

An AI-Integrated Hybrid Life Cycle Assessment Framework for CO₂ Emission Prediction in Dairy Supply Chains

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Abstract

The dairy sector generates substantial greenhouse gas emissions, necessitating specific methods to calculate carbon footprints and identify significant environmental hotspots. Life Cycle Assessment (LCA) is a standard tool for assessing the environmental impacts of dairy supply chains; however, it faces major limitations arising from differences in system boundaries, functional units, allocation techniques, and geographical locations. Hybrid LCA

methods address these problems by combining process-based and input–output LCA methods, yet they can be improved to enhance data outputs and system flexibility. Recent advancements in artificial intelligence (AI) and machine learning technologies enable researchers to analyze complex and heterogeneous datasets to generate CO₂-eq emission predictions. Nevertheless, existing AI applications in the dairy sector are largely fragmented and insufficiently integrated within LCA-consistent, system-level frameworks. This study develops a preliminary AI-integrated hybrid LCA system that predicts CO₂-eq emissions across dairy production supply chains. The research findings from this study inform developers in creating an ISO-aligned framework, through a user interface prototype, that enables users to enter specified supply chain and geographical data, view CO₂-eq emissions by location, and identify emission hotspots. The main contribution of this research is the development of a clear system structure that integrates AI prediction methods into established hybrid LCA guidelines. The proposed method provides a foundation for future implementations and supports policymakers and researchers in conducting assessments to enhance dairy-sector sustainability decision-making.

Keywords

Dairy Supply Chain, Hybrid Life Cycle Assessment, Artificial Intelligence, Carbon Footprint, Emission Hotspots.

1. Introduction

The dairy industry is a key element of the international agricultural system and is a key component in food safety and economic growth (Kumar et al. 2021). Given the industry's rapid growth, it is important to examine its environmental impacts, particularly its carbon footprint. According to the FAO, the global dairy industry accounts for approximately 4% of anthropogenic greenhouse gas (GHG) emissions (FAO, 2010). Methane (CH₄), nitrous oxide (N₂O), and carbon dioxide (CO₂) are the primary gases produced during dairy production (Rencricca et al. 2023). These emissions are attributed to dairy farming and production activities, stemming from enteric fermentation, fertilizer use and production, manure management, energy and water use, and the processing and transportation of dairy products (Astuti et al., 2024; Tamilselvan & Tyagi, 2024).

One of the widely used methodologies for assessing the carbon footprint of dairy production is Life Cycle Assessment (LCA), which provides an accurate representation of environmental hotspots in the dairy supply chain (Cortés et al., 2021). It assesses the carbon footprint of the entire supply chain, from cradle to grave, including raw resource extraction, manufacturing, distribution, use, and disposal (Agustin et al., 2021). However, challenges in the analysis arise from methodological inconsistencies. Recent studies analyze the carbon footprint of dairy products using various parameters, undermining methodological consistency and complicating cross-study comparisons. To explain, existing research employs a variety of functional units, system boundaries, co-product handling, and allocation techniques, resulting in differences in calculated emissions. Many published studies focus primarily on emissions associated with on-farm activities, neglecting the broader system boundary encompassing processing, packaging, and transportation, which significantly affect resulting emissions. Additionally, regional differences are crucial to consider, as dairy operations and practices vary with feed sources, farm activities, milk yield, and climatic conditions.

To enable cross-country comparisons and robust analyses, one can apply process-based LCA, which can reveal on-farm hotspots related to detailed processes and supply-chain inputs but may overlook upstream supplier networks and market-oriented effects (Yan et al., 2013). Input-Output LCA based on the Multi-Regional Input-Output (MRIO) technique can encompass wider cross-country economic relationships; however, it often fails to encompass detailed process requirements for quantifying farm-level emissions in a dairy production supply chain (Yan et al., 2013). A hybrid LCA methodology can be used to maximize the system's accuracy and robustness. It can track both direct and indirect emissions, therefore helping to assess environmental performance. While hybrid LCA approaches improve completeness and methodological robustness, artificial intelligence (AI) and machine learning can provide complementary benefits to support hybrid LCA. Recent developments in AI and machine learning technologies offer additional capabilities that support hybrid LCA by enhancing data management, pattern recognition, and emission forecasting. AI systems should function as predictive tools that apply the LCA methodology within an integrity-based framework, enabling scalable and policy-relevant assessment while preserving transparency and interpretability.

