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Examining the carbon emissions from dairy supply chains: An in-depth review

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Abstract
The dairy sector stands as a noteworthy contributor to global greenhouse gas emissions. However, the intricacies of comprehending the carbon footprint within dairy product supply chains render the task complex and multifaceted. This review of research delves into the most recent findings derived from both national and international studies. It meticulously examines the role played by crucial stakeholders in the endeavour to mitigate carbon emissions across the entirety of the dairy supply chain. Through the narrative lens of ten principal characters, each embodying diverse perspectives and specialized knowledge in sustainability, this article adeptly navigates the myriad challenges and opportune pathways for reducing the carbon footprint associated with dairy products.

Keywords: Carbon footprint, greenhouse gases, emission factor, supply chain, dairy products

Introduction

Amidst the burgeoning awareness surrounding climate change and sustainability, the carbon footprint of dairy products has emerged as a paramount concern. Recent years have witnessed a plethora of research endeavours aimed at assessing the environmental implications inherent in animal-derived goods and their respective distribution networks. While livestock operations significantly contribute to various pollutants, current scrutiny predominantly centres on the emission of greenhouse gases (GHGs) into the atmosphere. This focus persists as GHG emissions continue to escalate, exerting discernible impacts on global weather patterns and climate extremes (IPCC. Climate Change Report, 2023) [29]. The emissions of GHGs from livestock predominantly stem from methane (CH4) produced during enteric fermentation and from manure, encompassing both CH4 and nitrous oxide (N2O). These emissions account for 48.5% of the total emissions within the agricultural sector in Europe (Seront *et al*., 2023) [54]. This research review aims to furnish a comprehensive analysis of the carbon emissions associated with dairy product supply chains, drawing insights from an extensive array of national and international research studies. Through an examination of the roles assumed by diverse stakeholders within the dairy industry, this study elucidates strategies for mitigating carbon emissions and fostering environmental sustainability. Furthermore, it is envisaged that milk production will exhibit a faster growth trajectory compared to many other primary agricultural products between 2023 and 2032 (OECD *et al*., 2023) [50]. Instances where Life Cycle Assessment (LCA) has been applied to dairy products originating from "local" supply chains are scant. The designation of "local products" pertains to goods cultivated and distributed within close proximity, establishing a direct rapport between producers and consumers. This proximity affords environmental benefits by optimizing local resources and curtailing energy expenditures associated with product dissemination over shorter distances (Fiorillo D *et al*., 2023) [8].

Over the forthcoming decade, the dairy industry is poised for significant expansion, forecasted to experience a notable 17% increase in global milk production. In low- and middle-income nations, this growth will be propelled by escalating livestock numbers and enhanced yields, while high-income countries will witness yield improvements driven by optimization, enhanced animal health, and superior genetics. The surge in global milk production will be underpinned by increasing populations and per capita dairy consumption, spurring investment particularly in countries like India and Pakistan. These nations are anticipated to lead in absolute production growth, jointly contributing to 30% of global output by 2032, chiefly through herd expansion (OECD *et al.*, 2023) [50]. The dairy sector encompasses diverse production stages, including livestock rearing, feed cultivation, farming methodologies, transportation, processing, packaging, and distribution. Each of these stages significantly influences environmental outcomes (Singh *et al.*, 2024) [56].

The aim of supply chain management is to seamlessly and efficiently connect all processes from suppliers to customers. Supply chain networks predominantly focus on the physical movement of materials and entail decisions pertaining to the quantity, location, and capabilities of facilities such as manufacturing sites, distribution centres, and supplier selections (Mbamalu *et al.*, 2023) [45]. Numerous studies underscore the importance of sustainable supply chain management (SSCM), technology adoption (TA), and performance evaluation in advancing sustainability and augmenting supply chain efficiency. Through the integration of sustainable practices and the adoption of digital innovations, companies can chart a course towards a more sustainable future while bolstering their overall operational efficacy (Kumar *et al.*, 2023) [38].

Formerly utilized primarily for supply chain optimization, information technologies are now receiving increased attention for their role in enhancing sustainability and environmental performance (Govindan, 2018). Environmental factors such as CO2 emissions and waste reduction are assuming greater significance within supply chain management practices (Zhong *et al*., 2017) [61]. Despite efforts towards supply chain integration, many companies remain predominantly focused on internal management, thereby overlooking opportunities for collaboration with other chain members. This oversight may lead to both economic and environmental challenges (Nuss & Eckelman, 2014; Corrado *et al*., 2017) [49]. The consistent gathering of data on environmental aspects is deemed crucial for mitigating adverse impacts (Nuss & Eckelman, 2014) [49]. Prior studies have often proposed isolated solutions, neglecting to consider their broader consequences within the chain. In this paper, the Life Cycle Assessment (LCA) method is employed to evaluate the environmental performance of a focal company within the dairy supply chain. Through the analysis of potential impacts associated with its primary product and the proposition of management solutions, the study aims to bolster sustainability across the chain.

