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Life Cycle Assessment in Dairy Supply Chains: A Review and Framework for Sustainability Improvement in Indonesia

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A B S T R A C T

The sustainability of the dairy sector is a strategic issue in the development of the national economy and food system, given the significant environmental pressures across the supply chain and the limited capacity of business actors to manage these impacts systematically. Life Cycle Assessment (LCA) has been widely applied as an environmental evaluation tool in the dairy sector. However, its implementation remains fragmented and shows persistent gaps between field needs, public policies, business strategies, and actual practices. This study aims to systematically map LCA practices implemented in the milk supply chain and identify key sustainability hotspots and structural gaps relevant to the Indonesian dairy industry. The research employs a systematic literature review of selected international scientific publications, analyzed through qualitative content analysis to examine system boundaries, supply chain stages, environmental indicators, and principal findings, followed by gap analysis between existing practices, sector needs, and policy frameworks. The results reveal that dominant environmental hotspots are concentrated in the upstream production stage, particularly related to enteric methane emissions, feed production intensity, manure management, and resource use efficiency. Furthermore, the integration of LCA findings into business decision-making processes and sustainability policy formulation remains limited. These findings highlight the need for an integrative conceptual framework that connects LCA practices with business process improvement and policy interventions to support a more resilient and sustainable dairy sector model in Indonesia

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INTRODUCTION

The dairy sector is an important part of the global and national food system because of its contribution to food security, job creation, and agribusiness-based economic growth. However, the dairy supply chain is also known as one of the significant sources of environmental stress, especially related to greenhouse gas emissions, water use, and natural resource degradation (Bava et al., 2021). Globally, increasing demand for dairy products is driving production intensification that is not always balanced with adequate environmental management practices, giving rise to increasingly complex sustainability challenges (Mazzetto et al., 2020). This condition makes system-based environmental impact evaluation an urgent need in the management of the dairy supply chain.

Life Cycle Assessment (LCA) has developed as the most widely used scientific approach to assess the environmental impact of dairy products throughout their life cycle, from feed production, livestock rearing, processing, to distribution (Baldini et al., 2022). Various international studies show that LCA is capable of identifying critical points of environmental impact or hotspots, particularly at the upstream production stage related to enteric methane emissions and livestock waste management (Pirlo et al., 2021). However, the application of LCA in the dairy sector still shows high methodological diversity, both in the determination of system boundaries, functional units, and the selection of environmental indicators, thus limiting its use as a basis for strategic decision-making (Notarnicola et al., 2020).

A number of recent studies highlight the gap between the results of LCA studies and their implementation in public policies and business strategies in the dairy sector. Studies by Baldini et al. (2022) show that LCA outcomes often stop at the academic level and have not been effectively integrated into business planning or environmental regulations. On the other hand, business actors need recommendations that are applicable and contextual, while policymakers need a consistent and comparable evaluation framework across regions (Mazzetto et al., 2020). This gap indicates that existing LCA practices have not fully addressed the real needs of the multidimensional dairy sector.

In the Indonesian context, these challenges are becoming increasingly relevant due to the structure of the dairy industry dominated by small- and medium-scale farmers, technological limitations, and dependence on imports of dairy raw materials. The LCA research available in Indonesia is still partial and fragmented, and rarely links environmental findings to national policies and strategies to strengthen industrial competitiveness (Setyawan et al., 2023). As a result, there is no comprehensive mapping of the LCA practices that have been implemented, the main hotspots in the milk supply chain, and the gap between sector needs, policies, business strategies, and factual conditions on the ground.

Based on these conditions, this study identifies a significant research gap, namely the absence of a systematic review study that maps the practice of LCA in the dairy sector as a whole and explicitly links it to the needs of policies and business strategies, especially in the Indonesian context. Most previous studies have focused on measuring environmental impact without developing a

conceptual framework capable of bridging LCA outcomes with business process improvement and sustainability policy formulation (Pirlo et al., 2021; Baldini et al., 2022). This gap shows the need for an integrative approach that is not only evaluative, but also transformative.

