus in studying food losses in agro-food systems and their environmental impacts. A review of the literature on food loss quantification and its environmental impacts is presented in Table S2.

2.3 Data source

The study utilizes the Food Balance Sheet (FBS) from the FAOSTAT database and, based on maximum data completeness and analytical feasibility, maps the 98 countries listed in the FBS to the 49 countries and regions in the EXIOBASE database (Table S3).

The Food Balance Sheet (FBS) is a statistical tool compiled by the Food and Agriculture Organization (FAO) to comprehensively measure the production, trade, transformation, and consumption of food within a country or region over a specific period. The FBS provides detailed records of food availability, sources (such as domestic production and imports), utilization (including consumption, feed, and industrial use), and final consumption. Several studies have used the FBS to analyze global agricultural trade and its environmental impacts [37-38].

EXIOBASE was developed through EU-funded projects such as EXIOPOL, CREEA, and DESIRE [28-30]. It covers 44 countries and the Rest of the World (RoW), forming a unified global Multi-Regional Input-Output (MRIO) table. It is widely used to analyze the environmental pressures and footprints associated with 200 products and 163 industries [30-31]. EXIOBASE attributes the direct energy consumption and environmental impacts of domestic production to their originating products and industries, offering an extensive satellite account with over 309 indicators covering energy, emissions, and resource use [32]. Several studies have used EXIOBASE to investigate the environmental pressures of global consumption and trade [33-36].

2.4 Construction of global food trade matrix

This study follows the approach of previous research [22] to identify both the intermediate consumption stage (where food is used as an input in the agri-food and non-agri-food industries) and the final consumption stage (where households purchase food for consumption) within EXIOBASE. At the intermediate consumption stage, 26 agri-food industries were identified, including 15 related to agricultural production and 11 related to food processing (Table S4). Additionally, 16 additional EXIOBASE industries were delineated, including sectors such as hotels and public institutions.

Following the studies of Chepeliev (2022) [39] and Gatto (2024) [13] this study maps the food and non-food uses from the Food Balance Sheet (FBS) to different industries within the EXIOBASE database. Specifically, self-consumption in agriculture corresponds to seed use, while self-consumption in livestock corresponds to feed use. All processed foods are linked to the food processing sector, and the food consumption stage is associated with the food service sector and final consumption sector. Furthermore, although some primary agricultural products are used for industrial purposes, they fall under non-food use and do not contribute to food available for final consumers. The mapping of EXIOBASE industrial sectors to different stages of the food supply chain is presented in Table S4, with food uses (processing, food) and non-food uses (seed, feed, other uses) detailed in Table S5.

2.5 Tracing Food Loss & Waste along global food supply chains

2.5.1 Direct FLW: Mass balance analysis

To track the flow of food loss and waste (FLW) within the global food supply chain, we constructed a global food supply chain based on the EXIOBASE database. This framework links different stages of the supply chain, including food production, processing, distribution, and final consumption, allowing for a detailed analysis of FLW in global food trade and the inequalities in its associated environmental burdens.

This study employs a mass balance approach to quantify and map FLW across the entire supply chain (Figure S1). In this model, the starting point is Agricultural Production. First, the domestic supply (including both food and non-food uses) is calculated as:

$$Q_{r,i}^{Total} = \text{Production}_{r,i}^{1} + \text{Import quantity}_{ur,i}^{1} - \text{Export quantity}_{rs,i}^{1} - \text{Stock Variation}_{r,i}^{1}$$

$$= \text{Feed}_{r,i}^{1} + \text{Seed}_{r,i}^{1} + \text{Losses}_{r,i}^{1} + \text{Other uses (non-food)}_{r,i}^{1}$$

$$+ \text{Processing}_{r,i}^{1} + \text{Food}_{r,i}^{1}$$

Where $Q_{r,i}^{Total}$ represents the total food supply. Based on FAO's definition of food, this study excludes the non-food portion from food loss calculations. Thus, the net food supply at the Agricultural Production stage in country r is:

$$Q_{r,i}^{1} = \text{Processing}_{r,i}^{1} + \text{Food}_{r,i}^{1}$$

At the Agricultural Production stage, the food supply reported in the FBS represents the total amount after accounting for food loss during production. Therefore, the food loss at the Agricultural Production stage is:

$$FLW^{1}_{r,i} = \frac{Q^{1}_{r,i}}{(1 - R^{1}_{r,i})} - Q^{1}_{r,i}$$

Where $FLW^{1}_{r,i}$ represents the food loss of the ith food type in country r at the first stage (Agricultural Production), and $R^{1}_{r,i}$ denotes the food loss rate at this stage.

The food loss quantities for the remaining four stages can be summarized as follows:

$$FLW^{t}_{r,i} = Q^{t}_{r,i} \times R^{t}_{r,i}$$

Where t=2, 3, 4, 5 represent the stages of Post-harvest handling and storage, Manufacturing, Distribution and Retail, and Consumption, respectively. $Q^{t}_{r,i}$ denotes the net inflow at stage t:

$$Q^{t}_{r,i} = Q^{1}_{r,i} - \sum_{2}^{t-1} FLW^{k}_{r,i}$$

where $\sum_{2}^{t-1} FLW^{k}_{r,i}$ represents the cumulative loss from period 2 to period t-1.

2.5.2 Indirect FLW: IO analysis

This study estimates the indirect food loss and waste (FLW) of countries worldwide based on the MRIO framework. It further examines how changes in final demand propagate and expand through different stages of the supply chain—including agricultural production, processing, distribution, and retail—ultimately leading to additional indirect losses.

$$F_{indrect} = A_{flw} \times (I - A)^{-1} \times Y$$

where $F_{indrect}$ represents the quantity of indirect FLW, A_{flw} is the direct FLW intensity matrix, calculated based on direct food loss per unit of output. $(I - A)^{-1}$ denotes the Leontief inverse matrix, which reveals the interdependencies and indirect effects among industries in the food supply chain. Y represents the vector of final demand in the economy, including consumer final demand, government expenditure, and other components.

2.6 Tracking environmental burden within a MRIO framework

Input-output analysis is a top-down approach that utilizes sectoral transaction data to explain the complex interdependencies between industries. By incorporating environmental information related to each sector, such as greenhouse gas emissions or land use, input-output tables can be environmentally extended. EEMRIO analysis traces traded goods, services, and their associated materials back to their primary extraction sources, capturing both direct and indirect environmental pressures linked to a country's final consumption. We use conventional economic accounting to express the input-output relationship function as Equation (1):

$$X = (I - A)^{-1} \times Y \tag{1}$$

Where X represents the total output, A is the direct requirements coefficient matrix, $(\mathrm{I}-\mathrm{A})^{-1}$ is the Leontief inverse matrix, and Y is the final consumption vector. Subsequently, we incorporate environmental-related information using Equation (2):

$$E = f_i \times (I - A)^{-1} \times Y \quad (2)$$

Where E represents the environmental burden embedded in food loss and waste (FLW) across the flow of goods and services between sectors. f_i is the diagonal matrix of environmental intensity, indicating the environmental burden per unit of sectoral output for the *i*-th environmental factor. These factors include Water Consumption Green - Agriculture, Water Consumption Blue - Agriculture, Land Use (Crop, Forest, Pasture), GHG Emissions (GWP100), and Emission Relevant Energy Carrier.

This relationship can be expressed by Equation (3):

$$f_i = \frac{EFC_i}{X} \times FLW \quad (3)$$

Where X represents the total output of each sector, FLW denotes the amount of food loss and waste, and EFC_i represents the environmental burden of type i embedded in per-unit food consumption. This relationship can be further expressed by Equation (4):

$$EFC_i = \frac{EF_i}{FC} \quad (4)$$

Where EF_i represents the environmental burden of each sector, and FC represents food consumption.

