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Physical understanding of food systems towards sustainability with material flow analysis: A critical review

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ABSTRACT

Transforming food systems is essential for global sustainability and requires understanding from both socioeconomic and physical dimensions. However, sustainable food systems literature is largely dominated by socioeconomic dimension, while physical understanding of food systems remains limited. Such physical characterisation is often done using material flow analysis (MFA) to explore and quantify flows from farm to fork. This quantification translates food system dynamics into comparable and transparent metrics, making MFA a crucial tool in driving an efficient transformation. Here, using a critical literature review, we analysed 127 agrifood MFA studies on their systems, data, and indicators. We characterized food supply chain into five stages (primary production, processing and manufacturing, trade, distribution and retailing, and public and household consumption) and found very few covered all stages (16 studies). Among all stages, primary production was the most studied (99 studies), while distribution and retailing was the least studied (33 studies). Existing studies covered 12 food categories, primarily focusing on cereals (52 %), vegetables (46 %), and meats (43 %), with less attention on dairy products (34 %). Only 34 studies have a single food category resolution, while most aggregated multiple categories together. We found that over half of agrifood MFAs used data only from secondary sources (e.g., statistics), whereas less than 20 % used exclusively primary data. Agrifood MFAs commonly used indicators of substance, food, and bio-nutrient to quantify biomass associated flows, informing key food systems issues like nutrient circularity and waste management. Accordingly, we call for research on full chain MFAs, single food category analyses, and the use of more targeted datasets.

1. Introduction

Global food systems nourish over 8 billion human beings through a set of activities such as crop planting, animal husbandry, meat processing, and long-distance logistics (FAO, 2018). These activities, however, have posed considerable environmental concerns (FAO, 2019) such as greenhouse gas (GHG) emissions (Crippa et al., 2021) and resource depletion (Martínez-Valderrama et al., 2020). Given these significant impacts, food system transformation has attracted wide attention from policymakers, industry, and the general public across the world. The United Nations has put food systems at the core of their Sustainable Development Goals (SDGs), including SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) (UN, 2015). Region wise, European Union commits to transforming food systems towards fairness, health, and environmental sustainability (EU, 2020). As outlined in the European Union Farm to Fork Strategy, this transformation requires collaborative efforts across disciplines and stakeholders to achieve key targets including mitigating environmental burdens, reducing and preventing waste, promoting a circular economy, protecting social well-being, and strengthening

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legislative frameworks (EU, 2020).

Sustaining and transforming food systems requires understanding and characterization of the food systems from multiple social, economic, and environmental perspectives, which could be supported by various scientific disciplines (FAO, 2014, 2018). In the economic domain, food system analysis is largely monetary and societal oriented. For example, the effects of policy instruments like GHG taxation on production costs are stimulated using regression models (Chen et al., 2025) and the impacts of certain economic indicators, like price volatility, on food systems resilience are also assessed in economic research (Schneider et al., 2025). Consequently, such economic studies could inform food system transition through various economic strategies, such as circular bio-based economy practices (Khanna et al., 2024) and waste and byproducts valorisation (Yeo et al., 2024). The social science domain, instead, focuses on well-being and justice, addressing topics like access to adequate and nutritious food (Fei et al., 2023) and advancing gender equality in agrifood labour market (Schneider et al., 2025). It is important that such economic and social analyses should adopt a system perspective that does not address any food issues in isolation.

Beyond these socioeconomic perspectives, a physical understanding of food systems from farm to fork is also essential for sustainable food system transition. Based on system-wide accounting of material flows within a given system, this physical perspective focuses on the mass balance principle and can translate food system dynamics into comparable and transparent metrics, profiling how materials enter, accumulate, are processed, and are wasted. All these insights could inform policy and research with decision grade evidence as they i) provide detailed analyses into specific sustainability issues, such as nutrient circularity, which is closely linked to phosphorus and nitrogen flows (Mohammadpour and Grady, 2023); ii) improve food supply chain (FSC) efficiency, as inefficiencies like byproduct generation (Xue et al., 2019) and food loss and waste (FLW) (Caldeira et al., 2021) could be identified through food flows quantification; iii) advance circular economy strategies like biogas production by quantifying bio-resources along FSC (Koppelmäki et al., 2019); and iv) reveal food system resilience hotpots, for example the extent to which certain countries rely on foreign food products (Rezende et al., 2023). In addition, when conducted in a dynamic manner, physical understanding helps explore long-term changes in food systems, such as the effects of increased fertilization on nitrogen cycling over 150 years (Neset et al., 2008). Last but not least, the physical understanding of food systems is necessary to provide reliable system-based, data-driven, and evidence-supported solutions to inform strategies and decision makings (Müller et al., 2024). This strength, when combined with environmental and socioeconomic parameters, can also be applied to discuss environmental and socioeconomic implications (Jia et al., 2022; Xue et al., 2021).

A solid physical understanding of food systems relies on system tools, among which Material Flow Analysis (MFA) is widely recognized (Müller et al., 2024). In practice, MFA has been extensively applied to track material flows in food systems, commonly in the forms of substances, food items, and bio-nutrients. However, several issues were identified among MFA studies in the agrifood domain, but a comprehensive review to better synthesize these issues has been lacking to date. Specially, those issues are mainly related to the key components of physical understanding identified by Müller et al. (2024), including systems, data, and indicators. For systems, food systems encompass complex activities (FAO, 2018) and diverse food categories, making it challenging for agrifood MFA studies to develop an integrated system that covers all these activities and categories. For data, current agrifood MFAs commonly rely on data coming from a variety of sources that may employ inconsistent methodologies and then introduce uncertainty in their results. For instance, the amount of rice exported by Vietnam to China can vary by nearly 50 % between different databases (Liu et al., 2023). An overview of data sources across studies can guide future research by identifying data gaps and useful sources. For indicators, flow quantifications in agrifood MFAs differ in the indicators they used, for example, to track flows in cereals sector, studies have used indicators of either energy (Kheiralipour and Sheikhi, 2021) or phosphorus (Koppelmäki et al., 2019). These indicators offer diverse insights into food systems and should be systematic classified to facilitate their consolidation and effective use in these studies.

A critical synthesis is needed to address all these issues related to agrifood MFA and thereby enhance its application in food system transformation. Hence, aiming to provide an overview of how current agrifood MFAs contribute to physical understanding of food systems, we conducted a critical literature review on 127 peer-reviewed studies. Our review focused on the key components of physical understanding, including systems (spatial boundaries, coverages of FSC and food category), data, and indicators (for both flow quantification and impact assessment) (Müller et al., 2024). We sought to advance physical understandings of food systems by profiling current agrifood MFAs, identifying limitations, and offer directions for future research and policymaking.

2. Methodology

2.1. Literature selection

We employed the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) (Page et al., 2021) to select eligible literature. The workflow of literature selection across PRISMA stages is illustrated in Fig. 1 and described as follows.

2.1.1. Stage 1: identification

This study used both Scopus and Web of Science databases to ensure a wide coverage of peer-reviewed articles. We tested various keywords combinations for literature searching to ensure broad literature coverage while simultaneously identifying an operationally manageable number of literature entries. Table S1–S3 present detailed results of the number of entries retrieved in literature search tests. The final search strings (presented in Supporting Information, Section 1) combined the keyword “food” with terms including “MFA”, “material flow analysis”, “mass flow analysis”, “substance flow analysis”. We excluded the specific term of “SFA” from the search strings as it would yield an unmanageably large number of entries: 4453 compared to 954 in this study, making the literature selection process impractical. Our literature retrieval focused on English-language literature and did not apply any time frame filters. The final literature retrieval was performed on January 28, 2024 with a total of 954 studies being identified. After excluding 330 duplicates and 61 other records (e.g., errata and editorial materials), 563 studies were included in the literature screening stage.

2.1.2. Stage 2: screening

During the screening stage, we conducted content-based screening to identify eligible literature. This stage comprised two phases: Phase 2.1 focused on screening the title, abstract, and keywords of the studies, and the following Phase 2.2 focused on reviewing the full text. Both phases applied the same selection criteria: (i) the study must include any type of MFA application (e.g., material flow analysis, mass flow analysis, substance flow analysis), and (ii) it must address at least one food system activity like crop harvesting (these activities classified and described in Table S5). In Phase 2.1, 420 out of 563 studies did not meet the criteria and were excluded, leaving 143 studies. Among these, four studies were further excluded due to inaccessible full texts, resulting in 139 studies advancing to Phase 2.2. In Phase 2.2, 12 studies were eliminated because they failed to meet the criteria upon full-text review. Ultimately, 127 peer-reviewed studies were deemed eligible and included in this review.

2.2. Data processing and analysis

All eligible literature was imported into the open-source toolkit

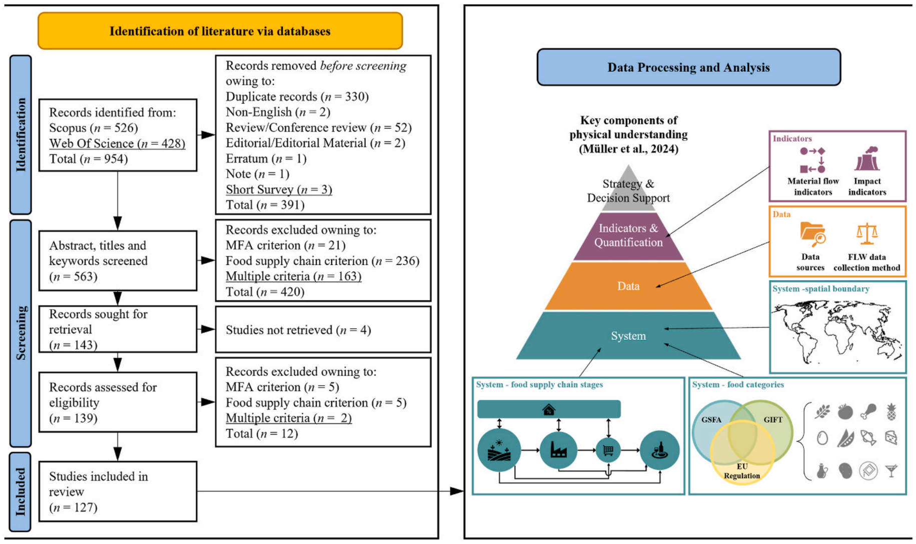


Fig. 1. Workflow of agrifood MFA literature selection and data analysis based on PRISMA (Page et al., 2021) and physical understanding components framework (Müller et al., 2024).