1.1. Objectives

The objective of the research is to conduct a systematic review to assess AI and machine learning systems that track environmental impacts and emissions data in dairy farming operations, and to evaluate their capacity to address current

barriers in dairy LCA methodology. The research aims to develop an initial ISO-compliant hybrid LCA framework that enables users to predict CO₂-eq emissions in the dairy supply chain through a policy-oriented interface.

2. Methods

This paper employs a structured approach to analyze recent papers and presents a comprehensive literature review on the benefits of developing an AI-hybrid LCA framework to address challenges in dairy production supply chains. It aims to examine how the environmental performance of dairy products intersects with AI. The focus of the literature review is to determine how AI technology can address estimation and integration problems affecting present LCA operations. In addition to predicting the carbon footprint of dairy production. The review employs a structured literature review to build on prior research, thereby establishing the basis for and justifying the use of the AI-hybrid LCA framework. **Error! Reference source not found.** summarizes the procedural framework used in the literature review. Step 1 was to define the research scope, outline the research keywords and inclusion and exclusion criteria, and organize the studies by methodology and analysis. Step 2 specified the research keywords, which were ("artificial intelligence" OR AI OR "data optimization" OR "machine learning" OR "deep learning" OR "data-driven" OR "intelligent system" OR "decision support system") AND ("dairy supply chain" OR dairy OR milk OR "milk supply chain" OR "animal production" OR "dairy cattle") AND ("life cycle assessment" OR LCA OR "life cycle inventory" OR "life cycle analysis" OR "carbon footprint" OR "GHG emissions" OR "greenhouse gas emissions" OR "emissions"). In addition, after the initial search identified 190 studies published between 2015 and 2025, the inclusion criteria were applied, yielding 18 studies. Step 3 entailed synthesizing results from various studies to determine the cumulative environmental effects of dairy production and identify emission hotspots (Figure 1).