Therefore, this study aims to systematically map the practices of Life Cycle Assessment that have been implemented in the dairy supply chain, identify hotspots and sustainability gaps between sector needs, public policies, business strategies, and actual practices, and develop a conceptual framework as a basis for improvement. This objective is designed to provide a comprehensive understanding of how LCA can be used more effectively as a decision-making support tool in the dairy sector. With this approach, research is expected to be able to bridge the gap between scientific knowledge and implementable practice.

Theoretically, this study contributes to the development of the literature on environmental economics and supply chain sustainability by integrating the results of the LCA review into a contextual and applicable conceptual framework. Practically, the proposed framework can be a reference for policymakers and industry players in designing more targeted interventions, both in improving business processes and strengthening environmental policies. Thus, this research is expected to encourage the development of a more resilient, competitive, and sustainable model of Indonesia's dairy sector.

METHODOLOGY

1. Research Approach and Design

This study uses a qualitative approach with a Systematic Literature Review (SLR) design combined with content analysis and gap analysis as the basis for the development of a conceptual framework. The qualitative approach was chosen because the main purpose of the research is not to test the quantitative relationship between variables, but to synthesize, interpret, and integrate scientific findings related to the practice of Life Cycle Assessment (LCA) in the milk supply chain systematically and contextually. The SLR design is used to ensure transparency, replication, and traceability of the literature search process, so that the results of mapping LCA practices can be accounted for academically (Page et al., 2021). This approach is appropriate for research aimed at identifying patterns, environmental hotspots, and conceptual gaps in the agribusiness sector sustainability literature.

2. Research Population and Sampling Techniques

The population of this study is in the form of international scientific articles that discuss the application of Life Cycle Assessment in the dairy sector and the dairy supply chain. The sampling technique uses non-probability sampling with the purposive sampling method, which is the selection of articles based on the inclusion criteria that have been set. These criteria include publication in internationally reputable journals, published in the period 2020–2025, discussing LCA in the dairy sector or dairy supply chain, and providing relevant information on system coverage, environmental indicators, and sustainability implications. The purposive sampling approach was chosen because it allows the selection of the most relevant and quality sources for in-depth conceptual analysis (Snyder, 2019; Xiao & Watson, 2019).

The literature search was conducted using two major international scientific databases, namely Scopus and Web of Science. These databases were selected due to their comprehensive coverage of peer-reviewed journals in environmental science and agri-food systems. The search was performed using a combination of keywords, including “life cycle assessment”, “dairy sector”, “milk supply chain”, and “environmental sustainability”, connected through Boolean operators. The search was limited to articles published between 2020 and 2025 to capture recent developments in LCA applications within the dairy sector.

3. Data Collection Procedure

Data collection was carried out through systematic literature search on international scientific databases, namely Scopus and Web of Science. The search process follows the PRISMA 2020 guidelines which include the identification, screening, feasibility assessment, and inclusion stages of articles (Page et al., 2021). The main keywords used include life cycle assessment, dairy sector, milk supply chain, and environmental sustainability, which are logically combined using Boolean operators. The data collected are secondary and derived from scientific documents, so they do not involve human respondents and do not require ethical approval of the research.

The study selection process was conducted following the PRISMA 2020 guidelines to ensure transparency and reproducibility. The stages of identification, screening, eligibility assessment, and inclusion were applied systematically. Figure 1 presents the PRISMA 2020 flow diagram summarizing the literature selection process.

