# QUANTIFYING THE ENVIRONMENTAL IMPACTS OF FOOD

## A REVIEW OF TRUE COST ACCOUNTING METHODS

GAIN Working Paper 59

November 2025

gain Global Alliance for Improved Nutrition

True Price™

NFP Netherlands Food Partnership

ATNi NUTRITION MARKETS IMPACT

**GAIN Working Paper n°59**

## Recommended citation

Global Alliance for Improved Nutrition (GAIN), True Price Foundation (TPF), Netherlands Food Partnership (NFP), Access to Nutrition Initiative (ATNI). Quantifying the Environmental Impacts of Food: A Review of True Cost Assessment Methods. Global Alliance for Improved Nutrition (GAIN). Working Paper Series #59. Geneva, Switzerland, 2025. DOI: https://doi.org/10.36072/wp.59



## Acknowledgments

### Core research team

This structured review was conducted by Flaminia Ortenzi[1], Eleonora Bassetti[2], Kerstin Damerau[2], Estefania Marti Malvido[3], Julia Boedecker[1], Natasha Bishop[4], Wendy Gonzalez[1], Ty Beal[1], and Stella Nordhagen[1].

### Contributors

The core research team received support and feedback by Pietro Galgani[3], Aurélie Reynier[5], Ninja Lacey[6], Daniel Mason-D'Croz[4], Teresa Miguel[2], Lucia Dal Balcon[1], Annette Mongina Nyangaresi[1], and María Rodríguez Sánchez[3].

### Affiliations of research team members and contributors

1. *Knowledge Leadership, Global Alliance for Improved Nutrition*
2. *Independent consultant, Global Alliance for Improved Nutrition*
3. *True Price Foundation*
4. *Cornell University*
5. *Access to Nutrition initiative*
6. *Netherlands Food Partnership*

## Funding

This review was funded by the Netherlands Food Partnership.

## SUMMARY

Global food systems face complex, multi-faceted challenges that greatly vary by context, and their environmental, health, and socio-economic impacts are equally diverse. A comprehensive understanding that integrates these disparate factors into unified, clear guidance is essential for decision-making, including policy measures and industry practices. True Cost Accounting (TCA) methodologies aim to meet this need by quantifying a wide spectrum of food systems-related benefits and costs in economic terms. We reviewed existing TCA frameworks, approaches, methods, and data sources used for measuring and monetising environmental externalities generated by food production and consumption. Our analysis of 85 recent publications (2018–2025) revealed several key patterns in current research. The literature shows a predominant focus on negative impacts, with greenhouse gas (GHG) emissions receiving primary attention. Studies mainly examined cereals, meat, and dairy, mostly in high-income and upper-middle-income country settings. TCA assessments employed three main methodological approaches: granular bottom-up, large-scale top-down, or comparative approaches, to capture environmental externalities.

Our results revealed a rapidly growing research area, characterised by a large variety of methods and data sources, while highlighting persistent technical challenges. The field faces several critical gaps, many of which reflect underlying methodological limitations in environmental impact assessments more broadly: little-to-no attention to lower-income countries; a predominant focus on high-value, commercially traded (often export-oriented) commodities; and limited consideration of systems dynamics and interconnections (e.g., product co-dependencies) in models. Addressing these challenges, combined with improved data availability, quality, and disaggregation, will be key for maximising TCA's potential as an evidence-based policy and advocacy tool.


**KEY MESSAGES**

- Food systems deliver essential health, economic, and sociocultural benefits, but impose hidden environmental costs that have become critically evident.
- In monetising these trade-offs, current TCA focuses predominantly on negative impacts (especially GHG emissions) from cereals, meat, and dairy, in high-income and upper middle-income countries.
- While TCA offers a promising approach for valuing food system-related environmental externalities, the field has significant gaps, many of which reflect underlying methodological challenges in environmental impact assessments more broadly. These include: (i) limited global applicability, due to the lack of context-specific data in lower-income countries, and (ii) methodological heterogeneity preventing meaningful comparisons across studies.
- Addressing these issues could help realise TCA's full potential to effectively support healthy, sustainable, and just food systems transformation.

## BACKGROUND AND OBJECTIVES

Food systems provide indispensable benefits through food and nutrition security, income generation, cultural identity, health and wellbeing. However, they also generate negative impacts that are often unaccounted for – such as climate change, biodiversity loss, disease burdens, and socioeconomic inequalities. These hidden costs, or externalities, are becoming increasingly evident and undermine the very foundations food systems are meant to support (1). To establish healthy, sustainable, and just food systems, there is a need to understand both their benefits and costs to inform research, policy, industry, and programmatic decisions. Yet quantifying and valuing the diversity of food system-related externalities remains conceptually, ethically, and empirically challenging (2), and is not currently integrated into traditional cost-benefit analyses.

Within modern economic thinking, however, various approaches and methods for estimating the monetary value of these externalities have been developed since the early 20th century (3). Interest in monetising[1] food systems' external costs – including environmental impacts – has rapidly grown in recent years through True Cost Accounting (TCA) methodologies (5). However, economically valuing environmental externalities is complex, with methodological, data, conceptual, and ethical challenges. Estimates should therefore be understood as indicative approximations rather than precise values.

Increasing interest in TCA led the United Nations Food and Agriculture Organization (FAO) to choose this topic for two consecutive State of Food and Agriculture (SOFA) editions in 2023 and 2024 (6,7). TCA aims to comprehensively assess and monetise positive and negative impacts across foods' entire lifecycle, from primary production to consumption and waste disposal. With regard to environmental externalities, both SOFA reports quantified and monetarily valued climate change, freshwater scarcity, land use change, and nitrogen surplus, estimating a total environmental cost of US$ 2.95 trillion in 2024 – approximately a third of the estimated revenue or economic output from global food systems in the same year (8,9). Several other recent studies also employ TCA for measuring environmental impacts, ranging from pesticide use and non-nitrogen air and water pollution, to natural resource scarcity and species loss (10–12).

A number of reports and academic manuscripts have recently reviewed monetisation methods for environmental externalities, either applied to Life Cycle Assessments (LCAs) in non-food sectors or within food systems / agriculture as a whole (13–20). This working paper, however, provides the first structured literature review of frameworks, approaches, methods, and data sources for quantifying and economically valuing positive and negative environmental impacts of individual foods, food groups, meals, and diets, across the entire value chain. In doing so, we also identify critical evidence gaps in the current literature landscape and provide recommendations for future research and practical applications. The working paper complements two additional reviews focusing on food-related health (21) and socioeconomic externalities (Bassetti et al., forthcoming).

[1] The term 'monetisation' (or monetary valuation) refers to assigning monetary values (e.g., US dollars) to environmental costs and benefits in food systems that are originally expressed in non-monetary units [e.g., changes in greenhouse gas (GHG) emissions, freshwater depletion] (4).

## METHODOLOGY

We employed a structured literature review to comprehensively identify, categorise, and synthesise existing frameworks, approaches, methods, and data sources for assessing and monetising food-related environmental costs and benefits. This review typology allowed us to examine recent conceptual and technical advancements in environmental TCA in a systemised way, balancing the need for greater methodological rigor than in a narrative review and more flexibility than in a scoping or systematic review (22,23).

Our study aimed to address the following research question: What frameworks, approaches, methods, and data sources are available for monetising environmental externalities associated with the production and consumption of individual foods, food groups, meals, and/or whole diets?

We examined relevant records published between January 1, 2018, and April 11, 2025. To identify key areas of consensus and debate in frameworks, approaches, and methods, we chose 2018 as our starting point, building on a foundational review conducted by the True Price Foundation (17). Our structured review followed an evidence synthesis protocol based on adapted versions of the PRISMA Statement Extension for Scoping Reviews and materials from The Campbell Collaboration (24–26).

### Search strategy and evidence selection

A comprehensive search strategy was iteratively developed by a research librarian and reviewed by three subject matter experts to ensure relevance and completeness. The final strategy used a broad range of keywords and subject headings to cover three core concepts: (1) TCA and True Pricing; (2) environmental externalities; and (3) food production, processing, packaging, distribution, retail, consumption, and waste disposal. Searches were conducted across academic databases as well as a broad set of grey literature sources (Annex Table 1).

The academic searches were carried out on April 8, 2025, in three electronic databases: Scopus, CABI, and Web of Science Core Collection. The full search strategy for Scopus is available in the Annex (Annex Table 2). Grey literature searches were conducted between April 2 and 11, 2025, across eight sources: the United Nations Environment Programme (UNEP), the Global Alliance for the Future of Food, the International Food Policy Research Institute (IFPRI), the Alliance of Bioversity International and CIAT (Bioversity-CIAT), the Food and Land Use Coalition (FoLU), FAO, the Impact Institute, and the True Price Foundation. Non-academic sources that could not be searched systematically were manually searched by two team members who entered keywords, applied relevant filters, and screened results for eligibility.

We used Covidence systematic review software (https://www.covidence.org) for citation management and evidence selection. Covidence automatically removed most duplicate records; a few remaining duplicates were manually labelled as such and deleted. We followed a two-step screening process: first, we screened titles and abstracts of all unique citations; for records passing this initial stage, we then retrieved and reviewed full texts. At each step, publications were assessed for eligibility based on our pre-defined inclusion and exclusion criteria by two independent reviewers, with a third resolving any disagreements.

## Eligibility criteria

Table 1 lists the inclusion and exclusion criteria used to assess study eligibility – organised according to the Population, Concept, Context (PCC) framework (27).

**Table 1. Inclusion and exclusion criteria for evidence selection**

| Aspect considered | Inclusion Criteria | Exclusion Criteria |
|---|---|---|
| Population and Context | Records on foods, food groups, meals, and/or whole diets in any geographical / population settings, covering any number of food system value chain stages, from primary agricultural production to household consumption and waste treatment | Studies focusing solely on non-food systems / sectors<br>Records focusing solely on the environmental costs of oral nutritional supplements |
| Concept | Studies discussing methods to quantify and monetise environmental externalities (positive and/or negative) of foods and diets, including methodological approaches and models | Studies focusing solely on non-environmental impacts<br>Records presenting environmental impact assessments without economic valuation<br>Studies lacking clear methodology for environmental externality quantification and/or monetisation |
| Evidence sources | Academic manuscripts in scientific journals<br>Working papers, reports, guidelines, inventories, and tools from relevant organisations<br>Books and book chapters from academic publishers | Publication types other than those listed under the inclusion criteria<br>Records for which full texts are not accessible through institutional subscriptions, open-access platforms, or Interlibrary loan services |
| Timeframe | Records published between January 1, 2018, and April 11, 2025 | Records published prior to January 1, 2018 |
| Language | English language publications | Non-English language records |

## Data extraction

One independent reviewer extracted relevant information from all included studies using a standardised data charting form – developed following the JBI template (27) (Annex Table 3). To ensure comprehensiveness and consistency, the data extraction form was pilot-tested before rolling out the full data charting process. Key variables extracted from each record comprised:

- Publication details (full citation and publication type);
- Study scope and context (geographic focus, country income group, supply chain stages considered, and reference period of input data);

- Research questions addressed, level of assessment (i.e., individual foods, food groups, meals, and/or whole diets), and types of foods, meals, and/or diets analysed.
- Environmental externalities examined (positive and negative);
- Monetisation methods and data sources used for quantifying and valuing environmental impacts;
- Methodological strengths and limitations and recommendations for future research, as stated by the original authors.

Additionally, we took note of further areas for methodological enhancement (not explicitly mentioned by the original authors) that emerged while critically reviewing records and charting data.

### Data analysis and evidence synthesis

First, we used frequencies to map the evidence distribution by key variables of interest to this review (e.g., country income group, externalities considered, assessment levels). We also analysed relationships between variables to identify emerging trends (e.g., correlation between geographic focus and environmental impacts measured). Findings from this exploratory relationship analysis are reported in the Annex (Annex Figures 1–4).

Second, we employed narrative content analysis to categorise and summarise existing frameworks (i.e., economic schools of thought), approaches (i.e., general strategies for assessing externalities), methods (i.e., specific analytical techniques), and data sources for quantifying and monetising food-related environmental externalities (Box 1).

Finally, we identified and critically synthesised overarching patterns, strengths, and limitations across all reviewed studies, highlighting common methodological and data availability / quality concerns, current knowledge gaps, and priority areas for future TCA research and applications.

**BOX 1. DEFINITIONS OF KEY TERMS: THREE-TIERED ANALYTICAL HIERARCHY**

**Tier 1 – Framework**: A broad conceptual structure that provides an overall theoretical foundation and boundaries for understanding a field of study. It establishes underlying assumptions, core concepts, and essential relationships between elements (e.g., environmental economics framework).

**Tier 2 – Approach**: A general strategy for addressing a problem that operates within a framework, representing a specific perspective for tackling an issue / challenge. More granular than a framework, it is still broader than individual methods (e.g., top-down approach).

**Tier 3 – Method**: A specific technique used to collect data, perform analysis, or implement an approach. Methods are the most detailed and operational level in this three-tiered hierarchy (e.g., cost-benefit analysis).

## FINDINGS

### Evidence distribution by key variables of interest

The PRISMA flow diagram (Figure 1) illustrates the outputs of the evidence search and selection processes. Most records were published in peer-reviewed academic journals (83%), with the remainder comprising technical reports, conference proceedings, working papers, and methodological guidelines. In terms of data recency, 47% of studies used data within 10 years of publication, 26% combined relatively recent (<10 years) and older (>10 years) data, 8% mixed data within the 10-year window with inputs of uncertain age, and 20% did not provide enough information to assess data recency.

