Review

Systematic Literature Review on the Application of the Life Cycle Sustainability Assessment in Agricultural Production

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ABSTRACT

This article highlights the implementation of the Life Cycle Sustainability Assessment (LCSA) in the agricultural industry and its potential for future improvement. A systematic literature review was employed, whereby a total of 186 articles on the LCSA across all sectors were analysed. Of these, 22 (12%) were related to the agricultural sector and studied further to ascertain the methodology used, including the techniques used to define sustainability. In addition, the integration of current LCSA approaches and various methods of measuring sustainability were explored to provide a more comprehensive technique to define sustainability. Within each specific context, environmental issues like climate change, air quality deterioration, and eutrophication were among the indicators of interest, together with high production costs (economic) and issues related to workers and local communities (social). For the benefit of future researchers, the authors also discussed the challenges and prospects of adopting new technologies such as the use of artificial intelligence for effective implementation of sustainability assessment in the agricultural sector.

KEYWORDS: agriculture; life cycle sustainability assessment (LCSA); sustainability measurement; life cycle thinking

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INTRODUCTION

The agricultural sector is a key driver of global economic growth. Nevertheless, it faces challenges, including the threat of climate change [1], uncontrolled inflation that leads to higher production costs [2], stiff land competition [3], and diverse forms of pollution [4]. These issues compel the industry to become more sustainable whithout compromising profitability. The concept of sustainable production and consumption is gaining traction as potential overarching solution to these issues, attracting significant interest from academics and industries [5]. This concept is currently undergoing a process of evolution and transformation that will affect agricultural practices, business operations, and the fulfillment of consumer demands. This transformation calls for a shift from conventional approaches to more advanced, comprehensive, and systematic agricultural methodologies [6]. Moreover, the development of life cycle studies has improved substantially. Currently, it is directed towards achieving these objectives, with the creation of various tools to evaluate different processes and target the absolute indicators to assess results and impacts [7].

The study of life cycles can be defined by several frameworks. The most popular approach is the life cycle assessment (LCA). Historically, it dates to the 1950s, when it was first developed for military accounting [8]. This was followed by the development of the environmental LCA in the late 1960s [9]. Simultaneously, the United States Department of Defense began implementing life cycle costing (LCC) in the mid-1960s [10,11]. Valdivia et al. [12], however, mentioned that LCC was adopted as early as the 1930s by the General Accounting Office (GAO) of the United States. Nonetheless, as scientific research progressed, more sophisticated frameworks emerged, including the recently developed life cycle sustainability assessment (LCSA). Initially defined by Kloepffer [13] as a three-pillar combination of LCC, LCA, and the social life cycle assessment (S-LCA), this integrated approach holds the potential to revolutionise product development. It promotes synergies between maximising profits, minimising environmental impacts, and optimising social impacts, thus, representing significant advancement in life cycle studies.

One unique aspect of the LCSA is the inclusion of the S-LCA in the framework, which underlines a broader concept featuring social dimensions rather than only the environmental and economic aspects of the LCA and LCC, respectively. The evolution of the LCSA has also led to the expansion of LCC so that it includes environmental costs. Therefore, the LCSA might now be defined as a combination of the LCA, environmental life cycle costing (ELCC) and the S-LCA [12,14]. The introduction of ELCC means a far broader concept is covered. Instead of only private costs and benefits, it encompasses relevant external costs and benefits, such as future environmental taxes on CO_2 emissions [12,15].

Finkbeiner et al. [16] highlighted that the three dimensions of sustainability in the LCSA must be addressed using a quantitative and transparent approach. The LCA, LCC (or ELCC), and S-LCA methods have different degrees of maturity. Therefore, harmony between the techniques is needed within the LCSA framework [17]. Any trade-offs between the three dimensions should be fully understood and supported with proper methodologies to achieve optimum results [18]. Hence, the LCSA framework is distinguished by quantitative data and statistics, consistently bolstered by empirical evidence [19,20]. Moreover, incorporating broader indicators and different mechanisms offers a thorough assessment, making the framework more comprehensive [21]. Regardless, any analysis should be effectively integrated, encompassing multiple stakeholders, and inclusiveness through forward and backward assessment, in addition to comprehensive spatial and temporal aspects [22].

The creation of the LCSA framework is crucial within the agriculture sector to ensure long-term economic, environmental, and social sustainability. In essence, agriculture is considered the primary sector in the four-sector model of the economy [23]. The production of raw materials is the core of the agricultural sector; this contributes to the secondary sector (manufacturing), which transforms the raw materials into goods and services [24]. This sector is of enormous significance in the economic hierarchy and plays a crucial role in ensuring food security. As a result, numerous stakeholders are actively pursuing more sustainable production methods [25]. Furthermore, the principles of persistence and resiliency greatly influence sustainability in agricultural systems [26]. The objective is to establish equilibrium and harmonise the environmental, economic, and social aspects, which can be facilitated by various strategies and areas of intervention [27–29]. Therefore, it is appropriate to examine the methodology used to assess sustainability in the agricultural sector using the LCSA approach.

This study has two distinct purposes. Its primary goal is to identify research publications focusing on LCSA in the agricultural sector. This will be achieved by conducting a comprehensive systematic literature review (SLR) of LCSA, encompassing all sectors. Secondly, the study aims to identify specific life cycle thinking elements or indicators in concerning LCA, LCC, and S-LCA that is important for the agricultural sector. Such approaches should have the capability of combining significant indicators to assess sustainability. The outcome will suggest a more effective and robust method to evaluate sustainability in the agricultural sector.

Overall, this paper comprises five sections. Section 1 (INTRODUCTION) introduces agriculture and the developments and progress in life cycle studies. Section 2 (LITERATURE REVIEW METHOD) details the methodology used for the systematic literature review (SLR). Section 3 (RESULTS AND DISCUSSION) presents the results and discussion. This section is divided into a description of the selected articles identified from the SLR and an analysis of articles related to the use of LCSA in other sectors. The section continues by discussing articles associated with the agricultural sector, followed by a discussion of the potential use of the sustainability assessment method. Section 4 (CHALLENGES AND FUTURE DIRECTIONS) elaborates on the challenges and future directions before the conclusion is presented in Section 5 (CONCLUSION).

LITERATURE REVIEW METHOD

The methodological approach followed the five important steps of conducting a systematic literature review (SLR). These include: keyword selection, searching for articles, appraisal, synthesis, and analysis, as outlined by Hanifah [30] and Grant and Booth [31]. These steps began by (1) identifying associated relevant keywords, followed by (2) searching for relevant articles from ScienceDirect, SCOPUS, and the Web of Science (WOS). These three databases are well-regarded due to their large quantities of high-quality peer-reviewed literature [32,33]. The appraisal or assessments followed the search process, whereby the related articles were selected based on inclusion and exclusion criteria.