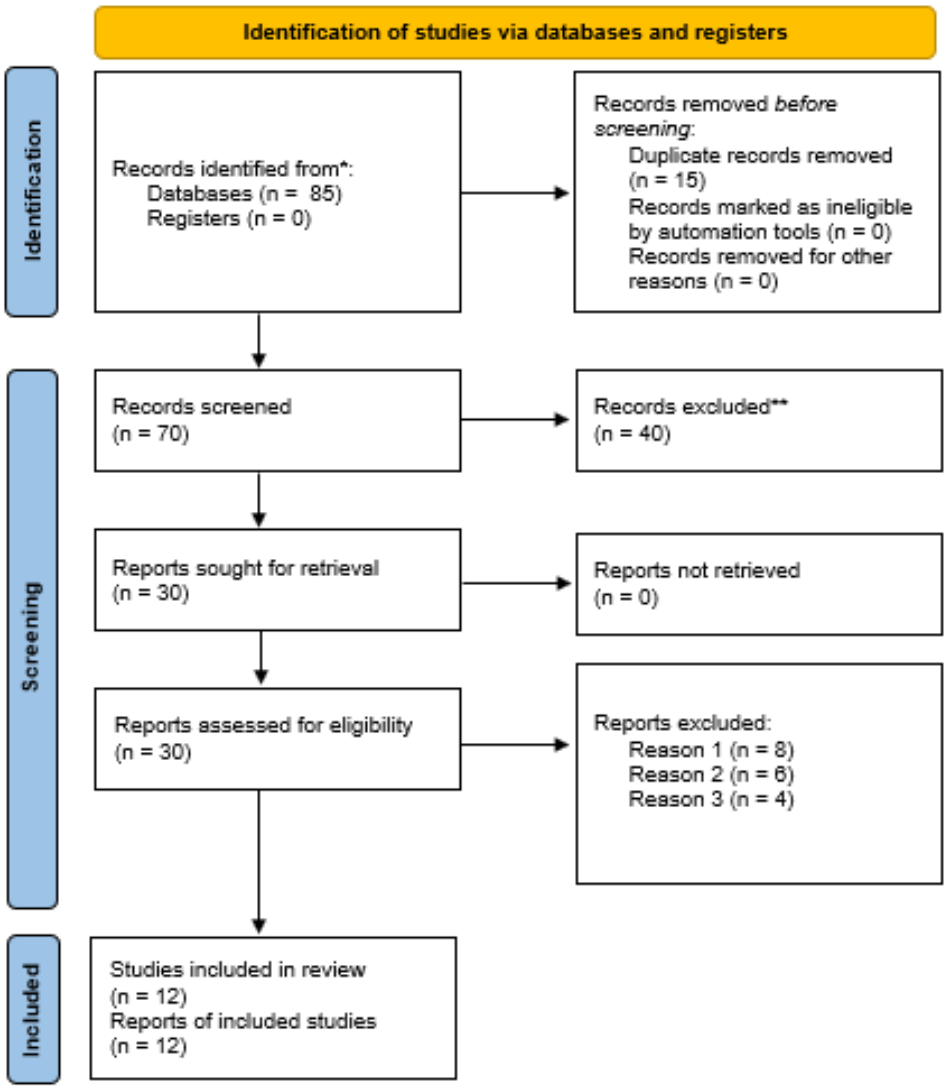

Figure 1. PRISMA 2020 flow diagram of the literature selection process

4. Bibliometric Analysis

In addition to the PRISMA-based systematic selection, a bibliometric analysis was conducted to visualize the structure of the selected literature. The bibliometric mapping aims to identify dominant research themes, keyword relationships, and collaboration patterns within Life Cycle Assessment studies in the dairy sector. The analysis was based on keyword co-occurrence and network visualization. This approach allows the identification of thematic clusters and research concentrations during the 2020–2025 publication period. Figure 2 presents the bibliometric network of the selected articles. The size of the nodes represents the frequency of keyword occurrence, while the links illustrate the strength of relationships between themes. The visualization supports the

systematic review findings by showing the dominance of upstream production and environmental hotspot discussions in the dairy LCA literature.