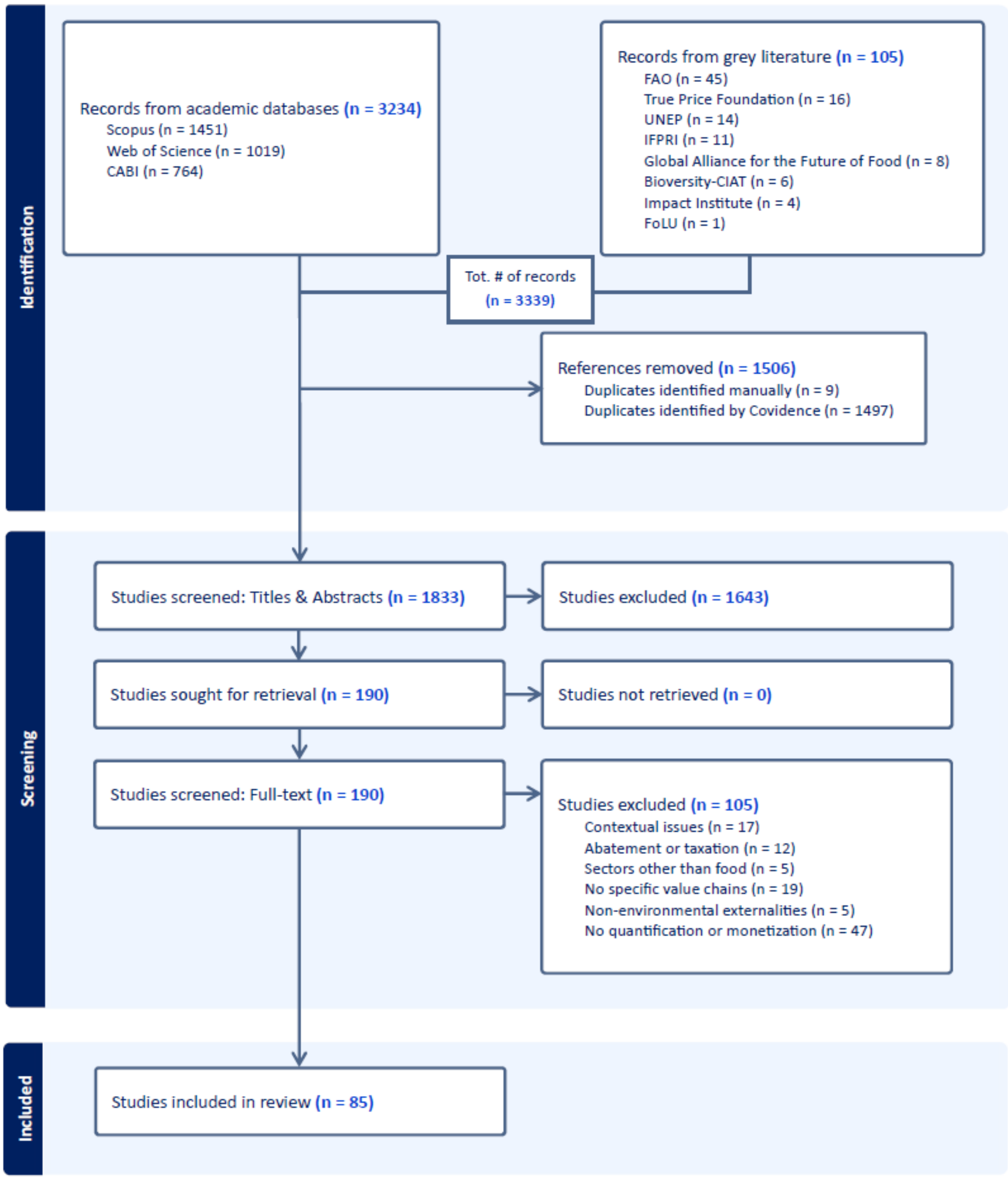



**Figure 1: PRISMA flow diagram with outputs of the search and selection processes**

### Income level classification and geographic focus

Most records quantified externalities in high-income (38%) and upper-middle-income (36%) countries (Figure 2). Lower-middle-income countries were less represented (14%), while low-income countries were only examined as part of global assessments (7%). Geographically, Asia (41%) and Europe (33%) dominated the research landscape. Africa (5%) and South America (4%) were rarely represented.

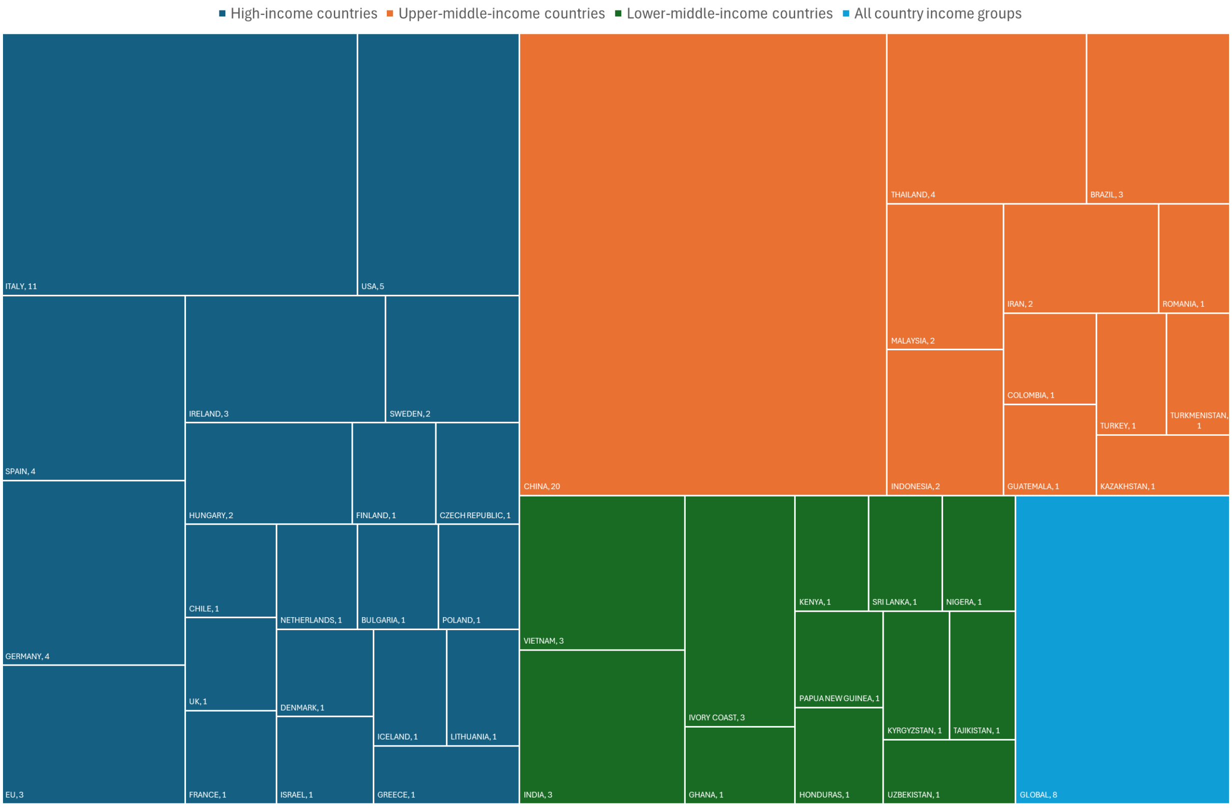



**Figure 2: Overview of countries represented in the included 85 records, classified by income groups as per the World Bank's rankings (2026) (28).** Numbers indicate the number of studies focusing on a given country.

### Life cycle stages considered

With most studies focusing on primary production (77%), other life cycle stages received less attention: pre-farm activities[2] (28%), primary and/or secondary processing (21%), waste management (16%), transport and distribution (11%), packaging (9%), retail (7%), and home preparation and consumption (6%). Only 10% of records adopted a full value-chain perspective, indicating a fragmented approach to understanding food system-related environmental impacts (Table 2).

[2] Pre-farm activities refer to all activities that occur before primary production, such as the extraction of raw materials and the manufacturing and transport of agricultural inputs like fertilisers and pesticides.

**Table 2. Life cycle stages assessed in included studies (n=85)**

| Life cycle stage | N (%)** |
|---|---|
| Pre-farm activities* | 24 (28%) |
| Primary production | 66 (77%) |
| Primary and/or secondary processing | 18 (21%) |
| Packaging | 8 (9%) |
| Transport and distribution | 9 (11%) |
| Retail | 6 (7%) |
| Home preparation and consumption | 5 (6%) |
| Waste management | 14 (16%) |
| All value chain stages covered | 9 (10%) |
| N/A | 5 (6%) |

* Pre-farm activities refer to all activities that occur before primary production, such as the extraction of raw materials and the manufacturing and transport of agricultural inputs like fertilisers and pesticides.
**As many studies focused on multiple value chain stages, the percentages add up to over 100%.

### Assessment level and types of foods and diets analysed

Most records quantified externalities at the individual food (78%) or food group (11%) levels. Only a small number evaluated whole diets (7%) or meals (1%). Whole-diet assessments typically compared observed / reported national average dietary patterns with alternative scenarios reducing or eliminating animal-source foods (i.e., vegetarian, vegan, pescetarian, flexitarian). At food group level, cereals and their products were most frequently analysed (34%), followed by terrestrial animal-source foods, which were examined in nearly half of records mentioning specific foods or food groups (n=74): dairy (20%), meat (19%), and eggs (5%). Vegetables; legumes, nuts, and oil seeds; and fruits each represented 11%, while starchy roots and tubers were at 10% (Table 3).

**Table 3. Food categories assessed in the 74 studies focusing on single foods or food groups, classified according to the FoodEx2 system developed by the European Food Safety Authority (29).**

| Food category | N (%)* |
|---|---|
| Cereals and cereal-based products | 25 (34%) |
| Milk and dairy products | 15 (20%) |
| Meat and meat products | 14 (19%) |
| Vegetables and vegetable products | 8 (11%) |
| Legumes, nuts, oil seeds and spices | 8 (11%) |
| Fruit and fruit products | 8 (11%) |
| Starchy roots and tubers and products thereof, sugar plants | 7 (10%) |
| Animal and vegetable fats and oils and primary derivatives thereof | 5 (7%) |
| Fish, seafood, amphibians, reptiles and invertebrates | 4 (5%) |
| Eggs and egg products | 4 (5%) |
| Coffee, cocoa, tea and infusions | 4 (5%) |
| Water and water-based beverages | 2 (3%) |
| Products for non-standard diets, food imitates and food supplements | 2 (3%) |
| Seasoning, sauces and condiments | 2 (3%) |

| | |
|---|---|
| Other ingredients | 2 (3%) |
| Sugar and similar, confectionary and water-based sweet desserts | 0 (0%) |
| Fruit and vegetable juices and nectars (including concentrate) | 0 (0%) |
| Alcoholic beverages | 0 (0%) |
| Food products for young population | 0 (0%) |
| Composite dishes | 0 (0%) |
| Major isolated ingredients, additives, flavours, baking and processing aids | 0 (0%) |

***** Numbers and percentages in this table are based on the total number of records (n=74) that examined foods groups and/or individual foods. As many studies assessed multiple food categories, the percentages add up to over 100%.

## Environmental impacts assessed

The reviewed literature showed a predominant focus on negative externalities, primarily air (73%), water (52%), and soil (44%) impacts (Annex Figure 5). Over one-third (37%) of records reported impacts with unclear origin or consequences. Studies frequently employed ***midpoint*** indicators – intermediate environmental impacts in the cause-effect chain before final ecosystem impacts (i.e., ***endpoint*** indicators such as species loss). These include GHG emissions (42%), climate change (14%), and/or global warming (13%); air pollution (31%); land use (change) (24%); freshwater use (14%); and mineral / fossil resource scarcity (26%) (which is both defined as mid- and endpoint). Only 8% of records assessed species loss as an endpoint indicator.

Positive externalities were rarely captured (Annex Figure 6)[3]. Of the included studies, only 9% addressed environmental health improvements (e.g., better air/water quality, carbon sequestration), 8% reported reductions in negative externalities (e.g., lower GHG emissions, reduced fertiliser-related pollution), and 2% mentioned preservation measures like biogas production or biological pest control.

## Classification of frameworks, approaches, and methods

### Theoretical frameworks

None of the reviewed records explicitly defined the overarching framework guiding their analyses, except for six studies authored by the True Price Foundation, which specify adopting a rights-based framework for evaluating the magnitude and severity of externalities (31–36). As for the remaining 79 studies, based on their characteristics, we classified them under an environmental economics framework. Indeed, these records either argue for the internalisation of externalities into market prices, or predominantly rely on monetisation methods and factors that are structurally linked to economic output and Gross Domestic Product (GDP; e.g., damage cost modelling that projects losses in future GDP growth). Both of these features can be attributed to environmental economics, a framework stemming from neoclassical economics theory (37,38). Environmental economics defines externalities as market failures and proposes policy

[3] For the purpose of this review, the term 'positive externalities' was used as a broad category encompassing both the creation of new environmental benefits (e.g., improved biodiversity) and the societal benefits resulting from the reduction or mitigation of negative environmental impacts (e.g., avoided climate change damage from lower GHG emissions) (4,6,30). This approach was chosen because a significant proportion of the reviewed literature quantifies positive outcomes in terms of mitigated / prevented costs.

solutions (e.g., regulation, taxation, subsidies) to internalise environmental costs into market prices for more efficient resource allocation (39). Within the reviewed literature, about one-fourth (26%) of studies framed possible solutions through market price adjustments or consumer behaviour perspectives, while only 5% focused on taxation – including for products receiving simultaneous subsidies aimed at ensuring food access and economic stability. One study proposed inter-provincial compensation for environmental degradation (40), while no other records specified directly actionable mechanisms.

### Approaches

With a relatively balanced distribution, we identified three distinct approaches employed by the reviewed studies[4] (Figure 3):

*Bottom-up approaches*, which collect and integrate locally gathered data for environmental impact assessments, sometimes supplemented by secondary data from official statistics or published literature. Records adopting bottom-up approaches quantified externalities at (sub)national level. However, eight of these (27%) – European studies utilizing restricted-access LCA databases – did not make their input data publicly available.

*Top-down approaches* that exclusively use secondary data sources for assessing and monetising environmental impacts. Records relying on top-down approaches mostly quantified externalities on national to global scales.

*Comparative approaches*, which may employ a combination of primary and secondary data, and consist in modelling different production and/or consumption patterns to compare the environmental impacts and costs of diverse assumptions and conditions. This category of approaches also includes scenario development where specific changes to the current policy and practice landscape are implemented.

[4] These three approaches represent generic classification tools in quantitative analyses, not unique properties of TCA assessments.

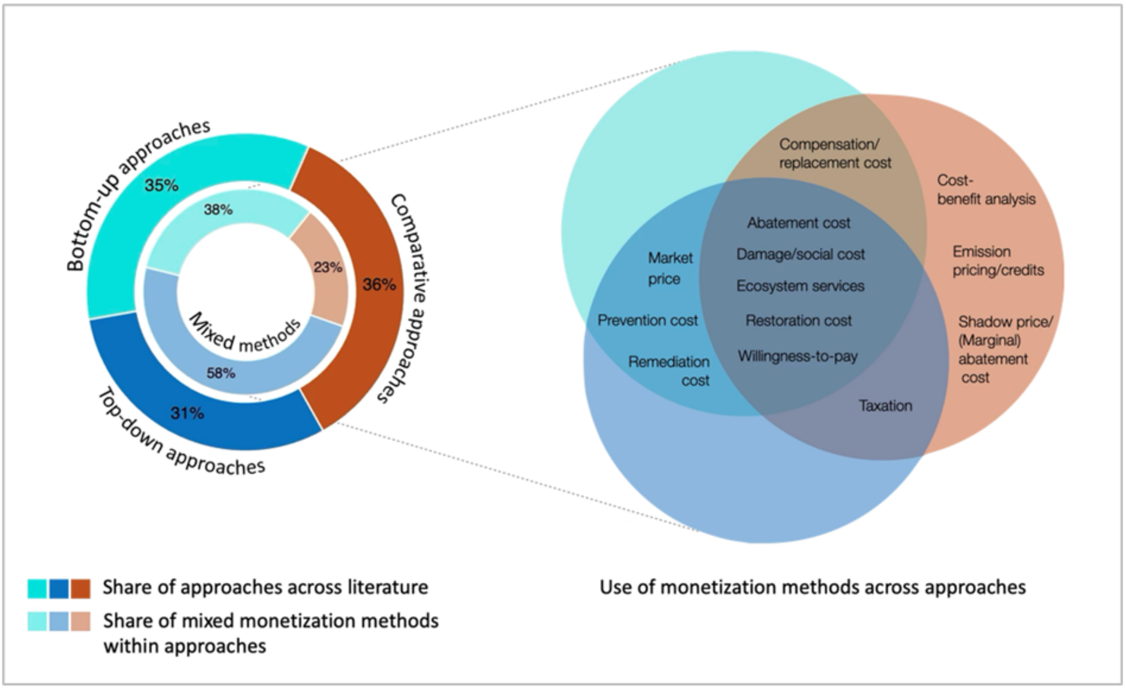



**Figure 3: Distribution of and relationship between approaches and monetisation methods used.** The outer pie chart (distinguished by deep colours) shows the frequency with which the three approach categories (i.e., bottom-up, top-down, and comparative) were employed across the reviewed literature. The inner pie chart (light colours) indicates the proportion of studies within each approach that used a mix of monetisation methods. On average (across all approach categories), 39% of records employed a mix of monetisation methods, ranging from 23% of studies adopting comparative approaches to 58% relying on top-down approaches. The Venn diagram on the right side of the figure illustrates which specific monetisation methods were applied within each approach, with overlapping areas indicating methods used by multiple approach categories.

