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*Review*

## **Exploring the role of LCA in advancing sustainable agri-food value chains: A systematic review using bibliometric and content analyses**

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**Abstract:** In this study, we aimed to explore the scientific literature development of life cycle assessment (LCA) in agri-food value chain analysis, provide a detailed LCA approach implementation at various stages of value chain networks, and propose future research directions and strategies for advancing sustainable agri-food value chains. We used the systematic literature review method and the PRISMA review reporting system with selected scientific research papers from the Scopus database via VosViewer, R-Biblioshiny, and Excel sheet software. Bibliometric analysis revealed that the LCA in the agri-food value chain increased with the three major clusters, and some crucial topics emerged, including waste valorization, a circular economy, and sustainability. Content analysis revealed that the most commonly evaluated commodity was fruit and vegetables, the studies focused on the production stage, and mostly used the economic LCA method. Although the LCA approach has been used to assess agri-food value chains, the simultaneous integration of economic, social, and environmental LCAs is rarely utilized to comprehensively evaluate sustainable agri-food value chains, particularly in the whole-chain system. We found that the method for assessing the agri-food value chain has experienced several developments and adjustments regarding the type of variables utilized, including the economic dimension, social, and environmental LCA. The development of studies refines the method for advancing sustainable agri-food value chain practices in the chain from production-to-consumer. This

study provides benefits for strengthening the application of LCA to foster a more sustainable agri-food value chain.

**Keywords:** value chain; sustainable value chain; life cycle assessment; agri-food value chain

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## 1. Introduction

As agriculture and food chain systems significantly contribute to greenhouse gas emissions, climate-neutral carbon labeling and certification for agricultural products will be essential in the future. Agriculture is a significant contributor for around 10% of the overall global emission, and when land-use changes and deforestation are included, this could possibly rise to 30% by 2050 [1,2]. Agriculture and associated land-use activities account for approximately one-quarter of total emissions generated across all economic activities [3]. Therefore, achieving net zero and carbon neutrality is crucial in addressing agri-food supply chain challenges and setting a future research agenda [4]. Applying a life-cycle viewpoint across the value chain and strategies such as plant-based materials, optimized logistics, and electrical transportation are critical for effectively mitigating environmental impact [5]. Circular economy strategies can significantly reduce greenhouse gas emissions throughout the value chain, such as increasing recycling rates and extending product lifetimes [6].

For the downstream side, consumers' awareness of a more environmentally food production system is developing. Consumers are starting to pay attention to the environmentally friendly products with lower impact emission. Consumers initially have awareness of environmental issues, and economic behavior positively influences their purchasing behavior, which is reflected in the premium price of consumers' willingness to Pay (WTP) (29.5%), toward sustainable products [7–9]. The trend of environmentally friendly products and sustainable value chains demand is increasingly shaping consumer behavior and marketing strategies, in which consumers prioritize sustainability certification and environmental impact in their purchasing decisions [10]. This emerging awareness drives buyers to seek out eco-friendly alternatives that minimize harm to the environment. This issue is also supported by green economy policies that consider economic growth with environmental protection due to decreasing natural resource consumption and the environmental footprint [11]. As a result, the market for green products is expanding rapidly, with consumers willing to pay an extra price for items that align with their values, signaling a significant shift toward more conscious consumerism.

In recent years, food research in business and economics has increasingly shifted toward the use of comprehensive frameworks such as the sustainability management system, triple bottom line (TBL), and life cycle assessment (LCA), moving beyond the traditional focus on standalone indicators or policy analysis [12]. The FAO defines value chain sustainability as the entire network of all actors, including farms and businesses, that collaborate in value-adding activities to produce raw agricultural materials, transform them into food products, and deliver them to consumers, ensuring profitability, societal benefits, and sustainable use of natural resources [13]. The sustainability of the value chain (VC) is crucial, and three dimensions should be applied simultaneously: economic, social, and environmental. From an economic perspective, the agri-food value chain (AFVC) system is considered sustainable when the activities undertaken by each actor are financially viable and profitable. In the social dimension, sustainability is related to the distribution of the inclusive benefits associated with increased value creation. In the environmental dimension, sustainability is determined largely by the ability of VC actors to show a less or no negative impact on the environment from their value-adding

activities. Some researchers have examined aspects of these chains, including food chain logistics, biobased products, retailer practices, consumption patterns, and crop-based biodiesel options. The TBL of sustainability has become an essential tool for measuring sustainability in the agri-food sector in each chain, in which all indicators can be used for specific purposes [14]. The integration of VC into a sustainability framework is expected to achieve a sustainable competitive advantage in businesses [15]. A study focused only on sustainable AFVC, highlighting environmental pillar without considering the life cycle thinking approach and methodology application [16]. In the methodological perspective, system dynamic has been reviewed as one of the value chain analyses for improving behavior, time delay, and modeling of the governance of actors and support system [17]. However, this analysis may not comprehensively capture sustainability impacts occurring across upstream and downstream stages of the value chain. Therefore, life cycle sustainability assessment (LCSA) can address this limitation by providing a more holistic analytical framework for identifying and assessing sustainability hotspots throughout the value chain.

As part of an integrated approach, LCSA, also known as Life cycle thinking (LCT), offers alternative solutions to ensure circularity and sustainability [14,18]. The sustainability assessment framework has developed a derivative LCA approach, encompassing all dimensions such as life cycle cost (LCC), social LCA (S-LCA), and LCA [19]. These tools can measure economic and social sustainability and consider resource prioritization, conservation, biodiversity, and ecological capacity. However, reviewing the LCA method to elaborate value chain analysis has not been conducted to explore its possible role in the agricultural food commodity value chain. To ensure terminological consistency throughout this review, LCSA is positioned as the conceptual framework for integrating environmental, economic, and social dimensions, while LCT is used as the methodological perspective of impact assessment across the agri-food value chain.

In this systematic literature review, we aim to: 1) Explore scientific literature developments and the application of LCSA approach in AFVC; (2) systematically evaluate, through content analysis, how LCSA and derivative methods have been implemented across commodities, value chain stages, system boundaries, methodological frameworks, and sustainability dimensions; and (3) identify research gaps and propose future research directions and strategic priorities for advancing sustainable agri-food value chain. Additionally, this study is expected to contribute practical recommendations for applying LCSA in future research and industry practices, promoting more sustainable development approaches throughout the value chain.

## 2. Materials and methods

A systematic literature review (SLR) involves identifying, selecting, and critically evaluating research to address a specific question [20]. It involves a comprehensive search of relevant literature, using explicit criteria for study selection and quality assessment [21]. This methodology is directed by a predefined protocol, which encompasses the formulation of a research question, the systematic investigation of databases, the recognition of pertinent studies, the evaluation of their methodological robustness, and the synthesis of the findings. The primary benefits include enhanced transparency, reproducibility, and dependability in knowledge creation. Researchers have developed guidelines and tools to support the SLR process to address these concerns, including formulating research questions, developing review protocols, and synthesizing data [22]. We employed a systematic literature review that integrated bibliometric and content analyses to harness the strengths of each method. We began with the retrieval of relevant articles from academic databases, followed by a bibliometric analysis encompassing author influence, keyword trends, institutional affiliations, citation patterns, and co-

citation networks. Finally, we performed a content analysis. In the literature, the steps of conducting an SLR are defined variably, particularly in economics and management research. Fisch and Block (2018) outlined the SLR process as follows [23]: (1) Formulating the research question, (2) selecting databases and data sources, (3) defining search terms, (4) combining results from multiple databases, (5) applying inclusion and exclusion criteria, (6) conducting the review, and (7) synthesizing the findings.