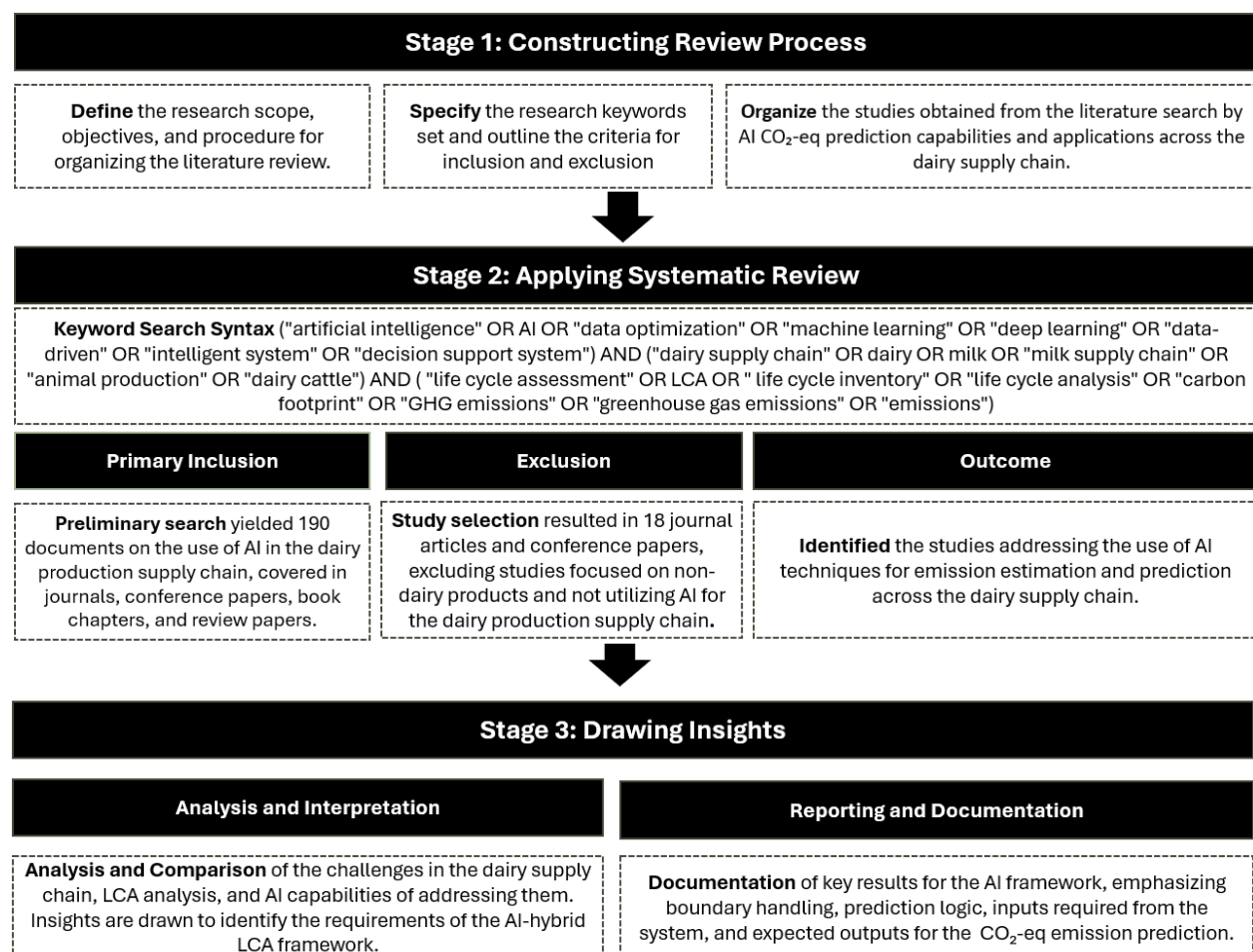


Figure 1. Methodology Flow of the Structured Literature Review.

Table 1 presents the challenges affecting dairy LCA assessment and the AI-based solutions identified in the papers studied that address these problems. This demonstrates how AI systems can improve hybrid LCA-based CO₂ prediction methods.

Table 1. Mapping of Key Dairy LCA Challenges to AI-Supported Capabilities Identified in Literature.

Challenge	AI/ Digital Solution
Pre-defined inventories limit adaptability (Bertagna et al., 2025).	Predictive manure/methane estimation via ML models(Ak et al., n.d.).
System boundary variability.	AI-enabled integration of multiple system components (Ak et al., n.d.; Neethirajan, 2024).
Multi-output system complexity and co-product allocation.	Pattern learning across complex, multi-variable datasets (Foschi et al., 2025).
Data heterogeneity and incompleteness.	ML integration of heterogeneous datasets (Neethirajan, 2024).
Regional heterogeneity undermines comparability (Zhang et al., 2022).	IoT-linked sensors providing standardized datasets (Neethirajan, 2024)
Lack of dynamic links between farm data & supply chain assessment (Bayram et al., 2023).	Digital Twin simulations feeding live parameters into larger system models (Ak et al., n.d.).

2.1. Differences in Functional Unit Utilized

Differences in results from dairy LCA studies arise from varying functional unit (FU) definitions, which are particularly due to dairy production emission results being measured per kilogram of raw milk, per kilogram of processed milk, or using uniform units such as ECM or FPCM (Cruz-Rivero et al., 2025; Mazzetto et al., 2022). Investigating different FUs can complicate comparisons of carbon footprints across studies. Multiple AI-based research studies demonstrate that data-driven models can discover emission-related output-system input connections through different data representations without needing an explicit functional unit. The study Jeong et al. (2022), demonstrates that machine learning models can predict emissions by analyzing production data and environmental information, including herd characteristics, feed inputs, and environmental conditions, rather than relying on predefined functional unit definitions. The research by Foschi et al. (2025), demonstrates how predictive modeling enables the calculation of carbon footprint indicators by accepting operational data, thereby showing that AI systems can operate across multiple dairy production system models. The studies do not directly address the functional unit inconsistency problem in LCA, but they demonstrate that AI can serve as a predictive system that helps users calculate emissions based on their selected functional units when used within a proper LCA framework. The use of this modeling logic is particularly valuable for hybrid LCA applications at the dairy supply chain level. This is because users can use AI to predict CO₂ emissions in the dairy production supply chain without requiring a predefined FU, while remaining consistent with the principles of ISO 14040/ 14044.

2.2. Variations in System Boundaries

In dairy LCA studies that extend from cradle-to-grave, like the one by Rossi et al. (2024), encompassing farming, processing, packaging, distribution, and consumer phases, a large proportion of studies end at the farm gate (Ben Abdallah et al., 2024; Carvalho et al., 2022), determining the extent of CO₂ emissions. The reviewed literature comprises studies that employ AI-based methods to establish connections among system components for conducting boundary-consistent evaluations. The research by Ak et al. (2023) developed a digital twin system that integrates farm production operations with emission monitoring through interconnected components. The research by Neethirajan (2024) demonstrates how AI-supported platforms integrate data from diverse dairy operations and supply chain stages to inform environmental assessments and decision-making. The study by (Bertagna et al., 2025) presents methods for tracking dairy production energy use and emissions data from the start to the end of the production cycle. The research data indicate that AI technology enables data integration across different stages, which is a vital factor in establishing system limits for hybrid LCA-

based CO₂ prediction systems. In addition, a predictive AI system developed by (Foschi et al., 2025) uses system-level input variables to predict emissions instead of relying on fixed process chains. AI-enabled frameworks employ data-driven models and digital representations to create a single analytical framework that integrates all elements of dairy supply chains. These approaches enable users to perform emission calculations for different system boundary configurations while preserving the consistency in essential data relationships among system elements.