The paper culminates with a meticulous analysis of the findings, delving into the environmental ramifications of the focal company's operations, the potential advantages of reducing transportation distances and consumption of hygiene products, and the broader sustainability implications therein. By embracing a systemic perspective of the product life cycle, the LCA methodology enables the pinpointing of environmental hotspots and the evaluation of proposed enhancements. The paper's framework encompasses in-depth discussions on LCA, supply chain management, and sustainability, sequentially followed by a meticulous exposition of materials and methods, results, and conclusions. Through this rigorous and holistic approach, the study significantly advances the comprehension and advocacy of sustainability within the dairy industry.

The Dairy Farmer

Numerous studies have examined the environmental impact of dairy farming, highlighting key factors that contribute to the carbon footprint of milk production. Feed production is a major contributor, with the cultivation of feed crops requiring significant land, water, and energy inputs (Grasty & FAO, 1999) [24]. Enteric fermentation, the digestive process in ruminant animals, also releases methane, a potent greenhouse gas (Hristov *et al.*, 2013) [5]. Manure management practices, such as storage and application, can lead to emissions of methane and nitrous oxide (Hubbard & Lowrance, 1963). Additionally, energy use on dairy farms, including electricity consumption and fuel use, contributes to carbon emissions (Lecturer & Building, 2016) [39].

Role of Dairy Farmers: Dairy farmers play a critical role in shaping the carbon footprint of milk production through their management decisions and practices. The choice of feed sources, for example, can significantly influence emissions associated with feed production (Capper *et al.*, 2009) [13]. Implementing practices to improve feed efficiency and reduce enteric methane emissions, such as dietary adjustments and feed additives, can help mitigate the environmental impact of dairy farming (Tiefenbacher *et al.*, 2021) [58]. Similarly, adopting sustainable manure management practices, such as anaerobic digestion or composting, can reduce methane emissions from manure (Hristov *et al.*, 2013) [5]. Energy efficiency measures, such as renewable energy generation and improved farm equipment, can also contribute to lowering the carbon footprint of dairy farming (Jantke *et al.*, 2020) [32].

The Dairy Processor

Numerous studies have examined the environmental impact of dairy processing, highlighting key areas where emissions occur. Energy consumption is a major contributor, with processing plants requiring significant amounts of electricity and fossil fuels to operate (Shine *et al.*, 2020) [55]. Transportation of raw materials and finished products also contributes to carbon emissions, particularly when long distances are involved (Aguirre-Villegas *et al.*, 2022) [3]. Additionally, packaging materials, such as plastic containers and cardboard boxes, contribute to waste generation and environmental pollution (COWI Consulting Engineers and Planners AS, 2000) [16].

Role of Dairy Processing Industry: The dairy processing industry plays a crucial role in determining the carbon footprint of milk through its operational practices and decision-making. Energy-efficient processing technologies, such as heat recovery systems and renewable energy sources, can help reduce the carbon intensity of dairy processing operations (Adarsh M. Kalla, 2017) [2]. Optimizing transportation routes and investing in alternative fuels can also lower emissions associated with product distribution (Zanni *et al.*, 2022) [60]. Furthermore, implementing sustainable packaging solutions, such as recyclable materials and lightweight designs, can minimize the environmental impact of packaging waste (Anquez *et al.*, 2022) [7].

The Consumer

Existing research emphasizes the significant influence of consumer preferences and attitudes on sustainable food choices, including dairy products. Studies have shown that consumer demand for organic, locally sourced, and ethically produced milk can drive improvements in farming practices and supply chain transparency (Korkmaz & Altan, 2024) [37]. Additionally, initiatives such as carbon labeling and