2.7 Nutrient loss embedded FLW

Based on the estimated food loss data for 98 types of food across 49 countries or regions worldwide, this study collected nutritional factors, including calories, protein, fat, and carbohydrates per 100 grams of primary and processed products, from multiple data sources[40-43] to assess the nutritional losses caused by food loss. The nutrient loss due to food loss for food i (i=1, ...98) in region r (r=1,...49) is calculated as follows:

$$\Delta N_{ij,r} = FLW_{i,j}^{r} \times NF_{i,j} \quad (5)$$

where $NF_{i,j}$ represents the nutrient content per 100 grams for nutrient j, where j=1, 2, 3, 4 corresponds to calories, protein, fat, and carbohydrates, respectively.

2.8 Unequal evaluation of environmental burden

This study builds on the Social Determinants of Health Inequality Index (SDHII) proposed by Zheng (2024)[44] in analyzing health burden inequalities in the food system and develops the Environmental Burden Inequality Index (EEI). The EEI measures the degree of inequality in the distribution of environmental burdens across different social groups, regions, or countries, aiming to assess whether environmental burdens — such as pollution and resource consumption — are equitably shared among various societal strata. This index accounts for the differences in environmental burdens between production-based and consumption-based FLW accounting for each country. By incorporating population weighting, it quantifies mortality inequality at the national level between production and consumption.

First, we calculate the difference in per capita FLW-related environmental burden attributed to food production (E_i^P) and food consumption (E_i^C) for each country, denoted as ΔE_i. This represents the discrepancy between the environmental burden of FLW caused by local food production and the expected FLW-related environmental burden associated with local food consumption within the same region. The calculation is expressed as follows:

$$\Delta E_i = E_i^P - E_i^C$$

where ΔE_i represents the difference between the supply-side rate E_i^P (i.e., the per capita FLW-related environmental burden of country i supplying food to other countries or regions) and the demand-side rate E_i^C (i.e., the per capita FLW-related environmental burden of country i receiving food from other countries or regions). Next, all ΔE_i values are ranked in ascending order and paired with the population data of each region to calculate the EEI index:

$$\text{EEI} = \frac{\sum_{i=1}^{n} POP_i \times |E_i^P - E_i^C|}{POP}$$

where POP and POP_i represent the population of a given country i and the global population, respectively. n denotes the total number of countries or regions. This index represents the degree of inequality in FLW-related environmental burdens at the national level.

By using the population proportion as a weighting factor, the index captures regional disparities in FLW-related environmental burdens attributed to food production and consumption. When the FLW-related environmental burden of a specific region aligns with the FLW burden based on food consumption, the region's ΔE_i value is zero, indicating no contribution to inequality.

2.9 Analysis of driving factors of FLW：SDA

By conducting a structural decomposition analysis (SDA) of indirect food loss and waste (FLW), the key influencing factors of a country's FLW-related environmental burden can be identified. Assuming that the food loss and waste in a country at two different periods, t_1 and t_0 are represented as $F_{flw,t1}$ and $F_{flw,t0}$, respectively, the difference in FLW-related environmental burden between these two periods can be calculated as:

$$\Delta F_{flw} = F_{flw,t1} - F_{flw,t0} \quad (1)$$

Different simplification methods can lead to different SDA decomposition results. Using the two-polar decomposition method, where $B = (I - A)^{-1}$, we can derive two different decomposition forms:

$$\Delta F_{flw} = \Delta A_{flw} B_{t1} Y_{t1} + A_{flw,t0} \Delta B Y_{t1} + A_{flw,t0} B_{t0} \Delta Y \quad (2)$$

$$\Delta F_{flw} = \Delta A_{flw} B_{t0} Y_{t0} + A_{flw,t1} \Delta B Y_{t0} + A_{flw,t1} B_{t1} \Delta Y \quad (3)$$

Taking the average, that is, applying the two-stage decomposition averaging method, we obtain:

$$\Delta F_{flw} = \frac{1}{2} \Delta A_{flw} (B_{t1} Y_{t1} + B_{t0} Y_{t0}) + \frac{1}{2} (A_{flw,t1} \Delta B Y_{t0} + A_{flw,t0} \Delta B Y_{t1}) + \frac{1}{2} (A_{flw,t1} B_{t1} \Delta Y + A_{flw,t0} B_{t0} \Delta Y) \quad (4)$$

Drawing on the research methodology of Liu Ruixiang et al. (2017), the Leontief inverse matrix can be divided into three components: the domestic multiplier coefficient matrix, the feedback coefficient matrix, and the spillover coefficient matrix, expressed as: B=L+M+N, where $L = (I - A^D)^{-1}$, $M = B^D - L$, $N = B - B^D$, and A^D and B^D represent the diagonal elements of matrices A and B, respectively. Therefore, food loss can be decomposed into three parts: domestic multiplier effect, feedback effect and spillover effect.

$$A_{flw} B Y = A_{flw} (L + M + N) Y = A_{flw} L Y + A_{flw} M Y + A_{flw} N Y \quad (5)$$

wher, $L = \begin{bmatrix} L^{11} & 0 & \cdots & 0 \\ 0 & L^{22} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & L^{gg} \end{bmatrix}$, $M = \begin{bmatrix} M^{11} & 0 & \cdots & 0 \\ 0 & M^{22} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & M^{gg} \end{bmatrix}$, $N = \begin{bmatrix} 0 & B^{12} & \cdots & B^{1g} \\ B^{21} & 0 & \cdots & B^{2g} \\ \vdots & \vdots & \ddots & \vdots \\ B^{g1} & B^{g2} & \cdots & 0 \end{bmatrix}$

$L^{ss} = (I - A^{ss})^{-1}$ represents the domestic Leontief inverse matrix, indicating the domestic multiplier effect generated when country s uses domestic intermediate goods. $M^{ss} = B^{ss} - L^{ss}$ represents the feedback effect on country s due to the import of intermediate products from abroad. N represents the spillover effect of food loss, referring to the external spillover effect generated when a country exports intermediate products abroad.

Accordingly, Y can be divided into three components: consumption (C), investment (I), and exports (Ex). Thus, food loss can be decomposed into three expansion effects:

consumption expansion effect, investment expansion effect, and export expansion effect.

Among them, the consumption expansion effect can be further divided into food consumption (C^{food}) and non-food consumption ($C^{non-food}$). The export expansion effect can be divided into exports for final consumption (Ex^C) and exports as capital goods or production materials (Ex^I).

$$A_{flw}BY = A_{flw}B(C^{food} + C^{non-food} + I + Ex^C + Ex^I) = A_{flw}BC^{food} + A_{flw}BC^{non-food} + A_{flw}BI + A_{flw}BEx^C + A_{flw}BEx^I \quad (6)$$

The change of food consumption in a country can be decomposed into:

$$\begin{aligned}\Delta F_{flw} = &\underbrace{\frac{1}{2}\Delta A_{flw}(B_{t1}Y_{t1} + B_{t0}Y_{t0})}_{C(\Delta A)} + \underbrace{\frac{1}{2}(A_{t1}\Delta LY_{t0} + A_{t0}\Delta LY_{t1})}_{C(\Delta L)} \\ &+ \underbrace{\frac{1}{2}(A_{t1}\Delta MY_{t0} + A_{t0}\Delta MY_{t1})}_{C(\Delta M)} + \underbrace{\frac{1}{2}(A_{t1}\Delta NY_{t0} + A_{t0}\Delta NY_{t1})}_{C(\Delta N)} \\ &\underbrace{\frac{1}{2}(A_{t0}B_{t0} + A_{t1}B_{t1})\,\Delta Y^{food}}_{C(\Delta C^{food})} + \underbrace{\frac{1}{2}(A_{t0}B_{t0} + A_{t1}B_{t1})\,\Delta Y^{non-food}}_{C(\Delta C^{non-food})} \\ &\underbrace{\frac{1}{2}(A_{t0}B_{t0} + A_{t1}B_{t1})\,\Delta Y^{I}}_{C(\Delta I)} + \underbrace{\frac{1}{2}(A_{t0}B_{t0} + A_{t1}B_{t1})\,\Delta Y^{Ex\_C}}_{C(\Delta Ex^C)} \\ &\underbrace{\frac{1}{2}(A_{t0}B_{t0} + A_{t1}B_{t1})\,\Delta Y^{Ex\_I}}_{C(\Delta Ex^I)}\end{aligned} \quad (7)$$

$C(\Delta A)$、$C(\Delta L)$、$C(\Delta M)$、$C(\Delta N)$、$C(\Delta C^{food})$、$C(\Delta C^{non-food})$、$C(\Delta I)$、$C(\Delta Ex^C)$、$C(\Delta Ex^I)$ respectively represent the change effect of food loss coefficient, the change effect of domestic multiplier, the feedback effect, the spillover effect, the expansion effect of food consumption, the expansion effect of non-food consumption, the expansion effect of investment, the consumption part of export expansion and the investment part of export expansion.