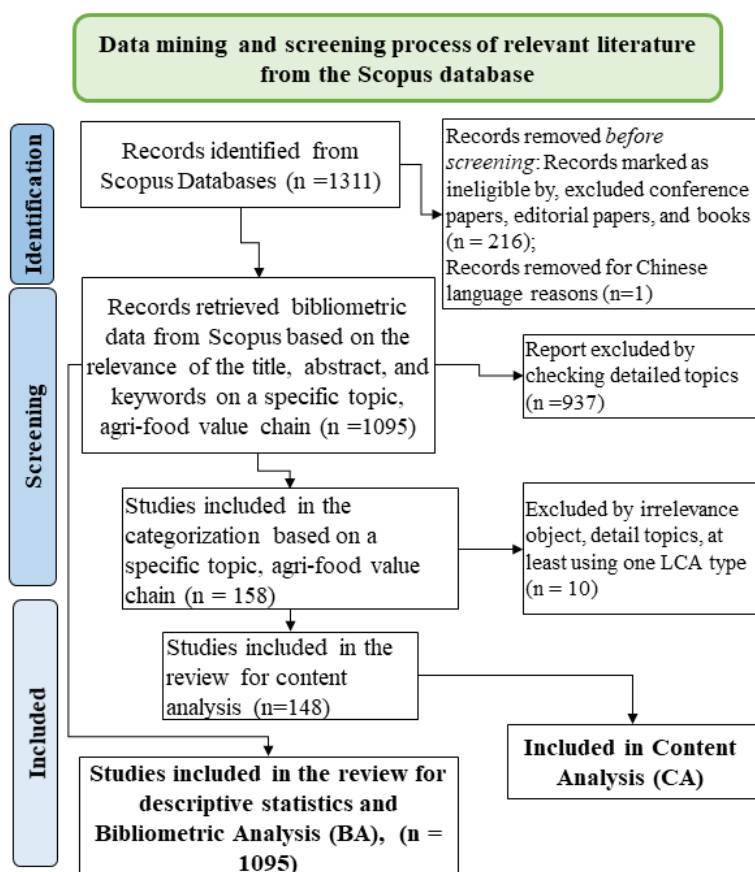
### 2.1. Sub search string and selection

The SLR selection criteria focused on Scopus as the primary database. Keywords such as “LCA”, “value chain”, and “supply chain” were used. The inclusion criteria targeted studies related to agri-food commodities, and the exclusion criteria were non-English and nonprimary articles. Publications from the last 15 years were considered. Some crucial keywords were selected to ensure the accuracy of the search and screening process and were used with the Scopus search query standard algorithm (Table 1).

**Table 1.** Syntax and inclusion-exclusion criteria for selecting articles from the Scopus database.

| Database | Screening  | Syntax                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | Results |
|----------|------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|
| Scopus   | Step 1     | (TITLE-ABS-KEY “value chain” OR “supply chain”) AND TITLE-ABS-KEY “ LCA” OR “life cycle analy”) AND TITLE-ABS-KEY (food OR agri* OR fish* OR fruit OR vegetable* OR forest))                                                                                                                                                                                                                                                                                                           | 1,311   |
|          | Step 2     | (TITLE-ABS-KEY (“value chain*” OR “supply chain*”) AND TITLE-ABS-KEY (“ LCA” OR “life cycle analy*”) AND TITLE-ABS-KEY (food OR agri* OR fish* OR fruit OR vegetable* OR forest)) AND (EXCLUDE (DOCTYPE , “ch”) OR EXCLUDE (DOCTYPE , “cp”) OR EXCLUDE (DOCTYPE , “cr”) OR EXCLUDE (DOCTYPE , “bk”) OR EXCLUDE (DOCTYPE , “dp”) OR EXCLUDE (DOCTYPE , “er”) OR EXCLUDE (DOCTYPE , “ed”) OR EXCLUDE (DOCTYPE , “sh”) OR EXCLUDE (DOCTYPE , “no”)) AND (LIMIT-TO (LANGUAGE , “English”)) | 1095    |
|          | Step 3     | Study included in the categorization based on specific topic, agri-food value chain ation based on particular topic, agri-food value chain                                                                                                                                                                                                                                                                                                                                             | 158     |
|          | Step 4     | Inclusion based on relevant objects, detailed topics, and at least one LCA.                                                                                                                                                                                                                                                                                                                                                                                                            | 145     |
|          | Retrieved: | August 15th 2025                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |         |

Figure 1 presents the systematic selection procedure, comprising database identification, search refinement, relevance screening, and final eligibility assessment for Bibliometric Analysis and Content Analysis. This staged process ensured that the final dataset included only studies directly relevant to the empirical application of LCA in agri-food value chains.



**Figure 1.** Flowchart of systematic literature review steps (Modified from M. Page et al. (2020) [24]).

## 2.2. Data analysis and reporting

We used software such as Excel sheets, VOSviewer, and R-biblioshiny to conduct data bibliometrics and content analysis. VOSviewer is a software program that generates, visualizes, and analyzes bibliometric networks. These networks may include writers, organizations, sources, and other entities. VOSviewer enables these networks' rapid and scalable visualization beyond what can be achieved via manual methods. Moreover, R-biblioshiny is a powerful bibliometric analysis tool integrated within the "R" programming language and is designed to facilitate the comprehensive evaluation and visualization of research trends and patterns across academic fields. R-Biblioshiny can summarize the research landscape, highlighting active countries and emerging topics. Elaborating on VOSviewer and R-biblioshiny would provide a clearer academic picture since both can be used to complement each other. R-biblioshiny has been used to investigate the current development of global land use system and sustainability, revealing emerging themes, innovation, and future research opportunities [25].

In conducting the CA, the consistency and inter-coder reliability of the content categorization were ensured through a structured and iterative coding procedure. The coding framework was developed from the research objectives, relevant literature, and a preliminary review of the selected articles, while the categories and operational definitions were collaboratively discussed, agreed upon, and refined by us to minimize ambiguity. Two authors collaboratively conducted the primary coding of all included studies based on the agreed coding framework using an Excel sheet to categorize the

data content and develop the informative tables and graphical visualizations. During the coding process, unclear or potentially overlapping cases were discussed with the other authors until consensus was reached. The final coding results were subsequently reviewed by us to assess consistency with the predefined categories and the original content of the articles. This procedure was in accordance with another study that suggests that the inter-rater reliability and consistency requires refine frame code, team discussion, collaboratively re-checking, and consensus-building, as well as adequate break to reduce fatigue and coder bias [26].

For reporting, we adopted and modified the PRISMA protocol approach for the SLR. PRISMA provides evidence-based guidelines for reporting systematic reviews and meta-analyses, not only for evaluating intervention impacts but also as a foundation for general systematic reviews [27]. The 2020 PRISMA statement, which updates the 2009 version, incorporates new reporting standards that account for advancements in study identification, selection, evaluation, and synthesis methods [24,28].