Bibliometrix (Aria and Cuccurullo, 2017) for bibliometric analysis, which included publication trend examination and CoWordNet and Word Cloud analyses on literature titles. Meta-data of all studies was then manually extracted and analysed from the following aspects, based on the key components of physical understanding identified by Müller et al. (2024): systems (including spatial boundary, FSC coverage, and food category coverage), data (including data source and FLW data collection method), and indicators (including material flow quantification and impact assessment indicators). The meta-data harmonizations are described in detail below.

Spatial boundary. We adopted the term "spatial boundary" as used in the study of Lanau et al., (2019) to refer to the geographical scope of MFA research, indicating the geographical extent within which all investigated food-related processes and associated material flows were considered. This review classified spatial boundaries into five scales: municipal or neighbourhood, sub-national, national, regional, and global levels (see their descriptions in Supporting Information, Section 2.1).

FSC stage. This study built on the common MFA framework proposed by Caldeira et al. (2021) to identify FSC stage coverage in literature. Our framework covers five stages along an entire FSC: (1) primary production, (2) processing and manufacturing, (3) trade, (4) distribution and retailing, and (5) public and household consumption. A detailed description of all stages is provided in Table S5.

Food category. Widely applied frameworks on food categorization include the Codex General Standard for Food Additives (GSFA) (FAO/WHO, 2019), EU Regulation (EC) No 1333/2008 on Food Additives (European Commission, 2022), and FAO/WHO Global Individual Food consumption data Tool (GIFT) (FAO/WHO, 2022). However, these frameworks differ in their classification of certain food categories. For instance, fruits and vegetables are typically grouped together as a single category in Codex GSFA and EU Regulation (EC) No 1333/2008, whereas they are defined separately in the GIFT framework. When such differences arise, we adopt the framework with the highest resolution of food categorization. Therefore, vegetables and fruits are treated as separate categories in this study, following the GIFT framework. For a detailed classification of food categories used in this study and their connections to the three referenced frameworks, please refer to Table S7.

Data source. The data used in studies were categorized into two major groups: primary data and secondary data. Primary data refers to data directly collected by the authors, such as using surveys, while secondary data refers to data previously collected and recorded in databases or literature. Moreover, specific secondary data sources include statistical data (mainly from official agencies/statistics), literature data (primarily reported in publications), and non-public data (such as datasets developed by research institutions or commercial data companies that are not publicly accessible). A detailed data classification including definitions and examples is presented in Table S6.

FLW data collection method. The FLW Protocol, developed by a steering committee of seven expert institutions such as the FAO, typically classifies FLW data collection methods into 10 types, including (1) direct weighing, (2) counting, (3) assessing volume, (4) waste composition analysis, (5) records, (6) diaries, (7) surveys, (8) mass balance, (9) modelling, and (10) proxy data (FLW Protocol, 2016). Our study classified all the methods used in agrifood MFAs to quantify FLW based on these 10 methods, and more specifically classified the first seven methods as the measurement or assessment of FLW and the remaining three methods (mass balance, modelling, and proxy data) as calculations of FLW.

Indicators. All indicators were first categorized into two groups: 1) material flow quantification indicators related to biomass along the supply chain, and 2) impact assessment indicators. The former refers to the units used to quantify or estimate biomass related flows within the food systems. Example could be substance flows quantified in the unit of phosphorus. All the material flow related indicators were classified into three clusters: substance, food, and bio-nutrient. The latter was used to assess the impacts of food systems, such as GHG emission, and those impact indicators were classified into three clusters: environmental, economic, and health.

3. Results

3.1. Bibliometric analysis

Publication trend. It is found that the application of MFA in agrifood research began in 2003 and maintained an average of around 2 publications per year until the first peak in 2015 (Fig. 2a). Although the number of publications declined in a few years after 2015, there was an overall growing trend, with over 80 % of total studies published afterwards. Notably, 2022 is the year with the most publications to date (n = 22, referring to the number of publications, the same applies to the following numbers).

Journal coverage. Reviewed studies were published in 51 different

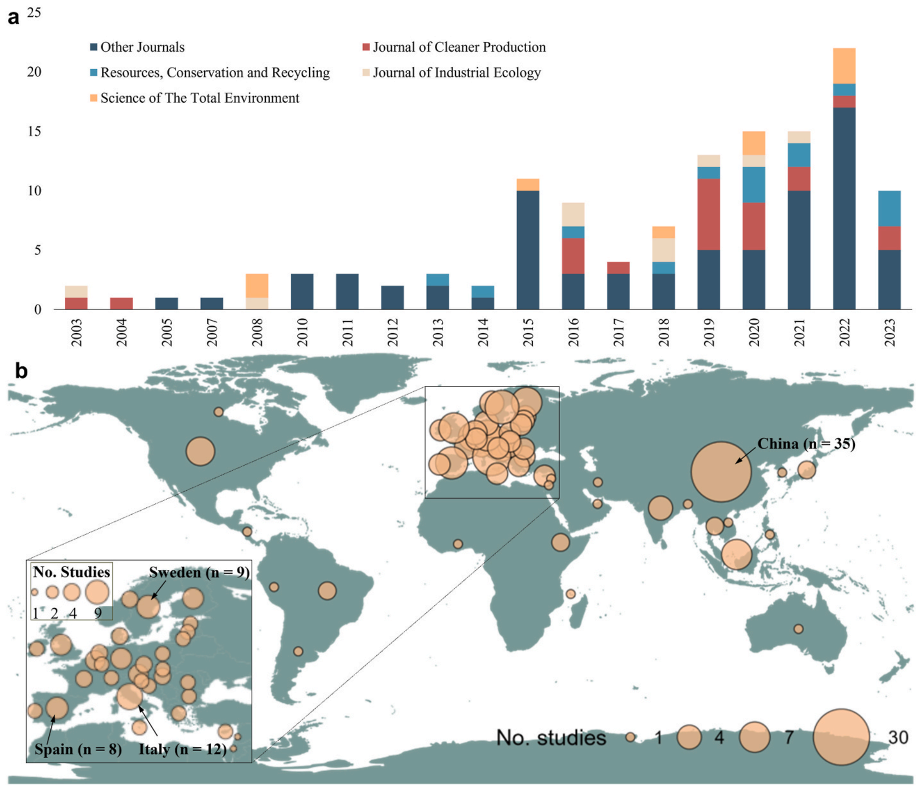


Fig. 2. a) Publication trends over the years across journals, with the top four journals specified. b) Geographic distribution of national agrifood MFA studies.

journals. The Journal of Cleaner Production has the highest number of publications (n = 21), followed by Resources, Conservation and Recycling (n = 14), Journal of Industrial Ecology (n = 9), and Science of The Total Environment (n = 9) (Fig. S1). These four journals collectively account for over 40 % of the total literature identified in this review (Fig. 2a).

Bibliometric analysis of titles. Fig. S2b shows that the titles of articles prevalently include production, environmental impacts, consumption, waste management, and specific substance (phosphorus and nitrogen) terms. These topics could be further divided into three clusters (Fig. S2a). The first cluster (in red) includes themes related to “food”, “flow”, “analysis”, “waste”, and “material”. The second cluster (in blue) consists of words such as “phosphorus”, “production”, “nitrogen”, and “consumption”. The third cluster (in green) mainly consists of impact assessment themes, focusing on both environmental and economic aspects.

Geographical distribution of literature. The reviewed studies covered all continents, but their distribution was clearly uneven (Fig. 2b). A majority of publications focused on Asia (n = 56) and Europe (n = 51), whereas only a few studies covered North America (n = 8), South America (n = 4), Africa (n = 4), and Oceania (n = 1). Under-researched continents, such as Africa and South America (accounting for only 6 % of publications combined), currently face severe food security challenges (FAO, 2023) and should receive greater research attention. Country wise, China received the most attention with approximately 30 % of reviewed studies related to its food systems, which is followed by Italy and Sweden. Specifically, studies related to (or parts of) China’s food systems were mostly conducted at the municipal or neighbourhood and national levels (Fig. S3). In contrast, studies on Italy’s food systems were primarily at the national level, while those on Sweden’s food systems were dominated by municipal analyses. Transforming food systems requires concerted efforts across the municipal, national, regional, and global levels (FAO, 2018). However, regional (n = 5) and global (n = 3) studies were relatively scarce across all studies, hindering an effective transformation.