Keyword Selection and Search Steps

To initiate an analysis, the initial step is to ascertain the keywords and synonyms linked to the particular issue being examined. Using a combination of keywords is necessary because a broad subject like "sustainability" encompasses a vast array of interconnected publications, thus, conducting independent evaluations of the topic would be advantageous. In addition, the search method necessitates the usage of double quotation marks (" ") when referring to specific topics. This guarantees that unconnected phrases are searched as a whole, preventing the individual search results from being lemmatised. The findings were synthesised by ensuring that each article contained information referencing all the keywords. The main term used is "LCSA", an acronym for "Life Cycle Sustainability Assessment", in conjunction with the specific subject matter or topic (clouds). These selected keywords are described in Table 1. The articles from the search were then extracted for analysis. The search process was carried out on March 23rd, 2023. Articles identified up to this date were analysed. After thoroughly reviewing the procedures for the LCSA's SLR analysis, the results were examined.

Appraisal, Synthesis and Analysis Steps

These steps involved selecting articles relevant to the study. First, several inclusion and exclusion criteria were developed (Table 2). Then, the articles were screened according to these criteria, and the final information retrieved was analysed. As mentioned previously, the LCSA is the combination of LCC, LCA, and S-LCA. It was considered to be developed in 2008 [13], thus, establishing the time frame for the article search. In addition, the definition of agriculture must be clarified to identify articles related to the agricultural sector. Harris and Fuller [34] defined the term as any practices related to the cultivation and domestication of plants using a form of land use that constitutes a change in the landscape. The definition also covers livestock management and production. As such, this definition served as our reference when selecting articles. Further analysis methods include mapping the author's country representatives (www.mapchart.net) and utilising the VOSViewer software for relational analysis of the related terms from the title and abstract of the analysed documents. They describe the relationship between selected articles, focusing on significant terms in sustainability assessment and agriculture.

Table 1. Steps of the methodological approach used for the systematic literature review (SLR).

Steps	Keywords, synonyms and examples	Number of documents (ScienceDirect)	Number of documents (SCOPUS)	Number of documents (Web of Science, WOS)
1. Topic (clouds): Life cycle sustainability assessment	"LCSA" OR "Life Cycle Sustainability Assessment"	1384	621	484
2. Topic (clouds): Combination of life cycle studies	("LCA" OR "Life Cycle Assessment") AND ("LCC" OR "Life Cycle Costing") AND ("SLCA" OR "S-LCA" OR "Social Life Cycle Assessment")	706	155	114
3. Retrieved items	Combination between both clouds ('AND')	406	102	70
4. Inclusion and exclusion criteria (Refer to Table 2)	Inclusion criteria no. 1 and no. 2, Exclusion criteria no. 1.	301	71	61
5. Content searching comprising of LCSA	Inclusion criteria no. 3, Exclusion criteria no 2., no. 3 and no. 4	133	67, new = 48	59, new = 5
6. Topics related to agriculture	Inclusion criteria no. 4	22	new = 0	new = 0
7. Number of articles related to the LCSA = 186				
8. Number of LCSA articles related to agriculture = 22				

Table 2. Criteria used for the literature search.

Inclusion criteria
1. The article is published only in one of the three database sources (SCOPUS, ScienceDirect and WOS).
2. The article must be published between 2008 and 2023.
3. The topic, abstract and content searching must comprise a complete study of the LCSA, having a triple bottom analysis of LCA, LCC and S-LCA.
4. The article addresses the scope for agricultural production that includes the cultivation stage.
Exclusion criteria
1. The article is not in English.
2. The article appears many times on the list within the same database.
3. The article describes a study on sustainability but does not apply the LCSA approaches.
4. Duplicated articles in both databases are considered a single article.

RESULTS AND DISCUSSION

Description of Selected Articles

The analysis identified a total of 186 articles related to the LCSA. It has been found that more articles were identified in ScienceDirect than in WOS and SCOPUS. By utilising the inclusion and exclusion criteria during the appraisal, duplicate articles were eliminated by cross-reviewing the sources. As a result, 133 LCSA articles are identified in ScienceDirect, 48 in SCOPUS, and 5 in WOS (Table 1). In addition, it seemed that most reviews and research articles were published in 2021 (Figure 1). The findings also highlighted a consistent increase in articles published from 2010 to 2021, illustrating the significant interest in research related to this field. Moreover, the analysis also determined that review articles comprised 28% of the articles, while the remaining 72% were research articles (Figure 2).

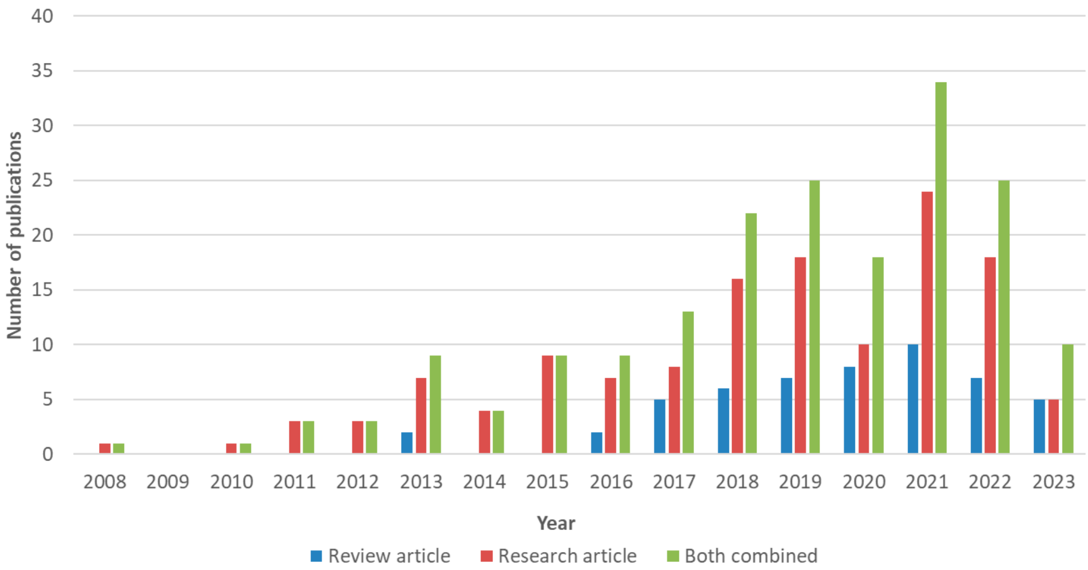

Figure 1. LCSA articles published from 2008 to 2023.