### *2.3. Theoretical and conceptual frameworks*

#### *2.3.1. Agri-food value chain (AFVC)*

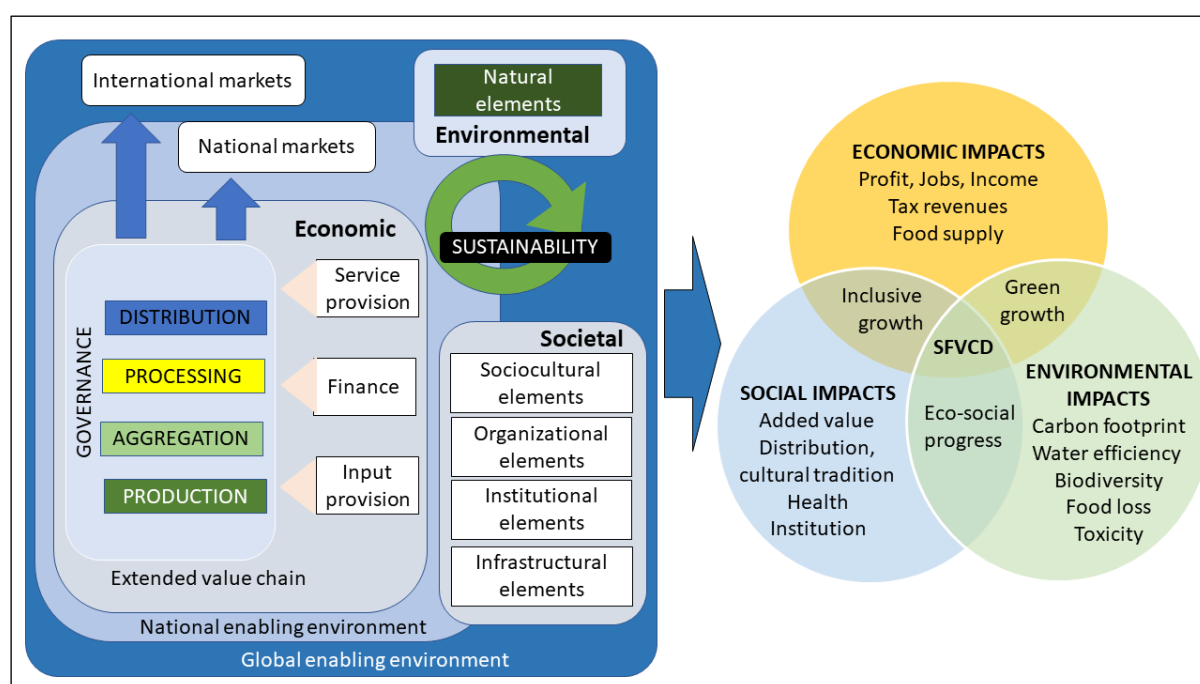
The agri-food value chain (AFVC) encompasses interconnected concepts and dimensions, including governance structure and competitiveness. Some key concepts in AFVC are resource allocation efficiency, value addition, vertical-horizontal integration, collaboration, traceability and transparency, market dynamic, resilience, and sustainability. In value addition, efficiency and innovation at each stage are crucial for maximizing value [29]. Sustainability in AFVC involves minimizing waste and integrating circular economy principles to address environmental challenges such as climate change and resource depletion [30]. To reduce transaction costs, governance among actors determine the integration and collaboration strategies. From the consumer perspective, the modern agri-food value chain increasingly demands a traceability system to monitor the long-term journey of food products and ensure compliance with safety, quality, consumer's trust, resilience, and sustainability standards.

On the supply side, the food system value chain requires competitive improvements, which reduce food product costs to consumers, transaction costs, and negative environmental impacts and increase benefits. According to Neven (2024), value chains play a vital role in driving economic growth by generating added value through increased wages for workers, profits for entrepreneurs, improved food availability for consumers, and measurable environments [13]. The concept of competitiveness is relative and dynamic and is assessed at multiple levels from country to firm. A comprehensive framework for measuring sustainable competitiveness should consider economic, social, and environmental factors [31]. On the market side, consumer awareness of green products is emerging as a response to the unsustainable food supply chain due to natural resource depletion and negative environmental impact. Ecolabeling is a strategy to increase market trust and awareness about value chain sustainability and promote low-adverse-externality practices throughout the food production system [32].

#### *2.3.2. Sustainable agri-food value chain*

The FAO defines the sustainable food value chain as the integrated network of farms, firms, and their coordinated activities that produce raw agricultural materials and transform them into food products for consumers, operating in a manner that ensures profitability, broad societal benefits, and

the preservation of natural resources [13]. The concept simultaneously highlights three bottom lines, which all actors in network chains should commit to, as they do in the economic aspect, paying attention to social and environmental concerns (Figure 2). Value chains are dynamic, market-oriented systems in which effective coordination among all actors constitutes a core structural component. At the aggregated level, the multidimensional measurement of added value and sustainability must be assessed comprehensively. VCAs have focused primarily on economic sustainability and often neglect social and environmental impacts. Fearn et al. (2012) argue that VCA needs to elaborate on the social and environmental dimensions to achieve a competitive advantage [15]. The meaning of “value” and the relationships within the chain must broaden the boundaries to create a sustainable agri-food value chain. The narrow scope of VC can lead to the neglect of competitive advantage opportunities from environmental and social aspects.



**Figure 2.** Sustainable agri-food value chain (SAFVC) framework and its impacts on development [15].

### 2.3.3. Life cycle sustainability assessment (LCSA)

Life cycle thinking (LCT) is a systems-based perspective that evaluates the environmental, economic, and social consequence of a product, process, or service across its life cycle, from raw material extraction and production to distribution, consumption, and end-of-life management. Theoretically, LCT is grounded in systems thinking and industrial ecology, which emphasize the interdependence of activities, material and energy flows, stakeholders, and impacts across interconnected production and consumption systems. This perspective helps prevent burden shifting, whereby improvements at one life cycle stage or in one sustainability dimension generate unintended impacts elsewhere [33,34]. Building on LCT, in 2011, UNEP/SETAC promoted the LCSA through a life cycle initiative program to provide an integrated methodological framework for assessing sustainability performance across the life cycle performance [18]. The LCSA framework combines LCA, LCC, and social LCA (S-LCA), commonly expressed as  $LCSA = LCA + LCC + S-LCA$  [33]. Within this framework, LCA evaluates environmental impacts associated with resource use, emissions,

production processes, and distribution to consumers; LCC assesses costs incurred across life cycle stages; and S-LCA examines social and socioeconomic impacts on workers, producers, consumers, and other stakeholders. Together, these three methods provide a multidimensional understanding of sustainability and help identify trade-offs and synergies across value-chain stages. Empirically, the integration of LCC and S-LCA into sustainability assessment remains a developing methodology, incorporating cost and social consideration to more holistic sustainable evaluation [35].

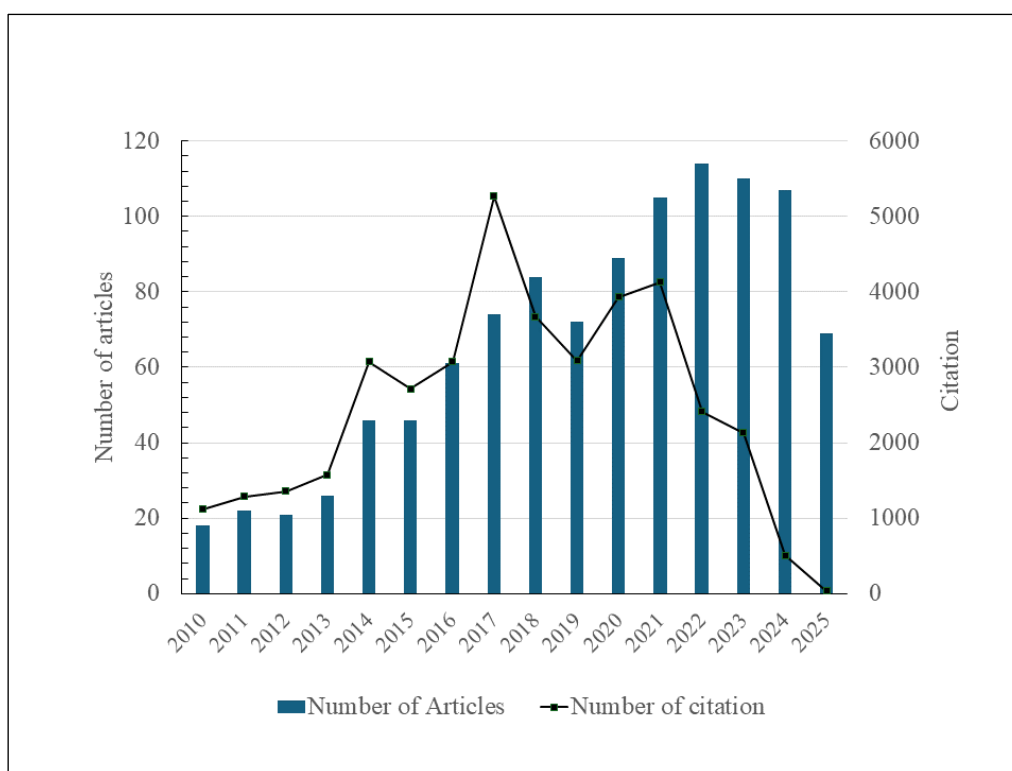
In the perspective of sustainable agri-food value chain, this theoretical and methodological framework is crucial for building value chain, which is economically profitable, socially inclusive, and environmentally sound. It comprehensively analyzes resource use, socioeconomic, and environmental effects throughout the production chain. LCA has been adapted to address the unique challenges of agriculture, including multiple products from a single system, regional variations, and nonpoint emission sources [36,37]. Despite agricultural LCA development, challenges, such as the need for improved environmental impact assessment indices and limited application of comprehensive LCSA across production networks, exist. Further research is needed to explore the status methodological application to support a sustainable agricultural decision-making.