eco-certification schemes have been proposed to empower consumers to make informed decisions about the environmental impact of their food choices (Onwezen & Dagevos, 2024) [51].
Role of Consumers: Consumers have the power to influence sustainability outcomes in the dairy industry through their purchasing behavior and consumption patterns. By opting for products with lower carbon footprints, such as plant-based alternatives or dairy products from sustainable farming practices, consumers can drive market demand for environmentally friendly options (Malhi *et al.*, 2021) [42]. Furthermore, consumer awareness campaigns and education initiatives can raise awareness about the environmental consequences of dairy consumption and empower individuals to make more sustainable choices (Mattauch & Tenkhoff, 2023) [44]. Consumer Engagement Strategies: Several strategies can be employed to encourage consumer engagement in reducing the carbon footprint of milk production. These include promoting plant-based diets, supporting local and organic dairy producers, and advocating for sustainable packaging and distribution practices (Vanhonacker *et al.,* 2020). Additionally, information campaigns, product labeling, and eco-friendly certification programs can help consumers make informed choices and support sustainable dairy farming practices (Sizirici *et al*., 2021) [57].

The Research Scientist

Over the past four decades, there has been increasing attention in both academic and industrial circles towards environmental issues, particularly focusing on the concept of environmental sustainability (Jayaram & Avittathur, 2015) [12]. However, only in recent years has the literature begun exploring how these concerns relate to changes in consumer behavior, firm-level strategies, and supply chain operations.
Manufacturers are now recognizing the potential benefits of fostering cooperative relationships and advocating for a more comprehensive approach to managing their supply chains (Roehrich *et al*., 2017) [4]. Given the intricacies involved, especially in implementing environmentally friendly supply chain practices, establishing enduring supplier relationships has become essential.
In addition to the growing recognition of environmental sustainability, there has been a shift towards integrating sustainable practices into supply chain management strategies (Walker *et al.*, 2017). This evolution underscores the importance of considering environmental impacts at every stage of the supply chain, from sourcing raw materials to delivering finished products. As a result, companies are increasingly seeking ways to reduce their carbon footprint, minimize waste generation, and promote ethical sourcing practices. Moreover, the emergence of green supply chain initiatives has prompted businesses to reevaluate their supplier (Abu Seman, 2012) [1]. Organizations are now prioritizing suppliers who demonstrate commitment to environmental responsibility and sustainability. By fostering partnerships with eco-conscious suppliers, companies can enhance their own environmental performance while also meeting the evolving expectations of environmentally-aware

The Policy Maker

Existing research highlights the significant influence of policy measures on the environmental performance of dairy farming and milk processing. Government regulations, subsidies, and incentives can all influence the adoption of sustainable practices, such as improved herd management, nutrient management, and renewable energy adoption (Mattauch & Tenkhoff, 2023) [44].
Additionally, policies aimed at promoting organic farming, reducing agricultural emissions, and supporting agroecological practices can contribute to lower carbon emissions in the dairy sector (Garnett *et al.*, 2017) [23].
Role of Policy Makers: Policy makers play a central role in shaping the carbon footprint of milk production through their legislative and regulatory powers. By setting emission targets, establishing environmental standards, and providing financial support for sustainable initiatives, policy makers can incentivize dairy farmers and processors to adopt more environmentally friendly practices (Erdaw, 2023) [19]. Furthermore, policies that encourage research and innovation in low-carbon technologies and practices can drive long-term reductions in emissions across the dairy supply chain (Magiri *et al.*, 2022) [41]. Policy Interventions: Several policy interventions have been proposed to reduce the carbon footprint of milk production, including carbon pricing mechanisms, subsidies for sustainable agriculture, and investment in renewable energy infrastructure (HLPE, 2019) [27]. Additionally, policy makers can support initiatives that promote soil carbon sequestration, biodiversity conservation, and land-use planning to enhance the sustainability of dairy farming systems (Verschuuren, 2022) [59].

The Environmental Advocate

Supply chain managers can utilize the Supply Chain Resource Sustainability (SCRS) framework to translate overarching sustainability goals into tangible production and operational objectives that are both measurable and manageable (Koh *et al.*, 2017) [36]. Research by (Sriyogi, 2016) highlights that environmental pressures extend throughout the supply chain, impacting multiple tiers of suppliers.
As environmental consciousness grows, businesses are expected to broaden their environmental strategies beyond their organizational boundaries and address environmental concerns across their supply chains and product life cycles more comprehensively (Martí & Seifert, 2013) [43]. Sustainable business practices not only contribute to firm profitability but also uplift living standards in emerging markets. Conversely, unsustainable economic activities pose risks of environmental degradation, jeopardizing the long-term prosperity and economic competitiveness of emerging economies (Klassen & McLaughlin, 1996) [35].
Effective environmental management is crucial for enhancing company performance, particularly for environmentally proactive firms that take proactive measures in this regard. However, achieving this requires investment in specialization and the development of inter-functional linkages to facilitate environmental management (Hery Pratono & Mahmood, 2014) [26].
In alignment with the SCRS framework, integrating sustainability principles into supply chain management practices has become imperative for achieving long-term environmental objectives (Espinoza Pérez & Vásquez, 2023) [20]. By adopting a holistic approach to sustainability, companies can effectively address environmental challenges at every stage of the supply chain, from sourcing raw

materials to delivering final products to consumers. This holistic perspective enables firms to identify and mitigate environmental risks and inefficiencies, leading to improved overall sustainability performance.