### Monetisation methods

Within the above-mentioned approach categories, we identified 13 monetisation methods used in the reviewed literature (Table 4). Most methods were employed across multiple approaches, though a small number were exclusively utilised within the comparative approach (Figure 3). Method definitions often overlapped and/or lacked precision across studies, meaning our categorisations in Table 4 may diverge from original authors' intent without our knowledge. Thirty-nine percent of records used a combination of monetisation methods, selecting different methods for various environmental impacts or summing several types of costs (e.g., restoration and social costs) (Figure 3). Yet, none of the included studies explicitly reported their rationale for choosing specific monetisation methods.

Across records and approaches, the most commonly used method is ***Damage / Social cost***, followed by ***Shadow price / Marginal abatement cost*** and ***Willingness-to-pay*** (Figure 4). However, only two of the studies using a Damage / Social cost method applied progressive cost assumptions over time (i.e., assuming that ongoing environmental degradation will exacerbate future costs) (41,42).

**Table 4. Classification and definitions of monetisation methods identified**

| Monetisation method | Definition adopted for the purpose of this review |
|---|---|
| Abatement cost | Reactive expenses to reduce or eliminate pollution or other environmental harm that has already occurred, including both the direct costs of pollution control measures and any associated opportunity costs, such as reduced production efficiency. Abatement cost can also be understood as mitigation cost to prevent further degradation. |
| Compensation / Replacement cost | The monetary amount required to compensate for or replace a lost environmental resource or service, including the cost of providing equivalent benefits elsewhere when an environmental asset has been damaged or destroyed. |
| Cost-benefit analysis | A systematic economic evaluation method that compares the total costs of a product or activity against its total benefits, both expressed in monetary terms. This includes quantifying environmental costs and benefits to determine whether a policy / intervention is economically justified. |
| Damage / Social cost | The total economic cost imposed on society by environmental degradation. Damage cost usually includes direct expenditures only (e.g., health care, property damage), whereas social cost comprises both direct and indirect costs (e.g., lost productivity, reduced quality of life, impaired GDP growth). Yet, these two terms are sometimes used interchangeably. |
| Ecosystem services | Benefits that human societies derive from functioning ecosystems, including provisioning services (e.g., food, water, timber), regulating services (e.g., climate regulation, water purification), cultural services (e.g., recreation, spiritual values), and supporting services (e.g., nutrient cycling, habitat provision). |
| Emission pricing / credit | A market-based mechanism that puts a price on GHG emissions or other pollutants. This includes carbon pricing systems, cap-and-trade programmes where companies can buy and sell emission allowances (i.e., credits), and other mechanisms that generate financial incentives to reduce emissions by making pollution costly. |
| Market price | A monetary value at which goods or services are traded in a competitive market. This also refers to the price of natural resources or environmental goods / services when traded commercially. |
| Prevention / Eco-cost | Proactive expenses to prevent environmental damage from occurring in the first place, including investments in cleaner technologies, pollution control, and/or sustainable practices that avoid harm. |
| Remediation cost | Reactive expenses required to repair environmental damage that has already occurred, including activities like soil decontamination, water treatment, or habitat restoration. While abatement cost focuses on ongoing pollution control, remediation can also include preliminary assessments, site investigations, feasibility studies, and remedial interventions as per the True Price Principles and methodology (43). Additionally, remediation cost can encompass prevention, restoration, or damage / social cost. |

| | |
|---|---|
| Restoration cost | Reactive expenses required to return a degraded ecosystem to its baseline / natural or desired state. It differs from remediation cost by focusing on rebuilding ecological function rather than just eliminating pollution / contaminants. |
| Shadow price / Marginal abatement cost (MAC) | The implied cost of resources lacking market prices, typically equated with marginal abatement cost (i.e., the expense of reducing one additional unit of pollution / damage). This method assumes hypothetical, ideal markets conditions. |
| Taxation | Government-imposed levies used to internalise environmental externalities and change behaviour, including carbon taxes or resource extraction taxes aimed at encouraging cleaner alternatives and generating revenue for environmental protection programmes. These levies are often defined as consumption taxes. |
| Willingness-to-pay (WTP) | The maximum amount individuals or society would be willing to pay for an environmental benefit or to avoid an environmental harm, often measured through surveys. |

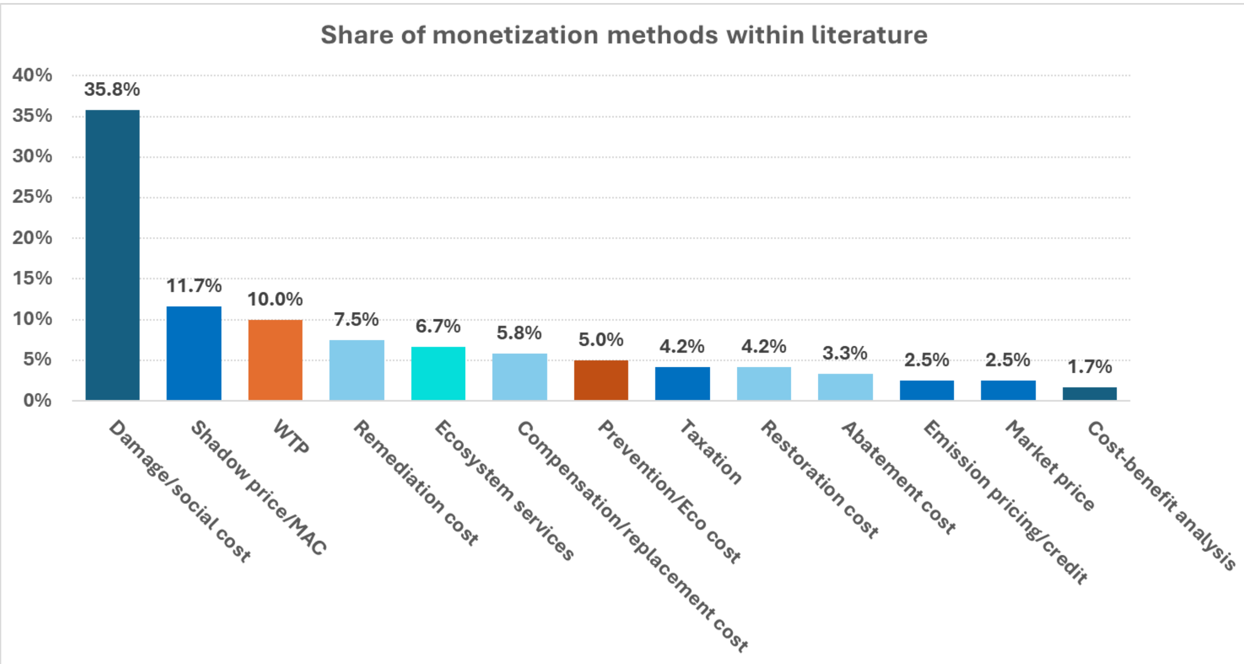



**Figure 4: Frequency of use of monetisation methods across the reviewed literature.**

While most of the identified monetisation methods are operationalised within an overarching environmental economics framework (i.e., assuming some degree of substitutability between natural resources and human-made capital), three methods rely on valuation principles that are not directly based on market utility, commodification, and damage metrics. These are: (i) *Prevention / Eco-costs*, where no underlying economic / profit motive needs to be inferred; (ii) *Willingness-to-pay*, which could be driven both by personal interest and altruistic societal and/or ecological concerns; and (iii) *Remediation costs*, which are interpreted as a human rights-based concept in records authored by the True Price Foundation (44). However, we acknowledge that willingness-to-pay, as several other method categories identified, can be used as an input for multiple cost estimates (e.g., damage, compensation, remediation).

## Data sources for impact quantification and monetisation

Environmental TCA assessments require two main types of data inputs: data quantifying physical environmental impacts (like GHG emissions or water pollution) and monetisation factors that translate these impacts into economic values.

### Impact quantification

The most common data sources for environmental impacts were publications from academic and research institutions (62%) and national or regional databases (59%), such as the China Rural Statistical Yearbook or European Union datasets. LCA-based analyses dominated the literature (44%), often using Life Cycle Inventory data from Ecoinvent and following the ReCiPe2016 model to translate collected input data into environmental impacts – reflecting the widespread prevalence of standardised LCA techniques. However, in eight studies, the origin of input data employed in LCAs could not be determined, demonstrating a lack of methodological transparency.

Over one-third (35%) of studies drew upon United Nations (UN) agency resources, while primary data use was limited (25%). Specialised Life Cycle Impact Assessment (LCIA) tools, such as USEtox, and foresight datasets were used in a small subset of records that did not conduct full-scope, standardised LCAs.

### Monetisation factors

As for data on environmental impacts, monetisation factors were most frequently sourced from academic and research institutions (53%) and from national or regional databases (40%). TCA and True Pricing inventories made up a significant share of data sources (25%). In contrast, UN agency sources (9%), foresight modelling datasets (7%), and market or consumer insight data (8%) were less frequently used.

Few organisations / institutions systematically develop and update monetisation factor databases. The most cited resources within the reviewed literature were CE Delft's Environmental Prices Handbook, Eco-costs, and True Price reports / tools. Most of these inventories are tailored to European contexts, limiting their applicability to other world regions. Other organisational datasets for monetary valuation exist beyond those surfaced in our review (e.g., those developed by the Capitals Coalition and International Foundation for Valuing Impacts) (45,46); however, these sources have not yet been applied or cited in environmental TCA literature specific to the food sector.

See Annex Tables 4 and 5 for further details on data source categories identified.

## Author-stated strengths and limitations

The most commonly reported strength across the included records (28%) was the ability to comprehensively capture the true cost of food production, by incorporating externalities within conventional economic assessments (47,48). Moreover, 11% of studies highlighted the compatibility of their analytical techniques and results with LCA and/or Life Cycle Costing approaches (11,49), and an equal share emphasised relying on established scientific literature, official statistics, and/or internationally recognised databases, improving credibility (50,51). Less frequent mentions included (i) the ability to compare environmental costs and benefits and identify life cycle 'hotspots' (7%) – i.e., the most impactful value chain stages (47,52); (ii) the use of empirical data to enhance reliability of results (6%) (53); and (iii) the integration of farm-level data to achieve greater context-specificity of estimates (5%) (53). In 17% of records, no strengths were explicitly reported by the authors.

The most frequently cited limitation (21%) was the presence of uncertainties in the overall modelling approach, particularly when applying results to specific geographies or decision-making settings (54,55). Limited scope in terms of life cycle stages or environmental impact categories considered was noted in 17% of studies (56,57). Fifteen percent of records highlighted the use of proxy or global average data instead of granular, (sub)national or regional inputs, limiting accuracy and applicability to local realities (31,58). Uncertainties in monetisation factors – such as reliance on assumption-based monetary unit values – were reported in 10% of studies (16,18). Limited representativeness or generalisability of cost estimates, due to small samples, narrow geographical focus, or methodological / data constraints, was mentioned in 8% of records (11,59). Authors did not explicitly report any identified limitations in 11% of the included studies.

## Author-stated recommendations for future research

The vast majority (84%) of records provided recommendations for future research. The most common (52%) was the need to expand the analytical scope to include additional life cycle stages (e.g., processing, retail, waste disposal) and environmental impact categories, like soil degradation or indirect land use change. Some authors (11% of records) also emphasised the importance of capturing positive externalities (e.g., carbon sequestration, enhanced pollination) and long-term environmental consequences often overlooked in current assessments (53,54,60).

The importance of improving data infrastructure was mentioned in nearly half of studies (49%), particularly the need for high-quality, context-specific datasets tailored to lower-income countries (35,48,61). Similarly, 32% of records called for broadening the geographical focus beyond the current concentration in Europe and China, and for adapting methods to diverse agroecological settings in Sub-Saharan Africa and Southeast Asia (56,62,63). Over one-third (39%) urged expanding application across diverse production systems and value chains, to capture the impacts of alternative practices (e.g., organic), emerging sectors (e.g., insect protein, seaweed), and novel or (ultra-)processed foods (60,64,65) .

Several authors (38% of studies) highlighted the need to adequately address uncertainty through sensitivity analyses, scenario testing / simulations, and transparent reporting of assumptions and confidence intervals (54,66,67). The lack of cross-study comparability and importance of methodological standardisation were only acknowledged in a small subset of records (14% and 21%, respectively) (35,36).

## Reviewer-identified areas for methodological refinement

In addition to the limitations and recommendations explicitly mentioned by the original authors of the included studies, our research team identified further opportunities for methodological improvement.

### Impact quantification

Environmental impact assessments, often in the form of LCAs, showed large variation in data quality and results interpretation. As noted above, while the vast majority (92%) of records measured midpoint indicators, such as climate change or freshwater use, few studies evaluated endpoint impacts like species loss (8%). Authors often do not provide a rationale for their specific indicator and impact assessment choices, making it difficult to examine the appropriateness of such choices against the goals and scope of studies.

Several Europe-centred records employed outdated, non-applicable, or non-publicly available data on natural resource use and emissions to air and/or water. Furthermore, a large number of studies followed the ReCiPe2016 approach (68), relying on partially outdated models (e.g., year 2000 baseline) and/or input data and analytical techniques tailored to European contexts – which may be non-transferrable to other world regions.

Additionally, we observed that, without exception, records converted methane from ruminant enteric fermentation and flooded rice paddies directly into climate change impacts, using the Global Warming Potential over 100 years (GWP100) – i.e., the standard metric for comparing the warming effect of different GHGs based on their impact over a century. While GWP100 is the currently accepted convention in LCA and GHG inventory reporting (69,70), this metric has recognised limitations as it is unable to capture the differential impact of long- versus short-lived GHGs. Methane has a short atmospheric lifespan of approximately 12 years (71) and accounts for about 90% of ruminant (72) and up to 80% of rice (73) emissions. Therefore, the choice of metric can significantly influence the estimated warming implications of stable or declining methane emission sources, such as constant ruminant herds or rice production levels (71,74). There is ongoing scientific debate regarding alternative metrics to the GWP100, such as GWP* and the Combined Global Temperature change Potential (CGTP), which are advanced climate metrics designed to more accurately assess the differential warming effects of various GHGs (74–76). Despite the above considerations, none of the reviewed studies provided a clear rationale for treating methane as equivalent to long-lived GHGs, despite its specific temporal dynamics and significant short-term mitigation potential (71,74,77).