### 3. Results and discussion

#### 3.3. Bibliometric analysis

##### 3.3.1. Article development

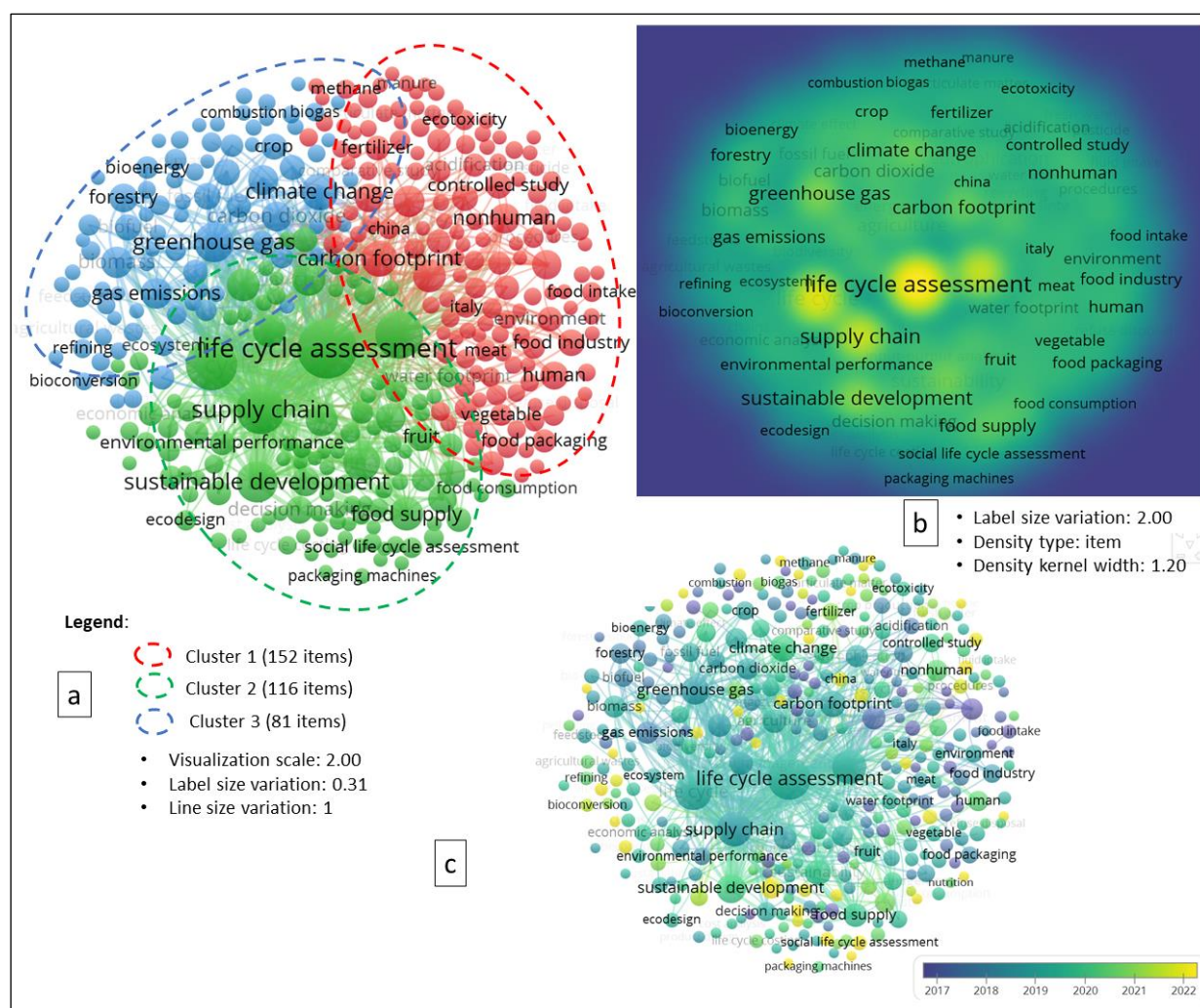
The status of manuscript publication was an unstable increase in publications from 2010–2025, peaking in 2022 with over 100 publications; however, there was a slight decline after 2022 (Figure 3). Likewise, the number of citations grew significantly between 2016 and 2018, peaking at over 4,000 in 2018. The low number of citations in 2025 may be due to the use of ongoing year data, which have not been well recorded or other word citation trend. The data indicate that the number of publications and citations increased steadily up to 2021, reflecting strong scholarly interest in the topic. The subsequent decline in article number and citations may suggest that research attention has gradually shifted toward broader and more integrated sustainability approaches rather than focusing solely on LCA. This slight decrease indicates that LCA research entered the stage of practical application. Moreover, LCA focuses on future-oriented scenarios and interdisciplinary research fields, converting environmental assessment results into workable strategies for sustainable agriculture system [38]. As science-based environmental policy making targets gain prominence, LCA is becoming increasingly embedded in public policy across sectors in OECD countries [39]. Moreover, Regulation (EU) 2023/1115 requires actors handling designated agricultural commodities to demonstrate due diligence, legal compliance, product traceability, and deforestation-free agricultural production [40]. This issue has contributed to the broadening of research trends into more diverse and integrated topics.



**Figure 3.** Number of articles and their citations related to LCA in the agri-food value (supply) chain (n=1095 papers).

### 3.3.2. Thematic cluster, density, and trend

In this review, keyword co-occurrence network analysis was utilized to explore knowledge, research, and topic development within the agri-food commodity value chain. Keyword co-occurrence analysis was performed using VOSviewer software (version 1.6.20). Author keywords and indexed keywords as unit of analysis with full counting were extracted from the 1,095 papers identified in Step 2 of the screening process (see Figure 1). A minimum threshold of ten keyword occurrences was applied to ensure statistical reliability; of the 7,948 unique keywords, 357 met this threshold and were included in the network analysis. To avoid redundant keywords of synonyms and single-plural words, the VOSviewer thesaurus file was created using notepad++ and Excel sheets. The relevance score option was selected to weigh keywords by their discriminatory power. The network visualization (Figure 4(a)) used the LinLog/modularity clustering algorithm with a resolution parameter of 1.0, which identified three distinct clusters. The density visualization (Figure 4(b)) used the same dataset with a kernel density estimation to highlight areas of high and low keyword concentration.