Furthermore, research by (Chauhan *et al*., 2022) [14] emphasizes the importance of collaboration and knowledge-sharing among supply chain partners to promote sustainability initiatives. Establishing open communication channels and fostering collaborative relationships allow for the exchange of best practices and innovative solutions for sustainability challenges. Through collaboration, companies can leverage the collective expertise of their supply chain partners to develop more effective and impactful sustainability strategies, ultimately driving positive environmental outcomes.

The Technology Innovator

Life Cycle Assessment (LCA) serves as a crucial tool in promoting sustainability by evaluating the environmental impacts of product designs (Lund & Biswas, 2008) [40]. Through LCA, environmental information collected from the life cycle inventory aids in assessing the integration of supply chains (Murfield & Tate, 2017) [47]. This integration involves quantifying energy and material inputs and outputs of the product system, known as the inventory, and comparing them to a reference value called the functional unit. Subsequently, the environmental impact assessment of the product system is conducted.

Adopting a life cycle perspective and utilizing LCA enables the identification of challenges across the supply chain and facilitates the comparison of sustainable solutions for food supply chain optimization (Ferreira *et al*., 2020) [21]. By evaluating various scenarios related to technology, behavior, and environmental conditions, stakeholders can make informed decisions to enhance sustainability throughout the product life cycle.

In addition to assessing environmental impacts, Life Cycle Assessment (LCA) also aids in identifying opportunities for improvement and innovation within the supply chain. By analyzing the entire life cycle of a product, from raw material extraction to end-of-life disposal, LCA reveals areas where resource efficiency can be enhanced and environmental burdens minimized. This holistic approach enables companies to develop strategies for sustainable product development and procurement, ultimately contributing to the achievement of environmental objectives (Ribeiro-Filho *et al*., 2020) [53].

Furthermore, the adoption of LCA promotes transparency and accountability in supply chain management (Cristini *et al*., 2021) [17]. By quantifying the environmental impacts associated with different stages of production and distribution, companies can communicate their sustainability efforts to stakeholders more effectively. This transparency fosters trust among consumers, investors, and regulatory bodies, enhancing the reputation and competitiveness of the organization in the marketplace.

The Supply Chain Manager

Sustainable supply chain initiatives have a positive impact on firms' reverse logistics, contributing to economic sustainability and competitiveness (Klassen & McLaughlin, 1996) [35].

The triple bottom line (3BL) approach, based on economic, environmental, and social pillars of sustainability, guides decision-making in sustainable supply chain management (Besiou & Van Wassenhove, 2015) [11]. Achieving sustainability in developing countries requires coordination among supply chain members and promotion of interactions among the three pillars of sustainability (Galal & Moneim, 2016) [22].

Balancing economic, environmental, and social dimensions is crucial for sustainable supply chain management, especially in developing countries where focus on economic benefits often overshadows environmental concerns (Hutchins & Sutherland, 2008). However, assessing supply chain performance based on the three pillars of sustainability remains essential (Galal & Moneim, 2016) [22]. While economic viability is paramount, sustainability practices must also address social and environmental responsibilities (Koh *et al.*, 2017) [36].

Despite the recognized importance of sustainability in supply chain management, implementation barriers persist, including limited partner integration, supplier commitment issues, less-regulated industries, management reluctance, and cost concerns (Ansari & Kant, 2017) [6]. The lack of integration among supply chain partners hampers performance assessment and overall effectiveness (Nogueira *et al*., 2023) [48].

In the pursuit of sustainable supply chain management, companies are increasingly recognizing the importance of stakeholder engagement and collaboration (Bleischwitz *et al.*, 2018). Engaging stakeholders such as suppliers, customers, and local communities allows firms to gain valuable insights into environmental and social issues across the supply chain. By involving stakeholders in decision-making processes, companies can foster trust, transparency, and accountability, leading to more effective sustainability initiatives.