Other identified issues with indicator / impact category definitions were:

- The conflation of water use and withdrawal, with records frequently measuring total freshwater use rather than quantifying critical, non-renewable water use.

- Land use being reported as a distinct environmental indicator without substantiating the specific associated impacts (e.g., land degradation, biodiversity loss). This is especially problematic when LCA-based studies apply arbitrary conservation goals that are not tailored to local contexts (e.g., a generic 50% land protection target). Given the global priority of ensuring food and nutrition security for all people and the widespread prevalence of biodiversity-rich smallholder farming systems worldwide (particularly in lower-income settings), such arbitrary goals are unwarranted as they may lead to policies and interventions that push countries towards increased import dependence (78–80).

- The lack of geographic granularity in global assessments, with frequent omission of critical, region-specific findings like localised nitrogen and phosphorus surplus.

### Monetisation methods

While comprehensive in integrating environmental, health, and socioeconomic dimensions of externalities, TCA assessments share limitations with other aggregation approaches, such as LCAs combining multiple environmental indicators into a single score. By incorporating distinct impact domains within a single cost estimate, these methodologies can obscure dimension-specific solutions required (81). For example, the environmental cost of wine produced using non-sustainable practices requires different policy actions (e.g., incentivising reductions in pesticide use) than the health cost of alcohol-attributable morbidity and mortality (e.g., conducting public health campaigns, imposing taxation). In addition to making these diverse policy pathways less visible, aggregation implies(81) assigning 'weights' to different impacts, which inevitably reflect subjective judgments about their relative importance (81).

Moreover, few studies explicitly addressed the ethical dilemma of expressing the value of natural capital in monetary terms (16,61,82). When acknowledged, this tension typically appeared in later methodological / discussion sections rather than being placed upfront, potentially misleading non-expert readers about the issue's fundamental prominence and complexity.

As for environmental indicator / impact category definitions, we observed lack of clarity around the classification of monetisation methods. This stems from two interconnected issues: first, the limited uptake of standardised terminology (or lack thereof) within the emerging field of food system-related TCA; and second, authors often using terminology inconsistently or without clear explanation / definition. For example, records frequently used distinct concepts, like ***Damage / Social cost*** and ***Abatement cost***, interchangeably. Some equated ***Abatement cost*** with ***Prevention cost***, assuming idealised, optimal economic conditions (e.g., complete and accurate information available to all economic actors at all times, fully efficient markets and rational behaviour) where the two methods would yield the same results. However, these methods differ in real-world applications and conflating them obscures these divergencies for decision-makers.

For many environmental impacts, existing monetisation factors present limited geographic granularity and application scope. This raises questions about the extent to which current economic valuation studies are aligned with real-life policy needs. For example, ecotoxicity assessments commonly relied on monetisation factors derived from broad spatial averages rather than region-specific estimates, making it difficult to accurately capture localised damage costs. This represents a circular challenge: the limited availability of granular environmental impact data might constrain context-specific valuation factor development; at the same time, the lack of geographically representative monetisation factors reduces the incentives for building regional / (sub)national Life Cycle Inventory databases. Advancements in either component hold potential to drive improvements in the other.

As for water use valuation factors, these were often applied to total freshwater consumption rather than being restricted to unsustainable use. We acknowledge that determining sustainability thresholds at the user level (e.g., farm / factory) can be technically challenging because hydrological boundaries exist at the watershed level, and that applying a flat price to total water use may enhance economic efficiency. However, from an environmental damage perspective, this practice can obscure the magnitude of the actual ecological impact, which is highly dependent on local water scarcity. Thus, this raises critical questions about the appropriate scope of application: should monetisation factors target all water use to signal intrinsic value, or only the portion that exceeds sustainable thresholds to reflect damage?

Finally, fossil / mineral resource scarcity monetisation often relied on static valuations rather than accounting for dynamic changes in demand and availability over time, which may limit relevance for long-term policy and intervention planning. This highlights the importance of periodically updating monetisation factors, in alignment with food systems' ever-evolving nature.

## DISCUSSION

TCA assessments aim to comprehensively capture food system-related costs and benefits through monetary valuation. Our structured review of 85 publications revealed several distinct patterns that characterise the current literature landscape within this rapidly growing field, focusing on the environmental externalities of foods and diets. Most reviewed studies exclusively assessed negative impacts, especially GHG emissions from cereals and terrestrial animal-source foods in high-income and upper-middle-income country settings.

The predominant focus on high-income (38%) and upper-middle-income (36%) economies reflects data availability but significantly limits the global applicability of current valuations. A large share of records acknowledged using proxy or global average data that may not accurately represent local agroecological conditions and/or economic contexts. This pattern is particularly concerning given that smallholder farming systems produce a substantial portion of the world's food (83), playing a crucial role in biodiversity conservation and food and nutrition security (78–80); yet, many smallholders operate outside formal market systems where TCA mechanisms would typically apply. Additionally, existing research mostly assesses high-value, commercially traded (often export-oriented) commodities, while attention to other nutritionally important food groups (e.g., vegetables, fruits, pulses, fish), regional / local supply chains, and traditional production practices is lacking. These scope and data limitations observed within the reviewed TCA literature often reflect broader challenges pervasive across environmental impact assessment research in food systems – including LCAs.

The identification of three distinct approaches – bottom-up, top-down, and comparative – and 13 monetisation methods demonstrates a diversity of perspectives and analytical techniques; as is to be expected, this comes at the cost of cross-study comparability. The classification and definitions of monetisation methods were often inconsistent across the literature, with records adopting widely different valuation techniques but presenting results as directly comparable monetary estimates. This obscures divergence in study-specific assumptions and analytical choices that should be carefully considered when using TCA-derived insights to guide decision-making. Moreover, our finding that 39% of records employed a combination of monetisation methods without clear rationale suggests a field that has not yet established consistent standards for method selection. Also, the lack of transparent data sourcing and reporting in 27% of bottom-up studies using LCA databases points to challenges for reproducibility and validation.

The emphasis on negative externalities, particularly GHG emissions (assessed in 42% of records), reflects both the urgency of halting climate change and recent advancements in carbon accounting methodologies. However, the limited attention to non-climate costs and environmental benefits represents a significant analytical gap, as sustainable food system transformation also requires recognising and incentivising best practices (e.g., carbon sequestration, biodiversity conservation), rather than solely reducing harmful ones.

Our review identified several technical issues that limit the reliability of current TCA estimates. These include conceptual and structural limitations in underlying environmental footprint assessments, inconsistent and poorly documented choices of monetisation methods and factors, and lack of transparency about data sources. The predominant focus on primary production (77% of studies) and the treatment of food systems as static snapshots fails to capture the dynamic, interconnected nature of value chains (84). While such approaches may adequately describe current conditions within a narrowly defined scope, their practical utility is limited when aiming to inform policy decisions about long-term food system transformation – which is the intended use of TCA-derived insights. When a new policy is introduced, such as a tax on meat consumption, this doesn't just affect meat production in isolation. On the contrary, it triggers system-wide ripple effects (e.g., demand shifts for substitute products, land use changes), which, in turn, generate further consequences. Most available methods cannot capture these chain reactions and assess specific production / consumption patterns in isolation, assuming conditions to remain constant through time.

Furthermore, only 10% of included records adopted a full life cycle perspective, meaning that while studies may usefully describe the current state of single value chain stages within pre-defined boundaries, they might be missing important environmental hotspots and systemic effects that could significantly alter impact assessment outcomes and related policy implications.

The ongoing scientific debate around different GHG accounting metrics, especially regarding the treatment of short-lived methane as equivalent to long-lived CO2, has significant implications on climate impact and cost estimates from ruminant livestock and rice production. As mentioned in previous sections, methane stays in the atmosphere for approximately 12 years, whereas CO2 persists for centuries (71). While methane's high global warming potential means it generates immediate societal costs during its short lifespan, the standard metric used to measure the climate effects of GHGs – the GWP100 – considers methane and CO2 as comparable over a century. On the one hand, employing a single impact assessment and monetisation method for all GHGs helps simplify measurements and results interpretation; but on the other hand, this approach obscures the critical, time-dependent policy leverage specific to methane, whose unique atmospheric behaviour requires distinct analytical choices (69–71,74,77).

Based on our findings, future environmental TCA research should prioritise: (i) expanding geographic and value chain coverage with methodologies adapted to diverse production systems in low- and middle-income countries; (ii) developing and/or improving the uptake of standardised terminology and protocols for impact assessment and monetisation method selection, to ensure scientific rigour while allowing for contextual flexibility; (iii) enhancing methodological transparency through data sharing and explicit reporting of assumptions, study limitations, and quantified uncertainties; and (iv) systematically integrating positive externalities and measuring a wider range of negative impacts beyond GHG emissions, to provide comprehensive assessments.

Additionally, the field should move towards building empirical (i.e., experimental) evidence that validates the ability of TCA-derived insights to positively influence real-world food system outcomes, such as producer behaviour, consumer choices, and subsidisation and taxation schemes. While exploring the real-life effectiveness of TCA assessments was beyond the scope of our review, this represents a fundamental open question for applying monetary valuation in diverse policy contexts, and is especially important given existing concerns about potential unintended consequences, such as rebound effects or unequal impact distribution between higher- and lower-income populations (81,85).

We acknowledge that, due to the rapid expansion of food system-related TCA of environmental externalities, our structured review may not have fully captured *all* recent methodological developments. Also, our search strategy may have missed relevant grey literature or regional / national publications not indexed in major academic and organisational databases.

TCA represents a promising approach for making 'hidden' environmental impacts visible in food system decision-making. By assigning economic value to externalities, it challenges the conventional market logic which does not account for the costs of environmental degradation. In doing so, TCA aims to (i) enable policymakers and value chain actors to identify the true ecological trade-offs between different production systems (e.g., intensive monocultures vs. regenerative practices), and (ii) provide a common language – monetary value – to incorporate environmental sustainability into financial and economic decision-making frameworks, where nature-based impacts of human activities have historically been ignored.

However, realising this potential requires addressing the fundamental technical limitations and data gaps that emerged in our review. The field's rapid growth generates both opportunities and risks: opportunities to establish rigorous standards and best practices, but risks of premature policy application before key issues are resolved. In summary, main challenges identified include: (i) systemic limitations in measuring and valuing diverse environmental impacts; (ii) frequent use of monetisation methods without clear rationale for selection, making cross-study comparisons difficult; (iii) heavy reliance on static snapshots that fail to capture how food systems respond to change; and (iv) significant gaps in geographic representativeness and transparency of input data. Tackling these issues through continued conceptual and methodological refinement, wider scope of application, and investments in granular data collection will be essential for establishing TCA as a reliable, evidence-based tool for supporting policy change toward food system transformation. This requires fostering cross-sectoral and multidisciplinary collaboration, and prioritising further development and expansion of non-neoclassical, rights-based TCA frameworks, as a critical future research area.

## REFERENCES

1. Schneider KR, Fanzo J, Haddad L, Herrero M, Moncayo JR, Herforth A, et al. The state of food systems worldwide in the countdown to 2030. Nat Food. 2023 Dec;4(12):1090–110.

2. Srinivasan UT, Carey SP, Hallstein E, Higgins PAT, Kerr AC, Koteen LE, et al. The debt of nations and the distribution of ecological impacts from human activities. Proc Natl Acad Sci. 2008 Feb 5;105(5):1768–73.

3. Pigou AC. The Economics of Welfare | [Internet]. London, UK: MacMillan and Co.; 1920 [cited 2025 Aug 12]. 983 p. Available from: https://oll.libertyfund.org/titles/pigou-the-economics-of-welfare

4. ISO. ISO Online Browsing Platform (OBP). 2019 [cited 2025 Aug 12]. ISO 14008:2019(en): Monetary valuation of environmental impacts and related environmental aspects. Available from: https://www.iso.org/obp/ui/#iso:std:iso:14008:ed-1:v1:en

5. de Adelhart Toorop R, van Veen B, Verdonk L, Schmiedler B. True cost accounting applications for agrifood systems policymakers. Background paper for The State of Food and Agriculture 2023. [Internet]. Rome, Italy: FAO; 2023 [cited 2025 Aug 12]. 114 p. (FAO Agricultural Development Economics Working Paper). Available from: https://openknowledge.fao.org/handle/20.500.14283/cc8341en

6. FAO. The State of Food and Agriculture 2023. Revealing the true cost of food to transform agrifood systems. [Internet]. Rome: FAO ; 2023 [cited 2025 June 3]. 150 p. (The State of Food and Agriculture (SOFA)). Available from: https://openknowledge.fao.org/handle/20.500.14283/cc7724en

7. FAO. The State of Food and Agriculture 2024: Value-driven transformation of agrifood systems. [Internet]. Rome, Italy: FAO; 2024 [cited 2025 July 8]. 171 p. (The State of Food and Agriculture (SOFA)). Available from: https://openknowledge.fao.org/items/65139780-d06c-4b7c-a2cd-3ed4256eaa1c

8. Patel T, Lang S. The Future of Food. 2024 [cited 2025 Aug 12]. Opportunities for Investors. Available from: http://view.ceros.com/savillsuk/the-future-of-food-2024

9. Dulin C, Alda M, Mizuno A, Biagi L, Mega Y. Statista. 2025 [cited 2025 Aug 12]. Food - Worldwide | Statista Market Forecast. Available from: http://frontend.xmo.prod.aws.statista.com/outlook/cmo/food/worldwide

10. Thambhitaks K, Kitchaicharoen J. Valuation of External Costs of Wet-Season Lowland Rice Production Systems in Northern Thailand. Chiang Mai Univ J Nat Sci. 2021 June;20(3).

11. Mehmeti A, Candido V, Canaj K, Castronuovo D, Perniola M, D'Antonio P, et al. Energy, Environmental, and Economic Sustainability of Saffron Cultivation: Insights from the First European (Italian) Case Study. Sustainability. 2024 Jan 30;16(3):1179.

12. Mankong P, Fantke P, Phenrat T, Mungkalasiri J, Gheewala SH, Prapaspongsa T. Characterizing country-specific human and ecosystem health impact and damage cost of agricultural pesticides: the case for Thailand. Int J Life Cycle Assess. 2022 Dec 1;27(12):1334–51.

13. Ruiz A de G, Baltussen W, Toorop R de A, Elzen F van den, Janssen B, Keeken R van, et al. Op weg naar de echte prijs, echte waarde en echte winst van voedsel: Een routekaart om te sturen op de maatschappelijke effecten van voedsel [Internet]. Wageningen Economic Research; 2018 [cited 2025 Aug 12]. (Wageningen Economic

Research rapport). Available from: https://research.wur.nl/en/publications/op-weg-naar-de-echte-prijs-echte-waarde-en-echte-winst-van-voedse

14. Markandya A. Accounting for the hidden costs of agrifood systems in data-scarce contexts: Background paper for The State of Food and Agriculture 2023. [Internet]. Rome, Italy: FAO; 2023 [cited 2025 July 9]. 62 p. (FAO Agricultural Development Economics Working Paper). Available from: https://openknowledge.fao.org/items/fdcfec2e-1cbf-4f26-bd2e-a82f8cd074a1

15. Amadei AM, De Laurentiis V, Sala S. A review of monetary valuation in life cycle assessment: State of the art and future needs. J Clean Prod. 2021 Dec 20;329:129668.