3 Results

Global food trade is highly uneven, with distinct regional roles and dependencies.

From the food trade flows in Figure 1, different countries and regions play distinct roles in the global food supply chain, and the structure of this trade network further exacerbates the unequal environmental burdens caused by food loss and waste. Major grain-exporting countries are typically concentrated in specific regions, such as rice and wheat exports mainly coming from Asia and North America, while trade in fruits, vegetables, and oilseeds exhibits stronger regional characteristics. This uneven trade pattern means that food undergoes different levels of loss during distribution. Losses at the production stage (e.g., post-harvest spoilage and transportation damage) are more prevalent in developing countries, whereas waste at the consumption stage (e.g., supermarket and household food disposal) is primarily seen in high-income countries. This pattern results in an unequal distribution of environmental burdens, with developing countries bearing more resource consumption and carbon emissions, while developed countries dominate food waste at the consumption level.

Moreover, different food categories' trade patterns also influence the regional distribution of environmental burdens. For instance, trade in oilseeds and sugar (Figures e, f) exhibits high cross-border mobility, implying higher loss rates during processing and transportation, which in turn increases the carbon footprint. In contrast, staple crops (Figures a, b, c), due to their strong global trade dependence, are susceptible to food losses at multiple stages of the international supply chain. From production and storage to transportation, losses at any stage can have profound environmental consequences. Therefore, food loss and waste are not only issues of resource efficiency but also matters of global environmental justice, highlighting the urgent need for policymakers and businesses to take targeted measures to mitigate the unequal environmental burdens within the global food supply chain.

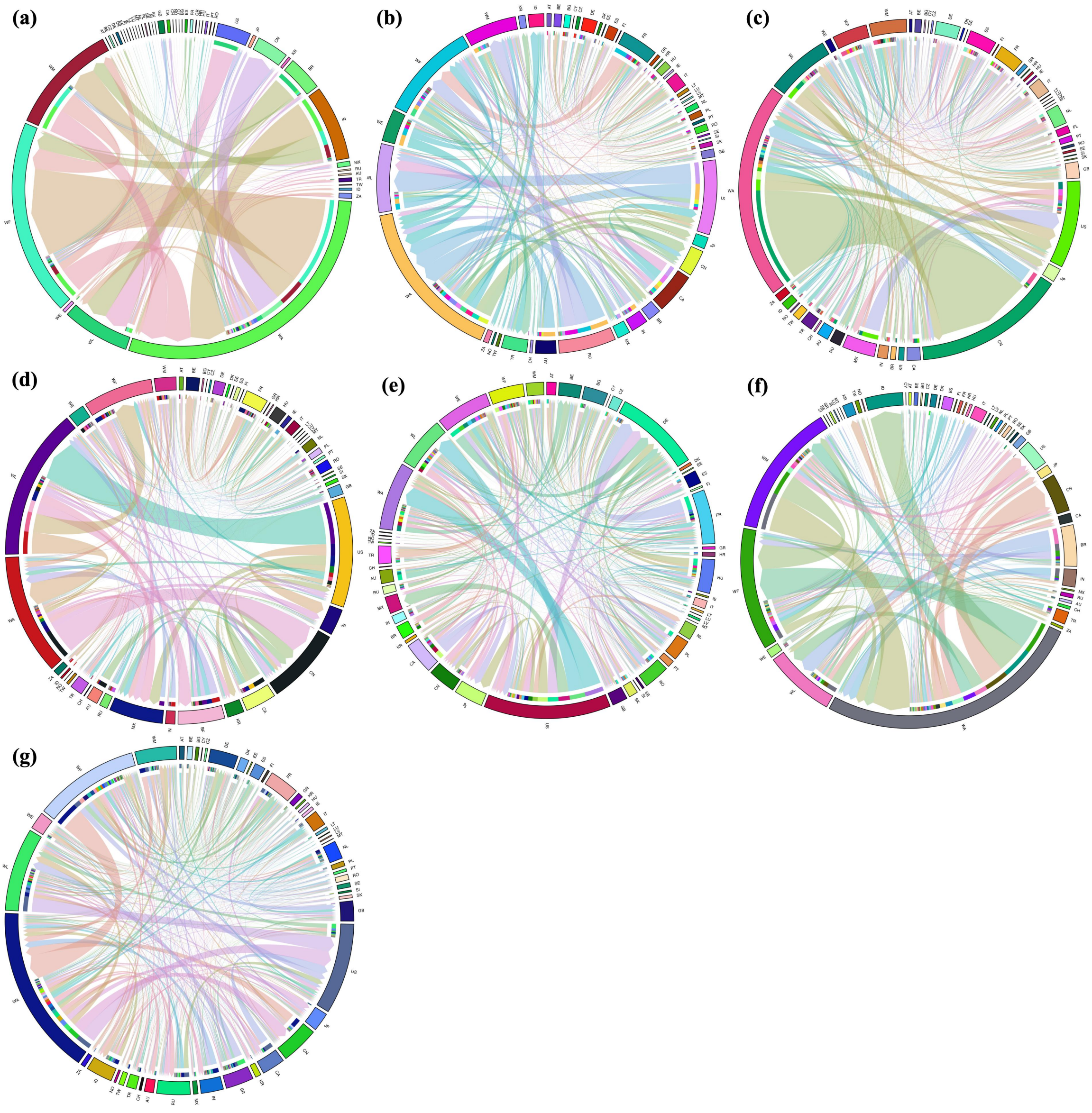


Figure 1 Bilateral food trade flows of plant-based products in the agro-food matrix in 2022. (a)Paddy Rice; (2)Wheat; (3)Grains; (4)Fruit & Vegetables; (5)Oil seeds; (6)Sugar cane/beet; (7)Other crops. The length of the arc represents the country's food trade volume (including imports and exports). The ribbons between two arcs represent the flow of food between exporting and importing countries. Each ribbon's color matches the color of the exporting country, and its width indicates the volume of food being transferred.

Figure 2 illustrates the bilateral trade flows of animal-based food products, revealing complex global interconnections in cattle meat, other animal products, raw milk, fish, and fish products. Compared to plant-based food trade, animal-based products exhibit higher trade concentration, with key exporters such as North America, Europe, and Oceania dominating global supply. The long-distance transportation of these perishable products contributes to higher food loss due to spoilage and inefficient cold chain logistics, especially in developing regions with limited infrastructure. This results in an unequal environmental burden, where resource-intensive livestock production occurs in exporting countries, while food loss during transit disproportionately affects regions with weaker food storage and distribution systems.

Furthermore, fish and fish product trade (Figures d, e) demonstrate high global mobility, often requiring energy-intensive processing and refrigeration, leading to increased carbon emissions. The environmental costs of overfishing and habitat destruction in major exporting countries contrast with the high levels of consumer waste in wealthier nations. These disparities underscore the urgent need for more sustainable trade policies, investment in cold chain infrastructure, and regional food system resilience to reduce unequal environmental burdens in the global animal-based food supply chain.