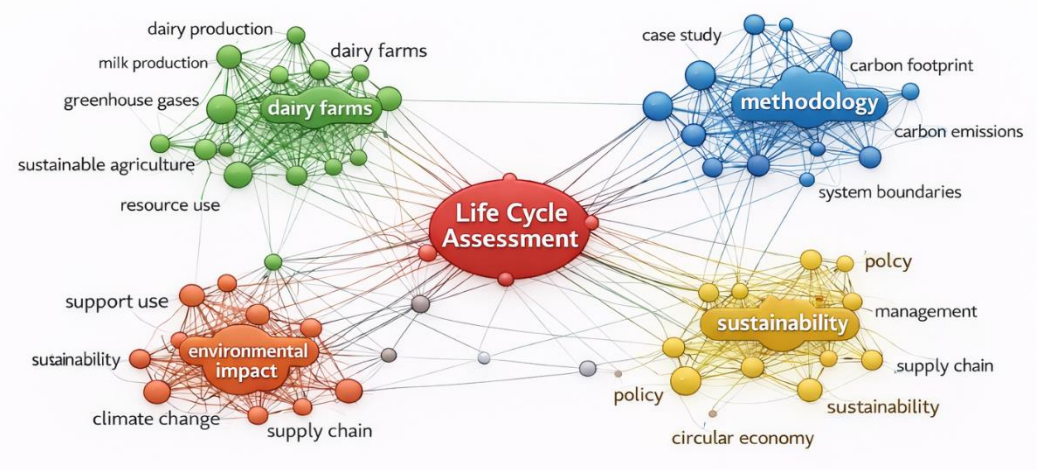

Figure 2. Bibliometric network visualization of thematic selected LCA dairy publications (2020–2025)

5. Data Extraction Instruments and Techniques

The data collection instrument is in the form of a data extraction sheet that is systematically compiled to record the main characteristics of each article. The information extracted included the study objectives, LCA system boundaries, functional units, stages of the supply chain analyzed, environmental impact indicators, key findings, and policy or managerial recommendations. These extraction sheets are compiled based on best practices in systematic review to ensure consistency and minimize researcher bias (Kitchenham et al., 2020). Given the study's qualitative design, standard statistical tests for validity and reliability were not applicable. Instead, the validity of the content is maintained through consistency of selection criteria and an iterative review process.

6. Data Analysis Techniques

Data analysis was carried out using qualitative content analysis with a thematic approach to classify and interpret the practices of LCA identified in the literature. This analysis aims to identify the pattern of LCA implementation, the main focus stages of the supply chain, and the environmental hotspots that are most frequently reported in previous studies. The content analysis approach was chosen because of its ability to reveal the substantive meaning of scientific texts in a systematic and structured manner (Mayring, 2021). The analysis process is carried out iteratively to ensure that the resulting thematic categories reflect the overall content of the literature being analyzed.

7. Gap Analysis Techniques

Furthermore, gap analysis was used to compare the findings of existing LCA practices with the needs of the dairy sector, sustainability policy directions, and relevant business strategies, especially in the Indonesian context. This analysis is focused on identifying gaps between the results of environmental evaluations and their implementation in business decision-making and public policy. The gap analysis approach allows researchers to identify areas that require strategic interventions as well as opportunities for systemic improvement in the dairy supply chain (Borges et al., 2021). This stage is the main foundation in the formulation of recommendations and the development of the framework.

8. Conceptual Framework Development

Based on the results of content analysis and gap analysis, this study develops an integrative conceptual framework that explicitly describes the relationships among four main components: (1) LCA methodological practices, (2) environmental hotspot identification along the dairy supply chain, (3) business process improvement strategies, and (4) sustainability policy interventions aimed at enhancing the sustainability of Indonesia's dairy sector. The framework positions Life Cycle Assessment (LCA) as the analytical foundation that generates structured environmental evidence across different stages of the milk supply chain. Through systematic hotspot identification, particularly in upstream production activities, LCA findings are translated into two complementary domains of intervention. The first domain concerns business-level improvements, including production efficiency, resource optimization, emission reduction strategies, and better waste management practices. The second domain relates to institutional and policy-level interventions, such as regulatory instruments, sustainability standards, incentives, and integration of environmental indicators into sectoral planning.

The development of the framework is carried out inductively by synthesizing the findings of the reviewed literature and adapting them to the structural characteristics of the Indonesian dairy industry, particularly the dominance of small-scale farmers, limited data availability, and fragmented supply chain integration. This contextual adaptation ensures that the framework does not merely reflect global LCA practices, but also responds to national structural constraints and policy needs. This approach is in line with the practice of developing conceptual frameworks in sustainability research that emphasizes integration between scientific evidence and implementation contexts (Geissdoerfer et al., 2020). The resulting framework is expected to function not only as an analytical tool but also as a strategic governance model that aligns environmental assessment, managerial decision-making, and public policy formulation. Figure 3 presents the proposed integrative conceptual framework and illustrates the relationships among its main components.