16. Michalke A, Köhler S, Messmann L, Thorenz A, Tuma A, Gaugler T. True cost accounting of organic and conventional food production. J Clean Prod. 2023 July 1;408:137134.

17. Galgani P, van Veen B, Kanidou D, de Adelhart Toorop R, Woltjer G. True Price Assessment Method for Agri-food Products [Internet]. True Price and Wageningen Economic Research; 2023 [cited 2025 July 9] p. 79. Available from: https://trueprice.org/assesment-method/

18. Azarkamand S, Fernández Ríos A, Batlle-Bayer L, Bala A, Sazdovski I, Roca M, et al. Calculating the true costs of protein sources by integrating environmental costs and market prices. Sustain Prod Consum. 2024 Sept 1;49:28–41.

19. Fernández-Ríos A, Laso J, Aldaco R, Margallo M. Environmental implications and hidden costs of artisanal spirulina (*Arthrospira platensis*) production and consumption. Environ Impact Assess Rev. 2024 Sept 1;108:107579.

20. Yien WS, Sharaai AH, Ismail MM, Keang LS, Abdullahi IK. Evaluation of POME-biogas production system for eco-efficiency improvement in palm oil mills. AIP Conf Proc. 2023 July 10;2785(1):030033.

21. Ortenzi F, Damerau K, Bassetti E, Boedecker J, Bishop N, Gonzalez W, et al. Quantifying the Health Externalities of Food: A Scoping Review of True Cost Assessment Methods [Internet]. Social Science Research Network; 2025 [cited 2025 Nov 18]. Available from: https://papers.ssrn.com/abstract=5413522

22. Kibbee M, Miller C, Eldermire E, Ghezzi-Kopel K. Planning Worksheet for Structured Literature Reviews. Cent Open Sci [Internet]. 2019 Mar 25; Available from: https://osf.io/ve8gc

23. Grant MJ, Booth A. A typology of reviews: an analysis of 14 review types and associated methodologies. Health Inf Libr J. 2009;26:91–108.

24. Tricco AC, Lillie E, Zarin W, O'Brien KK, Colquhoun H, Levac D, et al. PRISMA Extension for Scoping Reviews (PRISMA-ScR): Checklist and Explanation. Ann Intern Med. 2018 Oct 2;169(7):467–73.

25. PRISMA statement [Internet]. 2015 [cited 2025 Aug 12]. PRISMA-Protocols. Available from: https://www.prisma-statement.org/protocols

26. Campbell Collaboration [Internet]. [cited 2025 Nov 18]. Campbell Collaboration. Available from: https://www.campbellcollaboration.org

27. Peters MDJ, Godfrey C, McInerney P, Munn Z, Tricco AC, Khalil H. Scoping reviews. In: JBI Manual for Evidence Synthesis [Internet]. JBI; 2024 [cited 2025 July 7]. Available

from: https://jbi-global-wiki.refined.site/space/MANUAL/355862497/10.+Scoping+reviews

28. The World Bank. World Bank Country and Lending Groups (2026 fiscal year) [Internet]. [cited 2025 Aug 12]. Available from: https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups

29. European Food Safety Authority [Internet]. [cited 2025 Aug 12]. Food classification standardisation – The FoodEx2 system | EFSA. Available from: https://www.efsa.europa.eu/en/data/data-standardisation

30. Food and Agriculture Organisation of the United Nations, European Commission, Organisation for Economic Co-operation and Development, United Nations, The World Bank. System of Environmental-Economic Accounting 2012: Applications and Extensions [Internet]. United Nations; 2017. Available from: https://unstats.un.org/unsd/envaccounting/seeaRev/ae_final_en.pdf

31. Rusman A, de Adelhart Toorop R, van den Elzen F, Varoucha E, Scholte M, True Price team. The True Cost of Cocoa: Tony's Chocolonely 2018 progress report V3.2 [Internet]. Amsterdam, the Netherlands: True Price; 2018 [cited 2025 July 9] p. 43. Available from: https://trueprice.org/wp-content/uploads/2022/07/The-True-Price-of-Cocoa.-Progress-Tonys-Chocolonely-2018.pdf

32. Fobelets V, de Groot Ruiz A. The True Price of Cocoa from Ivory Coast: Joint report by IDH and True Price [Internet]. Amsterdam, the Netherlands: True Price; 2016 p. 38. Available from: https://trueprice.org/wp-content/uploads/2022/07/TP-Cocoa.pdf

33. Verkooijen L, de Groot Ruiz A, Fobelets V. The True Price of Coffee from Vietnam: Joint report by IDH and True Price [Internet]. Amsterdam, the Netherlands: True Price; 2016 Mar p. 36. Available from: https://trueprice.org/wp-content/uploads/2022/07/TP-Coffee.pdf

34. Bergman E, Fobelets V, de Groot Ruiz A. The True Price of Tea from Kenya: Joint report by IDH and True Price [Internet]. Amsterdam, the Netherlands: True Price; 2016 p. 38. Available from: https://trueprice.org/wp-content/uploads/2022/07/TP-Tea.pdf

35. Galgani P, Woltjer G, Kanidou D, Varoucha E, de Adelhart Toorop R. Air, soil and water pollution: True pricing method for agri-food products, Version 2 [Internet]. Amsterdam, the Netherlands: True Price and Wageningen Economic Research; 2023 Mar [cited 2025 Aug 12] p. 66. Available from: https://www.truepricefoundation.org/wp-content/uploads/230315_AirSoilAndWaterPollutionModule_PPSTrueAndFairPrice_v2-1.pdf

36. Galgani P, Woltjer G, de Adelhart Toorop R, de Groot Ruiz A, Varoucha E. Land use, land use change, biodiversity and ecosystem practices: True pricing method for agri-food products [Internet]. Amsterdam, the Netherlands: True Price and Wageningen Economic Research; 2021 Oct [cited 2025 Aug 12] p. 24. Available from: https://trueprice.org/wp-content/uploads/2022/07/LandUseBiodiversityandESSModule_PPSTrueAndFairPrice_finalVersion_2-1.pdf

37. Brahmachari D. Neoclassical Economics as a Method of Scientific Research Program : A review of existing literature. Munich Pers RePEc Arch [Internet]. 2016 Jan; Available from: https://mpra.ub.uni-muenchen.de/75341/

38. Mantzavinos C. Scientific Explanation. Int Encycl Soc Behav Sci Second Ed. 2015;302–7.

39. Morrissey K. Resource and Environmental Economics. Int Encycl Hum Geogr Second Ed. 2020;463–6.

40. Yang J, Gao B, Xia F, Wei H, Fan S. Internalizing the external costs to achieve environmental and economic Goals: A Case study of rice production in China. Food Policy. 2025 Apr 1;132:102857.

41. Springmann M, Clark MA, Rayner M, Scarborough P, Webb P. The global and regional costs of healthy and sustainable dietary patterns: a modelling study. Lancet Planet Health. 2021 Nov 1;5(11):e797–807.

42. Springmann M. Valuation of the health and climate-change benefits of healthy diets: Background paper for The State of Food Security and Nutrition in the World 2020. [Internet]. Rome, Italy: FAO; 2020 [cited 2025 July 7]. 32 p. (FAO Agricultural Development Economics Working Paper). Available from: https://openknowledge.fao.org/items/62ba9787-59ce-4b54-8f13-cf829fe319bd

43. True Price. Principles for True Pricing [Internet]. Amsterdam, the Netherlands: True Price; 2020 [cited 2025 July 7] p. 35. Available from: https://www.truepricefoundation.org/true-price-standard/

44. Galgani P, Woltjer G, Toorop R de A, Ruiz A de G, Olde E den, Schoenmaker D, et al. Valuation framework for true price assessment of agri-food products. 2021 [cited 2025 Oct 17]; Available from: https://research.wur.nl/en/publications/valuation-framework-for-true-price-assessment-of-agri-food-produc

45. Capitals Coalition [Internet]. The Value Commission. Available from: https://capitalscoalition.org/project/the-value-commission/

46. International Foundation for Valuing Impacts [Internet]. Available from: https://ifvi.org/about-us/

47. Bellon MR, Benard N, Vizcaino M, Merrigan K, Wharton C. True Cost Accounting Using Life Cycle Assessment Methods and Data: A Case Study Comparing Palm, Rapeseed, and Coconut Oils for Sustainability and Nutrition. Sustainability. 2024 Jan;16(23):10366.

48. Sandhu H, Scialabba N, Warner C, Behzadnejad F, Kieran K, Houston R, et al. Application of the TEEBAgriFood Evaluation Framework to Corn Systems in Minnesota, U.S.A. [Internet]. Global Alliance for the Future of Food; 2019 p. 135. Available from: https://futureoffood.org/wp-content/uploads/2021/01/GA_TEEB_MinnesotaCorn201905.pdf

49. Lucas E, Guo M, Guillén-Gosálbez G. Low-carbon diets can reduce global ecological and health costs. Nat Food. 2023 May;4(5):394–406.

50. Puri R, Pingali P. Reducing the true cost of food-based safety nets: evidence from India's subsidized food program. Environ Res Lett. 2024 May;19(6):064041.

51. Yang Z. The shadow price of nitrogen. China Agric Econ Rev. 2018;11(3):489–506.

52. Hentschl M, Michalke A, Pieper M, Gaugler T, Stoll-Kleemann S. Dietary change and land use change: assessing preventable climate and biodiversity damage due to meat consumption in Germany. Sustain Sci [Internet]. 2023 May 11 [cited 2025 Aug 12]; Available from: https://doi.org/10.1007/s11625-023-01326-z

53. Feketéné Ferenczi A, Szűcs I, Bauerné Gáthy A. Evaluation of the Pollination Ecosystem Service of the Honey Bee (Apis mellifera) Based on a Beekeeping Model in Hungary. Sustainability. 2023 Jan;15(13):9906.

54. Tamburini E, Krozer Y, Castaldelli G. How much are we paying for drinking water in (PET) bottles? A global assessment of the hidden costs and potential damage to the environment. Environ Chall. 2025 Apr 1;18:101083.

55. Mousavi SA, Sarshad Ghahfarokhi M, Soltani Koupaei S. Negative impacts of nomadic livestock grazing on common rangelands' function in soil and water conservation. Ecol Indic. 2020 Mar 1;110:105946.

56. Silva DV da, Pavan ALR, Faria LC de, Piekarski CM, Saavedra YMB, Lopes Silva DA. Opportunities to integrate Ecosystem Services into Life Cycle Assessment (LCA): a case study of milk production in Brazil. Ecosyst Serv. 2024 Oct 1;69:101646.

57. Nabavi-Pelesaraei A, Damgaard A. Regionalized environmental damages and life cycle cost of chickpea production using LC-IMPACT assessment. Environ Impact Assess Rev. 2023 Nov 1;103:107259.

58. Hou L, Keske C, Hoag D, Balezentis T, Wang X. Abatement costs of emissions from burning maize straw in major maize regions of China: Balancing food security with the environment. J Clean Prod. 2019 Jan 20;208:178–87.

59. Adenuga AH, Davis J, Hutchinson G, Donnellan T, Patton M. Environmental Efficiency and Pollution Costs of Nitrogen Surplus in Dairy Farms: A Parametric Hyperbolic Technology Distance Function Approach. Environ Resour Econ. 2019 Nov 1;74(3):1273–98.

60. Merida VE, Cook D, Ögmundarson Ó, Davíðsdóttir B. An environmental cost-benefit analysis of organic and non-organic sheep farming in Iceland. J Agric Food Res. 2024 Dec 1;18:101472.

61. Arrigoni A, Marveggio D, Allievi F, Dotelli G, Scaccabarozzi G. Environmental and health-related external costs of meat consumption in Italy: estimations and recommendations through life cycle assessment. Sci Total Environ. 2023 Apr 15;869:161773.

62. Gunawardena MA, Lokupitiya E. Comparison of conventionally and organically grown pineapple in Sri Lanka: An integrative approach applying life cycle assessment and externalities. Clean Environ Syst. 2024 Sept 1;14:100219.

63. Supasri T, Itsubo N, Gheewala SH, Sampattagul S. Life cycle assessment of maize cultivation and biomass utilization in northern Thailand. Sci Rep. 2020 Feb 26;10(1):3516.

64. Greenfeld A, Becker N, Bornman JF, Spatari S, Angel DL. Monetizing environmental impact of integrated aquaponic farming compared to separate systems. Sci Total Environ. 2021 Oct 20;792:148459.

65. Fernandez-Rios A, Laso J, Aldaco R, Margallo M. Life cycle assessment and energy return of investment of nutritionally-enhanced snacks supplemented with Spanish quinoa. Sci Total Environ. 2024;954:176542.

66. Zhang T, Jia Y, Ren K, Wang S, Li Z, Chen W, et al. Environmental–economic total factor productivity of vegetable production in China from the life cycle perspective. J Clean Prod. 2024 Oct 20;477:143806.

67. Baležentis T, Dabkienė V, Štreimikienė D. Eco-efficiency and shadow price of greenhouse gas emissions in Lithuanian dairy farms: An application of the slacks-based measure. J Clean Prod. 2022 July 1;356:131857.

68. Huijbregts MAJ, Steinmann ZJN, Elshout PMF, Stam G, Verones F, Vieira M, et al. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int J Life Cycle Assess. 2017 Feb 1;22(2):138–47.

69. Arias P, Bellouin N, Coppola E, Jones R, Krinner G, Marotzke J, et al. Climate Change 2021: the physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change: Technical Summary [Internet]. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2021. Available from: https://www.ipcc.ch/report/ar6/wg1/

70. ISO 14067:2018. Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification [Internet]. International Organization for Standardization; 2018 [cited 2025 Nov 20]. Available from: https://www.iso.org/standard/71206.html

71. Mar KA, Unger C, Walderdorff L, Butler T. Beyond CO2 equivalence: The impacts of methane on climate, ecosystems, and health. Environ Sci Policy. 2022 Aug 1;134:127–36.

72. Thacharodi A, Hassan S, Ahmed ZHT, Singh P, Maqbool M, Meenatchi R, et al. The ruminant gut microbiome vs enteric methane emission: The essential microbes may help to mitigate the global methane crisis. Environ Res. 2024 Nov 15;261:119661.

73. Jahangir MMR, Aguilera E, Ferdous J, Mahjabin F, Al Asif A, Hossan M, et al. Carbon footprint and greenhouse gas emissions of different rice-based cropping systems using LCA. Sci Rep. 2025 Mar 25;15(1):10214.

74. Costa C, Tedeschi LO, Gonzalez-Quintero R, Arango J, Burkart S, Grosjean G, et al. South america's pasture intensification can increase beef production, reduce emissions by 30% and mitigate warming from methane by 2050. Sci Rep. 2025 Oct 13;15(1):35734.