3.2. Systems for agrifood MFAs

3.2.1. Food supply chain coverage

Fig. 3a illustrates the supply chain coverages across all reviewed studies. We found that only 16 out of 127 studies covered all stages of the FSC (including primary production, processing and manufacturing, trade, distribution and retailing, public and household consumption). Among the remaining studies, 23 focused exclusively on the primary production stage, 21 covered all stages except distribution and retailing, and 16 focused exclusively on the public and household consumption stage. At the individual stage level, the primary production stage was the most frequently covered (n = 99), followed by the stage of public and household consumption (n = 82) and the stage of processing and manufacturing (n = 73). In contrast, only around 40 % of all the studies explored the trade stage (n = 55), while the distribution and retailing stage was more rarely covered (n = 33).

3.2.2. Food category coverage

Fig. 4a shows that a total of 12 food categories has been explored in agrifood MFAs, namely cereals, vegetables, meats, fruits, dairy products, eggs, pulses and legumes, fish and aquatic products, fats and oils, potato and other roots/tubers, sugars, and beverages. However, these categories are covered unbalanced. The most frequently covered food category was cereals (accounting for 51 % of the total studies), followed by vegetables (46 %), meats (43 %), fruits (37 %), and dairy products (35 %). In contrast, fewer studies focused on potatoes and other roots/tubers (16 %), sugars (14 %), and beverages (9 %).

This review found that agrifood MFAs commonly aggregated multiple food categories, while only a few studies concentrated on a single food category such as cereals, meats, and vegetables (Fig. 4a and c). In studies covering multiple food categories, vegetables were often explored alongside fruits, while meats were frequently studied with dairy products (Fig. S4). This research focus may stem from the similar consumption patterns of fruits and vegetables (Eurostat, 2019; USDA, 2018), or the shared production characteristics of meats and dairy

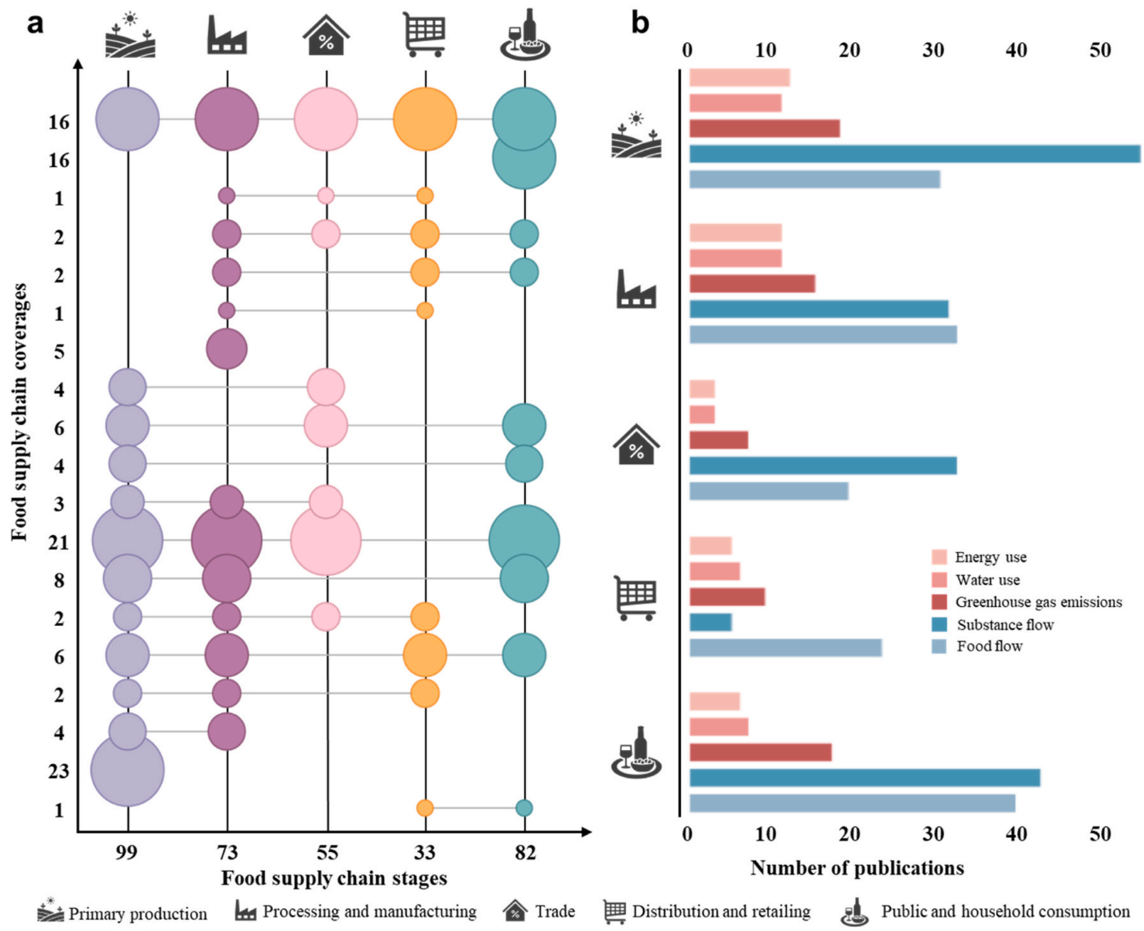


Fig. 3. a) FSC coverage across all studies. The bubbles connected by horizontal lines indicate which FSC stages are covered by the same study and the number of publications of such FSC coverage. The numbers on the horizontal axis indicate how many studies have covered each FSC stage. **b) Distributions of key indicators on material flow quantification (substance and food) and impact assessment (energy use, water use, greenhouse gas emission) across different FSC stages.** The bars represent the number of publications that apply a specific indicator at a given FSC stage.

products like livestock farming practices (Rothwell et al., 2020; Vingerhoets et al., 2023). When breaking down food categories across different FSC stages, cereals, vegetables, and meats dominating all the stages (Fig. 4b). Notably, studies focused on meats outnumbered those on cereals in all FSC stages, except for the primary production stage.

3.3. Data for agrifood MFAs

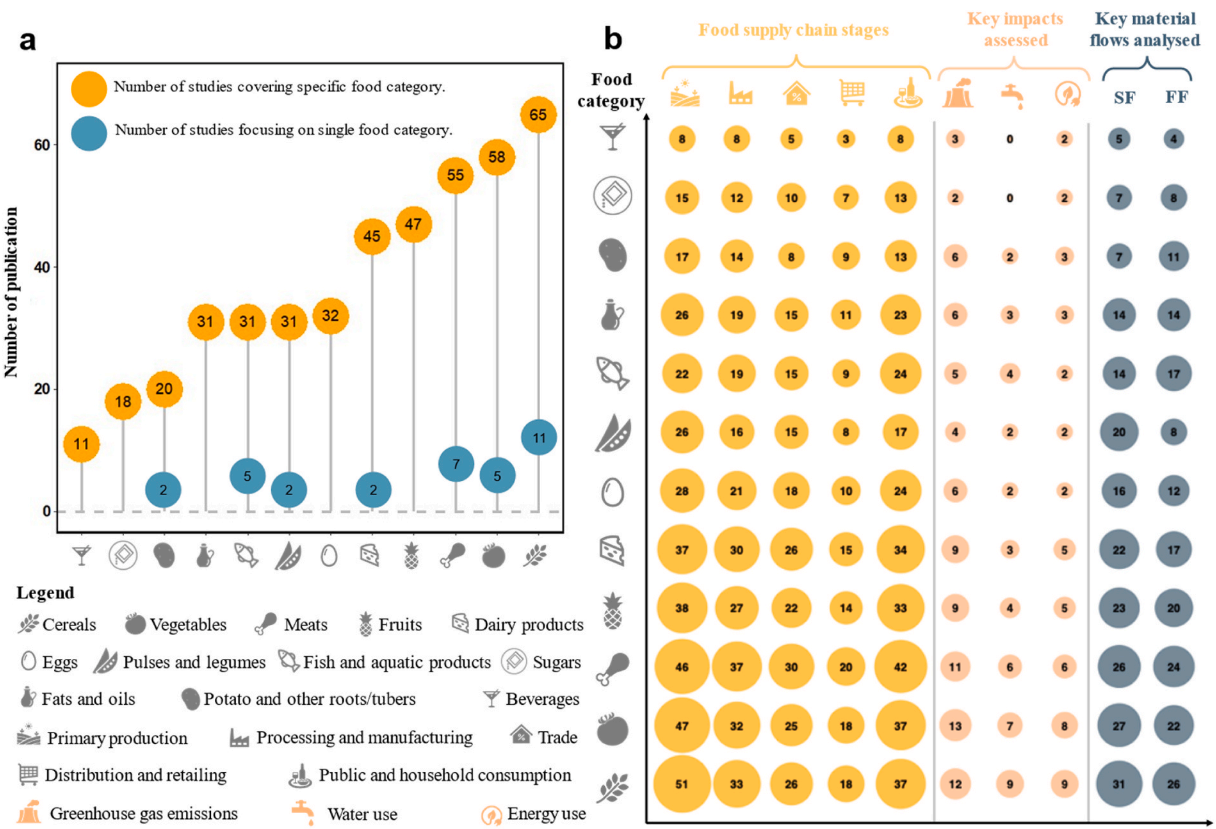
This review analysed the patterns of data usage by classifying their data sources into primary data and secondary data (Fig. 5a). We found that secondary data was widely employed in research (n = 105), with more than half of the total studies (n = 71) using only this data source. In contrast, primary data was used less frequently (n = 56), of which only 22 studies used data from this category exclusively.