2.3. Co-product Allocation Techniques

The choice of allocation method is a key source of variability in reported LCA results for dairy production systems, which remains a core problem. Dairy farms rarely produce milk alone; meat and manure are typically co-products. How environmental impacts are apportioned among these outputs, by mass flow, economic value, or biophysical relationships, can shift calculated footprints substantially (Battini et al., 2016; D. V. da Silva et al., 2025; González-Quintero et al., 2025). The reviewed AI studies lack direct analysis of allocation methods, yet they demonstrate how machine learning algorithms can identify relationships between production factors and emission metrics in complex datasets with multiple output variables. The study by (Foschi et al., 2025) applies AI to generate carbon footprint results from farm-system data entry without explicitly requiring predefined emission allocation techniques. Therefore, they are implicitly addressed during data training. The Jeong et al. (2022) study uses predictive modeling to estimate emissions at the system level, demonstrating that AI models can detect emission patterns when allocation methods introduce measurement uncertainties. The research shows that AI-based pattern-learning systems improve hybrid LCA methods by incorporating predictive models that reduce the impact of allocation-related variability on results.

2.4. Geographical and Management System Heterogeneity

The specific characteristics of dairy LCA studies, particularly with respect to scale and context, prevent their use in policy-based CO₂ assessments. Differences in geography impose substantial variation on measured carbon footprints of dairy systems, often exceeding the magnitude of uncertainties attributable solely to methodological choices. Across the literature, a wide range of countries and systems were investigated, but most studies focused on Italy, the United States, Spain, India, Brazil, China, Mexico, Ireland, and Ethiopia. Each of these countries has distinct climatic conditions that affect the resulting carbon footprint (Mazetto et al., 2022). Multiple studies reviewed show that AI systems can be applied across diverse regions, management systems, and settings, making them suitable for large-scale testing. The research demonstrates that AI systems perform environmental assessments at multiple scales by integrating diverse datasets. The research by Georgiades et al (2025) demonstrates that machine learning can be generalized across locations and time points, making it suitable for emission prediction. These capabilities are also studied in Jeong et al. (2022), which shows how predictive models are performed across various dairy production conditions. This study, along with Foschi et al. (2025), examines the ability of machine learning to integrate geographic and management-specific input variables, such as regional feed characteristics, climate conditions, and production intensity, to predict emissions. These AI models learn patterns across diverse data types, enabling them to generate emission estimates that adapt to specific local conditions rather than relying on generic coefficients and datasets.

The reviewed studies show that AI systems address current LCA challenges by predicting emissions in complex systems, integrating system elements, and detecting patterns in multi-output systems, as reported by Jeong et al. (2022). The capabilities are distributed across separate components and do not conform to hybrid LCA structures or policy-based CO₂ accounting requirements. The research results will direct the creation of the proposed AI-integrated hybrid LCA framework, which will combine AI predictive capabilities with LCA-approved system descriptions and financial reporting systems. The system allows users to select their preferred data input format and to set parameters for predicting CO₂ emissions and detecting hotspots across the entire dairy supply chain. Based on the synthesis, the following section presents preliminary results from the development of an AI-integrated hybrid LCA framework to predict CO₂ emissions across dairy supply chains worldwide.

3. Results and Discussion

3.1. Framework Design Principles

The proposed framework adheres to the principles of ISO 14040/ 14044 to ensure consistency across the fundamental LCA stages, including goal and scope definition, life cycle inventory (LCI) development, impact assessment, and interpretation. The study applies these standards to establish structural constraints that define the framework design, rather than treating them as methodological data. The framework employs a hybrid LCA

logic that integrates process-based and input-output based data to train the AI-based emission-prediction model. The LCI functions as an active data-entry system that integrates data on feed production, farm operations, dairy processing, packaging, dairy product distribution, retail, electricity consumption, and dairy product transportation. The system uses AI as a predictive support system operating within the LCA-consistent framework. AI models exist to support LCA methodology through emission estimation by discovering operational input-output relationships that affect CO₂ emissions.