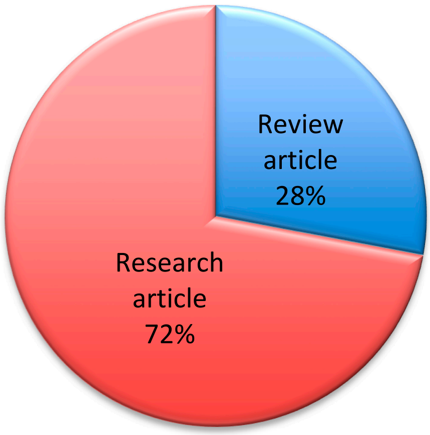

Figure 2. Article percentage based on the type of study.

Current Status of the LCSA in Other Sectors

Previous literature review studies on the LCSA include significant industrial sectors such as energy [35,36], building and construction [37,38], waste management [39], manufacturing [40], and agriculture [41]. This study has categorised articles into these sectors, as illustrated in Figure 3. For clarity, the articles in the energy sector must cover topics like electricity, fuels, crude oil, batteries, and bioenergy. Meanwhile, manufacturing sector involves process design, and non-bio and bio-product manufacturing. The building and construction category pertains to residential and commercial buildings, while the waste management category contains articles on waste re-utilisation and management. However, 57 articles were uncategorised and subsequently referred to as 'others' (Figure 3). These articles largely covered LCSA framework development, fundamental analysis methods, as well as articles covering other sectors such as transport, urban and rural development, water supply systems, and non-bio product and bioproduct value chains.

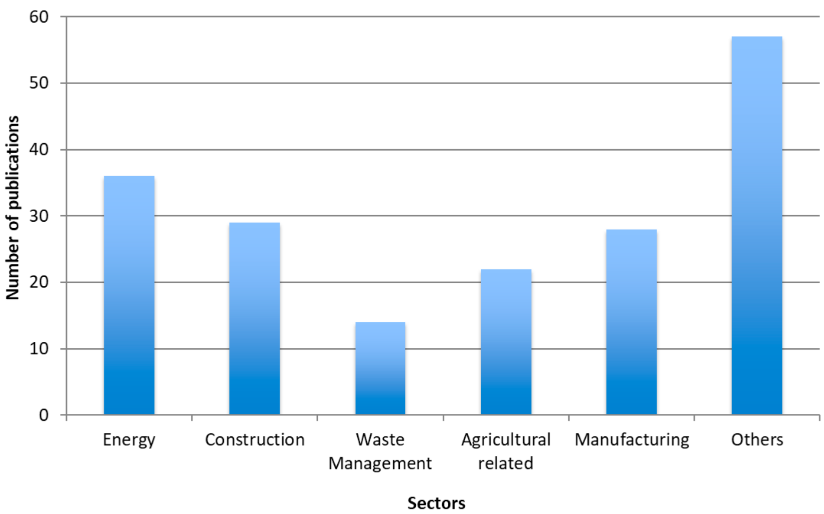

Figure 3. LCSA-related publications in different sectors.

A review conducted by Backes and Traverso [38] identified 42 articles related to the construction and building sector. Although the analysis from our study identified fewer articles (29), this number is still higher than those found in the other sectors. This indicates an increased interest in the building and construction sector; contributing to its maturity. Meanwhile, a systematic review analysis by Lassio et al. [42] identified 41 articles related to the energy sector, slightly higher than our study, which found 36. In contrast, a paper by Omran et al. [43] identified five articles about the waste management sector, whereas our findings stood at 14. The finding showed that this sector produced the lowest number of articles among all the fields. The differences in the findings could be attributed to the scope of LCSA studies. They may cover the cradle-to-grave product life-cycle or focus on a specific process within the product life cycle, which is the point of interest. For example, waste management studies might examine material manufacturing or products used for treating waste. However, the main objective and an important aspect of the study is the waste management stage.

LCSA Studies Related to the Agricultural Sector

The analyses identified 22 out of 186 articles related to LCSA in the agricultural sector (refer Table 1 and Figure 3). As mentioned earlier, agriculture is defined according to Harris and Fuller's definition [34]. As such, any studies covering complete or partial agricultural processes of crop cultivation and domestication, as well as livestock management, were considered during the categorisation process. Figure 4 provides information on the sources of the articles by country, along with their respective authors. From the figure, it is apparent that the majority of the articles were produced in Europe, with Italy (6 articles), Spain (5 articles), Sweden (3 articles) as the leading contributors. Whereas Germany, Norway, Finland, and Ireland each produced one related article. Furthermore, VOSViewer was used to analyse related terms within the title and abstract. The analysis identified 866 related terms from the 22 publications. Figure 5 shows 100 terms with the threshold of 3 occurences and a 60% terms selection. It was apparent that the terms 'lca' (LCA) had the highest occurrence with 17 times, followed by 'dimension' (14 times), 'social aspect', and 'scenario' (each 12 times). Moreover, the terms 'triple', 'plant', and 'life cycle assessment', each had 11 occurences. Another agricultural significant term, 'farm' also stands with a high occurence of 7. Nevertheless, it can also be seen that term occurences experience an increasing trend over time for most of the keywords (based on the timeline depicted in Figure 6).

Among the 22 LCSA articles pertaining to agriculture, seven are review articles as briefly described in Table 3. Meanwhile, Table 4 presents the case studies, with 15 articles. However, the article by Cirone et al. [44] is essentially a case study, despite it being presented in Table 3 as a review paper due to its structure. In general, the review articles primarily explore the sustainability of the agro-food chain supply, bio-based and plant-based product development, and methods to define and measure sustainability. The key findings from these articles were examinations of the life cycle (LC) method. This proved useful for a holistic measurement of sustainability, albeit it needs further development and improvements in some areas. In addition, harmonising the three pillars (environmental, economic and social) demands a comprehensive approach to address sustainability trade-offs, as discussed by Escobar and Laibach [45], D'amato et al. [46], De Luca et al. [47] and Milazzo et al. [48]. Importance is also placed on the significance of focusing on upstream agricultural production, namely the crop cultivation stage, and the necessity of developing continuous relationship with important stakeholders such as farmers or farm workers [41]. In view of this, studies of the S-LCA proved to be an important approach to investigate key ways to improve the socio-economic conditions of farmers and farm workers. Besides that, sustainable food systems also require technological advancement and improvements in crop production, as well as the conservation of cultivars and plant ecosystem services [44,46]. There was a clear indication that life cycle studies, commencing within the cradle context of crop production, could contribute significantly to the effective implementation of circular economy [47].