Reviewed studies most frequently used statistical data (n = 93) as secondary data, followed by literature data (n = 85), while non-public data (n = 15) was rarely used. Statistical data include specific volumes on food production, trade, and consumption, commonly retrieved from sub-national (Xing et al., 2023), national (Mohammadpour and Grady, 2023; Niu et al., 2022), and regional statistics (e.g., Eurostat (Rezende et al., 2023)). Other major statistical databases used across literature include UN Comtrade (Roy et al., 2019) and FAOSTAT (Caldeira et al., 2021). In contrast, only about 44 % of studies (n = 56) used primary data. These data were primarily collected through various methods, including surveys (Kheiralipour and Sheikhi, 2021), interviews (Pirani and Arafat, 2016), focus group discussion (Papargyropoulou et al., 2016), and direct weighing (Hanssen et al., 2017; Kasavan et al., 2021).

Given the significant impact of FLW on food systems transformation (EU, 2020) and the crucial role of data collection on their estimations (Xue et al., 2017), this study further classified all FLW data collection methods used across agrifood MFAs. A total of six methods outlined in the FLW Protocol (FLW Protocol, 2016) were employed across studies. These six methods could be categorized as: calculation of FLW and measurement or assessment of FLW (FLW Protocol, 2016) (Fig. 5b). Most of these studies (n = 20) rely on the calculation of FLW, using specific methods such as proxy data (n = 19), mass balance (n = 3), and modelling (n = 1). In contrast, 16 studies used measurement or assessment of FLW, by direct weighing (n = 11), surveys (n = 6), and waste composition (n = 2). The heavy reliance on proxy data to estimate FLW highlights a lack of innovative tools for FLW data collection and underscores the challenges in accurately understanding FLW issues. Nevertheless, this study identified a growing trend in the adoption of more reliable methods, such as direct weighing, compared to nearly a decade ago (Xue et al., 2017). However, this approach has been predominantly limited to the public and household consumption stages (Ab Aziz et al., 2022; Kasavan et al., 2021). Further research is needed to explore how this method could be effectively extended to broader areas, such as the stage of processing and manufacturing.

3.4. Indicators for agrifood MFAs

Fig. 6 presents the indicator patterns of material flow quantifications and food system impacts assessment across all reviewed studies. We found that material flows related to biomass were quantified by various



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Research Features

Food Categories	National study	Primary data included	Whole FSC covered	FLW included	Substance flows quantification	Food flows quantification	Total	%
Cereals	2	8	1	3	2	7	11	32.4
Meats	6	3	3	2		7	7	20.6
Vegetables		3	1	1		1	5	14.7
Fish and aquatic products	3	2		1	2	2	5	14.7
Potato and other roots /tubers	2			2		2	2	5.9
Pulses and legumes	2	1			1		2	5.9
Dairy products		1					2	5.9

Fig. 4. Food category analysis. a) Distribution of food categories across studies. b) Distribution of food categories across different FSC stages, along with key indicators of material flow quantification (substance and food) and impact assessment (greenhouse gas emission, water use, energy use). The bubbles and values inside represent the number of publications that cover a specific food category at a given FSC stage or employing a given indicator. SF: Substance flow. FF: Food flow. **c) Research characteristics of studies focusing on a single food category.** The values in the cell indicate the number of publications with a specific research feature covering a given food category.

indicators that could be classified into three clusters: substance, food, and bio-nutrient (Fig. 6a). On the other hand, assessed indicators for food system impacts were mainly grouped into environmental, economic, and health clusters (Fig. 6b).

3.4.1. *Indicators for material flow quantification*

Of all the material flow quantification indicators, the flows of substance (n = 60) within food systems were the mostly quantified. This set of indicators primarily covers chemical elements that transfer between key processes in the food system, which can help understand several key food system issues like the circularity of nutrients. To track and quantify the flow of substances, it is crucial to identify all their sources and carriers. For example, for nitrogen flows, fertilizers, crops, animal products, and manure are some of the primary sources of nitrogen (Mohammadpour and Grady, 2023). Besides, it is also important to clarify their forms (like NH_3, N_2O, N_2 for nitrogen) or the content ratio in the carriers and sources when conducting flows measurement. This review found that substance flows were quantified mainly in the forms of phosphorus (n = 39) and nitrogen (n = 32), while carbon (n = 3), potassium (n = 3), and calcium (n = 1) were rarely considered. The emphasis on phosphorus and nitrogen is likely attributable to the substantial impact of food system activities on their flows. For instance, one-third of total human-induced nitrogen emissions originate from the livestock sector (Uwizeye et al., 2020). In contrast, other substance flows, such as that of carbon, are also crucial in food systems (Crippa et al., 2021), yet their dynamics within food systems remain under-researched.

Following the indicator of substance, agrifood MFAs also track food flows (n = 51), primarily focusing on revealing the physical movement of food products and monitoring the logistical aspects. Unlike the substance flow quantification typically covers the elements that are compound-based, food flows quantification mainly deals with material flows that are commodity-based. As the physical form of food commodities can change during their movements within the food supply chain, the use of consistent units in flow quantification, such as dry matter of meat products (Xue et al., 2019), is crucial. We found that estimating FLW is a prevalent application of food flow tracking (n = 34), which is one of the key steps to achieve efficient waste management. These FLW studies applying MFA reveal that national-level studies dominate (n = 18), with the majority focusing on the household and public consumption stage (Details in Table S4). However, compared to the indicators of substance and food, only eight studies measured

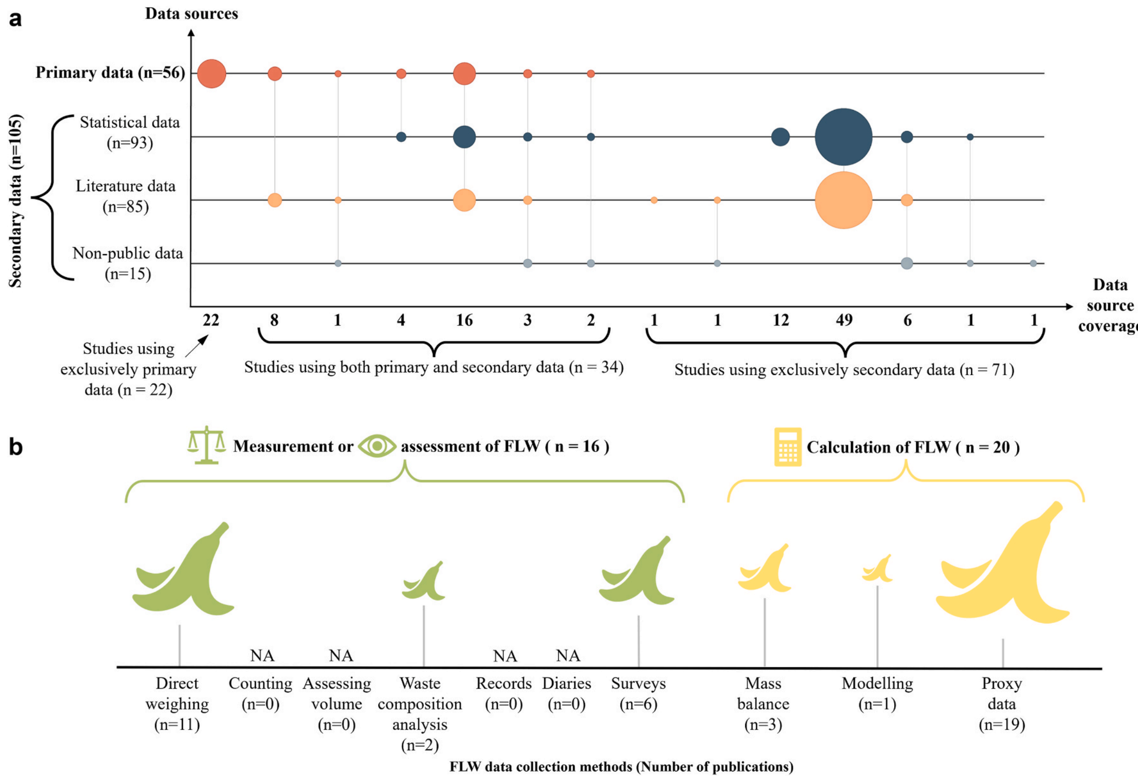

Fig. 5. a) Distribution of data sources and their coverage across studies. The bubbles connected by vertical lines indicate which data sources were used in the same study and the number of publications of such data source coverage. The numbers on the vertical axis indicate how many studies employed each data source. **b) FLW data collection methods applied across studies,** classifications basing on FLW Protocol (FLW Protocol, 2016).

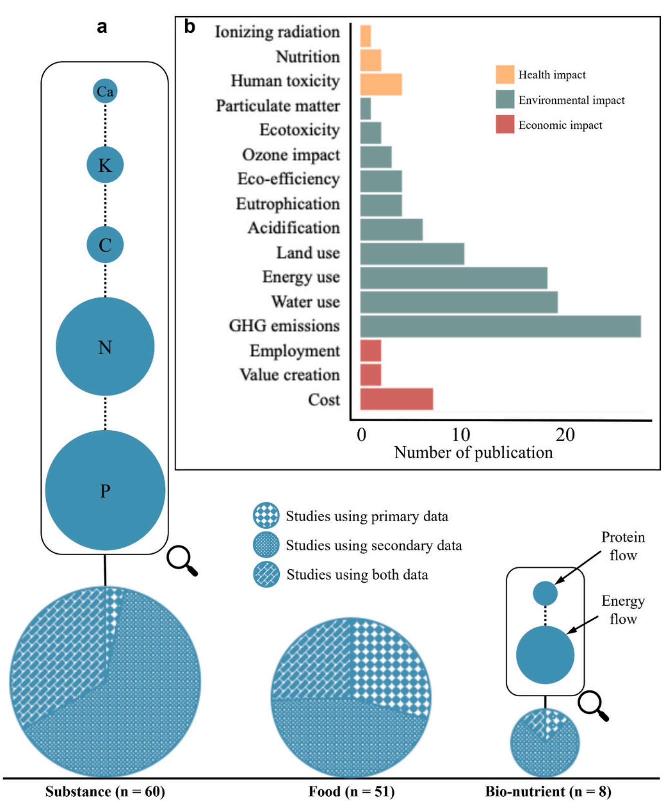

Fig. 6. a) Distribution of material flow quantification indicators. P: Phosphorus. N: Nitrogen. C: Carbon. K: Potassium. Ca: Calcium. **b) Classification and distribution on impact assessment indicators.**

bio-nutrient flow, focusing on energy (n = 7) or protein (n = 1) content in food. These bio-nutrient flows illustrate the movement of essential nutrients within food systems and support the evaluation of their efficiency. They provide data-driven evidence on how food systems sustain human populations (Haberl et al., 2011), and highlight the role of specific food items, such as salmon, in promoting human health and growth (Abualtaher and Bar, 2020).