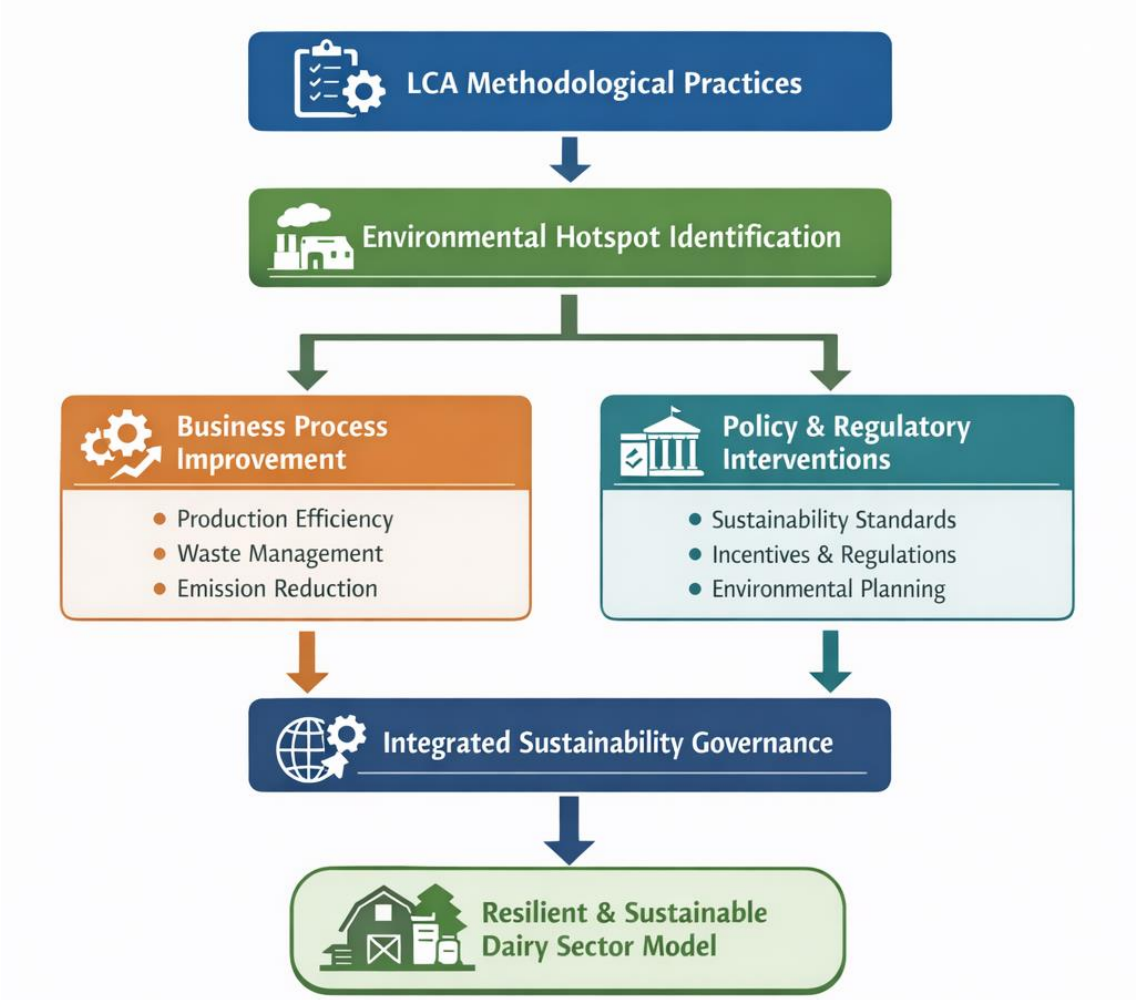

Figure 3. Integrative Conceptual Framework for Sustainable Dairy Sector Improvement in Indonesia

RESEARCH RESULTS

1. Mapping Life Cycle Assessment Practices in the Milk Supply Chain

Based on the results of the Systematic Literature Review compiled following the flow of PRISMA 2020, it was found that the practice of Life Cycle Assessment in the dairy sector globally is still dominated by partial studies that focus on one or two stages of the supply chain. This pattern appears consistently in the data extraction process, where most articles analyze primary production systems without attributing them to downstream dynamics. According to Baldini et al. (2022), this partial approach reflects the limitations of research design in capturing the complexity of value chain-based food systems. As a result, the resulting LCA results tend to represent local impacts, rather than systemic impacts. These findings suggest that existing LCA practices do not fully reflect the character of an integrated milk supply chain.