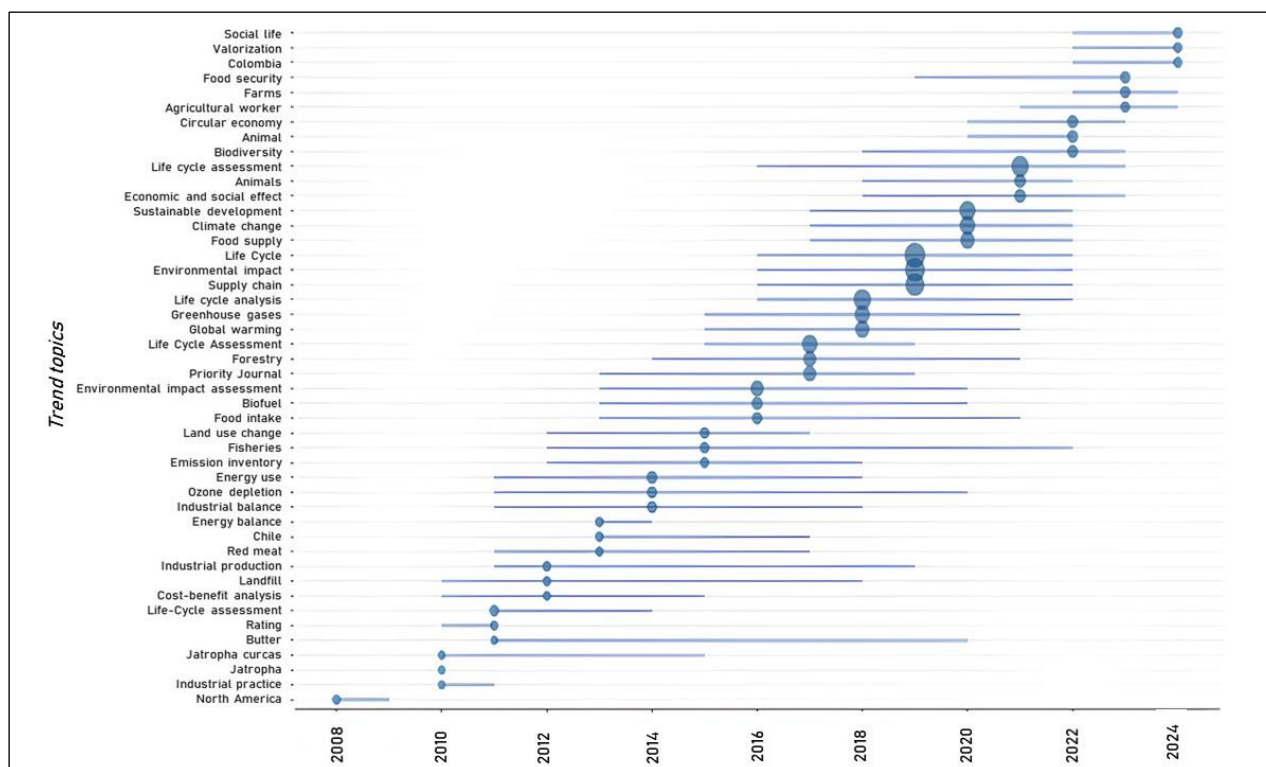


**Figure 4.** (a) Network visualization; (b) Density visualization; and (c) Overlay visualization of primary keywords occurrence analysis using VOSviewer Software.

The VOSviewer categorized primary keywords into three concentrated thematic keyword clusters (Figure 4(a)). In the distance-based approach, nodes in a bibliometric network are arranged so that the distance between any two nodes roughly reflects their level of relatedness [41]. The analysis of individual clusters presents the major keywords and their characteristics concerning this map, including co-occurrence and total link strength. The first cluster, the circling red dashed line, represents close issues related to carbon footprint, eutrophication, environmental LCA, agricultural production, agricultural management, and agricultural land. The leading crucial word is carbon footprint, which has a strong link and relation to other keywords in the cluster and another cluster. The second cluster, circling green dashed line, is associated with key terms such as sustainable development, sustainability, LCA, food supply, and decision making, led by LCA as a crucial keyword. The third cluster, blue dashed line, highlights keywords related to the impact category, such as climate change impact, carbon dioxide, methane, greenhouse gas, and fossil fuel. The category keyword became a link bridge between the external and internal green dashed circles. The density visualization (Figure 4(b)) highlights emerging keywords associated with LCA in the agri-food value chain. Terms such as ‘food supply chain’, ‘food packaging’, ‘social LCA’, and ‘sustainable development’ appear less prominent, suggesting that these topics have received comparatively limited attention in the literature. This niche

can be addressed as a gap that can be considered for further research. From a temporal perspective, keywords such as “economic and social effects”, “social LCA”, “value chain”, “sustainable development”, “bioconversion”, and “biorefinery” have emerged relatively recently in the literature (Figure 4(c)). This represents emerging research themes that have gained attention only in recent years.

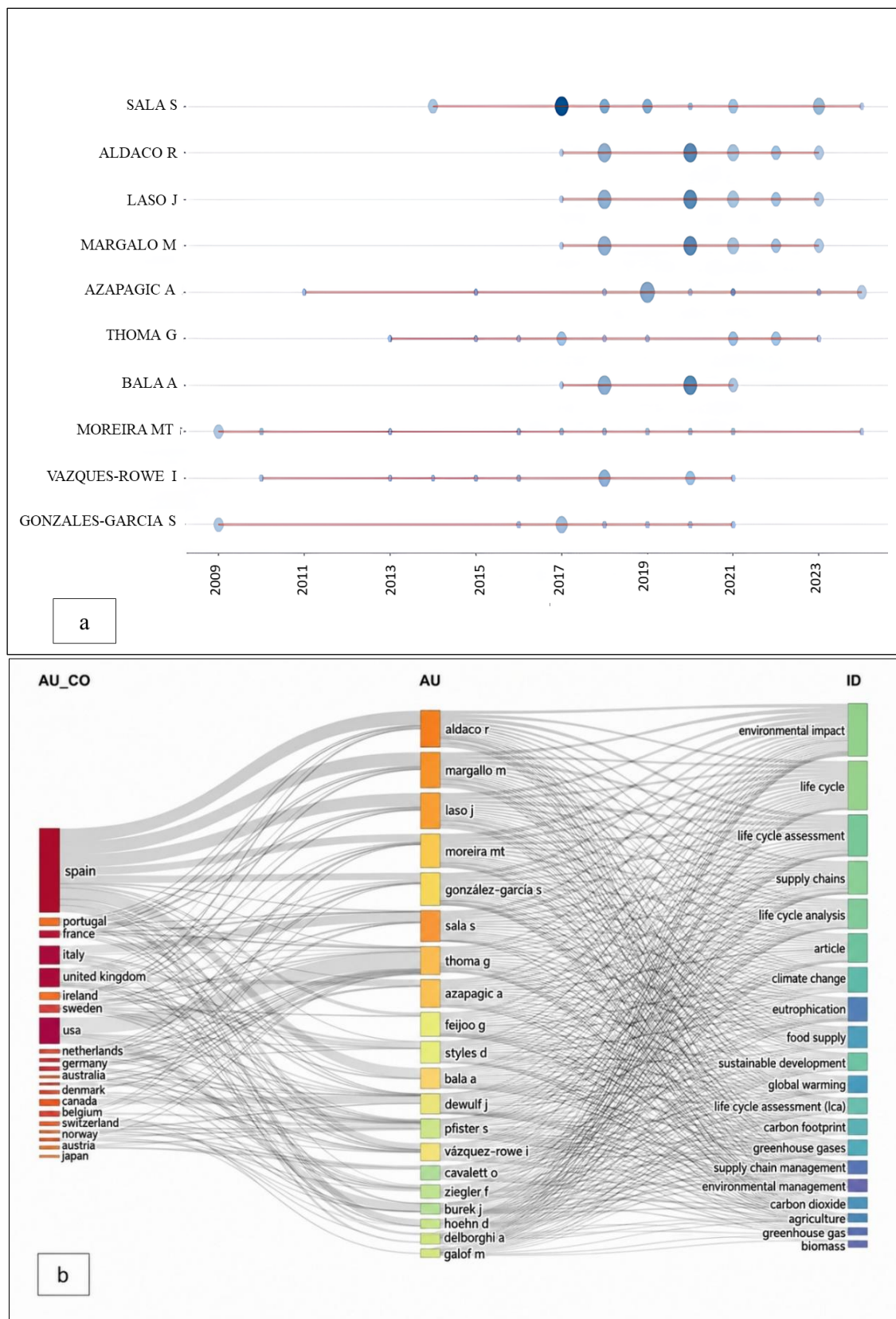
Additionally, the trend of topics has changed, and some essential trend topics have emerged. R-biblioshiny reported that in the last five years, valorization, food security, the circular economy, social LCA, biodiversity, economic–social impact, and sustainable development have become the major concerns of researchers. Research on the agri-food value chain has shown a trend not only in terms of the environmental aspects but also in terms of the social and economic aspects (Figure 5).



**Figure 5.** Trend topics empirical study related to LCA from 2008–2025 (R-biblioshiny visualization).

### 3.3.3. Article authorship

The timeline chart (Figure 6(a)) illustrates the research development trend of authors applying LCA methods over the years. Notably, authors such as Sala et al. (2017), Aldaco et al. (2020), and Laso et al. (2017) have shown consistent research activity from 2014 onward, with a peak in publications approximately 2018–2020 [42–44]. Sala S and Aldaco R stand out for their increased research output during this period, indicating a growing focus on sustainability and LCA applications in recent years. Azapagic has the most consistent research focus related to LCA over 20 years. Researchers such as Laso et al. (2018) have contributed steadily, with more recent publications [45]. This trend suggests an expanding interest in LCA methodologies for assessing sustainability in various sectors, particularly in the agri-food value chain, as reflected by the clustering of research in the late 2010s.