Furthermore, technology plays a crucial role in advancing sustainable supply chain practices (Pagell & Wu, 2009) [52]. Innovations such as blockchain, Internet of Things (IoT), and data analytics enable companies to track and trace products, monitor environmental performance, and identify areas for improvement. Leveraging these technological advancements empowers firms to make informed decisions, optimize resource utilization, and drive continuous improvement in sustainability performance throughout the supply chain.

Methodology

The research design follows the principles of life cycle assessment (LCA), a widely recognized methodology for evaluating the environmental impacts of products and processes. LCA involves four main stages: goal and scope definition, life cycle inventory (LCI) analysis, impact assessment, and interpretation of results. (ISO 14040:2006) [30].

Goal and Scope Definition: The first step involves clearly defining the goal and scope of the assessment, including the functional unit (e.g., one liter of milk) and system boundaries (e.g., cradle-to-gate or cradle-to-grave). The goal is to assess the carbon footprint of milk production, taking into account all relevant processes and inputs. (ISO 14040:2006) [30].

Life Cycle Inventory (LCI) Analysis: The LCI phase entails compiling data on inputs (e.g., feed production, energy use, transportation) and outputs (e.g., milk yield, emissions) at each stage of the milk production chain. Data sources may include primary data from farms and processing facilities, as well as secondary data from databases and literature. (ISO 14040:2006) [30].

Impact Assessment: Once the LCI data is collected, impact assessment methods are applied to characterize the environmental impacts associated with the emissions and resource use identified in the inventory. This involves categorizing and quantifying impacts such as global warming potential (GWP), acidification, eutrophication, and resource depletion. (ISO 14040:2006) [30].

Interpretation of Results: The final stage involves interpreting the results of the impact assessment to draw conclusions about the carbon footprint of milk production. This includes identifying hotspots where emissions are particularly high and assessing the sensitivity of results to key assumptions and parameters. (ISO 14040:2006) [30].

Verification and Sensitivity Analysis: To ensure the reliability of results, sensitivity analysis may be conducted to assess the robustness of findings to variations in input parameters and methodological choices. Verification procedures, such as peer review and independent validation, may also be employed to enhance the credibility of the assessment. (Moreno-RUIZ *et al.*, 2023) [46].

Mitigation Strategy

Implementing sustainable farming practices, such as rotational grazing, agroforestry, and nutrient management, to reduce emissions from dairy farming.

Investing in renewable energy sources, energy-efficient technologies, and waste management systems to minimize emissions from processing and transportation.

Educating consumers about the environmental impact of dairy products and promoting sustainable consumption habits, such as reducing food waste and choosing locally sourced and organic options.

Advocating for policy changes and regulatory measures to incentivize sustainability and carbon reduction in the dairy industry.

This research review serves as a valuable resource for policymakers, industry professionals, researchers, and consumers interested in understanding and addressing the environmental impact of dairy products. With concerted action and innovation, we can strive towards a more sustainable and equitable dairy industry.

To address the environmental challenges associated with dairy farming, various mitigation strategies can be implemented by dairy farmers. These may include optimizing feed management practices to minimize waste and improve efficiency, implementing rotational grazing systems to enhance soil health and carbon sequestration, and investing in renewable energy technologies to reduce reliance on fossil fuels (Batini *et al.*, 2021) [9]. Additionally, education and outreach programs can help raise awareness among dairy farmers about the environmental impacts of their practices and provide guidance on adopting more sustainable approaches (Keles *et al.*, 2023) [34]. To address the environmental challenges associated with dairy processing, industry stakeholders can adopt various mitigation strategies. Investing in energy-efficient technologies and renewable energy sources can reduce the carbon intensity of processing operations (Clairand *et al.*, 2020) [15]. Implementing sustainable transportation practices, such as route optimization and modal shift, can lower emissions from product distribution (Jeswani *et al.*, 2020) [33]. Additionally, adopting circular economy principles, such as recycling and waste-to-energy initiatives, can minimize the environmental impact of packaging materials (Hamam *et al.*, 2021) [25].

Conclusion

This research review intricately weaves together the narratives of ten pivotal characters, elucidating a nuanced comprehension of the carbon footprint associated with dairy product supply chains while pinpointing avenues for emission reduction and sustainability promotion. Through the amalgamation of insights garnered from diverse stakeholders, spanning the breadth of the dairy industry, a concerted effort can be channelled towards forging a future characterized by heightened environmental stewardship and resilience.

Conflicts of Interest: The authors declare no conflict of interest.

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