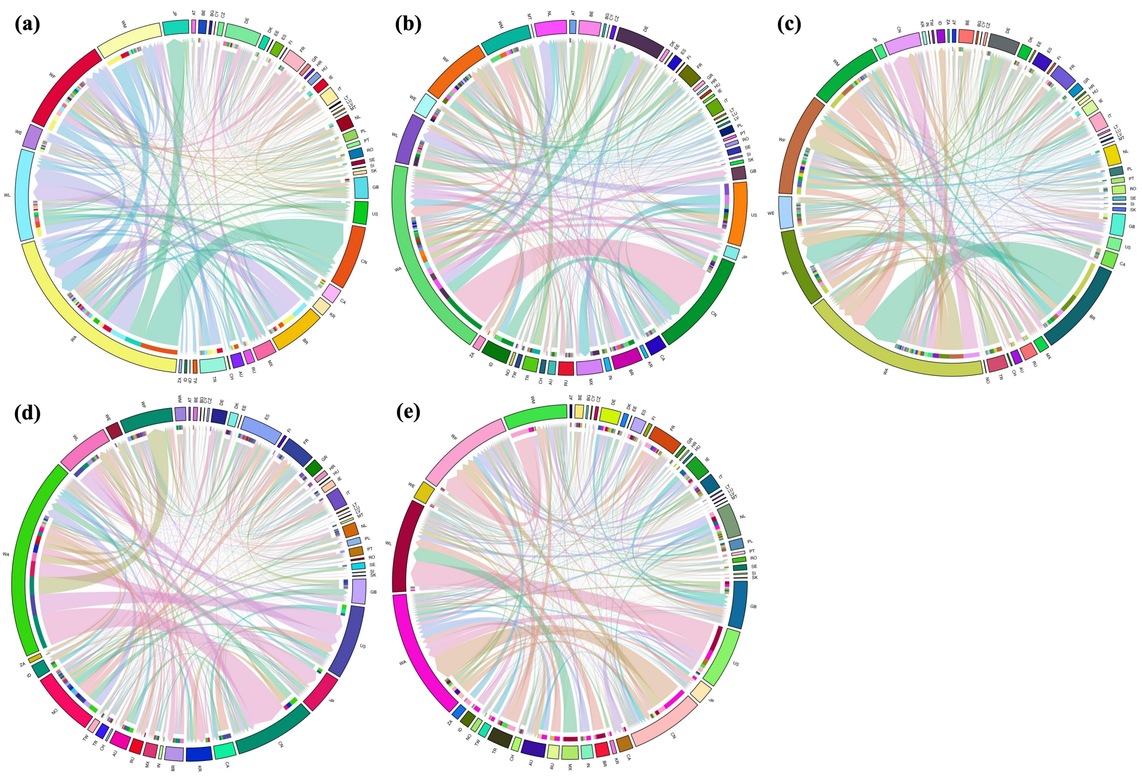


Figure 2 Bilateral food trade flows of animal-based products in the agro-food matrix in 2022. (a)Cattle meat; (b)Other animal products; (c)Raw milk; (d)Fish; (e)Fish products. The diagram is the same as Figure 1.

Figure 3 illustrates the global trade flows of processed food products, revealing a complex network where high-income countries dominate both imports and exports. Unlike raw agricultural commodities, processed foods have lower spoilage rates but entail higher environmental costs due to energy-intensive production, packaging, and refrigeration—particularly for dairy and beverages. The trade of vegetable oils and fats also raises concerns about deforestation in major producing regions. These patterns highlight the unequal distribution of environmental burdens and the need for sustainable supply chain strategies to mitigate carbon footprints and food waste.

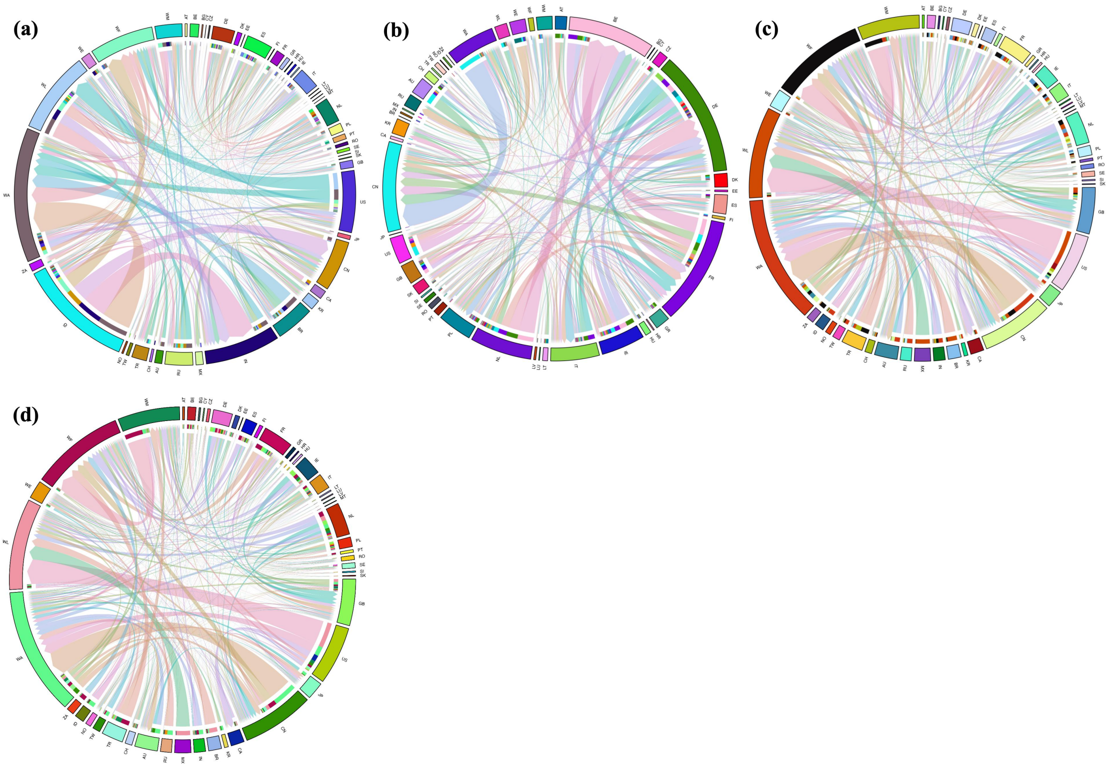


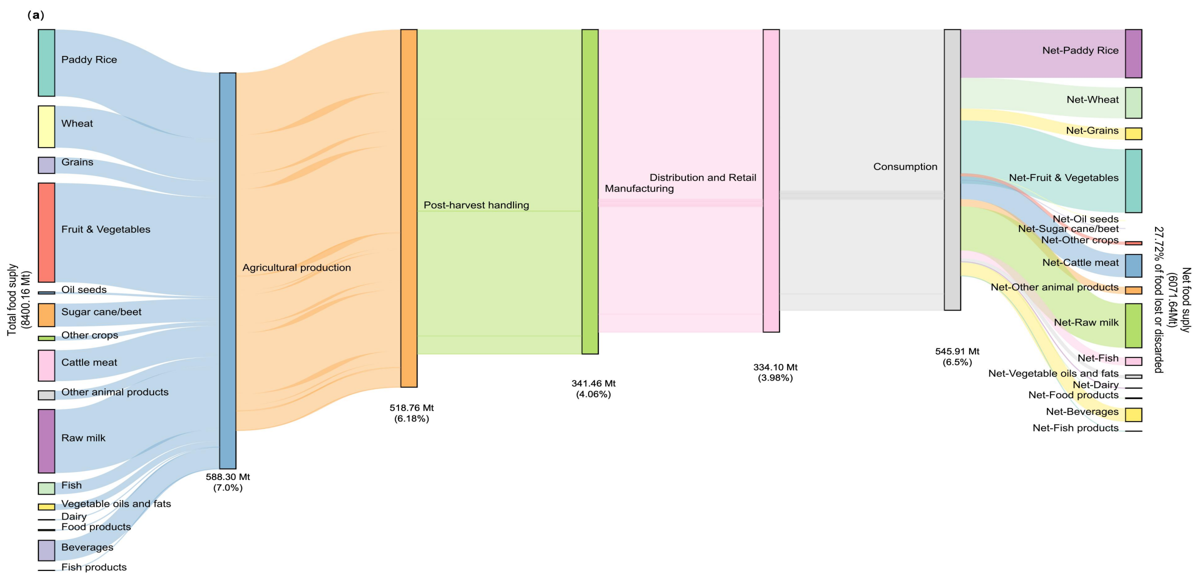
Figure 3 Bilateral food trade flows of processed food products products in the agro-food matrix in 2022. (a)Vegetable oils and fats; (b)Dairy; (c)Food products; (e)Beverages. The diagram is the same as Figure 1.