**Figure 6.** (a) Author's chronological production, and (b) the Sankey diagram relation of countries of publication, authors, and main topics (R-biblioshiny visualization).

The Sankey diagram highlights the strong collaboration among authors and countries and critical topics related to the use of LCA in assessing the sustainability of the agri-food value chain. Most researchers, particularly those from Spain, Portugal, Italy, and the United Kingdom, have extensively (Figure 6(b)) applied LCA methodologies to analyze the environmental impact, life cycle, and supply chain sustainability. There are a few empirical studies from developing countries. These authors, such as Laso et al. (2017), Aldaco et al. (2020), and Fernández-Ríos et al. (2023), are prominently linked to crucial keywords such as “environmental impact”, “LCA”, and “supply chains” [44,46,47]. The diagram illustrates how specific countries are strongly associated with leading research in sustainability and LCA methods, reflecting their pivotal role in advancing agri-food value chain studies.

### 3.4. Content analysis

To explore the experience of using the LCA in the agri-food value chain, we used content analysis to categorize the selected scientific papers on the assessed commodities, derivative products, unit analysis in the stage of the chain, the methods used, and the parameters in each dimension, which were implemented in the agri-food value chain. Therefore, the main structure of content analysis of LCA utilization is as follows.

#### 3.4.1. Agricultural commodities and derivative products

LCAs have been widely employed to assess the social, economic, and environmental value of some agricultural commodities and derivative products. For the purposes of this review, commodities were categorized as follows: (1) Fruits and vegetables: Fresh produce including tomatoes, apples, lettuce, avocado, strawberries, and citrus; (2) estate crops: Perennial tree crops including palm oil, olive oil, coffee, and cocoa; (3) food crops: Staple annual crops including cereals, grains, and legumes (e.g., rice, wheat, maize, soybeans); (4) meat and dairy: Animal products including beef, pork, poultry, milk, cheese, and eggs; (5) fisheries: Wild-caught and farmed fish and seafood; and (6) food loss and waste: Researchers focused on waste valorization, byproduct utilization, or food waste management. This categorization scheme was developed iteratively by us based on the commodities identified in the selected papers and refined through team discussion until consensus was reached. To improve readability and provide a more comprehensive presentation of the topics, the categories were visualized using two sunburst charts (Figure 7).

LCA studies have predominantly focused on upstream activities (accounting for more than 60%), particularly raw material production, input use, cultivation, and primary processing of food crops, fruits, vegetables, and estate crops (Figure 7(a)). In the upstream level value chain, most researchers have focused on fruit and vegetable commodities, such as tomatoes, apples, lettuce, potatoes, avocado, strawberries, citrus, and kiwi. Estate crops also receive substantial attention, especially olives and palm oil farming, followed by coffee and cocoa. By contrast, food crops such as rice, wheat, maize, and pulses account for relatively smaller shares. This gap significantly requires scholar attention as food crops have a crucial role in global food security toward climate-environmental pressure. Therefore, in the whole value chain studies, LCA research has mainly been applied to assess environmental impacts on primary agricultural production, while other stages of the value chain have received less attention. This emphasis reflects the substantial environmental burdens associated with energy consumption, fertilizer application, land use, and resource extraction at the production stage.

In contrast, downstream activities such as distribution, retailing, consumption, product use, and end-of-life management remain comparatively underexplored. Figure 7(b) presents the emerging focus

of LCA studies at the downstream level, covering food processing, industrial production, by-product utilization, and food loss and waste (FLaW) management. Processed food and industrial products constitute a major research area, with wine and beer accounting for the largest share, followed by tomato puree and olive oil. Fisheries and marine processing are also increasingly examined, including fisheries, salmon, seaweed, shrimp, and seafood products. Studies on meat and dairy products focus on beef, milk, and eggs, reflecting growing concern over the environmental burdens of processing, storage, and distribution. The prominent share of by-products and food loss and waste, particularly flour-related waste, further demonstrates an expanding interest in circular economy strategies, resource recovery, waste reduction, and improved efficiency across downstream food value chains. However, LCA application on a downstream level, processed product, and fishery are active, highlighting the need for more integrated studies covering processing, packaging, distribution, consumption, and post-consumer waste. This imbalance limits a comprehensive understanding of environmental impacts across the value chain. Therefore, researchers should extend LCA applications to downstream stages to capture impacts related to derivative products, packaging, byproducts, food loss, waste, recycling, disposal, and consumer behavior. Practically, the future interest should focus on circularity, resource recovery, waste reduction, and downstream efficiency.

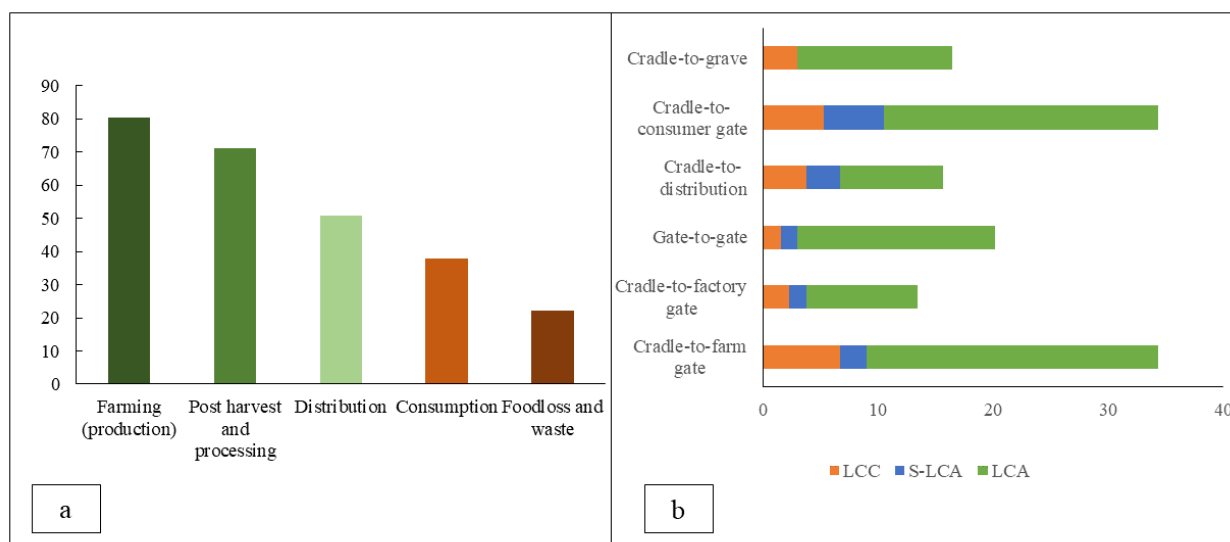


**Figure 7.** Percentage of the assessed commodities in the agri-food value chain through LCA (n=145): (a) Upstream commodity categories; and (b) Meat-dairy, fishery and downstream categories including by product and FLaW.

### 3.4.2. LCA application and system boundary

In the supply chain, the farming stage has the highest percentage, reflecting the broad application of these LCA methods in evaluating resource use, emissions, and socioeconomic impacts (Figure 8(a)). The postharvest and processing stages are assessed via LCA to measure energy consumption, water usage, pollution potential, and social impacts on workers. The distribution of economic inputs related

to transportation emissions, packaging efficiency, and associated environmental and social impacts was analyzed. The consumption phase incorporated LCA to assess energy use in food preparation, food waste generation, and consumer behaviors from environmental, economic, and social perspectives. Finally, the food loss and waste stage applied these LCA methods to quantify the effects of waste management on economic efficiency, social implications, and environmental degradation.



**Figure 8.** (a) Percentage of LCA approach number in each chain; and (b) percentage of LCA type based on the system boundary number implemented in the value chain (n=145).