75. Lynch J, Cain M, Pierrehumbert R, Allen M. Demonstrating GWP*: a means of reporting warming-equivalent emissions that captures the contrasting impacts of short- and long-lived climate pollutants. Environ Res Lett. 2020 Apr;15(4):044023.

76. Collins WJ, Frame DJ, Fuglestvedt JS, Shine KP. Stable climate metrics for emissions of short and long-lived species—combining steps and pulses. Environ Res Lett. 2020 Feb;15(2):024018.

77. Forster P, Storelvmo T, Armour K, Collins W, Dufresne JL, Frame D, et al. The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. In: Climate Change 2021: The Physical Science Basis Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Internet]. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2021. p. 923–1054. Available from: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter07.pdf

78. Fujimori S, Wu W, Doelman J, Frank S, Hristov J, Kyle P, et al. Land-based climate change mitigation measures can affect agricultural markets and food security. Nat Food. 2022 Feb;3(2):110–21.

79. Schleicher J, Zaehringer JG, Fastré C, Vira B, Visconti P, Sandbrook C. Protecting half of the planet could directly affect over one billion people. Nat Sustain. 2019 Dec;2(12):1094–6.

80. Damiani M, Sinkko T, Caldeira C, Tosches D, Robuchon M, Sala S. Critical review of methods and models for biodiversity impact assessment and their applicability in the LCA context. Environ Impact Assess Rev. 2023 July 1;101:107134.

81. Brooks J, Eugenio DB. How helpful are the “hidden costs of food systems” numbers? Food Policy. 2025 Feb;131.

82. Raynaud J, Fobelets V, Georgieva A, Joshi S, Kristanto L, de Groot Ruiz A, et al. Improving business decision making: valuing the hidden costs of production in the palm oil sector [Internet]. True Price; 2016 p. 149. (The Economics of Ecosystems and Biodiversity for Agriculture and Food (TEEBAgriFood) Program). Available from: https://trueprice.org/wp-content/uploads/2022/07/TEEBAgriFood_PalmOil_Report.pdf

83. Ricciardi V, Ramankutty N, Mehrabi Z, Jarvis L, Chookolingo B. How much of the world’s food do smallholders produce? Glob Food Secur. 17:64–72.

84. Land use modeling: from farm to food systems. In: Food Systems Modelling: Tools for Assessing Sustainability in Food and Agriculture [Internet]. Academic Press; 2022 [cited 2025 Nov 20]. p. 89–105. Available from: https://www.sciencedirect.com/science/chapter/edited-volume/abs/pii/B9780128221129000114

85. Patel R. A democratic alternative to true cost pricing. Nat Food 2. 2021 Sept 20;632–4.

## ANNEX

Annex Table 1. List of all evidence sources searched, including both academic and grey literature databases.

| Database | No. of hits | Last searched | Platform |
|---|---|---|---|
| CABI | 764 | 02-April-25 | Clarivate |
| Scopus | 1,451 | 08-April-25 | Elsevier |
| Web of Science Core Collection | 1,019 | 02-April-25 | Clarivate |
| UNEP | 14 | 02-April-25 | https://wedocs.unep.org/discover |
| Global Alliance for the Future of Food | 8 | 02-April-25 | https://futureoffood.org/insights/ |
| IFPRI | 11 | 02-April-25 | https://gardian.cgiar.org/home |
| Bioversity-CIAT | 6 | 02-April-25 | https://gardian.cgiar.org/home |
| FoLU | 1 | 02-April-25 | https://www.foodandlandusecoalition.org/knowledge-hub/ |
| FAO Knowledge Repository | 45 | 02-April-25 | https://openknowledge.fao.org/ |
| Impact Institute (hand-searched) | 4 | 11-April-25 | https://www.impactinstitute.com/publications/ |
| True Price Foundation (hand-searched) | 16 | 11-April-25 | https://trueprice.org/true-price-resources/ |
| **Total** | **3,339** | | |

**Annex Table 2.** Search strategy for Scopus, as executed on April 8, 2025. Designed to identify English-language records published during the period 2018–2025, the search strategy for Scopus yielded 1,451 citations. Our full search strategy, across all included academic and grey literature databases, retrieved a total of 3,339 records. Annex Table 1 provides a list of all evidence sources searched.

| Row # | Search string |
|---|---|
| 1 | TITLE-ABS("indirect cost*" OR "hidden cost*" OR "shadow cost*" OR "external cost*" OR "external benefit*" OR "indirect benefit*" OR "hidden benefit*" OR "shadow benefit*" OR "abatement cost*" OR "true price*" OR "true pricing" OR "true cost*" OR "full cost*" OR monetization OR "monetary unit*" OR "monetary valuation*" OR ("holistic assessment" AND agrifood) OR "adjusted price*" OR ((cost* OR risk*) W/1 internalization) OR "food impact cost*" OR ((measur* OR assess* OR calculat* OR evaluat* OR monetiz* OR valuat* OR "cost benefit" OR "risk benefit" OR quantif*) W/4 externalit*) OR "impact weighted accounting" OR (("impact assessment" OR "impact measurement" OR "impact evaluation" OR "impact valuation") W/10 (cost* OR econom* OR quantit* OR monet*))) OR AUTHKEY("indirect cost*" OR "hidden cost*" OR "shadow cost*" OR "external cost*" OR "external benefit*" OR "indirect benefit*" OR "hidden benefit*" OR "shadow benefit*" OR "abatement cost*" OR "true price*" OR "true pricing" OR "true cost*" OR "full cost*" OR monetization OR "monetary unit*" OR "monetary valuation*" OR ("holistic assessment" AND agrifood) OR "adjusted price*" OR ((cost* OR risk*) W/1 internalization) OR "food impact cost*" OR ((measur* OR assess* OR calculat* OR evaluat* OR monetiz* OR valuat* OR "cost benefit" OR "risk benefit" OR quantif*) W/4 externalit*) OR "impact weighted accounting" OR (("impact assessment" OR "impact measurement" OR "impact evaluation" OR "impact valuation") W/10 (cost* OR econom* OR quantit* OR monet*))) |
| 2 | TITLE-ABS(environment* OR sustainab* OR ecosystem* OR "land-system change*" OR "biosphere integrit*" OR biogeochemical OR ecolog* OR agroecolog* OR "one health" OR planet*) OR AUTHKEY(environment* OR sustainab* OR ecosystem* OR "land-system change*" OR "biosphere integrit*" OR biogeochemical OR ecolog* OR agroecolog* OR "one health" OR planet*) |
| 3 | TITLE-ABS(((Water OR freshwater OR groundwater) W/1 (scarcity OR pollut* OR deplet* OR conserv* OR contaminat* OR health OR use OR qualit* OR footprint*)) OR "dead zone*" OR "hypoxi* area*" OR "algal bloom*" OR eutroph* OR "sea level*" OR "ocean level*" OR acidification OR "ocean warming" OR "plastic pollut*" OR "microplastic*" OR ("nutrient loss" W/5 (Water OR freshwater OR groundwater)) OR "nutrient runoff" OR "nutrient leach*" OR "nutrient leak*") OR AUTHKEY(((Water OR freshwater OR groundwater) W/1 (scarcity OR pollut* OR deplet* OR conserv* OR contaminat* OR health OR use OR qualit* OR footprint*)) OR "dead zone*" OR "hypoxi* area*" OR "algal bloom*" OR eutroph* OR "sea level*" OR "ocean level*" OR acidification OR "ocean warming" OR "plastic pollut*" OR "microplastic*" OR ("nutrient loss" W/5 (Water OR freshwater OR groundwater)) OR "nutrient runoff" OR "nutrient leach*" OR "nutrient leak*") |
| 4 | TITLE-ABS(((soil OR land) W/1 (degradat* OR loss OR fertilit* OR erosion OR erode* OR pollut* OR contaminat* OR health OR use OR qualit* OR conserv* OR footprint*)) OR overgraz* OR pesticide* OR nitrogen OR phosphorus OR ("nutrient loss*" W/5 (soil OR land))) OR AUTHKEY(((soil OR land) W/1 (degradat* OR loss OR fertilit* OR erosion OR erode* OR pollut* OR contaminat* OR health OR use OR qualit* OR conserv* OR footprint*)) OR overgraz* OR pesticide* OR nitrogen OR phosphorus OR ("nutrient loss*" W/5 (soil OR land))) |

| | |
|---|---|
| 5 | TITLE-ABS("climate change" OR "climate crisis" OR "global warming" OR "extreme weather" OR "greenhouse gas*" OR "greenhouse effect" OR ozone OR "weather hazard*" OR ecotoxic* OR "carbon footprint" OR "carbon sequestration" OR "carbon stock*" OR "air pollut*" OR "air qualit*" OR emission* OR "particulate matter" OR "nitrous oxide" OR "carbon dioxide" OR "atmospheric CO2" OR methane) OR AUTHKEY("climate change" OR "climate crisis" OR "global warming" OR "extreme weather" OR "greenhouse gas*" OR "greenhouse effect" OR ozone OR "weather hazard*" OR ecotoxic* OR "carbon footprint" OR "carbon sequestration" OR "carbon stock*" OR "air pollut*" OR "air qualit*" OR emission* OR "particulate matter" OR "nitrous oxide" OR "carbon dioxide" OR "atmospheric CO2" OR methane) |
| 6 | TITLE-ABS(landfill* OR leachate OR "biodegradable waste" OR "nonbiodegradable waste" OR "non-biodegradable waste" OR "food loss" OR "food waste" OR "organic waste" OR "solid waste" OR "residue burn*" OR "waste burn*" OR "manure management" OR "waste management" OR "waste treatment*") OR AUTHKEY(landfill* OR leachate OR "biodegradable waste" OR "nonbiodegradable waste" OR "non-biodegradable waste" OR "food loss" OR "food waste" OR "organic waste" OR "solid waste" OR "residue burn*" OR "waste burn*" OR "manure management" OR "waste management" OR "waste treatment*") |
| 7 | TITLE-ABS("Resource deplet*" OR biodivers* OR "species loss*" OR "potentially disappeared fraction" OR "fossil fuel*" OR "energy insecur*" OR "renewable energy" OR "nonrenewable energy" OR "non-renewable energy" OR (hydro OR solar OR wind) W/0 (power or energ*) OR biogas* OR biofuel* OR "habitat destruction" OR "habitat loss" OR deforest* OR overfish* OR desertification OR "species extinction" OR "monoculture agricultur*" OR "monoculture crop*" OR "natural resource*") OR AUTHKEY("Resource deplet*" OR biodivers* OR "species loss*" OR "potentially disappeared fraction" OR "fossil fuel*" OR "energy insecur*" OR "renewable energy" OR "nonrenewable energy" OR "non-renewable energy" OR (hydro OR solar OR wind) W/0 (power or energ*) OR biogas* OR biofuel* OR "habitat destruction" OR "habitat loss" OR deforest* OR overfish* OR desertification OR "species extinction" OR "monoculture agricultur*" OR "monoculture crop*" OR "natural resource*") |
| 8 | #2 OR #3 OR #4 OR #5 OR #6 OR #7 |
| 9 | TITLE-ABS(vegan* OR vegetarian* OR pescatarian* OR "lacto ovo" OR whole30 OR "intermittent fasting" OR flexitarian* OR "dietary choice*" OR "dietary pattern*" OR "dietary practice*" OR "dietary habit*" OR "dietary behavio*" OR "consumption behavio*" OR "consumption pattern*" OR ((paleo OR keto OR carnivore OR omnivore OR mediterranean OR "low carb" OR "sugar free" OR "gluten free" OR "plant based" OR "animal based") W/2 diet*)) OR AUTHKEY(vegan* OR vegetarian* OR pescatarian* OR "lacto ovo" OR whole30 OR "intermittent fasting" OR flexitarian* OR "dietary choice*" OR "dietary pattern*" OR "dietary practice*" OR "dietary habit*" OR "dietary behavio*" OR "consumption behavio*" OR "consumption pattern*" OR ((paleo OR keto OR carnivore OR omnivore OR mediterranean OR "low carb" OR "sugar free" OR "gluten free" OR "plant based" OR "animal based") W/2 diet*)) |
| 10 | TITLE-ABS(agricultur* OR agrobiodivers* OR farm* OR crop OR cropping OR livestock* OR "animal husbandry" OR ranching OR rancher OR pastoralis* OR apiculture OR apiary OR permaculture OR aquacultur* OR aquaponic* OR hydroponic* OR agroforestry OR orchard* OR garden* OR vineyard* OR viticulture OR forag* OR hunting OR hunter* OR fishing OR fisher* OR fairtrade) OR AUTHKEY(agricultur* OR agrobiodivers* OR farm* OR crop OR cropping OR livestock* OR "animal husbandry" OR ranching OR rancher OR pastoralis* OR apiculture OR apiary OR permaculture OR aquacultur* OR aquaponic* OR hydroponic* OR agroforestry OR orchard* OR garden* OR vineyard* OR viticulture OR forag* OR hunting OR hunter* OR fishing OR fisher* OR fairtrade) |