The results of the literature mapping also show that the cradle-to-farm gate system boundary is the most commonly used approach in the study of dairy sector LCA. In many articles, the stages of processing and distribution are treated only as an assumed extension of primary production, rather than as the main object of analysis. As noted by Mazzetto et al. (2020), the selection of narrow

system boundaries is often driven by data limitations and measurement complexity. However, the consequence is the loss of important information related to the shift in impact between stages. Therefore, these results confirm that existing LCA practices still have limitations in supporting cross-actor decision-making.

An analysis of the methodological characteristics of the study showed that only a small percentage of studies adopted a cradle-to-grave or cradle-to-consumer approach. A study by Sala et al. (2020) shows that the full life cycle approach is more relevant for sustainable food policy because it is able to capture the interactions between stages. However, the results of this review show that this approach is still rarely applied to the dairy sector. This condition strengthens the finding that LCA practices in the dairy sector are still in the early evaluative stage. Thus, the practice mapping shows that there is a large room for the development of a more holistic approach.

In the context of the SLR methodology, the results of mapping this practice were obtained through a rigorous selection process and consistent thematic extraction. This approach allows the identification of dominant patterns without relying on a single study. According to Snyder (2019), the strength of SLR lies in its ability to uncover structural tendencies in the literature, rather than just individual outcomes. The results of this study use this power to show that the practice of LCA in the dairy sector is still fragmentary. Therefore, this mapping provides a strong empirical basis for the development of conceptual frameworks.

Overall, the results of the mapping of LCA practices show that there is an imbalance of analytical focus in the milk supply chain. The upstream stage is the center of attention, while the downstream stage is relatively marginalized in environmental studies. These findings are in line with observations by Zucali et al. (2021) who suggest that downstream complexity is often avoided in LCA studies. Thus, the results of this study confirm that existing LCA practices have not fully answered the need for a comprehensive evaluation of supply chain sustainability. This condition is one of the main bases in the development of the proposed framework.

2. *Identify Environmental Hotspots at the Upstream Production Stage*

The results of the thematic analysis show that the most dominant environmental hotspots in the milk supply chain are in the upstream production stage. This pattern appears consistently in almost all studies analyzed, especially related to greenhouse gas emissions and resource use. Pirlo et al. (2021) identified that enteric fermentation is a major contributor to the carbon footprint of milk production. In addition, livestock waste management also plays a significant role in increasing emissions. These findings indicate that the primary production stage is a major critical point in the LCA of the dairy sector.

In addition to emissions, the intensity of feed and water use has also been identified as a significant environmental hotspot. A study by Bava et al. (2021) shows that feed production accounts for a large proportion of indirect environmental impacts. In this context, the results of the review show that the efficiency of input use is a key factor in reducing the total impact of the system. However, few studies have linked these findings to long-term feed management

strategies. Therefore, these results highlight the importance of a systemic approach in upstream hotspot mitigation.

Further analysis showed that environmental hotspots are contextual and influenced by the production systems used. According to O'Brien et al. (2020), grassland-based systems have a different impact profile than concentrated feed-based intensive systems. The results of this study found that these differences are often not explicitly taken into account in the interpretation of LCA results. As a result, the resulting recommendations become less context-specific. These findings suggest that hotspot identification needs to be accompanied by an understanding of local production systems.

In the content analysis methodology, the category of environmental hotspots emerged as the theme with the highest frequency. This shows that the focus of LCA research in the dairy sector is still very much focused on measuring impact, rather than on integrating results into decisions. A study by Reisinger et al. (2021) emphasizes that reducing upstream emissions requires a combination of technical and institutional interventions. However, the results of this review show that the institutional dimension is rarely discussed. Thus, the identified hotspots have not been fully translated into an implementable strategy.