In LCA terminology, system boundary defines the limitation scope, which life-cycle stages, unit process, and activities flows are included in or excluded from the assessment. Its selection determines the study's scope, completeness, and comparability. Based on the system boundaries applied, cradle-to-farm gate and cradle-to-consumer gate are dominated the empirical studies in this review (Figure 8(b)). System boundaries are typically defined as: 'cradle-to-gate' (from raw material extraction to the farm or factory gate, excluding downstream stages), 'cradle-to-consumer' (from raw material extraction to the point of purchase or consumption), and 'cradle-to-grave' (from raw material extraction to disposal, recycling, or waste management). Figure 8(b) shows that most studies (approximately 65%) used cradle-to farm gate boundaries, assessing value only at the production stage. Approximately 25% of studies used cradle-to-consumer boundaries, assessing value from production through consumption. Fewer than 10% of studies included end-of-life stages such as food waste management, valorization, or circular economy strategies, despite 'valorization' and 'circular economy' being identified as emerging trend topics (Figure 5). This represents a significant gap: Assessing the full cradle-to-grave chain, including waste valorization, is essential for advancing circular agri-food systems. Additionally, Figure 8(b) represents the percentages of different LCA methods applied across various system boundary of food value chain stages. Each bar indicates how extensively specific LCA methodologies, LCC, S-LCA, and LCA, have been utilized to assess the impacts at each stage, from farming through food loss and waste. Most studies have used LCA to assess all values at the level of the cradle-to-farm gate. This means that the assessment was saturated at the farm level using the LCA method and needs to be expand to other value chain level. This finding was supported by another study where LCC and S-LCA were an emerging application [35]. There is a gap to assess the comprehensive multiple chain levels from farming to consumption (cradle-to-consumer gate) and the downstream sectors considering

integrative LCSA.

### 3.4.3. Economic, social, and environmental dimension

Integrating the LCSA approach into the agri-food value chain in agriculture provides a comprehensive method for assessing and managing the social, economic, and environmental impacts of agricultural practices, with an extended “economic value” meaning. The LCSA-VCA framework is a meticulous method based on perspective value chain analysis in each or the whole chain. LCSA offers a holistic view of value impacts throughout the life cycle of agricultural products, from raw material extraction to disposal, allowing the quantification of various environmental impacts, such as greenhouse gas emissions, water usage, soil degradation, and biodiversity loss. This comprehensive analysis helps identify hotspots or stages in the value chain with the highest value impact, enabling targeted interventions that are environmentally, economically, and socially sustainable. By combining LCSA with value chain analysis, stakeholders in each chain can make more informed decisions that balance multiple sustainability objectives, enhancing policy and strategy development for sustainable agricultural practices. This integrated approach improves resource efficiency by optimizing input values such as water, fertilizers, and pesticides and reducing waste, thus enhancing the circularity of agricultural systems. It is expected to lead to better communication and stakeholder engagement by increasing transparency and building trust through a demonstrated commitment to sustainability. Moreover, integrating LCSA into VCA offers economic benefits by identifying product value and the resulting value of inefficiencies and waste, leading to cost savings and improved profitability for all actors in the chain network. This approach provides a competitive advantage by differentiating products with lower environmental footprints as sustainable options. Therefore, integrating LCSA into VCA is crucial for advancing sustainable and resilient agricultural systems.

Several studies in the agri-food supply chain have used the LCA method, either by using it as a single method or combining it with other research methods, such as multicriteria decision analysis (MCDM), the analytical hierarchy process (AHP), data envelopment analysis (DEA), and social network analysis. The advantage of combining the LCA approach with other methods is that it can provide a more comprehensive analytical approach according to the research objectives. Likewise, the use of the LCA method has undergone significant developments, which can be seen from the derivative methods that have been developed on the basis of the dimensions of sustainability, including social LCA, economic LCA, and environmental LCA. Each method in the sustainability dimension has also been developed and has different measurement indicators. All dimensions, types of LCA, and variable development can be seen in Table 2.

Although LCA is extensively employed to evaluate supply chain sustainability, the comprehensive integration of its social, economic, and environmental dimensions remains underutilized, particularly in the context of agri-food value chains. Most researchers have focused primarily on measuring environmental sustainability indicators, whereas the social and economic dimensions remain underdeveloped in comprehensive value chain assessments. Some researchers have employed comprehensive three-dimensional LCA. For example, Maffia et al. (2022) assessed the social, economic, and environmental value of organic and nonorganic olive oil production systems [48]. Hingsamer et al. (2022) performed an LCA of root chicory production [49]. However, studies lacked scientific literature that prioritizes or weighs the importance of these three dimensions of sustainability. Focusing on only one dimension can reveal trade-offs that must be addressed to prioritize and create more sustainable value. Researchers may hold differing views on which aspects should take precedence. This line of thinking could serve as a foundation for developing robust indicators and

advancing methodologies for measuring sustainability comprehensively.

**Table 2.** Antecedents of the LCT method experience and its application in agri-food value chain assessment in three sustainability dimensions.

| Dimension of Sustainability | Type of Utilized LCAs                                | Variable issues                                                                                                                                                                                                                                               | Researcher (author/s) |
|-----------------------------|------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------|
| Economic dimension          | Economic Input–Output                                | Income, livelihood, added value                                                                                                                                                                                                                               | [49–51]               |
| Social dimension            | Life Cycle Cost (LCC)                                | Cost value in each stage                                                                                                                                                                                                                                      | [48,52,53]            |
|                             | Benefit–Cost (BC) Analysis                           | Cost-revenue analysis, Benefit–cost ratio, Net Present Value (NPV)                                                                                                                                                                                            | [53–55]               |
|                             | Social-Life Cycle Assessment (S-LCA)                 | Employment of labor, fair salary, child labor, equal opportunity, health and safety, cultural heritage, fair competition, respect of human rights, absence of corruption, local community participation, philanthropic activities, and technology development | [48,49,56–59]         |
| Environmental impact        | Social-Organizational Life Cycle Assessment (SO-LCA) | Governance of organizational facilities, geographical area, and brand                                                                                                                                                                                         | [60]                  |
|                             | Environmental Life Cycle Assessment (LCA)            | All value indicators related to environmental dimensions, such as food loss, waste, freshwater footprint, carbon footprint, eutrophication, acidification, and energy consumption                                                                             | [55,57,61–64]         |

In the economic dimension, the LCT approach has a crucial role in measuring the value of economic and financial perspectives in assessing a sustainable value chain in agri-food commodities. The LCA method has been extended to include economic and social aspects, which can be utilized to assess the economic value and impacts on the agri-food value chain, such as income level, livelihood, added value, profit, benefit, cost of the chain, transaction cost, and opportunity cost. In terms of the method, we found that the employed LCT were categorized into the economic input–output LCA (EIO–LCA), LCC, and benefit–cost analysis (BCA), whether using that method at a certain level of the chain or in the whole chain. While LCA (LCA) has traditionally focused on those economic impacts, the integration of negative value and risk remains limited, particularly in capturing risk impact, negative externalities, and value distribution along the supply chain. On the basis of export and import data at the Swedish country level, EIO LCA could be used to calculate the economic and environmental impact of the trade-off between imported tomatoes and domestic production [65]. Hingsamer et al. (2022) also measured the impact level of some scenarios of adopting new technology in root chicory breeding with respect to the sustainability adoption effect, not only in terms of environmental impact but also in

socioeconomic dimensions, from production to consumption [49]. Additionally, assessing the socioeconomic impact of estate crop policy production (coffee, cocoa, and sugarcane) has been researched with several indicators, such as income benefits and financial risk [50]. LCA could also be applied to process the greening value chain at the industry level, including management services and distribution. However, the extension of economic value to incorporate risk and negative externalities has not been thoroughly explored in whole-chain actors' activities, representing a gap for future research. Using LCA, researchers could choose the most sustainable production method and evaluate the selection of a food-waste valorization strategy for creating added value along the chain [66–68]. Overall, the LCA approach is a promising method for assessing the sustainability of the AFVC from the production to the consumer stage, which can consider the positive and negative economic value of the part or the whole chain. The economic aspects of profit distribution and margin equity among actors have not been adequately addressed in other studies, despite their critical importance for understanding fair and sustainable value chains. This represents a key area for future research.