| | |
|---|---|
| 11 | TITLE-ABS( meatpack* OR canning OR canner OR canned OR "processing plant*" OR Milling OR mills OR Pasteuri* OR slaughterhouse* OR "nutrition label*" OR "ready to eat" OR "ready to drink" OR "ready to heat" OR "atmosphere packaging" OR "vacuum packaging" OR "vacuum packing" OR silage OR ferment* OR pickl* OR "shelf stable") OR AUTHKEY( meatpack* OR canning OR canner OR canned OR "processing plant*" OR Milling OR mills OR Pasteuri* OR slaughterhouse* OR "nutrition label*" OR "ready to eat" OR "ready to drink" OR "ready to heat" OR "atmosphere packaging" OR "vacuum packaging" OR "vacuum packing" OR silage OR ferment* OR pickl* OR "shelf stable") |
| 12 | TITLE-ABS(supermarket* OR "farmers market*" OR "open air market*" OR restaurant* OR diner OR cafe OR canteen* OR grocer* OR superstore* OR "super store*" OR "coop" OR "co op" OR delicatessen OR bodega* OR ((corner OR convenience) W/3 (shop OR shops OR store*)) OR "terminal market*" OR barbequ* OR cooktop* OR stove* OR oven* OR "open burning" OR broil* OR bake OR baking OR grill* OR frying OR fry OR fried OR "brine cur*" OR din* OR cook* OR "agricultural waste" OR "food waste" OR compost*) OR AUTHKEY(supermarket* OR "farmers market*" OR "open air market*" OR restaurant* OR diner OR cafe OR canteen* OR grocer* OR superstore* OR "super store*" OR "coop" OR "co op" OR delicatessen OR bodega* OR ((corner OR convenience) W/3 (shop OR shops OR store*)) OR "terminal market*" OR barbequ* OR cooktop* OR stove* OR oven* OR "open burning" OR broil* OR bake OR baking OR grill* OR frying OR fry OR fried OR "brine cur*" OR din* OR cook* OR "agricultural waste" OR "food waste" OR compost*) |
| 13 | TITLE-ABS(food* OR agrifood* OR "agri food*" fruit* OR vegetable* OR grain* OR legume* OR nut* OR seed* OR dairy* OR meat* OR pork OR poultry OR fish* OR shellfish* OR seafood* OR beef OR chicken* OR goat* OR lamb* OR veal OR venison OR koumiss OR "alternative protein" OR "plant source" OR "plant based" OR "animal source" OR "animal based" OR egg OR eggs OR "leafy green*" OR cheese OR yog?urt OR milk* OR cereal* OR bean* OR "ultra-processed" OR candy OR dessert* OR sugar* OR "fast food" OR "snack*" OR "meal*" OR lunch* OR brunch* OR dinner* OR breakfast* OR "beverage*" OR drink* OR alcohol OR beer* OR wine* OR sake* OR liquor* OR kefir OR cream OR juice* OR soda* OR coffee OR tea OR soy OR tofu OR tempeh OR sausage* OR "hot dog*" OR bacon OR hamburger OR cookie* OR cake* OR pastry OR pastries OR chips OR chocolate* OR pasta* OR pizza* OR bread* OR condiment* OR "sodium nitrite*" OR "artificial color*" OR "artificial flavor*" OR "artificial sweetener*" OR "flavor enhancer*" OR "trans fat*" OR "hydrolyzed protein*" OR lard OR vinegar* OR flour* OR "corn syrup" OR "monosodium glutamate" OR MSG OR "hydrogenated oil*" OR "hydrogenated fat*") OR AUTHKEY(food* OR agrifood* OR "agri food*" fruit* OR vegetable* OR grain* OR legume* OR nut* OR seed* OR dairy* OR meat* OR pork OR poultry OR fish* OR shellfish* OR seafood* OR beef OR chicken* OR goat* OR lamb* OR veal OR venison OR koumiss OR "alternative protein" OR "plant source" OR "plant based" OR "animal source" OR "animal based" OR egg OR eggs OR "leafy green*" OR cheese OR yog?urt OR milk* OR cereal* OR bean* OR "ultra-processed" OR candy OR dessert* OR sugar* OR "fast food" OR "snack*" OR "meal*" OR lunch* OR brunch* OR dinner* OR breakfast* OR "beverage*" OR drink* OR alcohol OR beer* OR wine* OR sake* OR liquor* OR kefir OR cream OR juice OR soda OR coffee OR tea OR soy OR tofu OR tempeh OR sausage* OR "hot dog*" OR bacon OR hamburger OR cookie* OR cake OR pastry OR pastries OR chips OR chocolate* OR pasta* OR pizza* OR bread* OR condiment* OR "sodium nitrite*" OR "artificial color*" OR "artificial flavor*" OR "artificial sweetener*" OR "flavor enhancer*" OR "trans fat*" OR "hydrolyzed protein*" OR lard OR vinegar* OR flour* OR "corn syrup" OR "monosodium glutamate" OR MSG OR "hydrogenated oil*" OR "hydrogenated fat*") |
| 14 | #9 OR #10 OR #11 OR #12 |
| 15 | #1 AND #8 AND #14 |
| 16 | Date filter: 2018-present |

**Annex Table 3.** Standardised data charting form used for extracting information from all included studies. The form was developed following the JBI template (27).

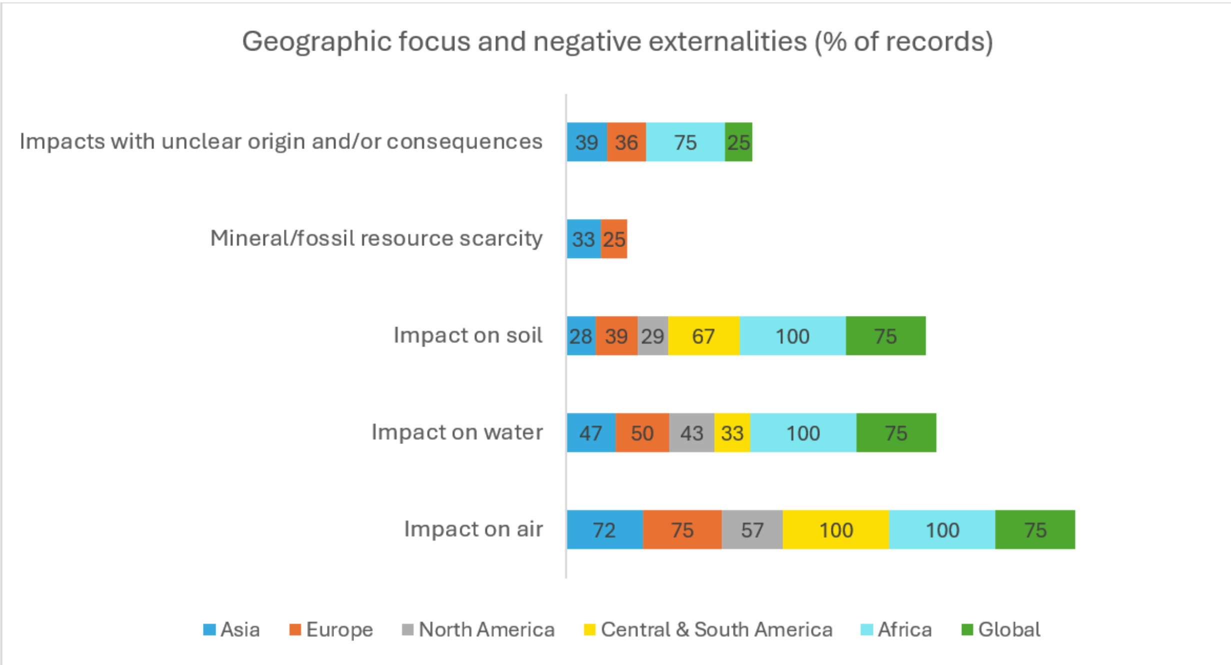
| Section 1: Record details | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Record # | Full record citation in Harvard referencing style | Publication type* | Geographic focus: country(ies), region(s), or global | Country income group(s)* | Life cycle stage(s)* | Reference year(s) / period(s) of input data | Primary research question(s) | Secondary research question(s) |
| 1. | | | | | | | | |
| 2. | | | | | | | | |
| 3. | | | | | | | | |
| 4. | | | | | | | | |
| ... | | | | | | | | |

| Section 2: Key variables of interest to this review | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Record # | Environmental externalities - positive | Environmental externalities - negative | Assessment level(s) * | Food / meal / diet type(s) | Monetization methods | Data sources (impact assessment) | Data sources (valuation factors) | Author-stated strengths | Author-stated limitations | Author-stated research recommendations |
| 1. | | | | | | | | | | |
| 2. | | | | | | | | | | |
| 3. | | | | | | | | | | |
| 4. | | | | | | | | | | |
| ... | | | | | | | | | | |
| * Closed-ended variable | | | | | | | | | | |

## Relationship analysis between key variables

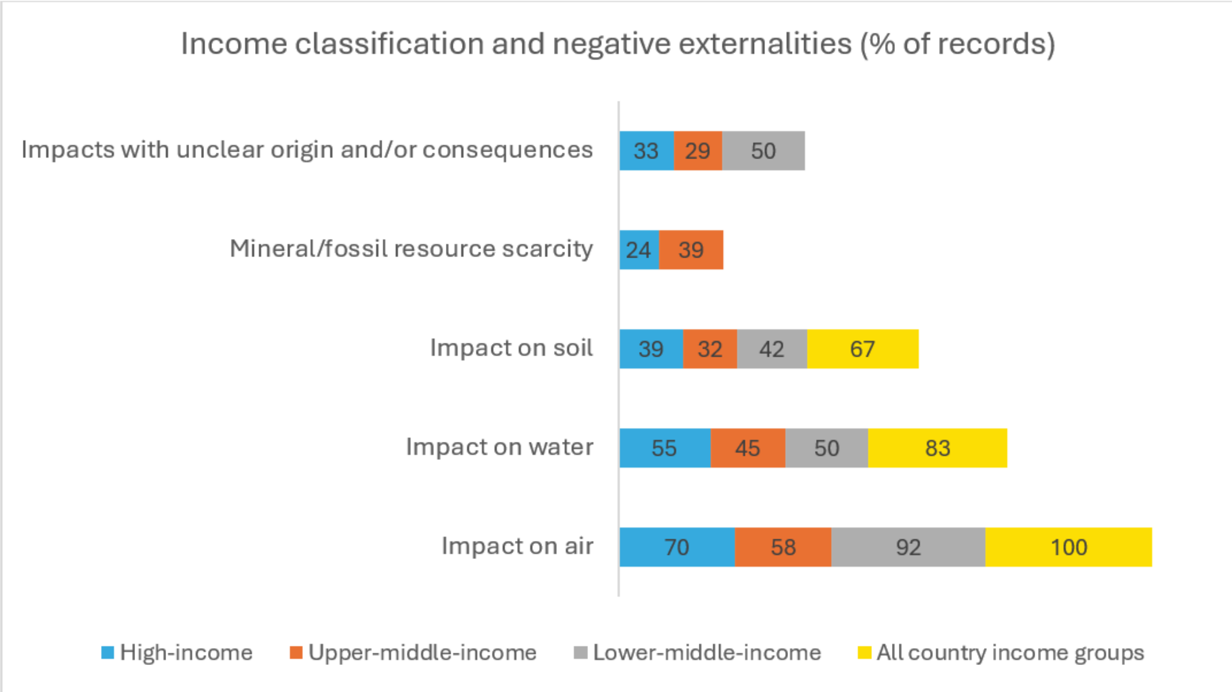
We conducted an exploratory analysis of relationships between key variables extracted from the 85 included records, to identify meaningful patterns and trends emerging from the evidence base.

Analysis of the relationship between geographic setting and the types of negative environmental externalities assessed revealed a consistent focus on impacts on air, soil, and water across all world regions (Annex Figure 1). Most studies set in Asia (72%), Europe (75%), North America (57%), and Central and South America (100%) prioritised air-related impacts. Notably, mineral and fossil resource scarcity was only examined in Asia- and Europe-centred records.




**Annex Figure 1: Relationship between geographic focus and the types of negative environmental externalities assessed (% of records).**

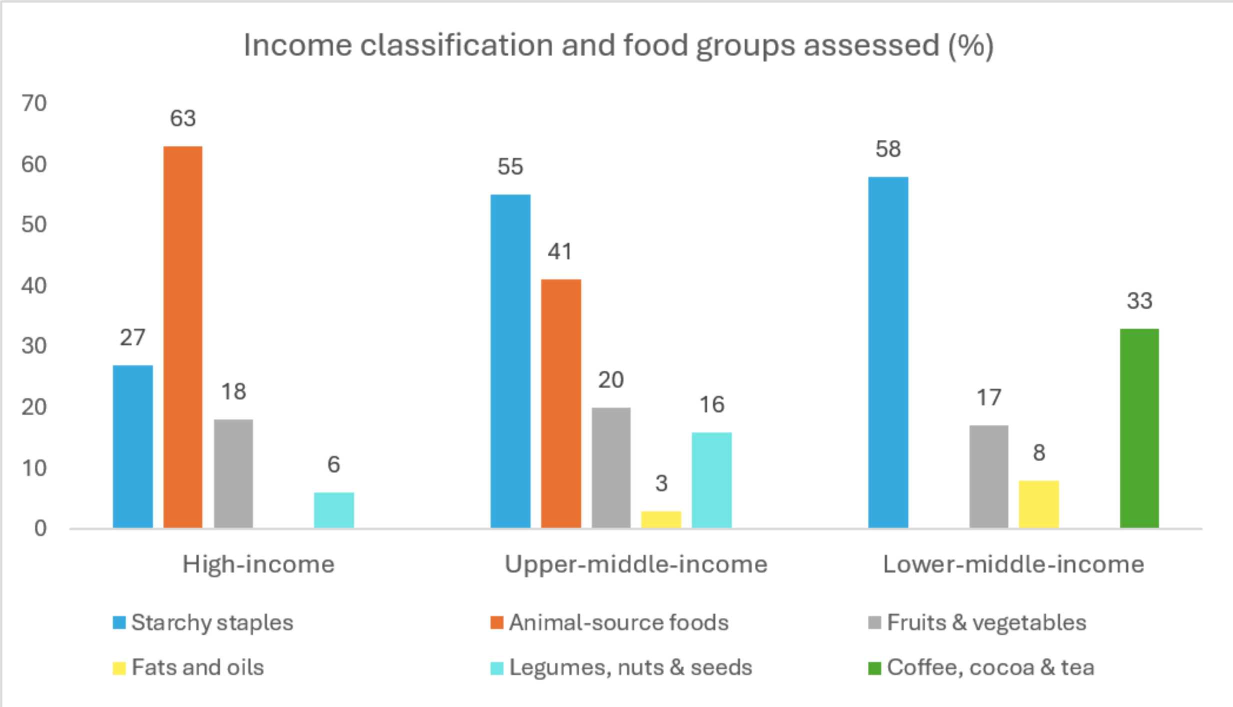
As for the geographic analysis, the predominant focus on negative environmental impacts on air, soil, and water was common across all country income groups (Annex Figure 2). Air-related impacts emerged as the most frequently assessed externality category regardless of income level. Conversely, the evaluation of mineral and fossil resource scarcity was exclusive to studies focusing on high-income and upper-middle-income countries.



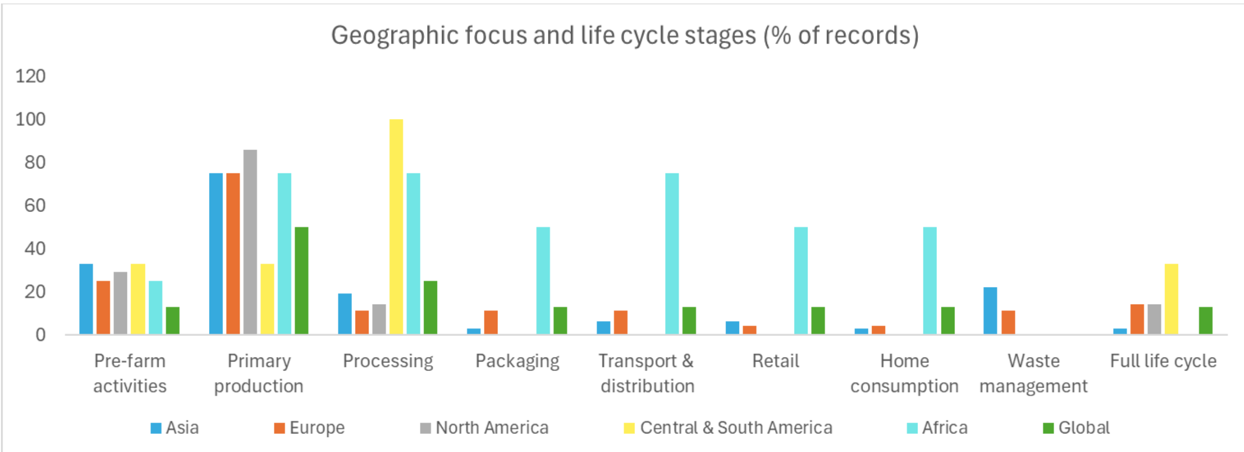

**Annex Figure 2: Relationship between income classification and the types of negative environmental externalities assessed (% of records).**

The analysis of food groups revealed distinct research priorities across different country income levels (Annex Figure 3). Records examining high-income countries showed a predominant focus on animal-source foods (63%) and, to a lesser extent, starchy staples (27%), and fruits and vegetables (18%). In upper-middle-income countries, the primary focus was directed towards starchy staples (55%) and animal-source foods (41%), followed by fruits and vegetables (20%), and legumes, nuts, and seeds (16%). Research in lower-middle-income countries was also dominated by starchy staples (58%) but was unique in its significant focus on coffee, cocoa, and tea (33%). Overall, across all income groups, fruits and vegetables received a consistent but moderate level of attention, while legumes, nuts, and seeds were under-represented.