3.4.2. *Indicators for impact assessment*

By using all the indicators mentioned in the previous section to quantify material flows, the current agrifood MFAs have built physical layers that can provide solid foundations for further impact analysis such as environmental assessment (Müller et al., 2024) and thereby inform key issues like climate change mitigation. This study further identified and classified all the indicators used for impact assessment, revealing that agrifood MFAs evaluated a total of 16 different indicators, which were mainly divided into three categories: environmental, economic, and health impacts.

We found that most studies assessed environmental impacts, particularly in the form of GHG emissions (n = 27), water use (n = 19), energy use (n = 18), and land use (n = 10), contributing to climate change mitigation. While other environmental impacts were less conducted, such as acidification (n = 6), eco-efficiency (n = 4), eutrophication (n = 4), ozone impact (n = 3), and ecotoxicity (n = 2). In contrast, economic and health impacts were under-explored. The most frequently assessed economic impact was cost (n = 7), primarily focusing on economic losses, such as those caused by FLW (Kasavan et al., 2021) and input costs (Amicarelli et al., 2023). Besides, other economic impacts such as employment (n = 2) and value creation (n = 2) were examined in a few studies. Current studies lack research on certain economic indicators, such as stakeholders' income and wealth (MUFPP, 2015; Nesheim et al., 2015). The indicators for health impact were assessed in limited studies, including human toxicity (n = 4), nutrition (n = 2), and ionizing radiation (n = 1). Certain health impacts, such as sustainable diets (EU, 2020) and nutrient balance (Chaudhary et al., 2018), were not yet addressed across studies. Moreover, social impacts, such as individual life quality (Nesheim et al., 2015), food security for vulnerable groups (MUFPP, 2015), and gender equality (FAO, 2014; Nesheim et al., 2015), have not yet been addressed. Incorporating all these overlooked impacts into future research will benefit the overall sustainability of food systems.

3.4.3. FSC stage and food category levels breakdown of indicators

This review further analysed the distributions of indicators for material flow quantification and impact assessment across FSC stages and food categories. Fig. 3b shows that food flow tracking dominated the distribution and retailing stage, while it was nearly as common as substance flow quantification in the processing and manufacturing stage. In other stages, quantifying substance flow was the predominant approach. We further noted that studies focusing exclusively on the primary production stage often addressed nutrient management issues using substance flow quantification (mostly linked to phosphorus and nitrogen) (Hou et al., 2018; Pang et al., 2023). In contrast, studies concentrating exclusively on the household and public consumption stage most commonly explored FLW generation through food flow tracking (Betz et al., 2015; Kasavan et al., 2021). For the impact analysis, GHG emission was the most frequently assessed factor across all stages. This trend is particularly pronounced at the stages of trade and public and household consumption, highlighting the urgency to reduce GHG at these stages.

When breaking down the indicators by food category, quantifying substance flows dominated across all food categories except four categories: fish and aquatic products, fats and oils, potatoes and other roots/tubers, and sugars, for which food flow was the mainstay of tracking (Fig. 4b). For impact indicators, GHG emissions dominated in all food categories except sugars, where energy use was equally assessed.

4. Discussion

Physical understandings based on MFA could offer solid basis for addressing food system challenges and informing policy. For instance, tracking substance flows can characterize the circularity and recycling of nutrients, quantifying food flows can enable efficient waste management and valorisation, and assessing environmental impacts can highlight priorities for the climate change mitigation. Therefore, this review recommends MFA as a crucial tool in food system transformation planning, as its system-wide accounting can translate food system complexities into comparable outcomes and actionable initiatives. Nonetheless, significant gaps remain, particularly in full chain MFAs, single category research like dairy products, and the use of more targeted datasets. To strengthen the evidence base, we detail these gaps and propose research and policy recommendations in the following sections, focusing on agrifood MFAs key components, including system coverage (FSC stages and food categories), data, and indicators.

Incomplete supply chain coverages. From system-wide perspective, our results reveal that full chain agrifood MFAs are rare, with key stages such as trade and distribution and retailing are consistently underrepresented. The overlook on certain stages might underestimate impacts, losses, and inefficiencies, and misdirect decision making, as in practice all stages play distinct roles and are significantly interconnected. For example, 59 % of nitrogen emissions in feed-exporting countries are attributed to the stage of trade (Uwizeye et al., 2020), and 23 % of quality losses in U.S. aquatic products occur during distribution (Love et al., 2023). In addition, studying all stages together can build a comprehensive understanding of the FSC by maximizing the advantages of MFA in analysing problems at the system level. It is worth noting that, in reality, the FSC is far more complex than the five stages we classified, involving multiple interconnected sub-processes within each stage. For instance, the processing and manufacturing stage in the pork supply chain can be further refined considering important sub-processes such as cutting and boning (Danish Agriculture and Food Council, 2010). Future agrifood MFA research should delve into more refined stages of the FSC to identify all relevant processes, enabling a more tailored physical understanding of food systems.

Over-aggregated food categories. For the food category coverages, we found that most research focused on food categories of cereals, vegetables, and meats, while other key categories, such as dairy products, potatoes and other roots/tubers, remain relatively under-studied. This imbalance in attention may be because cereals, vegetables, and meats are major nutritional sources for humans (Cocking et al., 2020). Additionally, their significant impacts, such as GHG emissions from meat and dairy production (Notarnicola et al., 2017; Scarborough et al., 2023), high FLW levels like cereal loss (Jiang et al., 2023), and health concerns related to processed meats and refined cereals (Fadnes et al., 2023), may also drive the extensive exploration of these food categories in MFA research. However, potatoes and other roots/tubers can help meet increasing food demand while reducing the total impact of staple crops on carbon, land, and water by up to 25 % (Liu et al., 2021); similarly, dairy losses, such as the more than 6.8 billion litters of raw milk lost in Canada since 2012 (Elliot et al., 2025), warrant greater research attention on these overlooked categories. More importantly, we found that food categories were commonly analysed in an aggregation manner rather than as single food categories. In fact, focusing on a single food category enables a deeper understanding of its supply chain characteristics, which often vary significantly across different food categories. For instance, vegetables can be distributed for consumption immediately after harvesting (Xue et al., 2021), whereas dairy products require additional processing procedures before they are ready to eat (Sonesson and Berlin, 2003). Based on devoted research on a single food category, tailored actions for transforming food systems specific to each category can be identified. In addition, current MFA research on single food categories is not only limited in quantity but also faces challenges in research in-depth, for example, limited use of primary data, rare coverage of the entire FSC, and less inclusion of key food issues like FLW (Fig. 4c). To advance the understanding of food systems, we call for higher resolution research that focuses on single food categories, employs reliable data sources (e.g., primary data), covers all supply chain stages, and includes food system transformation priorities like FLW. Of course, this does not imply that broader coverage studies encompassing multiple food categories are unnecessary, as potential interactions between strategies targeting specific food categories or FSC stakeholders may be better covered in a broader manner.

Integrating substance and food flow analysis is valuable yet still rare. Existing studies primarily focus on two groups of indicators to quantify material flows within food system: food and substance. These two groups of indicators contribute to the understanding of food systems from different perspectives, but they are rarely combined in a single study. Specifically, food flow quantification mainly provides insights into where food is produced, distributed, consumed (Liu et al., 2023; Xue et al., 2021), as well as lost and wasted (Jiang et al., 2023), informing FSC efficiency improvement. Quantifying substance flows, in comparison, sheds light on the entry, transformation, deposition, and loss of key substances within the food system. This allows for the exploration of specific issues such as nutrient efficiency (Rothwell et al., 2022), substance circularity (Van Der Wiel et al., 2021), manure management, and ecosystem conservation (Wu et al., 2016). However, the food and substance flows in existing agrifood MFAs were often examined independently. Integrating their quantification could support the dual goals: reducing environmental impacts through substance flow analysis, and ensuring food security by efficiently managing supply chain via food flow tracking. Accordingly, we recommend integrating these approaches in future studies.