The direct and indirect losses at different stages of the global food supply chain are severe.

Direct losses refer to food loss and waste that occur at specific stages of the supply chain, such as agricultural production, post-harvest handling, distribution, retail, manufacturing, and consumption. This includes crop losses, spoilage, and inefficiencies directly associated with these activities. Indirect losses, on the other hand, arise from economic activities within the supply chain, such as agricultural inputs, processing, and transportation. These losses do not occur at a specific stage but propagate through related industries and markets. Indirect losses reflect waste that is not immediately visible at a particular stage but emerges through interactions between different industries and demand flows, such as energy consumption, transportation inefficiencies, and inefficiencies in other sectors.

Figure 4(a) illustrates the distribution of direct food loss and waste (FLW) across the global food supply chain. At the agricultural production stage, approximately 5.08 billion tons of food enter the supply chain, with 17.8% (about 910 million tons) lost during post-harvest handling, primarily affecting grain crops and perishable foods. As food moves into the distribution and retail stages, losses decrease to 340 million tons (about 3.6% of the total), though high-value foods such as fruits, vegetables, and meat still experience significant waste. Ultimately, around 490 million tons of food are wasted at the consumption stage, accounting for 5.2% of the global food supply. This is particularly pronounced in developed countries, highlighting differences in food loss and waste across supply chain stages.

Figure 4(b) presents indirect food loss and waste, which mainly results from supply chain inefficiencies such as overproduction, market demand fluctuations, and insufficient storage capacity. At the agricultural production stage, indirect losses amount to approximately 5.02 billion tons, representing 9.2% of the global food supply, with oilseeds, sugar, and animal-based foods experiencing the highest losses. During post-harvest handling, indirect losses decrease to 870 million tons (8.5%), primarily affecting grain crops and fruits. As food moves through distribution, retail, and consumption, indirect losses continue to decline, but significant losses still occur in cross-border trade of meat, dairy, and fish products. These figures indicate that different food categories and supply chain stages shape distinct loss patterns, underscoring the need to optimize logistics, improve storage conditions, and balance market supply and demand.



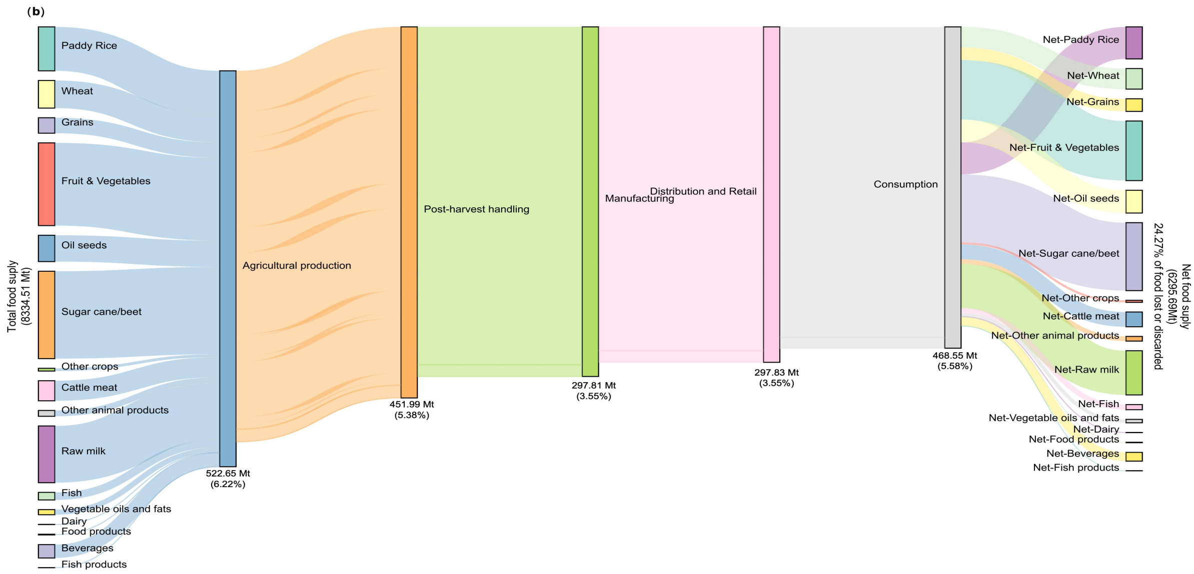


Figure 4 Global FLW generated across stages of the FSC (by reference year). (a)Direct FLW; (b)Indirect FLW.

Food loss is severe in developing countries due to infrastructure and economic constraints.

High-loss areas are typically located in developing or low-income countries, where food loss is more severe. Possible reasons include inadequate infrastructure, inefficiencies in food storage and transportation, cultural differences in consumption, and economic constraints that make food waste management more challenging. Overall, developed countries are generally more effective in reducing food loss, while developing countries face greater challenges. This disparity is closely related to differences in agricultural technology, infrastructure development, food storage and transportation systems, and public awareness.

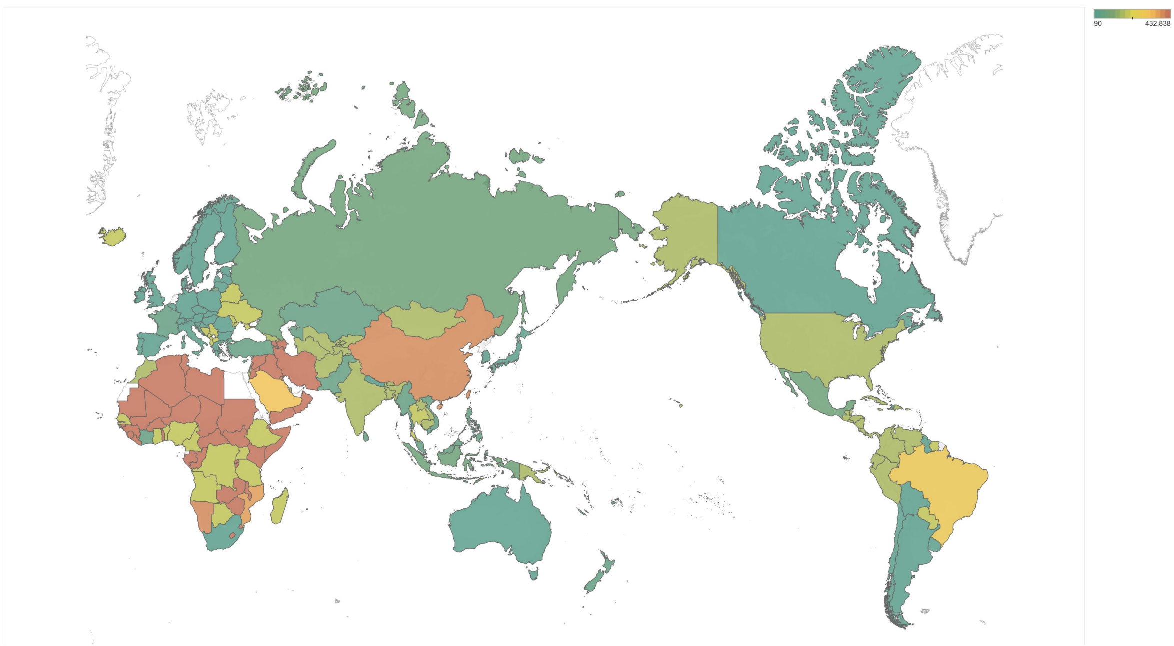


Figure 5 Regional distribution of global FLW in 2022

There is a significant imbalance in global food loss, with low-income countries experiencing more severe losses of key nutrients such as carbohydrates, fats, and proteins.