3.2. Functional Unit Utilized

The proposed framework defines 1 kg of dairy product as the FU, serving as a standardized measure for predicting emissions and enabling comparisons across supply-chain stages. Although AI frameworks support flexible FU specification, this study adopts a mass-based product unit to demonstrate the conceptual implementation of the AI-integrated hybrid LCA framework

3.3. System Boundary Selection

The applied system boundary is a user-configurable framework layer that enables researchers to model various assessment areas commonly used in dairy supply chain research. The system enables users to establish boundaries that span from feed production and farm operations, distribution, until retail. The framework enables users to define system boundaries using an ISO-aligned structure and to track emissions across the selected extent of the dairy supply chain.

3.4. Life Cycle Inventory (LCI)

The framework uses data from established databases for the LCA, including EXIOBASE for environmentally extended input-output representations, Ecoinvent for process-based inventory data, and FAO GLEAM for livestock-related emission information.

3.5. Life Cycle Impact Assessment (LCIA)

The proposed framework follows the guidelines of ISO 14040/ 14044 for goal and scope definition, inventory compilation, impact assessment of CO₂-eq emissions, and interpretation. The assessment used the ReCiPe 2016 v1.03 Midpoint (H) method in Ecoinvent 3.11 for the climate change category. GWP₁₀₀ was used as the unit for measuring climate change impacts. The framework enables researchers to link AI-based emission predictions to LCA assessments through its structured design.

3.6. Structure of the AI-Integrated Hybrid LCA Framework

The proposed AI-integrated hybrid LCA framework prototype user interface (UI) structure is illustrated in Figure 2. The system's UI portrays the farm-to-retail system boundary, enabling users to define essential LCI data points across the dairy production network, from feed production through dairy farming, processing, transportation, distribution, and retail. It can also be used with various system boundary conditions, depending on the user's requirements. The UI AI framework enables users to enter all necessary inventory data, which includes feed amounts, milk production, transportation miles, water usage, and electrical power usage. The country selection component enables users to specify geographic information and select emission data for their region within a hybrid LCA framework. The AI-based emission prediction model uses these inputs to generate CO₂-eq emission estimates, which the system presents through combined metrics and visualizations. The emission hotspot panel illustrates how different parts of the supply chain contribute to emissions through activities such as enteric fermentation and feed production, manure management, and energy consumption during processing.



Figure 2. AI-Hybrid Life Cycle Assessment (LCA) Framework.

3.7. Intended Outputs and Scope of Application

The framework serves as an assessment tool that enables users to measure CO₂-eq emissions for policy development and research without conducting individual product certification assessments. The system generates results that help users evaluate different dairy production systems through comparative analysis, detect areas with high emission rates, and assess the initial effects of system modifications based on Life Cycle Assessment principles.

The framework constitutes the preliminary conceptual contribution and requires both numerical verification and evidence from real-world applications. The framework includes essential architectural and methodological elements that will enable the creation of upcoming models, data consolidation, and experimental research. The proposed framework addresses various methodological issues identified during the structured literature review. The system enables users to define their own functional units and system boundaries through a framework that handles system variability. The study addresses the challenges of geographic and system variability in traditional dairy LCA by combining AI-based prediction with heterogeneous input patterns. The framework enables researchers to identify emission patterns from inventory data, thereby enabling large-scale assessments of dairy production systems across different settings. The system demonstrates how AI technology integrates with hybrid LCA to produce flexible results through a method that differs from current AI systems that operate independently of established LCA frameworks.

4. Conclusion

Our study presents a preliminary AI-hybrid LCA framework that uses AI to predict CO₂-eq emissions in dairy production supply chains by analyzing existing AI applications and the challenges of dairy LCA assessment.

The proposed framework demonstrates how AI prediction models can integrate with hybrid LCA structures by implementing new data-driven methods that maintain both methodological consistency and system transparency. The system operates through a prototype interface that enables users to customize their systems and to predict emissions from inventory data, thereby detecting both exploratory and policy-based assessments. The framework provides a systematic structure for researchers to study data integration, model calibration, uncertainty analysis, and real-world applications for decision support in sustainable dairy production systems. The proposed framework constitutes an initial contribution and does not yield established numerical emission results. Its performance is inherently dependent on the quality and representativeness of inventory data and the robustness of AI model training. The framework provides an organized structure to guide future research by requiring experimental validation, full analysis of inventory data, and scenario creation. The system-level integration approach of this method, makes it an attractive solution for CO₂ assessment in the dairy sector, thereby supporting policy development.

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