Limited use of primary data. From the data perspective, this review found that current agrifood MFAs heavily relied on secondary data (for instance literature data) rather than primary data. Secondary data used across studies tend to be coarse in resolution, limiting their ability to capture local variations and differences (Biswas et al., 2024). And when multiple secondary data sources were applied, their data collection methods might be differed and could potentially introduce inconsistence in the data analysis. This study suggested future research involving a robust data harmonization process when incorporating secondary data, especially those from multiple sources. In addition, we found that even when primary data were used, it was limited to particular topics like FLW estimation), primarily focused on specific FSC stages such as public and household consumption (Xing et al., 2021), and typically covered small spatial boundary levels such as municipal or neighbourhood areas (De Sadeleer et al., 2020). Overall, the current data usage patterns pose challenges for conducting tailored strategies discussion with high-resolution solid data. A few primary data-based studies provide insights into improving data accuracy and collection efficiency, offering valuable guidance for future research. These studies utilized methods like surveys, interviews, and focus groups to collect detailed, up-to-date data, and were able to cover multiple FSC stages with large spatial boundaries (e.g., national level) (Guo et al., 2022; Papargyropoulou et al., 2016; Skaf et al., 2019). We also found that, to quantify different material flows, while secondary data was predominantly used for both substance flow quantification and food flow tracking, primary data was more frequently applied in food flow tracking (Fig. 6a). It would be beneficial to apply primary data broadly to all types of flow quantification.

Short supply chains and FLW remain underexplored. To further the understanding of using MFA for food systems transformation, this review discusses two key issues where the application of MFA is still limited: short supply chains and FLW. First, short supply chains (e.g., urban FSC) play increasingly important roles in promoting food systems transition (Fei et al., 2023; Stein and Santini, 2022) but receive less attention in agrifood MFAs. Notably, the carbon footprint of food produced through urban agriculture is six times greater than that of food produced by conventional agriculture (Hawes et al., 2024), highlighting the need for a deeper understanding of urban-produced food. Existing studies on short supply chains using MFA were limited to case studies at experimental sites (Chance et al., 2018) or focus on specific topics such as food flow tracking (Corbin et al., 2021). Expanding the use of MFA in short supply chains studies is strongly recommended. On the other hand, addressing FLW plays a core role in transforming food systems (EU, 2020; FAO, 2014), which can benefit from a systemic physical understanding on their estimations (Caldeira et al., 2021; Garcia-Herrero et al., 2018). Our review gave special attention to FLW studies using MFA and found that their distribution across FSC stages was uneven (Table S4). Only a few studies estimated FLW for the entire FSC (Caldeira et al., 2021; Dong et al., 2022; Garcia-Herrero et al., 2018; Jiang et al., 2023), while a significant portion of FLW studies focused only on the public and household consumption stage (Betz et al., 2015; Favis et al., 2022; Kasavan et al., 2021; Sha'ari et al., 2023). In contrast, the processing and manufacturing stage, a major contributor to FLW (Dong et al., 2022; Eurostat, 2023), was rarely examined across studies. Additionally, existing FLW quantifications using MFA largely rely on literature data, which can pose challenges in achieving accurate results due to potential variations in their data collection methods and differences in FLW definitions. Therefore, addressing the FLW issue requires a comprehensive framework that spans the entire supply chain and employs robust data collection methods. Frameworks proposed by Caldeira et al. (2021) and Garcia-Herrero et al. (2018) exemplify efficient approaches for estimating FLW. In particular, the Nutritional Food Losses and Waste Footprint index proposed by Garcia-Herrero et al. (2018) offers valuable insights to support FLW reduction decision-making.

Policy implications and limitations. MFA is currently integrated into economic and environmental policy instruments, such as EU Regulation 691/2011 on environmental-economic accounting (European Commission, 2011) and the UN Environment Programme's guidance on economy-wide MFA of natural resources (UNEP, 2021), but a dedicated food system framework to enforce and operationalize MFA is still lacking. Establishing such a framework would help standardize metrics within the food system, foster interdisciplinary collaboration, and provide targeted solutions for food systems transformation. High quality data is crucial for a solid physical understanding. Presently, several EU regulations mandate data reporting, which boost targeted data collection but might lack harmonization and transparency. For example, data on resource use and environmental impacts, which are mandatorily reported by meat and dairy practitioners under the Industrial Emissions Directive (2010/75/EU) (European Commission, 2010) could be valuable for meat and dairy MFAs. However, in practice, data collection efforts across countries and sectors often lack a harmonized framework, leading to potential inconsistencies in subsequent data analysis. Meanwhile, the limited public accessibility of reported data restricts its ability to contribute effectively to research advancements. In pursuit of sustainable food system transition, policymakers should consider establishing standardized frameworks that: 1) harmonize data collection and reporting across FSC stages and products, 2) mandate interoperable data sharing to enhance comparability, and 3) regulate regular data update to ensure reliability. Including all these implications into policy improvement will help effectively transform food systems. It is worth noting that our review only focused on biomass-related material flows within food systems (in the form of substance, food, and bio-nutrient flows). Non-biomass flows within food systems (like microplastic flows) are not considered because their attribution and quantification also rely on external systems, such as the construction system. To assess all material flows within food sytems more comprehensively, particularly by including the non-bioms joint persher systems should be adopted. In addition, wd articles, ich may iasingly used in the literature and also non-English language studies. All these potential literatures, once included in the review, can further improve the robustness of the results and discussion.

CRediT authorship contribution statement

Zhuang Qian: Conceptualization, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Wu Chen:** Conceptualization, Supervision, Writing – review & editing. **Li Xue:** Writing – review & editing. **Andrea Adelmo Della Penna:** Writing – review & editing. **Jeanine Ammann:** Writing – review & editing. **Carole Liechti:** Writing – review & editing. **Dario Dongo:** Writing – review & editing. **Gang Liu:** Conceptualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.

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Data availability

No data was used for the research described in the article.

References

Ab Aziz, N.S.A., Hasmady, N.I.I., Shafie, F.A., Yatim, S.R.M., Azmi, A., Clark, A., 2022. Food waste and carbon footprint assessment of eateries in Kelantan, Malaysia. Malaysian. J. Med. Health. Sci. 18 (1), 1–8. https://doi.org/10.47836/mjmhs18.s15. Scopus.

Abualtaher, M., Bar, E.S., 2020. Food-Loss control at the macronutrient level: protein inventory for the Norwegian farmed salmon production System. Foods 9 (8), 1095. https://doi.org/10.3390/foods9081095.

Amicarelli, V., Lombardi, M., Varese, E., Bux, C., 2023. Material flow and economic cost analysis of the Italian artisan bread production before and during the Russia-Ukraine conflict. Environ. Impact Assess. Rev. 101, 107101. https://doi.org/10.1016/j.eiar.2023.107101.

Aria, M., Cuccurullo, C., 2017. Bibliometrix: an R-tool for comprehensive science mapping analysis. J. Informetr. 11 (4), 959–975. https://doi.org/10.1016/j.joi.2017.08.007.

Betz, A., Buchli, J., Göbel, C., Müller, C., 2015. Food waste in the Swiss food service industry – Magnitude and potential for reduction. Waste Manag. 35, 218–226. https://doi.org/10.1016/j.wasman.2014.09.015.

Biswas, A., Maddocks, I., Dhar, T., Dube, L., Dutta, A., Talukder, B., Ponnambalam, K., 2024. Guiding sustainable transformations in food systems. Nat. Rev. Earth Environ. 5 (9), 607–608. https://doi.org/10.1038/s43017-024-00588-0.

Caldeira, C., De Laurentiis, V., Ghose, A., Corrado, S., Sala, S., 2021. Grown and thrown: exploring approaches to estimate food waste in EU countries. Resour. Conserv. Recycl. 168, 105426. https://doi.org/10.1016/j.resconrec.2021.105426.

Chance, E., Ashton, W., Pereira, J., Mulrow, J., Norberto, J., Derrible, S., Guilbert, S., 2018. The Plant—An experiment in urban food sustainability. Environ. Prog. Sustain. Energy 37 (1), 82–90. https://doi.org/10.1002/ep.12712.

Chaudhary, A., Gustafson, D., Mathys, A., 2018. Multi-indicator sustainability assessment of global food systems. Nat. Commun. 9 (1), 848. https://doi.org/10.1038/s41467-018-03308-7.

Chen, D.M.-C., Bodirsky, B., Wang, X., Xuan, J., Dietrich, J.P., Popp, A., Lotze-Campen, H., 2025. Future food prices will become less sensitive to agricultural market prices and mitigation costs. Nat. Food 6 (1), 85–96. https://doi.org/10.1038/s43016-024-01099-3.

Cocking, C., Walton, J., Kehoe, L., Cashman, K.D., Flynn, A., 2020. The role of meat in the European diet: current state of knowledge on dietary recommendations, intakes and contribution to energy and nutrient intakes and status. Nutr. Res. Rev. 33 (2), 181–189. https://doi.org/10.1017/S0954422419000295.

Corbin, L., Bichler, T., Bolumburu, P., Browne, S., Chatel, E., Coudard, A., Garmulewicz, A., Kamps, M., Powell, Z., Ritter, F., Singh, A., Smith, C., Streefland, T., Thibault, F., 2021. URBAN METABOLISM ANALYSIS: INITIAL ASSESSMENTS. Zenodo. https://zenodo.org/records/5094865.

Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F.N., Leip, A., 2021. Food systems are responsible for a third of global anthropogenic GHG emissions. Nat. Food 2 (3), 198–209. https://doi.org/10.1038/s43016-021-00225-9.

Danish Agriculture & Food Council, 2010. Danish Pig Producers and Food Safety.

De Sadeleer, I., Brattebø, H., Callewaert, P., 2020. Waste prevention, energy recovery or recycling—Directions for household food waste management in light of circular economy policy. Resour. Conserv. Recycl. 160, 104908. https://doi.org/10.1016/j.resconrec.2020.104908.

Dong, W., Armstrong, K., Jin, M., Nimbalkar, S., Guo, W., Zhuang, J., Cresko, J., 2022. A framework to quantify mass flow and assess food loss and waste in the US food supply chain. Commun. Earth Environ. 3 (1), 83. https://doi.org/10.1038/s43247-022-00414-9.