Low-income regions face more severe nutrient losses, particularly in key nutrients such as carbohydrates, fats, calories, and proteins. While developed countries also experience some level of loss, they have a greater advantage in reducing food waste and optimizing food supply chains. Carbohydrate losses are especially pronounced in certain parts of Africa, particularly in West and Central Africa, indicating significant losses across food production, distribution, and consumption stages. In contrast, developed countries, such as those in Europe, North America, and parts of Asia, experience relatively lower carbohydrate losses.

Similarly, fat losses follow a comparable distribution pattern, with high losses observed in parts of Africa and South Asia. This suggests that these regions struggle with food storage inefficiencies and supply chain limitations. In contrast, developed countries show relatively lower fat losses, likely due to differences in dietary structures, advanced food storage technologies, and consumption habits. These disparities highlight the need for targeted interventions to improve food security and nutritional sustainability in low-income regions.

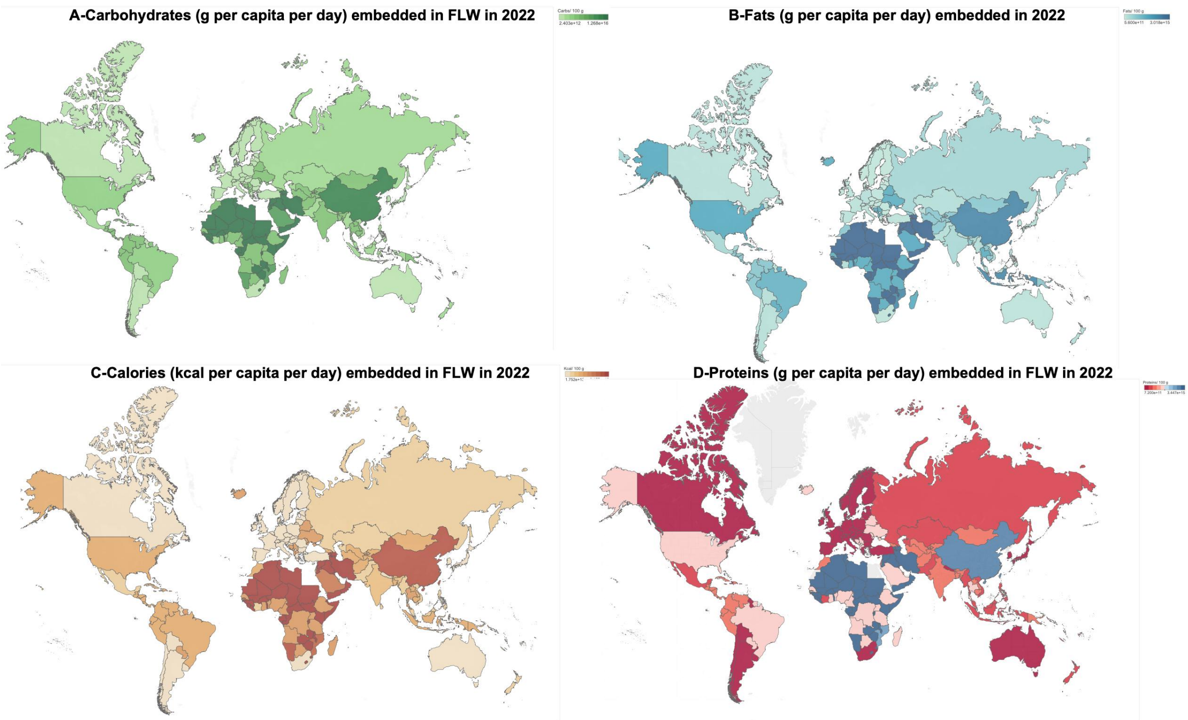


Figure 6 Nutrient loss due to FLW in different countries or regions in 2022

Discussion

The global food trade is highly uneven, with distinct regional roles and dependencies that exacerbate unequal environmental burdens. Low-income countries experience significant food losses during production and distribution due to inadequate infrastructure, inefficient supply chains, and resource constraints. In contrast, high-income countries, which dominate global food imports and exports, see higher levels of food waste at the consumption stage, largely driven by consumer behavior, retail practices, and surplus production. This imbalance results in a disproportionate environmental burden, with developing countries bearing the brunt of resource depletion and carbon emissions, while wealthier nations contribute more to post-consumer waste.

Different food categories exhibit varying trade patterns that influence the regional distribution of environmental burdens. Staple crops, oilseeds, and perishable foods such as dairy and meat face higher losses due to long-distance transportation, inadequate cold chain infrastructure, and inefficient processing methods. Developing regions suffer greater losses during storage and transit, while developed countries generate waste through overconsumption and disposal. Addressing these disparities requires targeted policies, investment in sustainable food systems, and improved global trade practices to mitigate food loss, reduce carbon footprints, and promote environmental justice.

Supplementary Figures

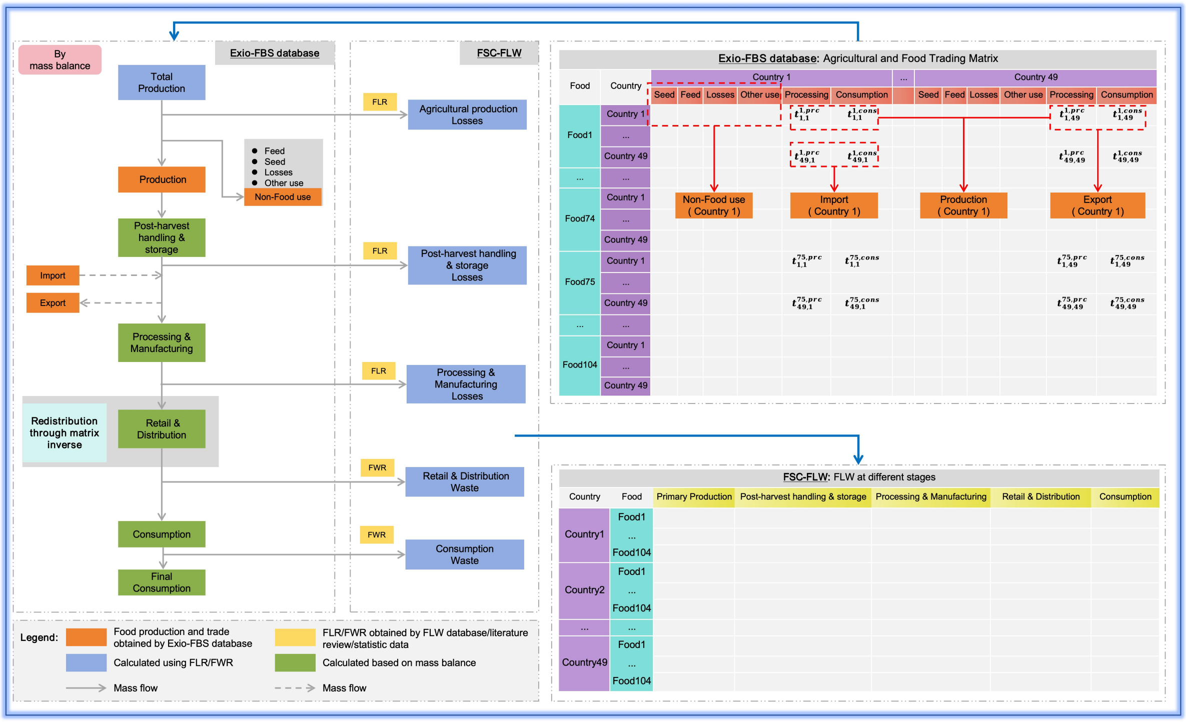


Figure S1 Measurement of direct FLW。

The methodology for tracking FLW along the food supply chain and its data sources are as follows. FLR (Food Loss Rate) refers to the food loss rates in the Agricultural Production, Post-harvest handling and storage, and Manufacturing stages. FWR (Food Waste Rate) represents the food waste rates in the Distribution and Retail, and Consumption stages.