Overall, the case studies related to the agricultural LCSA are comprised of various sub-sectors within the agricultural sector (Table 4). They cover topics on a range of crops such as olives, palm dates, sugarcane, soybean, vegetables, maize, tomatoes, and poplar. Meanwhile, livestock studies cover dairy and animal husbandry, which includes pig and cattle farming. Moreover, in studies discussing system boundaries, the majority of them address either cradle-to-farm gate or cradle-to-gate, with a smaller subset exploring cradle-to-cradle. Further analysis identified three articles that focus directly on the production of raw agricultural materials at the farm gate. These studies include research on olive-growing systems by Abdallah et al. [49], De Luca et al. [50], and soybean production by Zortea et al. [51]. Specific crop cultivation studies within agricultural LCSA refer to system boundaries that cover a cradle-to-farm gate system, instead of subsequent phases such as product manufacturing, consumer usage, or waste management. This approach expounds on the scope of cultivating farms and the need for intensive studies on the crop production stage. Therefore, indicating that the main objective of the studies is to evaluate and understand the cycle within the cultivation boundaries.

In other studies, however, the scope of agriculture covers a comprehensive range of upstream stages. The studies mainly involve crops (raw materials) and by-products before they are used for other purposes such as in the industrial processes and other products. Based on the LCSA-related articles, these products include supplemental food products [52], edible [53] and inedible oil, or bio-based fuels [54–59]. Interestingly, biofuel production attracted substantial interest within the LCSA studies. One main reason for this is the regulatory requirements concerning global production and export [60]. The global market share for renewable energy, which includes biofuels, is expected to represent 29% of the primary energy demands by 2040 [61,62]. This indicates an optimistic trend of demand in the near future. Other market segments within agriculture also suggest a transition towards sustainable products. For example, organic foods are considered to be sustainability enablers in global agriculture as consumer demand within this niche segment has grown considerably over the years [63]. Although, reducing food losses is also considered important as part of the Sustainable Development Goals (SDGs) [64]. In other areas, the certification of Roundtable Sustainable Palm Oil (RSPO) was notably preferred for consumers when buying palm oil products [65].

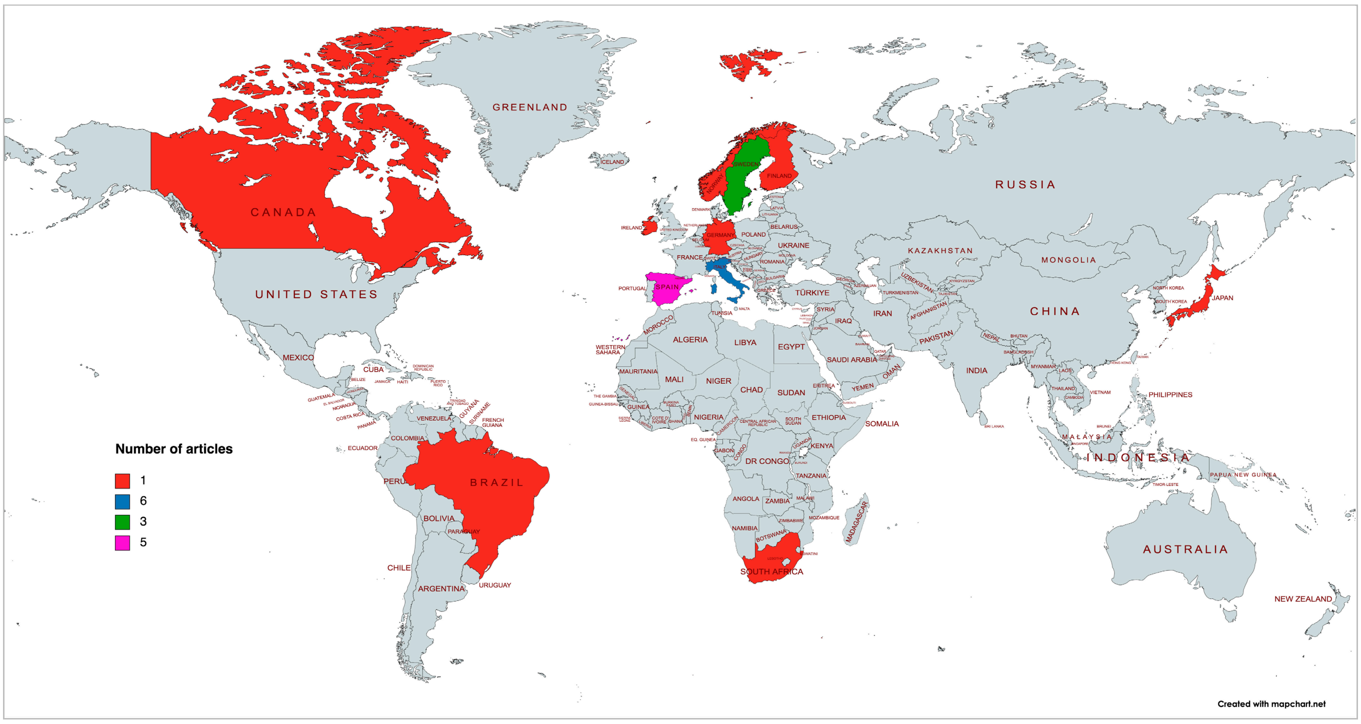

Figure 4. Sources of LCSA articles related to agriculture based on its corresponding author.