Elliot, T., Goldstein, B., Charlebois, S., 2025. Over 6 billion liters of Canadian milk wasted since 2012. Ecol. Econ. 227, 108413. https://doi.org/10.1016/j.ecolecon.2024.108413.

EU, 2020. Farm to Fork Strategy.

European Commission, 2010. Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on Industrial Emissions (Integrated Pollution Prevention and Control).

European Commission, 2011. Regulation (EU) No 691/2011 of the European Parliament and of the Council of 6 July 2011 on European Environmental Economic Accountstext with EEA Relevance.

EUROPEAN COMMISSION, 2022. Guidance document describing the food categories in Part E of Annex II to Regulation (EC) no 1333/2008 on Food Additives. https://food.ec.europa.eu/system/files/2022-12/fs_food-improvement-agents_guidance_1333-2008_annex-2.pdf.

Eurostat, 2019. Nutritional habits statistics. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Nutritional_habits_statistics.

Eurostat, 2023. Food waste and food waste prevention—Estimates. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Food_waste_and_food_waste_prevention_-_estimates.

Fadnes, L.T., Celis-Morales, C., Økland, J.-M., Parra-Soto, S., Livingstone, K.M., Ho, F.K., Pell, J.P., Balakrishna, R., Javadi Arjmand, E., Johansson, K.A., Haaland, Ø.A., Mathers, J.C., 2023. Life expectancy can increase by up to 10 years following sustained shifts towards healthier diets in the United Kingdom. Nat. Food 4 (11), 961–965. https://doi.org/10.1038/s43016-023-00868-w.

FAO, 2014. SAFA (Sustainability Assessment of Food and Agriculture systems) Guidelines VERSION 3.0. https://openknowledge.fao.org/items/84c84661-7172-415c-b66e-7c1eee5db675.

FAO, 2018. Sustainable food systems – concept and framework. http://www.fao.org/3/ca2079en/CA2079EN.pdf.

FAO, 2019. Food Systems at Risk. New Trends and Challenges. FAO, CIRAD. https://doi.org/10.19182/agritrop/00080.

FAO, 2023. *Africa—Regional Overview of Food Security and Nutrition 2023*. FAO; AUC; United Nations Economic Commission for Africa (ECA). WFP. https://doi.org/10.4060/cc8743en.

FAO/WHO, 2019. Food Standards CODEX alimentarius-GSFA online. https://www.fao.org/gsfaonline/foods/index.html.

FAO/WHO, 2022. FAO/WHO Global Individual Food consumption data Tool (GIFT): methodological document. https://openknowledge.fao.org/server/api/core/bitstreams/836a65eb-1f12-4286-b62e-77ba4beedf16/content.

Favis, A.M., Gotangco Gonzales, C.K., Lareza, A.E., 2022. Addressing rice waste in university cafeterias using material flow analysis and System dynamics modeling. Philipp. J. Sci. 151 (3). https://doi.org/10.56899/151.03.20.

Fei, S., Qian, Z., Santini, G., Ni, J., Bing, Y., Zhu, L., Fu, J., Li, Z., Wang, N., 2023. Towards the high-quality development of City Region Food Systems: emerging approaches in China. Cities 135, 104212. https://doi.org/10.1016/j.cities.2023.104212.

FLW Protocol, 2016. GUIDANCE ON FLW QUANTIFICATION METHODS.

Garcia-Herrero, I., Hoehn, D., Margallo, M., Laso, J., Bala, A., et al., 2018. On the estimation of potential food waste reduction to support sustainable production and consumption policies. Food Policy 80, 24–38. Elsevier. https://www.sciencedirect.com/science/article/pii/S0306919217309119.

Guo, Y., Li, R., Ning, P., Jiao, X., 2022. A Way to sustainable crop Production through Scientist−farmer engagement. Front. Agricul. Sci. Eng. 9 (4), 577. https://doi.org/10.15302/J-FASE-2022467.

Haberl, H., Erb, K.-H., Krausmann, F., Bondeau, A., Lauk, C., Müller, C., Plutzar, C., Steinberger, J.K., 2011. Global bioenergy potentials from agricultural land in 2050: sensitivity to climate change, diets and yields. Biomass Bioenergy 35 (12), 4753–4769. https://doi.org/10.1016/j.biombioe.2011.04.035.

Hanssen, O.J., Vold, M., Schakenda, V., Tufte, P.-A., Møller, H., Olsen, N.V., Skaret, J., 2017. Environmental profile, packaging intensity and food waste generation for three types of dinner meals. J. Clean. Prod. 142, 395–402. https://doi.org/10.1016/j.jclepro.2015.12.012.

Hawes, J.K., Goldstein, B.P., Newell, J.P., Dorr, E., Caputo, S., Fox-Kämper, R., Grard, B., Ilieva, R.T., Fargue-Lelièvre, A., Poniży, L., Schoen, V., Specht, K., Cohen, N., 2024. Comparing the carbon footprints of urban and conventional agriculture. Nature. Cities. 1 (2), 164–173. https://doi.org/10.1038/s44284-023-00023-3.

Hou, Y., Wei, S., Ma, W., Roelcke, M., Nieder, R., Shi, S., Wu, J., Zhang, F., 2018. Changes in nitrogen and phosphorus flows and losses in agricultural systems of three megacities of China, 1990–2014. Resour. Conserv. Recycl. 139, 64–75. https://doi.org/10.1016/j.resconrec.2018.07.030.

Jia, L., Zhang, J., Qiao, G., 2022. Scale and environmental impacts of food loss and waste in china—A material flow analysis. Int. J. Environ. Res. Publ. Health 20 (1), 460. https://doi.org/10.3390/ijerph20010460.

Jiang, S., Chen, H., Yang, S., Wang, Y., Xu, M., 2023. Assessment and scenario hypothesis of food waste in China based on material flow analysis. Npj. Urban. Susta. 3 (1), 2. https://doi.org/10.1038/s42949-022-00081-x.

Kasavan, S., Ali, N.I.B.M., Ali, S.S.B.S., Masarudin, N.A.B., Yusoff, S.B., 2021. Quantification of food waste in school canteens: a mass flow analysis. Resour. Conserv. Recycl. 164, 105176. https://doi.org/10.1016/j.resconrec.2020.105176.

Khanna, M., Zilberman, D., Hochman, G., Basso, B., 2024. An economic perspective of the circular bioeconomy in the food and agricultural sector. Commun. Earth Environ. 5 (1), 507. https://doi.org/10.1038/s43247-024-01663-6.

Kheiralipour, K., Sheikhi, N., 2021. Material and energy flow in different bread baking types. Environ. Dev. Sustain. 23 (7), 10512–10527. https://doi.org/10.1007/s10668-020-01069-2.

Koppelmäki, K., Parviainen, T., Virkkunen, E., Winquist, E., Schulte, R.P.O., Helenius, J., 2019. Ecological intensification by integrating biogas production into nutrient cycling: modeling the case of Agroecological Symbiosis. Agric. Syst. 170, 39–48. https://doi.org/10.1016/j.agsy.2018.12.007.

Lanau, M., Liu, G., Kral, U., Wiedenhofer, D., Keijzer, E., Yu, C., Ehlert, C., 2019. Taking stock of built environment stock studies: progress and prospects. Environ. Sci. Technol. 53 (15), 8499–8515. https://doi.org/10.1021/acs.est.8b06652.

Liu, B., Gu, W., Yang, Y., Lu, B., Wang, F., Zhang, B., Bi, J., 2021. Promoting potato as staple food can reduce the carbon–land–water impacts of crops in China. Nat. Food 2 (8), 570–577. https://doi.org/10.1038/s43016-021-00337-2.

Liu, X., Guo, J., Xue, L., Zhao, D., Liu, G., 2023. Where has all the rice gone in China? A farm-to-fork material flow analysis of rice supply chain with uncertainty analysis. Resour. Conserv. Recycl. 190, 106853. https://doi.org/10.1016/j.resconrec.2022.106853.

Love, D.C., Asche, F., Fry, J., Nguyen, L., Gephart, J., Garlock, T.M., Jenkins, L.D., Anderson, J.L., Brown, M., Viglia, S., Nussbaumer, E.M., Neff, R., 2023. Aquatic food loss and waste rate in the United States is half of earlier estimates. Nat. Food 4 (12), 1058–1069. https://doi.org/10.1038/s43016-023-00881-z.

Martínez-Valderrama, J., Guirado, E., Maestre, F.T., 2020. Discarded food and resource depletion. Nat. Food 1 (11), 660–662. https://doi.org/10.1038/s43016-020-00186-5.

Müller, D.B., Billy, R.G., Simoni, M.U., Petavratzi, E., Liu, G., Rechberger, H., Cullen, J., 2024. Maps of the physical economy to inform sustainability strategies. In:

Handbook of Recycling. Elsevier, pp. 27–44. https://doi.org/10.1016/B978-0-323-85514-3.00038-5.

Mohammadpour, P., Grady, C., 2023. Regional analysis of nitrogen flow within the Chesapeake Bay watershed food production chain inclusive of trade. Environ. Sci. Technol. 57 (11), 4619–4631. https://doi.org/10.1021/acs.est.2c07391.

MUFPP, 2015. The Milan Urban Food Policy Pact Monitoring Framework.

Neset, T.-S.S., Bader, H.-P., Scheidegger, R., 2008. Food consumption and nutrient flows: nitrogen in Sweden since the 1870s. J. Ind. Ecol. 10 (4), 61–75. https://doi.org/10.1162/jiec.2006.10.4.61.