Supplementary Tables

Table S1 Food grouping

Food Group	FBS commodity

Paddy Rice	Rice and products
Wheat	Wheat and products
Grains	Barley and products
	Maize and products
	Rye and products
	Oats
	Millet and products
	Sorghum and products
	Cereals,Other
Fruit &Vegetables	Cassava and products
	Potatoes and products
	Sweet potatoes
	Yams
	Roots,Other
	Beans
	Peas
	Pulses,Other and products
	Nuts and products
	Soyabeans
	Groundnuts (Shelled Eq)
	Coconuts -Incl Copra
	Tomatoes and products
	Onions
	Vegetables,Other
	Oranges,Mandarines
	Lemons,Limes and products
	Grapefruit and products
	Citrus,Other
	Bananas
	Plantains
	Apples and products
	Pineapples and products
	Dates
	Grapes and products (excl wine)
	Fruits,Other
Oil seeds	Sunflower seed
	Rape and Mustardseed
	Sesameseed
	Olives (including preserved)
	Oilcrops,Other
	Palm kernels
	Cottonseed
Sugar cane/beet	Sugar cane
	Sugar beet
	Sugar non-centrifugal
	Sugar (Raw Equivalent)
	Sweeteners,Other
Other crops	Coffee and products
	Cocoa Beans and products

	Tea (including mate)
	Pepper
	Pimento
	Cloves
	Spices,Other
Cattle meat	Bovine Meat
	Pigmeat
	Poultry Meat
	Mutton &Goat Meat
	Meat,Other
Other animal products	Honey
	Offals, Edible
	Fats,Animals,Raw
	Eggs
Raw milk	Milk - Excluding Butter
Fish	Freshwater Fish
	Demersal Fish
	Pelagic Fish
	Marine Fish,Other
	Crustaceans
	Cephalopods
	Molluscs,Other
	Aquatic Animals,Others
	Aquatic Plants
	Meat,Aquatic Mammals
Vegetable oils and fats	Soyabean Oil
	Groundnut Oil
	Sunflowerseed Oi
	Rape and Mustard Oil
	Cottonseed Oil
	Palmkernel Oi
	Palm Oil
	Coconut Oil
	Sesameseed Oil
	Olive Oil
	Ricebran Oi
	Maize Germ Oil
	Oilcrops Oil,Other
Dairy	Butter,Ghee
	Cream
Food products	Infant food
	Miscellaneous
Beverages	Wine
	Beer
	Beverages, Fermented
	Beverages, Alcoholic
	Alcohol, Non-Food
Fish products	Fish, Body Oil
	Fish, Liver Oil

Table S2 Literature review quantifying food loss and its environmental impact

Author	Research object	Method	Data	FLW		Environmental analysis included				
				Food products	Stage	GHG	Water	Energy	Land	Nutrition
Gatto et al. (2024)[14]	Global	IO	GTAP-FBS	All (11)	All (5)	√	√	√	√	√
Li et al. (2021)[13]	China	Mass balance	Field research, literature	All (7)	All (6)	√	√	√	√	
Osei-Owusu et al. (2020)[12]	European	IO	Exiobase	All (11)	All (4)	√	√	√	√	
Read et al. (2020)[16]	United States	IO	U.S. Bureau of Economic Analysis (BEA)	All (10)	All (4)	√	√	√	√	√
Zhu et al. (2023)[17]	Global	LCA	FAO	All (4)	All (8)	√				
The study	Global	IO	Exiobase	All (98)	All (5)	√	√	√	√	√

Table S3 Countries in the FAOSTAT mapped to the EXIOBASE

Country/region abbreviation	Country/region in EXIOBASE	Country in FBS
AT	Austria	Austria
BE	Belgium	Belgium
BG	Bulgaria	Bulgaria
CY	Cyprus	Cyprus
CZ	Czech Republic	Czechia
DE	Germany	Germany
DK	Denmark	Denmark
EE	Estonia	Estonia
ES	Spain	Spain
FI	Finland	Finland
FR	France	France
GR	Greece	Greece
HR	Croatia	Croatia
HU	Hungary	Hungary
IE	Ireland	Ireland
IT	Italy	Italy
LT	Lithuania	Lithuania
LU	Luxembourg	Luxembourg
LV	Latvia	Latvia
MT	Malta	Malta
NL	Netherlands	Netherlands (Kingdom of the)
PL	Poland	Poland
PT	Portugal	Portugal
RO	Romania	Romania

SE	Sweden	Sweden
SI	Slovenia	Slovenia
SK	Slovakia	Slovakia
GB	United Kingdom	United Kingdom of Great Britain and Northern Ireland
US	United States	United States of America
JP	Japan	Japan
CN	China	China
CA	Canada	Canada
KR	South Korea	Republic of Korea
BR	Brazil	Brazil
IN	India	India
MX	Mexico	Mexico
RU	Russia	Russian Federation
AU	Australia	Australia
CH	Switzerland	Switzerland
TR	Turkey	Türkiye
TW	Taiwan	China, Taiwan Province of
NO	Norway	Norway
ID	Indonesia	Indonesia
ZA	South Africa	South Africa
WA	RoW Asia and Pacific	Kenya
		Thailand
		Nepal
		Bangladesh
		Côte d'Ivoire
		Malaysia
		Kazakhstan
		Sri Lanka
		Pakistan
		Fiji
		Philippines
		Bahrain
		New Zealand
		Viet Nam
		New Caledonia
		Myanmar
		Cambodia
		Lao People's Democratic Republic
		Saudi Arabia
		Israel
		French Polynesia

		Qatar
		Samoa
		Georgia
		Uzbekistan
		Kyrgyzstan
		Maldives
		Papua New Guinea
		Mongolia
		Vanuatu
		Bhutan
		Afghanistan
		Solomon Islands
		Marshall Islands
		Tajikistan
		Tonga
		Timor-Leste
		Turkmenistan
		Kiribati
		Nauru
		Micronesia (Federated States of)
		Tuvalu
WL	RoW America	Guatemala
		Honduras
		Colombia
		Peru
		Costa Rica
		Dominican Republic
		Ecuador
		Morocco
		Jamaica
		Trinidad and Tobago
		Belize
		Venezuela (Bolivarian Republic of)

Table S4. Activities in the EXIOBASE mapped to the food supply chain stages.

Food supply chain stage	Resolved EXIOBASE activity
Primary agriculture production	Cultivation of paddy rice Cultivation of wheat Cultivation of cereal grains n.e.c Cultivation of vegetables, fruit, nuts Cultivation of oil seeds Cultivation of sugar cane, sugar beet Cultivation of plant-based fibres Cultivation of crops n.e.c Cattle farming Pigs farming

	Poultry farming
	Meat animals n.e.c
	Animal products n.e.c
	Raw milk
	Fishing, operating of fish hatcheries and fishfarms; service activities incidental to fishing
Processing	Processing of meat cattle
	Processing of meat pigs
	Processing of meat poultry
	Production of meat products n.e.c
	Processing vegetable oils and fats
	Processing of dairy products
	Processed rice
	Sugar refining
	Processing of Food products n.e.c
	Manufacture of beverages
	Manufacture of fish products
Food service	Hotels and restaurants
	Transport via railways
	Other land transport
	Transport via pipelines
	Sea and coastal water transport
	Inland water transport
	Air transport
	Supporting and auxiliary transport activities; activities of travel agencies
	Other service activities
	Private households with employed persons
Institutional	Other business activities
	Public administration and defence; compulsory social security
	Education
	Health and social work
	Recreational, cultural and sporting activities
	Extra-territorial organizations and bodies