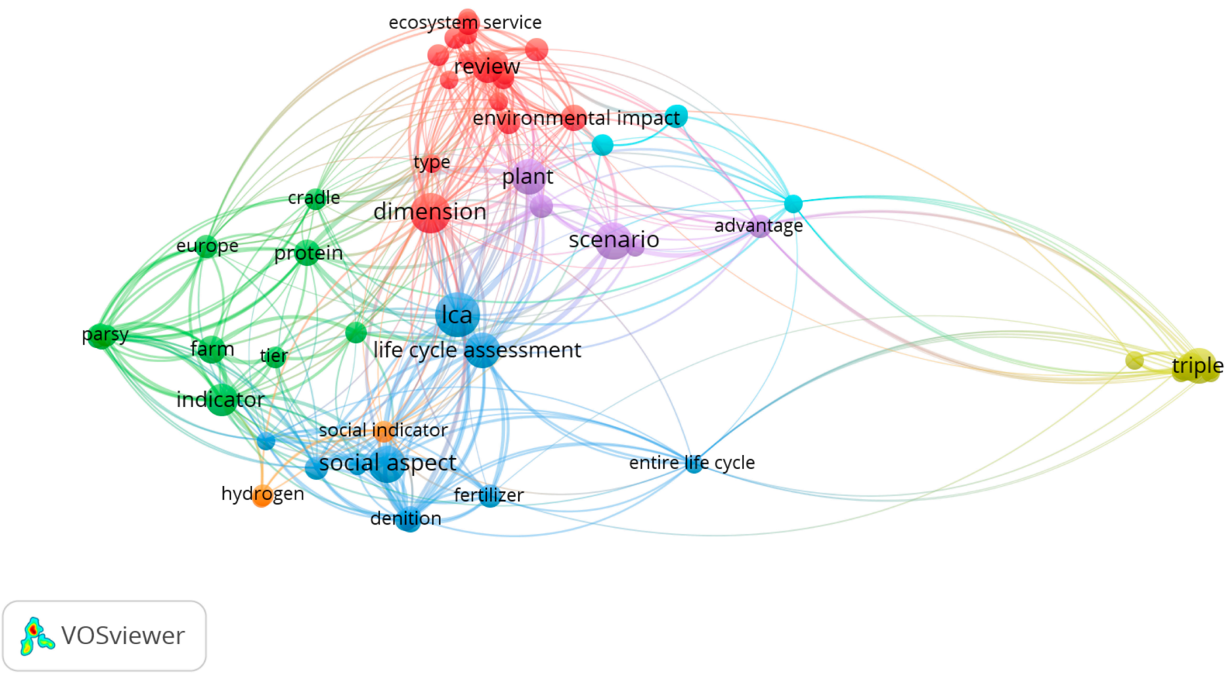

Figure 5. Network visualisation of the terms related to agricultural LCSA.

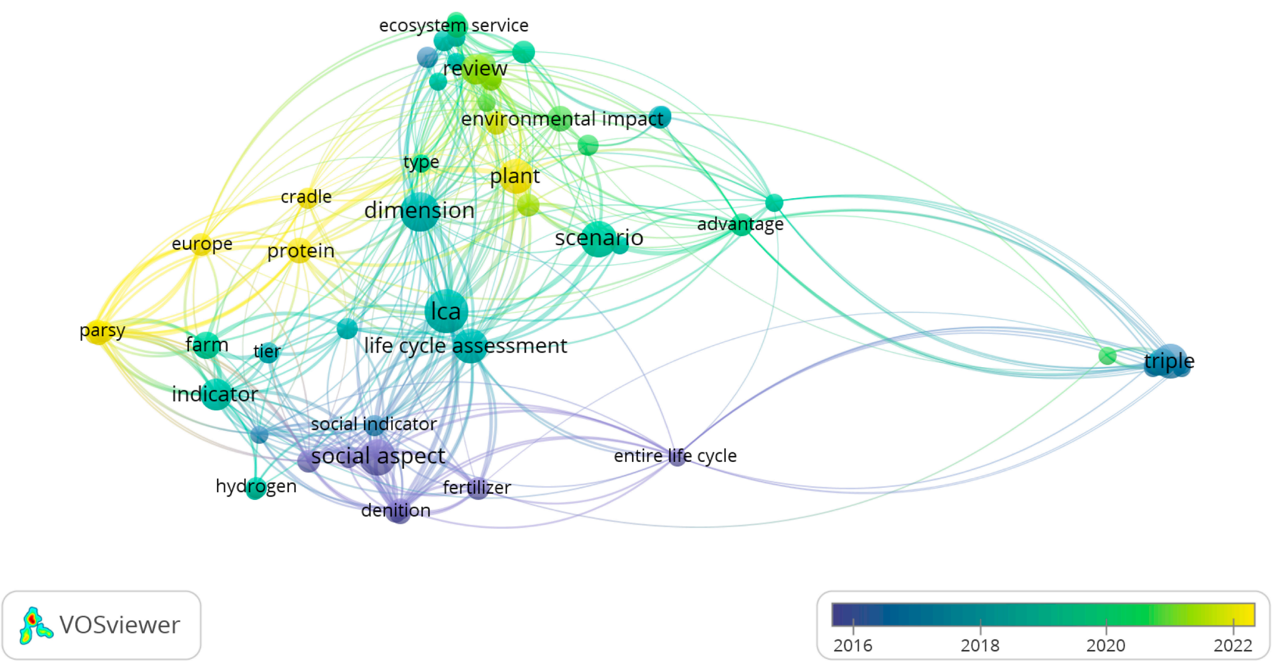

Figure 6. Trend visualisation of the terms related to agricultural LCSA.

Table 3. Summary of review articles on LCSA studies related to the agricultural sector.

No.	Authors	Topic/description of study	Key findings	Relationship between the study and the agricultural* sector
1.	Allotey et al. [52]	Processing and product formulations of plant-based protein.	• The need to develop more databases and studies to show that improved sustainability performance of plant-based proteins can be obtained in comparison to traditional animal-based proteins.	Cultivation stage as one of the main stages in plant-based protein food value chain.
2.	Arcese et al. [41]	Sustainability assessments of the supply chain of agri-food products.	• An S-LCA study is imperative to improve the socio-economic conditions of related stakeholders in agri-food sectors. • Connections between Sustainable Development Goals (SDGs) and life cycle sustainability assessment (LCSA).	Stakeholder relationships with the agri-food chain includes farmers and farm workers involved in agricultural cultivation.
3.	Cirone et al. [44]	Sustainability assessments using scoring system to evaluate city region food systems.	• Sustainability scoring for a city region food system is developed based on the life cycle thinking methodology. The aim is to provide a holistic and transparent single sustainability scoring method.	Sustainable food systems include technology to enhance crop production and adapt cultivars (new and ancient) to improve cultivation.
4.	Escobar & Laibach [45]	Overview of advanced bio-based technologies. The study highlights the often overestimated advantages of the bio-economy.	• Study suggests that no superior technologies can currently address the sustainability dimensions across all sectors. • Further harmonisation of LCA, LCC and S-LCA is proposed to address sustainability trade-offs.	Crop cultivation was considered in feedstock preparation through cradle-to-cradle, cradle-to-gate and cradle-to-grave analysis.

Table 3. *Cont.*

No.	Authors	Topic/description of study	Key findings	Relationship between the study and the agricultural* sector
5.	D'amato et al. [46]	LCA (including LCC and S-LCA) assessments of bio-economy products.	• Perspective on bio-economy was observed through ecosystem and related services. • Trade-offs exist when land use and industrial activities might affect a specific ecosystem. • Thus, life cycle techniques can be utilised to assess the bio-economy's impacts and reliance on ecosystem services.	Cultivation of plants (including fungi and algae) is a central element of ecological balance.
6.	De Luca et al. [47]	Approach to achieving agricultural sustainability through a combination of life cycle (LC) methodologies, multi-criteria decision analysis (MCDA) and a participatory approach.	• Effective evaluation tools are needed to justify an agricultural transition to the circular economy and towards high-productivity and better product qualities that fulfill market demands and health consciousness among the public. • A combination of LC methodologies and MCDA can provide options to reduce negative effects while simultaneously avoiding burden shifts from trade-offs.	Sustainable crop cultivation and production are important elements in achieving agricultural sustainability.
7.	Milazzo et al. [48]	Evaluation of the prospects of using soy biodiesel as a sustainable approach that contributes to energy security.	• Assessment of over 30 life cycle analyses related to the main productive areas. • Soybean is expected to continue to be a major crop for biodiesel production. • Trade off from the cost competitive advantage include avoiding deforestation and net-carbon results.	Discussed in the article were methods and impacts of soybean cultivation (including large-scale intensive transgenic farming), as well as proposals to ensure sustainable agriculture can avoid various adverse environmental impacts.