Nesheim, M.C., Oria, M., Yih, P.T., Committee on a Framework for Assessing the Health, E., Board, F. and N., Resources, B. on A. and N., Medicine, I. of, & Council, N. R., 2015. Social and economic effects of the U.S. food System. In: A Framework for Assessing Effects of the Food System. National Academies Press (US). https://www.ncbi.nlm.nih.gov/books/NBK305168/.

Niu, Z., Ng, S.J., Li, B., Han, J., Wu, X., Huang, Y., 2022. Food waste and its embedded resources loss: a provincial level analysis of China. Sci. Total. 823, 153665. https://www.sciencedirect.com/science/article/pii/S0048969722007574.

Notarnicola, B., Tassielli, G., Renzulli, P.A., Castellani, V., Sala, S., 2017. Environmental impacts of food consumption in Europe. J. Clean. Prod. 140, 753–765. https://doi.org/10.1016/j.jclepro.2016.06.080.

Page, M.J., McKenzie, J.E., Bossuyt, P.M., Boutron, I., Hoffmann, T.C., Mulrow, C.D., Shamseer, L., Tetzlaff, J.M., Akl, E.A., Brennan, S.E., Chou, R., Glanville, J., Grimshaw, J.M., Hróbjartsson, A., Lalu, M.M., Li, T., Loder, E.W., Mayo-Wilson, E., McDonald, S., et al., 2021. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. Int. J. Surg. 88, 105906. https://doi.org/10.1016/j.ijsu.2021.105906.

Pang, A., Li, C., Liu, L., 2023. Can China reach the win-win goals for food security and pollution control from the perspective of nitrogen flow analysis? J. Clean. Prod. 423, 138757. https://doi.org/10.1016/j.jclepro.2023.138757.

Papargyropoulou, E., Wright, N., Lozano, R., et al., 2016. Conceptual framework for the study of food waste generation and prevention in the hospitality sector. Waste Manag. 49, 326–336. Elsevier. https://www.sciencedirect.com/science/article/pii/S0956053X16300174.

Pirani, S.I., Arafat, H.A., 2016. Reduction of food waste generation in the hospitality industry. J. Clean. Prod. 132, 129–145. Elsevier. https://www.sciencedirect.com/science/article/pii/S095965261501077X.

Rezende, V.T., Ali, S., Bonaudo, T., Gameiro, A.H., 2023. Brazilian soybeans as feed for livestock in Europe: an insight into the nitrogen flows. Reg. Environ. Change 23 (1), 33. https://doi.org/10.1007/s10113-023-02034-1.

Rothwell, S.A., Doody, D.G., Johnston, C., Forber, K.J., Cencic, O., Rechberger, H., Withers, P.J.A., 2020. Phosphorus stocks and flows in an intensive livestock dominated food system. Resour. Conserv. Recycl. 163, 105065. https://doi.org/10.1016/j.resconrec.2020.105065.

Rothwell, S.A., Forber, K.J., Dawson, C.J., Salter, J.L., Dils, R.M., Webber, H., Maguire, J., Doody, D.G., Withers, P.J.A., 2022. A new direction for tackling phosphorus inefficiency in the UK food system. J. Environ. Manag. 314, 115021. https://doi.org/10.1016/j.jenvman.2022.115021.

Roy, B.B., Biswas Chowdhury, R., Baroi, A.R., Rahman, S., Powers, S.M., Milne, N., Sujauddin, M., 2019. Unravelling the anthropogenic pathways of phosphorus in the food production and consumption system of Bangladesh through the lens of substance flow analysis. J. Ind. Ecol. 23 (6), 1439–1455. https://doi.org/10.1111/jiec.12935.

Scarborough, P., Clark, M., Cobiac, L., Papier, K., Knuppel, A., Lynch, J., Harrington, R., Key, T., Springmann, M., 2023. Vegans, vegetarians, fish-eaters and meat-eaters in the UK show discrepant environmental impacts. Nat. Food 4 (7), 565–574. https://doi.org/10.1038/s43016-023-00795-w.

Schneider, K.R., Remans, R., Bekele, T.H., Aytekin, D., Conforti, P., Dasgupta, S., DeClerck, F., Dewi, D., Fabi, C., Gephart, J.A., Masuda, Y.J., McLaren, R., Saisana, M., Aburto, N., Ambikapathi, R., Arellano Rodriguez, M., Barquera, S., Battersby, J., Beal, T., et al., 2025. Governance and resilience as entry points for transforming food systems in the countdown to 2030. Nat. Food. https://doi.org/10.1038/s43016-024-01109-4.

Sha'ari, N.S.M., Sazali, U.S., Zolkipli, A.T., Vargas, R.Q., Shafie, F.A., 2023. Environmental assessment of casual dining restaurants in urban and suburban areas of peninsular Malaysia during the COVID-19 pandemic. Environ. Monit. Assess. 195 (2), 346. https://doi.org/10.1007/s10661-023-10937-z.

Skaf, L., Buonocore, E., Dumontet, S., Capone, R., Franzese, P.P., 2019. Food security and sustainable agriculture in Lebanon: an environmental accounting framework. J. Clean. Prod. 209, 1025–1032. https://doi.org/10.1016/j.jclepro.2018.10.301.

Sonesson, U., Berlin, J., 2003. Environmental impact of future milk supply chains in Sweden: a scenario study. J. Clean. Prod. 11 (3), 253–266. https://doi.org/10.1016/S0959-6526(02)00049-5.

Stein, A.J., Santini, F., 2022. The sustainability of "local" food: a review for policy-makers. Review. Agr. Food. Environ. Studies. 103 (1), 77–89. https://doi.org/10.1007/s41130-021-00148-w.

UN, 2015. UN Sdgs TRANSFORMING OUR WORLD- THE 2030 AGENDA FOR SUSTAINABLE DEVELOPMENT. pdf.

UNEP, 2021. The Use of Natural Resources in the Economy. A Global Manual on Economy Wide Material Flow Accounting.

USDA, 2018. Consumer demand for fresh fruit drives increases across sector. https://www.ers.usda.gov/amber-waves/2018/april/consumer-demand-for-fresh-fruit-drives-increases-across-sector/.

Uwizeye, A., De Boer, I.J.M., Opio, C.I., Schulte, R.P.O., Falcucci, A., Tempio, G., Teillard, F., Casu, F., Rulli, M., Galloway, J.N., Leip, A., Erisman, J.W., Robinson, T. P., Steinfeld, H., Gerber, P.J., 2020. Nitrogen emissions along global livestock supply chains. Nat. Food 1 (7), 437–446. https://doi.org/10.1038/s43016-020-0113-y.

Van Der Wiel, B.Z., Weijma, J., Van Middelaar, C.E., Kleinke, M., Buisman, C.J.N., Wichern, F., 2021. Restoring nutrient circularity in a nutrient-saturated area in Germany requires systemic change. Nutrient Cycl. Agroecosyst. 121 (2–3), 209–226. https://doi.org/10.1007/s10705-021-10172-3.

Vingerhoets, R., Spiller, M., De Backer, J., Adriaens, A., Vlaeminck, S.E., Meers, E., 2023. Detailed nitrogen and phosphorus flow analysis, nutrient use efficiency and circularity in the agri-food system of a livestock-intensive region. J. Clean. Prod. 410, 137278. https://doi.org/10.1016/j.jclepro.2023.137278.

Wu, H., Zhang, Y., Yuan, Z., Gao, L., 2016. A review of phosphorus management through the food system: identifying the roadmap to ecological agriculture. J. Clean. Prod. 114, 45–54. https://doi.org/10.1016/j.jclepro.2015.07.073.

Xing, L., Lin, T., Hu, Y., Lin, M., Liu, Y., Zhang, G., Ye, H., Xue, X., 2023. Reducing food-system nitrogen input and emission through circular agriculture in montane and coastal regions. Resour. Conserv. Recycl. 188, 106726. https://doi.org/10.1016/j.resconrec.2022.106726.

Xing, L., Lin, T., Xue, X., Liu, J., Lin, M., Zhao, Y., 2021. Urban metabolism of food-sourced nitrogen among different income households: a case Study Based on Large Sample Survey in Xiamen City, China. Foods 10 (11), 2842. https://doi.org/10.3390/foods10112842.

Xue, L., Cao, Z., Scherhaufer, S., Östergren, K., Cheng, S., Liu, G., 2021. Mapping the EU tomato supply chain from farm to fork for greenhouse gas emission mitigation strategies. J. Ind. Ecol. 25 (2), 377–389. https://doi.org/10.1111/jiec.13080.

Xue, L., Liu, G., Parfitt, J., Liu, X., Van Herpen, E., Stenmarck, Å., O'Connor, C., Östergren, K., Cheng, S., 2017. Missing food, missing data? A critical review of global food losses and food waste data. Environ. Sci. Technol. 51 (12), 6618–6633. https://doi.org/10.1021/acs.est.7b00401.

Xue, L., Prass, N., Gollnow, S., Davis, J., Scherhaufer, S., Östergren, K., Cheng, S., Liu, G., 2019. Efficiency and carbon footprint of the German meat supply chain. Environ. Sci. Technol. 53 (9), 5133–5142. https://doi.org/10.1021/acs.est.8b06079.

Yeo, Y.T., Lim, C.M., Huaco, A.I.V., Chen, W.N., 2024. Food circular economy and safety considerations in waste management of urban manufacturing side streams. Npj. Sci. Food. 8 (1), 65. https://doi.org/10.1038/s41538-024-00309-3.