In line with the economic dimension, social-LCA was developed from the LCA framework to measure the social sustainability of a product or service's value, either along part of the value chain or the entire chain. S-LCA has four major phases similar to those of environmental LCA: Goal and scope definition, social inventory analysis, impact assessment, and result interpretation. Although the application of S-LCA in agri-food value chains is limited, social indicators have been well developed depending on the research direction and objectives. Several researchers have also combined S-LCA with LCC and environmental LCA, applying it at various levels of the chain, from farming to consumption. We found that some research has been conducted on a multilevel chain, from farming to consumption.

From the perspective of the research object, S-LCA approaches can be categorized into two types: (1) Assessment of the social value of product value chains and (2) assessment of social governance across the value chain. In governance, it was familiar with social-organizational LCA. The latter is known as social-organizational LCA (SO-LCA). Although S-LCA and SO-LCA share significant methodological similarities, they differ in their analytical scopes: S-LCA focuses on the social impacts of a product throughout its life cycle, whereas SO-LCA adopts a broader, organization-wide perspective [69]. S-LCA evaluates social impacts throughout a product's life cycle, from raw material extraction, production, and distribution to use and end-of-life stages such as recycling or disposal. This evaluation includes aspects such as fair wages, equity, food security, social responsibility, occupational health and safety, community involvement, and fair competition [70,71]. In contrast, SO-LCA adapts the product-based LCA approach to an organizational perspective, as outlined in ISO/TS 14072 (ISO, 2014) and UNEP's guidance on organizational LCA [72]. SO-LCA is intended not to replace existing approaches but rather to complement them by broadening their scope. SO-LCA aims to assess social impacts across product life cycles, focusing on the organizational level rather than just the product level [73]. SO-LCA assesses various social aspects of an organization, such as transparency in decision-making, leadership structure, compliance with legal and ethical standards, employee well-being, contributions to local communities, and the geographic impact of organizational facilities. SO-LCA builds upon SLCA frameworks and methodologies, such as the Guidelines for Social LCA of Products and the Methodological Sheets for Subcategories of Social LCA [74]. Studies have shown that social issues evaluated by management and certification tools such as SA8000 and GRI are largely aligned with the subcategories set out in the SO-LCA guidelines. Data collected through these tools can be used in SO-LCA implementation, particularly to assess impacts on key stakeholder groups such as workers, local communities, and consumers [73].

As an illustration, a S-LCA study in the palm oil smallholder value chain assessed major social issues and the contributions of all stakeholders, from workers and landowners to local

communities. This study used an advanced S-LCA method version of the United Environment Programme (UNEP)/SETAC guidelines, which are rich in social indicators such as fair salary, equity, food security, social responsibility, health, safety, opening opportunities, and good competition. This study also selected crucial indicators that are appropriate for the agricultural sector, such as child labor, forced labor, community engagement, and corruption-free practices in palm oil production [57]. This shows that the S-LCA and SO-LCA approaches are evolving to better capture the complexity and social realities within the value chain of modern agribusiness systems. Some variables and indicators from previous guidance should be adjusted with the particular context of the agri-food value chain from production to consumption and even adapted to suitable geographical and cultural characteristics.

In environmental dimension, most studies of LCA in agri-food value chains have concentrated on the environmental aspects. The main objective of conducting research using environmental LCA is to assess the value level of a product or service not only in the socioeconomic aspect but also in the environmental dimension. In the agri-food value chain, most LCA methods are focused on assessing environmental value related to externality value, such as biodiversity, freshwater use and depletion, carbon emission, eutrophication, acidification, and energy consumption [75,76]. Some research was complemented with particular scenarios for minimizing impact and analyzed further via a multicriteria decision analysis (MCDA) approach. Moreover, Gosaltvit et al. (2024) utilized those methods to evaluate the most sustainable coffee from cultivation, processing, transportation, consumption, and end-waste [63]. Similarly, Stone et al. (2020) researched the waste valorization of barley straw to create valuable added value [55]. In other advanced studies, life cycle sustainability assessment (LCSA), which analyzes LCC, social impacts, and the carbon footprint [77], was comprehensively used to assess the sustainability of production of goat meat in Nepal. Unfortunately, this study focused only on the production chain and did not cover other chains. For future research in advancing the agri-food value chain, sustainability assessment via LCA can be further developed, as can the positive impact on each chain. This comprehensive method is crucial for providing insight into the product value of each stage or the whole agri-food value chain. Additionally, in contrast with the economic dimension, the externality value of environmental LCA was considered more in terms of negative impact than in measuring positive externality. However, few researchers have discussed positive environmental benefit vectors, resulting in positive externalities.

### *3.5. Implications and future suggestions*

To advance the scientific environment using LCA in the agri-food value chain, future efforts should focus on standardizing LCA methodologies, variables, and indicators that incorporate multidimensional impact assessments, including economic, social, and environmental factors, to create a LCSA guideline. The LCA in the agri-food value chain should be comprehensively assessed, not only by focusing on the production chain but also by studying other actors, including the consumer chain. To create a more comprehensive dimension, the researcher could detail the LCSA subdimension, such as the institutional and technological dimensions. Governance and technology-oriented innovations play crucial role in transforming more efficient, inclusive, traceable, and adaptive agri-food value chain [78]. These aspects are crucial perspectives for supporting high-value creation. Furthermore, conducting diverse case studies will provide practical insights and stakeholder collaboration, which can ensure that research addressing real-world needs to create surplus value for all actors. Furthermore, enhancing education and capacity building on LCA among stakeholders within the agri-food value chain is essential for fostering informed decision-making. Active engagement with value chain actors and policymakers can further facilitate the integration of LCA insights into effective

and actionable sustainability policies. Collectively, these strategies will strengthen the application of LCA, fostering a more resilient and environmentally sustainable agri-food value chain system.

#### **4. Conclusions**

In conclusion, this review highlights the significant role of the LCA method in enhancing the sustainability of agri-food commodity value chains. Scientific studies have explored the development and trend of LCA in the agri-food value chain. The findings underscore the emergence of LCA as a pivotal tool for evaluating the environmental, economic, social, and institutional aspects of agricultural commodities throughout the value chain. As researchers refine LCA parameters and methodologies, a comprehensive understanding of these impacts is essential for advancing sustainable agri-food value chain practices. To implement LCA in the agri-food value chain, a comprehensive approach should be used for the production-to-consumer chain. LCSA can be considered an integrative method for analyzing the sustainable agri-food value chain. In the economic dimension, value not only focuses on positive benefits but also on negative externality value, risk, and equity among actors in the whole chain. In the social dimension, several variables should be adjusted into the agri-food system context, including determining whether workers are laborers or farmers. In terms of the environment, the variables focus on negative impacts and do not include positive externalities. The review illustrates that LCA not only serves to identify environmental hotspots but also offers strategic insights for optimizing resource allocation, improving overall efficiency, and minimizing negative externalities emitted in agricultural systems. By integrating value in the economic, social, and environmental dimensions by maximizing benefits, minimizing costs, increasing social benefits, and reducing environmental impacts, all chain stakeholders can provide competitive green products that respond to growing consumer demand, ultimately leading to improved value chain sustainability outcomes. This study provides a foundation for future research directions, building on variables and indicators, and emphasizing the need for more nuanced LCA applications at various stages of the agri-food value chain. The insights gleaned from this review encourage further potential in driving sustainable development within the agricultural sector, supporting a holistic approach to value chain management that aligns with global sustainability goals.

#### **Author contributions**

All the authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Sujianto Sujianto, Suharno Suharno, Rita Nurmalina, and Suci Wulandari. The first draft of the manuscript was written by Sujianto Sujianto and Suci Wulandari. All the authors commented on previous versions of the manuscript. All the authors read and approved the manuscript.

#### **Use of AI tools declaration**

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

#### **Acknowledgments**

We extend our heartfelt appreciation to our colleagues in the Department of Agribusiness, IPB University, for their invaluable feedback and guidance during the preparation of this manuscript,

especially Dr. Yanti Nuraeni Muflikh, SP., M. Agribuss., and Dr. Suprehatin, SP., M.AB. Their thorough review, perceptive observations, and constructive suggestions greatly enhanced the clarity, rigor, and overall quality of this work. We are deeply grateful for their time, expertise, and dedication in helping refine this study.

### Conflict of interest

The authors declare that they have no competing interests.

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