* Agriculture as defined by Harris and Fuller [34].

Table 4. Summary of case studies on the LCSA in relation to the agricultural sector.

No.	Authors	Topic/description of study	Sub-sectors/ crop	Scale	System boundary	Functional unit used
1.	Zira et al. [66]	Sustainability evaluation of cattle systems by combining LCSA with assessments of economic robustness and feed-food competition (livestock).	Cattle systems (beef and dairy)	Regional (South-West Europe)	Cradle-to-farm gate	1000 kg of protein of animal origin
2.	Stillitano et al. [53]	A study on the agri-food supply chain. A multi-cycle approach to measure the sustainability of the circular pathway.	Olive oil	Regional (Mediterranean)	Cradle-to-cradle	1 litre of extra virgin olive oil (EVOO)
3.	Abdallah et al. [49]	Assessment of the sustainability of olive growing systems using LCSA and MCDA.	Olive growing systems	National (Tunisia)	Cradle-to-farm gate	Two functional units (1 ha and 1 ton of olive produced)
4.	Zira et al. [67]	LCSA of organic and conventional pork supply chain (livestock).	Organic and conventional pork supply chain	National (Sweden)	Cradle-to-grave (until consumer)	Two functional units (1 ha and 1 ton of pork fork weight)
5.	Hnich et al. [54]	LCSA of synthetic biofuels from date palm waste. Life cycle inventory includes feedstock cultivation and transportation.	Date palm waste	National (Tunisia)	Cradle-to-gate (date palm waste generation to biofuel production)	1 GJ of synthetic biofuels—diesel and gasoline from lower heating values

Table 4. *Cont*.

No.	Authors	Topic/description of study	Sub-sectors/ crop	Scale	System boundary	Functional unit used
6.	Valente et al. [68]	LCSA study of an innovative slaughter concept (livestock). Life cycle inventory includes feedstock production.	Pork meat	National (Norway)	Cradle-to-gate	1000 kg of pork carcass at the slaughterhouse
7.	Nieder-Heitmann et al. [55]	Analysis of sugarcane biorefinery scenarios using the LCSA and MCDA. Sugarcane cultivation was included in life cycle impact analysis (LCIA).	Sugarcane lignocellulose	National (South Africa)	Cradle-to-grave	Two functional units (1 kWh electricity produced and 1 kg bioproduct produced)
8.	Valente et al. [56]	Assessment of hydrogen generation from biomass gasification using the LCSA. Comparison was made with natural gaseous. Biomass cultivation was included in the analysis.	Biomass, including poplar cultivation	National (Spain)	Cradle-to-gate (hydrogen plant)	1 kg of hydrogen (99.9 vol% purity—200 bar and 25 ℃)
9.	Contreras-Lisperguer et al. [57]	Assessment of the sustainability of cogeneration of electricity from sugarcane bagasse. Agricultural phase included and analysed in the study.	Sugarcane (bagasse)	National (Jamaica)	Cradle-to-gate (electricity generation)	Generation of bioelectricity for a year in a sugar mill
10.	Chen and Holden [69]	LCSA of a grazing dairy farm (tiered analysis). Analysis included farm records and agri-footprint.	Dairy (farm)	National (Ireland)	Cradle-to-farm gate	1 kg of fat and protein corrected milk (FPCM) delivered (in one year) at the farm gate

Table 4. *Cont.*

No.	Authors	Topic/description of study	Sub-sectors/ crop	Scale	System boundary	Functional unit used
11.	De Luca et al. [50]	LCSA of sustainability innovations in olive growing systems.	Olive growing systems	National (Italy)	Cradle-to-farm gate	1 ha of olive cultivated surface
12.	Ekener et al. [58]	LCSA of biomass-based and fossil fuel transportation. Feedstock cultivation for biofuel production were highlighted in the study.	Sugarcane and corn/maize	National (corn/maize in the US and sugarcane from Brazil)	Cradle-to-grave	1 Euro/MJ
13.	Zortea et al. [51]	Sustainable assessment through life cycle analysis of soybean production.	Soybean	National (Brazil)	Cradle-to-farm gate farm	1 kg of soybean collected (produced)
14.	Nguyen et al. [59] and Nguyen et al. [70]*	A study on vegetable oil-based biodiesel production. Sustainability analysis involved integrating the Inclusive Impact Index and LCSA. Feedstock cultivation was clearly highlighted as part of the life cycle process.	Inedible vegetable (oil based)	National (Vietnam)	Cradle-to-grave (until biodiesel distribution and use)	1 year of biodiesel combustion by cruise ship
15.	Martínez-Blanco et al. [71]	Publication highlighted the challenges of applying the S-LCA within the LCSA framework. The study discussed the production and transportation of fertiliser. Its application for tomato cultivation was discussed as a case study.	Two mineral fertilisers and one industrial compost for use in tomato production	National (Spain)	Cradle-to-farm gate	1 tonne of fertilised tomato

* The articles were published in two parts; some information was obtained in Part II of the journal.

Important Indicators for LCSA in Agriculture

From the SLR analysis conducted on the agricultural sector, there are several indicators within the life cycle thinking framework that are important for sustainability assessment. These important indicators are discussed below.

Life cycle assessment (LCA)

Life cycle studies are highly synonymous with the life cycle assessment (LCA) approach. In agricultural production, LCA has emerged as an approach widely used to balance ecosystem preservation and environmental considerations [72], rather than prioritizing excessive profit making in agricultural ventures. In this context, 'excessive' implies a negative business conduct that compromises the environment to fulfil market demands. One key takeaway in LCA studies related to agriculture is that it ensures awareness regarding product footprints from resource depletion to emissions. All the stakeholders in a product supply chain must be informed, whether they are farmers, consumers, wholesalers, or even policy makers. This ensures that any signs of problems can be rectified immediately. In agricultural production, greenhouse gas (GHG) emissions contributing to the global warming potential (GWP) remain as a pressing issue. This stems from the utilisation of fertiliser in the agricultural sector [73]. Therefore, future studies should focus on this particular input in crop cultivation to evaluate its impact across the entire crop production process.