Overall, the results of the hotspot identification confirm that upstream production is the main leverage point in dairy sector sustainability efforts. However, the dominance of focus on upstream also risks ignoring the potential shift of impact to other stages. As noted by Bjørn et al. (2020), a lifecycle approach is necessary to prevent burden shifting. Therefore, these results reinforce the argument that hotspot identification should be part of the systemic framework. These findings are an important basis for the formulation of framework-based recommendations.

3. Methodological Variation and Inconsistency of LCA Indicators

The results of the study show that there is a high methodological variation in the application of LCA in the dairy sector. These variations include differences in system boundaries, functional units, allocation methods, and environmental impact categories. Notarnicola et al. (2020) stated that this variation is a major challenge in the synthesis of LCA results across studies. In the process of data extraction, this variation causes difficulties in conducting direct comparisons. These findings suggest that LCA methodological practices are still not standardized.

Functional units are one of the most significant sources of variation. Some studies used a liter of milk as a functional unit, while others used a nutrient-content-based approach. Weidema (2020) emphasizes that the selection of functional units affects the interpretation of results and their relevance to policy. The results of this review show that these differences are rarely critically discussed in articles. As a result, readers often have difficulty understanding the implications of comparisons between studies.

In addition to functional units, the selection of impact indicators also showed significant inconsistencies. A study by Salou et al. (2021) shows that most dairy sector LCAs are still focused on climate change, while other impacts such as eutrophication and biodiversity have received less attention. The results of this

study confirm this pattern in the literature analyzed. The inequality of focus of these indicators has the potential to produce an unbalanced picture of sustainability. Therefore, the harmonization of indicators is an important need.

In the context of the SLR methodology, these variations emerge as consistent structural findings. The content analysis approach allows the identification of such variations without ignoring the context of each study. According to Guinée et al. (2021), methodological transparency is a prerequisite for LCA to be used as a decision-making tool. The results of this study show that this transparency has not always been met. This condition reinforces the urgency of developing more uniform methodological guidelines.

Overall, the results show that methodological inconsistency is one of the main factors limiting the strategic use of LCA. This variation is not only technical, but also has an impact on the relevance of business policies and strategies. A study by Laurent et al. (2020) emphasizes that methodological standardization can increase the usefulness of LCA. These findings provide an empirical basis for the development of a framework that incorporates aspects of methodological harmonization. Thus, methodological variation is a central issue in the results of this study.

4. The Gap between LCA Practices and Sustainability Policy Needs

The results of the gap analysis show that there is a clear gap between the findings of the Life Cycle Assessment and the need for sustainability policies in the dairy sector. Most LCA studies conclude at the identification of environmental impacts without directly linking them to specific policy instruments. A study by Sala et al. (2021) shows that although LCA has great potential as a basis for policy formulation, its utilization is still limited to the conceptual stage. In the literature analyzed, few articles linked the results of LCA to national regulatory or policy targets. These findings indicate that LCA practices have not fully functioned as a public policy support tool.

Thematic analysis also reveals that LCA results are rarely translated into operational policy indicators. Most studies use technical language that is difficult for policymakers to adapt. According to Nilsson et al. (2021), one of the main obstacles to the integration of science into policy is the lack of knowledge translation mechanisms. The results of this study show that this condition also occurs in the context of LCA in the dairy sector. Thus, there is a communication gap between the academic world and policy formulation.

In the context of sustainable food policy, the results of the review show that LCA has not been systematically used to evaluate the impact of existing policies. The study by Mazzocchi et al. (2022) emphasizes the importance of an evidence-based approach in food policy, including the use of LCAs. However, the results of this study show that most LCA studies do not attribute their findings to actual policy evaluations. As a result, the potential of LCA as a policy evaluation tool has not been utilized optimally. These findings reinforce the identification of the gap between scientific practice and policy needs.