Value chain stages considered differed by geographic region (Annex Figure 4). Studies set in Asia, Europe, and North America showed a strong emphasis on primary production (75%, 75%, and 86%, respectively) and pre-farm activities (33%, 25%, and 29%, respectively). All records (100%) with a Central and South American focus examined primary and/or secondary processing, while Africa-centred studies covered most life cycle stages more evenly. Waste management was only assessed in a small proportion of records focusing on Asia (22%) and Europe (11%).

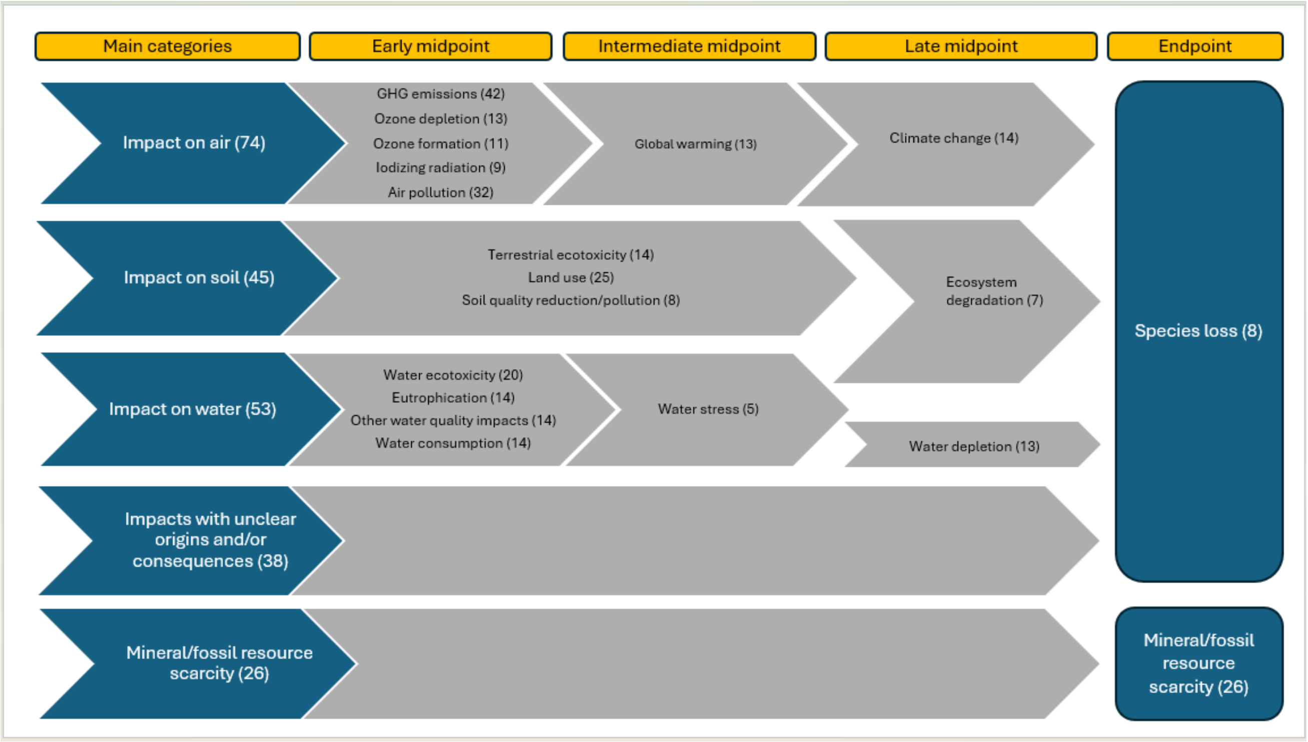



**Annex Figure 3: Relationship between income classification and food groups assessed (% of records).**

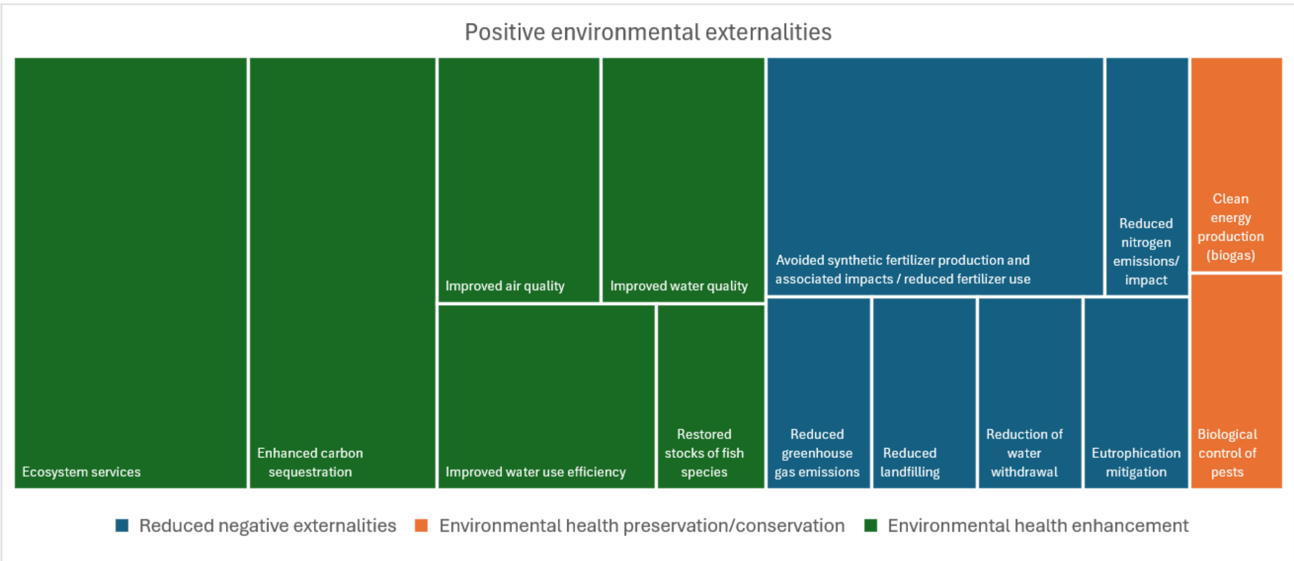



**Annex Figure 4: Relationship between geographic focus and value chain stages considered (% of records).**

## Environmental impacts assessed




**Annex Figure 5: Flowchart illustrating the main categories of negative environmental externalities assessed, as well as the mid- and endpoint indicators measured across the reviewed literature.**




**Annex Figure 6: Heatmap illustrating the main categories and sub-categories of positive environmental externalities assessed.**

## Data sources for impact quantification and monetisation

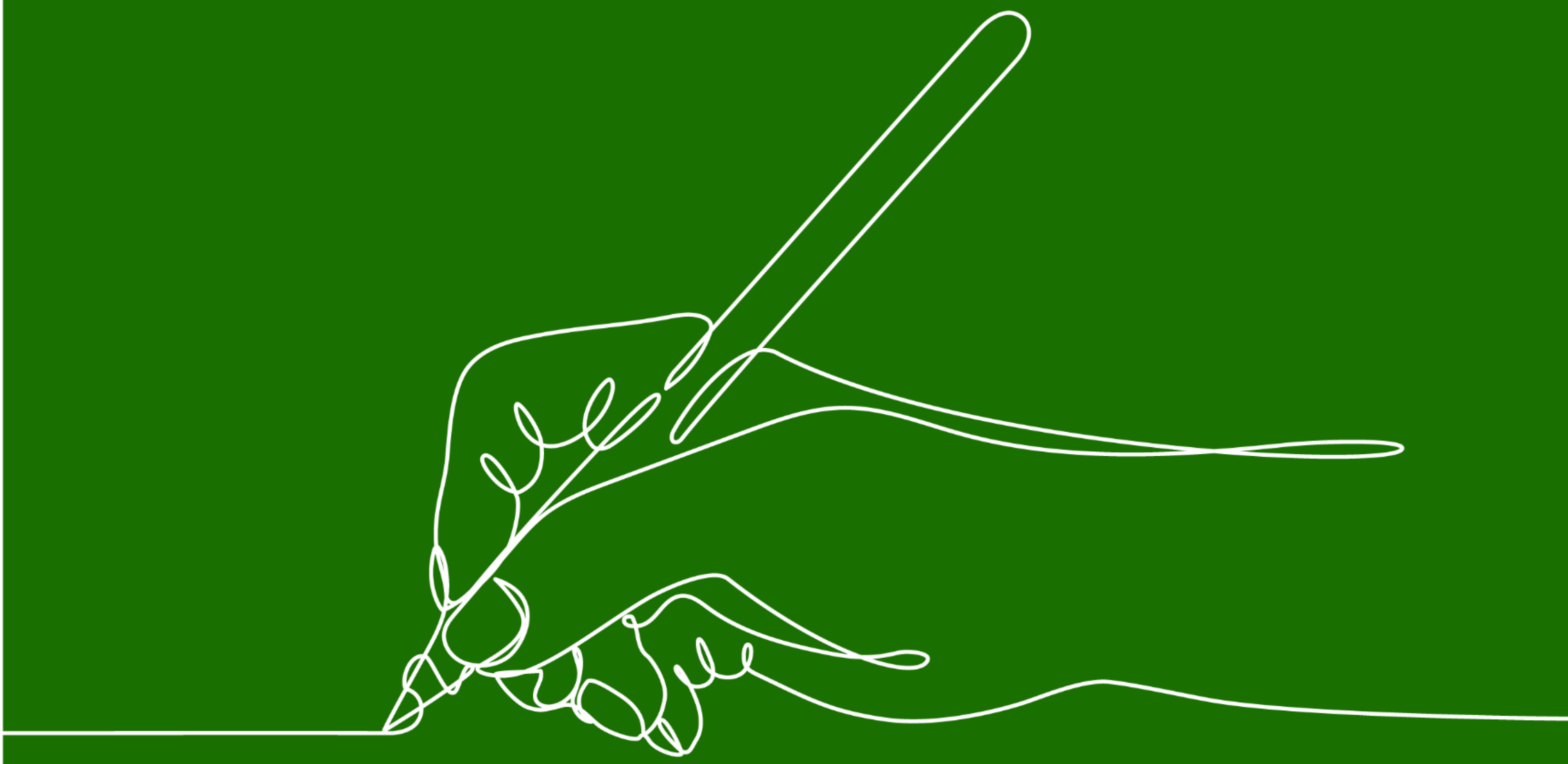
**Annex Table 4: Categorisation and frequency of use of data sources for quantifying environmental impacts surfaced across the 85 reviewed records.**

| Data source category | Main purpose & use case | # (%) of records using this category |
|---|---|---|
| Academia and research institutes | To obtain parameters like resource use, yields, emissions, characterisation factors, and economic values from scientific literature, published studies, and datasets. | 54 (64%) |
| National / regional institutional databases and resources | To obtain official (sub)national and/or regional statistics on demographics, dietary patterns, economic indicators, food systems performance, and environmental impacts. | 50 (59%) |
| LCA models, databases, and inventories | To source Life Cycle Inventory input and output data, characterization factors, and methodological guidance for conducting LCAs. | 38 (45%) |
| Resources by UN agencies | To use technical reports, guidelines, conceptual frameworks, and standardised databases produced by UN agencies to obtain methodological guidance and internationally comparable data across sectors. | 31 (36%) |
| Primary data | To collect new, context-specific information directly from value chain actors through surveys, interviews, or direct measurement / observation. | 22 (26%) |
| (Non-LCA) Specialised environmental impact assessment databases and inventories | To source specific data on environmental processes, emissions, and impacts from specialised databases. | 12 (14%) |
| Datasets for foresight modelling | To obtain specific input data and parameters for running future-oriented simulation models. | 8 (9%) |
| Non-governmental (NGOs) and civil society (CSOs) organizations | To use methodological guidelines, conceptual / theoretical frameworks, programmatic reports, datasets, and other resources published by NGOs and CSOs, including on specific local contexts and production systems. | 5 (6%) |
| Market data and consumer insights | To obtain data on market prices, consumer behaviour, and industry trends from market research firms and commercial data providers. | 4 (5%) |
| TCA and True Pricing databases and inventories | To use pre-existing environmental impact data and valuation factors from established TCA and True Pricing frameworks and initiatives. | 2 (2%) |
| *As many studies relied on multiple data source categories, the percentages add up to over 100%. | | |

**Annex Table 5: Categorisation and frequency of use of data sources for applying monetisation factors surfaced across the 85 reviewed records.**

| Data source category | Main purpose & use case | # (%) of records using this category* |
|---|---|---|
| Academia and research institutes | To obtain parameters like resource use, yields, emissions, characterisation factors, and economic values from scientific literature, published studies, and datasets. | 45 (53%) |
| National / regional institutional databases and resources | To obtain official (sub)national and/or regional statistics on demographics, dietary patterns, economic indicators, food systems performance, and environmental impacts. | 34 (40%) |
| TCA and True Pricing databases and inventories | To use pre-existing environmental impact data and valuation factors from established TCA and True Pricing frameworks and initiatives. | 21 (25%) |
| LCA models, databases, and inventories | To source Life Cycle Inventory input and output data, characterization factors, and methodological guidance for conducting LCAs. | 10 (12%) |
| Resources by UN agencies | To use technical reports, guidelines, conceptual frameworks, and standardised databases produced by UN agencies to obtain methodological guidance and internationally comparable data across sectors. | 8 (9%) |
| Market data and consumer insights | To obtain data on market prices, consumer behaviour, and industry trends from market research firms and commercial data providers. | 8 (9%) |
| Datasets for foresight modelling | To obtain specific input data and parameters for running future-oriented simulation models. | 6 (7%) |
| (Non-LCA) Specialized environmental impact assessment databases and inventories | To source specific data on environmental processes, emissions, and impacts from specialised databases. | 3 (4%) |

*As many studies relied on multiple data source categories, the percentages add up to over 100%.



## ABOUT GAIN

The Global Alliance for Improved Nutrition (GAIN) is a Swiss-based foundation launched at the UN in 2002 to tackle the human suffering caused by malnutrition. Working with governments, businesses and civil society, we aim to transform food systems so that they deliver more nutritious food for all people, especially the most vulnerable.

## ABOUT THE GAIN WORKING PAPER SERIES

The GAIN Working Paper Series provides informative updates on programme approaches, research and evaluations, and on topics of relevance for our work. The full series may be accessed at https://bit.ly/gainpub

**The Global Alliance for Improved Nutrition**

Rue de Varembé 1202 | Geneva | Switzerland| info@gainhealth.org

www.gainhealth.org

GAINalliance

GAINalliance

Gainadm

GAINalliance

Global Alliance for Improved Nutrition