Moreover, fertiliser is not the only major contributor to GHG emissions when various agricultural crops are considered. A study on the paddy sub-sector indicated that emissions from anaerobic cultivation far surpassed emissions from fertiliser use [74]. In tropical countries, the influence of soil types on cropland cultivation may also contribute to differing values obtained for environmental impacts [75]. Therefore, factors such as demographics, soil attributes [76], and the effects of land use change [77] may also result in emissions; necessitating increased sccrutiny. It is also imperative to discuss the association between the use of machinery (and other equipment) and higher dependencies on fossil fuels as an energy source [78,79]. Therefore, more efforts should be spent on producing comprehensive documentation detailing the utilization of energy-efficiency equipment or using alternatives such as bioenergy-based products. In turn, this can help support initiatives that promote low-emission agricultural systems.

In addition to the analysis of the agricultural LCSA carried out via the systematic literature review (SLR), as highlighted in the Supplementary Materials (Supplementary Table S1), environmental indicators from LCA studies were also associated with several other impacts such as acidification, eutrophication, land use, and water resource (scarcity). Some studies included the evaluation of over five environmental impact parameters within the environment pillar. Examples include the studies conducted by Chen and Holden [69], Zira et al. [67], Zira et al. [66], Contreras-Lisperguer et al. [57], and Stillitano et al. [53]. Furthermore, more attention should be given to other waste management issues like burning crop waste [80,81]. This is because waste burning resulted in an elevated $PM_{2.5}$ in the atmosphere [82], thus, impacts of fine dust or respiratory inorganics should be studied. In addition, nutrient loss through the leaching of nitrogen (N) and potassium (K) from agricultural practices is also an important issue, justifying further analysis of its impacts on eutrophication potential [83].

Life cycle costing (LCC)

Life cycle costing (LCC) is primarily applied in agriculture to improve the economic aspects of production [84]. It emphasises the viability assessment of a project through a detailed evaluation of all costs and revenues [85]. The aim of integrating LCC and the LCA is to incorporate an economic dimension. For example, monetary flows from inputs and outputs might be observed and analysed in parallel with environmental processes [86]. This integration has led to the development of environmental life cycle costing (ELCC), which provides further progress towards achieving sustainable agriculture [53].

Cost distribution can be divided into several categories, such as startup costs, fixed costs, operational costs, and end-of-process costs [87]. Startup costs refer to infrastructure and construction costs, major equipment outgoings, and contingencies [88]. Operational (or variable costs) are normally attributed to input costs, labour costs, and maintenance costs [84,89,90]. On the other hand, fixed costs can be defined as those expended on land rental, shares of insurance, and taxes [90,91].

In some countries, elements of fixed costs related to agriculture may not be implemented. This is because land could be privately owned in the case of smallholder farmers. While agricultural insurance is practiced in certain parts [92], it does not apply to most farmers. In addition, operational costs may involve several issues, such as the high cost of planting materials [93] and limited farm operation budgets [94]. Referring to a case study on a developing country like Malaysia, the inclusion of external costs through a willingness to pay for environmental benefits [95] is still in its early stages. However, the recently launched voluntary carbon market was met with much enthusiasm [96]. Therefore, research in ELCC would be highly relevant to the agricultural sector in the future which will spearhead the concept of the green economy in this sector.

Social life cycle assessment (S-LCA)

Social analysis may differ between one study and another, more so than across LCA and LCC studies. Nevertheless, the studies should still be within the framework developed for the S-LCA [97,98]. Literature has been published on social issues related to the agricultural sector, such as proper working conditions [99,100] and occupational hazards [101] that require workers' attention. In addition, several other S-LCA studies related to agriculture can be used as references for further research. Muhammad et al. [102] highlighted the importance of assessing the satisfaction level among workers and local communities. Therefore, these issues should be explored to better understand the needs and gaps in the agricultural sector.

Current S-LCA studies have also been undertaken on specific crops cultivated in tropical areas, such as sugarcane [103] and banana [104], as well as on tea plantations [105], which encompass important social criteria. Prasara-A et al. [103] listed two stakeholder groups who appeared in S-LCA studies: farm owners and workers. The authors set a threshold for each indicator and conducted socio-economic studies based on the S-LCA approach. Feschet et al. [104] prioritised population health, among other important indicators in their approach. Meanwhile, Sharaai et al. [105] identified three stakeholders within S-LCA studies: (a) workers, (b) local communities and (c) consumers. Moreover, the social perspectives among domestic and foreign workers need to be explored in the context of S-LCA studies. In essence, the integration of LCC, the LCA and the S-LCA can offer various potential approaches to evaluating sustainability.

Improved sustainability assessment methods in the agricultural sector

Developing sustainability assessment methods is crucial in any LCSA study. It completes the whole process of a study cycle and converts analysis into useful data that is easily understood by stakeholders. In a sustainability assessment, the three dimensions—environmental, economic and social—carry equal weight and burden, and should not to be compromised [106]. Nevertheless, this objective is impossible to achieve, thus, certain trade-offs may be required. In this instance, compensating for one indicator should benefit others [107]. Several methods have been used to formulate an LCSA that features sustainability. The Life Cycle Sustainability Dashboard (LCSD) was one of the earliest approaches developed, while the Life Cycle Sustainability Triangle (LCST) is slightly different to the LCSD [16]. In the years following the introduction of the LCSA, several approaches have emerged that could be applied in various sustainability studies. These included the Pareto approach, which can be affiliated with the LCST method. This method requires the normalisation of different indicators before an optimum solution can be selected based on a specific intersection method [18]. Another popular method is the multi-criteria decision analysis (MCDA), which is used to define sustainability. Generally, no single scenario covers all three pillars of sustainability. This is because selecting the best approach for one pillar might mean disadvantages to the others [108]. MCDA enables stakeholders to choose the best approach based on the trade-offs between all pillars [109].

In addition to the approaches outlined above, several others have been used, particularly in the agricultural sector. Additional information related to the sustainability assessment methods, as revealed by the SLR of 15 articles about agricultural LCSA, is listed in the Supplementary Materials (Supplementary Table S1). This information highlights the approaches used to define sustainability and the related indicators for environmental, economic, and social impacts. Sustainability analysis in this study is categorised as either an individually separated method of horizontal sustainability assessment or vertical convergence. This is primarily achieved through normalisation and scoring approaches like those of the LCSD and MCDA. The analysis presented in Supplementary Table S1 identifies how individual assessments have integrated various methods, including relative unsustainability points (RusP) [66], relative sustainability points (RSP) [67], the expansion of system boundaries through sensitivity analysis [53], a comparison of methods [53,56], and the visualisation of each respective data impact [68]. Two studies used the LCSD, those by Zortea et al. [51] and Martínez-Blanco et al. [71]. Interestingly, five articles that applied the vertical convergence approach of MCDA used different methods: multi-attribute value theory (MAVT) [58], multi-attribute utility theory (MAUT) [55], the Analytical Hierarchy Process (AHP) [49,50], and tiered analysis [69].