In the methodology of this study, the gap was identified through a systematic comparison between the LCA findings and the relevant policy

documents. The gap analysis approach allows for the identification of areas that are not reached by existing LCA practices. Studies by Plevin et al. (2020) show that environmental policies often require simple but science-based indicators. The results of this study show that complex LCA outcomes are often not simplified for these needs. This condition clarifies the source of the gap between LCA and policy.

Overall, the results show that the gap between LCA practice and policy needs is not due to a lack of scientific evidence, but rather to a lack of integration and communication. The study by Grunert et al. (2021) emphasizes that sustainability policy requires a consistent and understandable cross-sectoral evaluation framework. The findings of this study indicate that the LCA of the dairy sector has not fully met these criteria. Therefore, these results are an important basis for the development of a framework that links LCA to sustainability policy. This policy gap is one of the main findings of the study.

5. Indonesia's Context in the Practice and Challenges of Implementing LCA in the Dairy Sector

The results of the study show that the application of Life Cycle Assessment in the dairy sector in Indonesia is still very limited compared to the global context. Most of the studies analysed focused on specific cases with limited data coverage. According to Wiedemann et al. (2020), the availability of data is a major prerequisite for the success of LCA in developing countries. The results of this review show that limited inventory data is still the main obstacle in Indonesia. This condition limits the ability of LCA to provide a comprehensive picture of environmental impact.

The structure of Indonesia's dairy industry, which is dominated by small-scale farmers, also affects the implementation of LCA. Studies by Poore and Nemecek (2020) show that smallholder-based production systems have high variability in environmental performance. The results of this study found that these variabilities are rarely adequately captured in Indonesian LCA studies. As a result, evaluation results often do not reflect the full field conditions. These findings suggest the need for a more adaptive LCA approach to local contexts.

In addition, the low integration of the national milk supply chain also limits the implementation of LCA as a whole. A study by van der Vorst et al. (2021) emphasizes that effective LCA requires data connectivity across supply chain stages. The results of this study show that this connection is still weak in the Indonesian milk sector. This condition causes the analysis to often end at the primary production stage. These findings reinforce the results of practice mapping that show the dominance of upstream analysis.

In the context of national policies, the results of the review show that LCA has not yet become an integral part of the dairy sector's development planning. A study by the OECD (2022) emphasizes the importance of integrating environmental evaluation tools in sustainable agriculture policies. However, the results of this study show that LCA is still rarely used as a basis for policy formulation in Indonesia. This causes the dairy sector's sustainability policy to not be fully based on environmental evidence. These findings indicate a gap between policy needs and evaluation practices.

Overall, the results of the study show that the Indonesian context presents challenges as well as opportunities for the development of LCA in the dairy sector. A study by Herrero et al. (2020) shows that the transformation of food systems in developing countries requires a contextual and gradual approach. The results of this review confirm that LCA in Indonesia needs to be adjusted to industrial structure, data availability, and institutional capacity. These findings clarify the urgency of developing a conceptual framework that is adaptive to national conditions. Thus, the Indonesian context is a key element in the results of this study.

CONCLUSIONS AND RECOMMENDATIONS

This study confirms that the practice of Life Cycle Assessment (LCA) in the milk supply chain is still dominated by a partial approach that focuses on the upstream production stage, so that although it is able to identify key environmental hotspots, especially related to emissions and resource use intensity, the results have not been fully integrated into business decision-making and public policy formulation. Through systematic literature review combined with content analysis and gap analysis, this study succeeded in mapping the existing LCA practices and uncovering the structural gaps between field needs, policy frameworks, business strategies, and actual practices, especially in the context of the Indonesian dairy industry dominated by small-scale farmers and limited data. These findings suggest that the main challenge lies not in the availability of scientific evidence, but in the methodological fragmentation and weak translation mechanisms of LCA results into operational policy instruments and managerial tools. Based on the results of the mapping, this study developed a conceptual framework that integrates LCA practices, business process improvement, and policy interventions as the basis for the transformation of the dairy sector towards a more resilient and sustainable model. Thus, this research makes a theoretical contribution in strengthening the role of LCA as an analytical tool in a sustainable economy, as well as a practical contribution in the form of a strategic reference for policymakers and industry players in encouraging the sustainability of Indonesia's dairy sector.

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