Table S5 Activities in the EXIOBASE mapped to different food uses

Activity name	Different food uses in FBS
Cultivation of paddy rice	seed
Cultivation of wheat	seed
Cultivation of cereal grains nec	seed
Cultivation of vegetables, fruit, nuts	seed
Cultivation of oil seeds	seed
Cultivation of sugar cane, sugar beet	seed
Cultivation of plant-based fibers	seed
Cultivation of crops nec	seed
Cattle farming	feed
Pigs farming	feed
Poultry farming	feed
Meat animals nec	feed
Animal products nec	feed
Raw milk	feed
Wool, silk-worm cocoons	Other uses (non-food)
Manure treatment (conventional), storage and land application	Other uses (non-food)
Manure treatment (biogas), storage and land application	Other uses (non-food)
Forestry, logging and related service activities	Other uses (non-food)

Fishing, operating of fish hatcheries and fish farms; service activities incidental to fishing (05)	feed
Mining of coal and lignite; extraction of peat	Other uses (non-food)
Extraction of crude petroleum and services related to crude oil extraction, excluding surveying	Other uses (non-food)
Extraction of natural gas and services related to natural gas extraction, excluding surveying	Other uses (non-food)
Extraction, liquefaction, and regasification of other petroleum and gaseous materials	Other uses (non-food)
Mining of uranium and thorium ores	Other uses (non-food)
Mining of iron ores	Other uses (non-food)
Mining of copper ores and concentrates	Other uses (non-food)
Mining of nickel ores and concentrates	Other uses (non-food)
Mining of aluminium ores and concentrates	Other uses (non-food)
Mining of precious metal ores and concentrates	Other uses (non-food)
Mining of lead, zinc and tin ores and concentrates	Other uses (non-food)
Mining of other non-ferrous metal ores and concentrates	Other uses (non-food)
Quarrying of stone	Other uses (non-food)
Quarrying of sand and clay	Other uses (non-food)
Mining of chemical and fertilizer minerals, production of salt, other mining and quarrying n.e.c.	Other uses (non-food)
Processing of meat cattle	processing
Processing of meat pigs	processing
Processing of meat poultry	processing
Production of meat products nec	processing
Processing vegetable oils and fats	processing
Processing of dairy products	processing
Processed rice	processing
Sugar refining	processing
Processing of Food products nec	processing
Manufacture of beverages	processing
Manufacture of fish products	processing
Manufacture of tobacco products	Other uses (non-food)
Manufacture of textiles	Other uses (non-food)
Manufacture of wearing apparel; dressing and dyeing of fur	Other uses (non-food)
Tanning and dressing of leather; manufacture of luggage, handbags, saddlery, harness and footwear (19)	Other uses (non-food)
Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials (20)	Other uses (non-food)
Re-processing of secondary wood material into new wood material	Other uses (non-food)
Pulp	Other uses (non-food)
Re-processing of secondary paper into new pulp	Other uses (non-food)

Paper	Other uses (non-food)
Publishing, printing and reproduction of recorded media	Other uses (non-food)
Manufacture of coke oven products	Other uses (non-food)
Petroleum Refinery	Other uses (non-food)
Processing of nuclear fuel	Other uses (non-food)
Plastics, basic	Other uses (non-food)
Re-processing of secondary plastic into new plastic	Other uses (non-food)
N-fertiliser	Other uses (non-food)
P- and other fertiliser	Other uses (non-food)
Chemicals nec	Other uses (non-food)
Manufacture of rubber and plastic products	Other uses (non-food)
Manufacture of glass and glass products	Other uses (non-food)
Re-processing of secondary glass into new glass	Other uses (non-food)
Manufacture of ceramic goods	Other uses (non-food)
Manufacture of bricks, tiles and construction products, in baked clay	Other uses (non-food)
Manufacture of cement, lime and plaster	Other uses (non-food)
Re-processing of ash into clinker	Other uses (non-food)
Manufacture of other non-metallic mineral products n.e.c.	Other uses (non-food)
Manufacture of basic iron and steel and of ferro-alloys and first products thereof	Other uses (non-food)
Re-processing of secondary steel into new steel	Other uses (non-food)
Precious metals production	Other uses (non-food)
Re-processing of secondary preciuos metals into new preciuos metals	Other uses (non-food)
Aluminium production	Other uses (non-food)
Re-processing of secondary aluminium into new aluminium	Other uses (non-food)
Lead, zinc and tin production	Other uses (non-food)
Re-processing of secondary lead into new lead, zinc and tin	Other uses (non-food)
Copper production	Other uses (non-food)
Re-processing of secondary copper into new copper	Other uses (non-food)
Other non-ferrous metal production	Other uses (non-food)
Re-processing of secondary other non-ferrous metals into new other non-ferrous metals	Other uses (non-food)
Casting of metals	Other uses (non-food)
Manufacture of fabricated metal products, except machinery and equipment	Other uses (non-food)
Manufacture of machinery and equipment n.e.c.	Other uses (non-food)
Manufacture of office machinery and computers	Other uses (non-food)
Manufacture of electrical machinery and apparatus n.e.c.	Other uses (non-food)
Manufacture of radio, television and communication equipment and apparatus	Other uses (non-food)
Manufacture of medical, precision and optical instruments, watches and clocks	Other uses (non-food)
Manufacture of motor vehicles, trailers and semi-trailers	Other uses (non-food)
Manufacture of other transport equipment	Other uses (non-food)
Manufacture of furniture; manufacturing n.e.c.	Other uses (non-food)
Recycling of waste and scrap	Other uses (non-food)

Recycling of bottles by direct reuse	Other uses (non-food)
Production of electricity by coal	Other uses (non-food)
Production of electricity by gas	Other uses (non-food)
Production of electricity by nuclear	Other uses (non-food)
Production of electricity by hydro	Other uses (non-food)
Production of electricity by wind	Other uses (non-food)
Production of electricity by petroleum and other oil derivatives	Other uses (non-food)
Production of electricity by biomass and waste	Other uses (non-food)
Production of electricity by solar photovoltaic	Other uses (non-food)
Production of electricity by solar thermal	Other uses (non-food)
Production of electricity by tide, wave, ocean	Other uses (non-food)
Production of electricity by Geothermal	Other uses (non-food)
Production of electricity nec	Other uses (non-food)
Transmission of electricity	Other uses (non-food)
Distribution and trade of electricity	Other uses (non-food)
Manufacture of gas; distribution of gaseous fuels through mains	Other uses (non-food)
Steam and hot water supply	Other uses (non-food)
Collection, purification and distribution of water (41)	Other uses (non-food)
Construction (45)	Other uses (non-food)
Re-processing of secondary construction material into aggregates	Other uses (non-food)
Sale, maintenance, repair of motor vehicles, motor vehicles parts, motorcycles, motor cycles parts and accessoiries	Other uses (non-food)
Retail sale of automotive fuel	Other uses (non-food)
Hotels and restaurants	food
Transport via railways	food
Other land transport	food
Transport via pipelines	food
Sea and coastal water transport	food
Inland water transport	food
Air transport (62)	food
Supporting and auxiliary transport activities; activities of travel agencies	food
Other business activities	food
Public administration and defence; compulsory social security	food
Education	food
Health and social work	food
Recreational, cultural and sporting activities	food
Other service activities	food
Private households with employed persons	food
Extra-territorial organizations and bodies	food
Final consumption expenditure by households	food
Final consumption expenditure by non-profit organisations serving households (NPISH)	food

Final consumption expenditure by government	food

Table S6 Research on FLW in existing literature

Author	Research object	FSC stage	Result in the literature (%)	Result in our study in 2022(%)
Gatto et al. (2024)[13]	Global(141 countries)	Production	6.6	7.00
	2014 yrs	Post Harvest Handling & Storage	7.3	6.18
		Manufacturing	3.1	4.06
		Distribution & Retail	4.0	3.98
		Consumption	7.2	6.50
		Total	28.2	27.72

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