The AHP approach could be an interesting technique to use in MCDA. In brief, it includes stakeholder opinions within the qualitative and quantitative data collected [49,110]. The cultural profile used within the AHP framework can adopt one of three perspectives: individualist, hierarchist, and egalitarian [111]. Meanwhile, these three perspectives were used by Ekener et al. [58] within the MAVT structure to represent different stakeholder priorities. Concerning agricultural practice, this representation may reflect different local scenarios and perspectives since agriculture and cultivation vary across regions and countries. Generally, individualists are those whose choices are attributed to a short-term outlook, egalitarians champion long-term solutions, and the choices of the hierarchists are balanced between those of the other two [112]. Furthermore, from a domestic point of view, stakeholders can also be differentiated according to the perspectives of economic, environmental, or social experts. Some advocate the economic viewpoint over the environmental and social, while others champion social stability over excessive economic gains. These stakeholder categories should be included in the framework of stakeholder opinions that can explain local perspectives.

CHALLENGES AND FUTURE DIRECTIONS

Advancing Methodologies for Sustainability Measurements

Initially, one challenge identified in this study was the limited number of articles related to the agricultural sector. A majority of articles addressed sectors such as energy, construction, and manufacturing. However, subsequent analysis revealed that certain methods employed in other sectors, such as MCDA, had also been used in agriculture. However, our analysis revealed that other MCDA methods such as the Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE) and Elimination and Choice Expressing the Reality (ELECTRE) [58], have yet to be used with regard to agriculture. Consequently, their extensive use in this sector can be anticipated. Other outstanding challenge identified is to continuously improve the measurement of the sustainability dimensions and the presentation of the results [113–115]. Furthermore, it is imperative to highlight that, ultimately, it is the key stakeholders who will benefit from an LCSA study. Therefore, LCSA analysis results should also reflect local demographic and societal demands so that any sustainability indicator developed would benefit the targeted groups.

Regarding the application of LCSA in the agricultural sector, the analysis identified crop cultivation as an important stage in raw material production. Although positioned at the higher tier in the production stage, it faces challenges to remain low-cost and thus, sustainably enter the manufacturing or processing stages. In a broader context, the LCSA indicators encompassing LCA, LCC, and S-LCA should represent local and global sustainability scenarios. As many scientific studies suggest, environmental loads play important roles in any life cycle research [116]. Economic and social issues are also equally important, such as economic survival, livelihood, local political scenarios, demographic factors, and perceptions of a fair and just society [117–120]. Therefore, optimising the outputs through a meaningful presentation of the results by improving the measurement of the sustainability dimensions should be a primary objective of a future study.

Prospects of Utilising Artificial Intelligence in the Measurement of Sustainability

As the world progresses towards achieving a more sustainable society, the use of artificial intelligence is important as one of the tools to effectively assist in the measurement of important environmental impacts related to life cycle assessment (LCA). Various novel technologies have been developed, such as the explainable artificial intelligence (XAI) which can model for energy consumption based from the prediction of climate change impacts [121]. The modeled climate impacts have the ability to directly predict the amount of energy consumption in future. Therefore, this will provide comprehensive information to decision makers on the various effective mitigation potential such as the use of renewable energy to replace the use of fossil fuels. This model data can be potentially synergised with the LCA methodologies that can precisely estimate potential future emission reductions. Currently, the use of XAI has found its potential use for measuring various sustainable indicators (particularly environmental) through machine learning operations within the life cycle framework [122,123]. In addition to this, the broad-based application use of XAI include the prediction on the effects of changes in land cover to local climate [124], as well as provide analysis of the flow through vegetation [125]. In addition, it can also potentially provide an advertent measure of inputs on water availability in certain agricultural areas for consideration in future LCA studies. Ultimately, XAI and other potential artificial intelligence technologies may have a profound impact in future sustainability assessments in the advancement of science.

CONCLUSION

To achieve overall sustainability in the agricultural sector, it is crucial to develop a robust LCSA methodology. Multiple sources of literature indicate that LCSA applications are highly appropriate for wide-scale implementation, including in agriculture. The study demonstrates that in recent years, particularly in the past few decades, there have been significant advancements that have led to the establishment of more all-encompassing, and detailed definitions of sustainability. There has been an increased focus on quantitative attributes, and multiple indicators have been created to meet specific local and national sustainability standards. The triple-pillar assessment guarantees that all components are considered in the process, allowing for a comprehensive analysis to be conducted. The systematic literature review (SLR) found that out of the 186 articles on LCSA studies, 22 (12%) were specifically focused on the agriculture sector. Furthermore, a detailed analysis of the agricultural LCSA studies revealed the methods employed to assess sustainability were consistent with those applied in other sectors. It was also found that one of the main indicators are the global warming potential (GWP) which is a significant environmental measure, giving the opportunity to utilize an economic-environmental assessment through environmental life cycle costing (ELCC). Other indicators highlighted include those from each of the three pillars: environmental indicators such as the decline in air quality and eutrophication, economic indicators such as increased production costs, and social indicators that focused on workers and local communities. Also emphasised is the significance of addressing the requirements and deficiencies within a particular sub-sector (including those related to local stakeholders) to enhance the effectiveness and advantages of the study outputs for society. This study also highlight the prospect for the potential use of artificial intelligence to spearhead the effective measurement of sustainability.

SUPPLEMENTARY MATERIALS

The following supplementary materials are available online at https://doi.org/10.20900/jsr20240069. Supplementary Table S1: Method to measure sustainability and indicator used for articles (case studies) related to agricultural LCSA.

DATA AVAILABILITY

The dataset of the study is available from the authors upon reasonable request.

AUTHOR CONTRIBUTIONS

MHAR, AHS, ZP, NNRNAR, NAAB, MFMS, MNZ, NAS: Visualisation, investigation and analysis; NASH: Investigation and analysis; MHAR and AHS: writing—original draft preparation.

Abbreviations: MHAR: Mohammad Hariz Abdul Rahman; AHS: Amir Hamzah Sharaai; ZP: Zakiah Ponrahono; NNRNAR: Nik Nor Rahimah Nik Ab Rahim; NAAB: Nurul Ain Abu Bakar; NASH: Nurul Atilia Shafienaz Hanifah; MFMS: Mohd Fairuz Md Suptian; MNZ: Mohd Nizam Zubir; NAS: Norsyuhaida Ahmad Shafawi.

CONFLICT OF INTEREST

The authors declare that there are neither competing financial interests nor any known personal relationships that may have influenced the work reported in this article.

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