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Carbon Neutrality

REVIEW **Open Access**

Towards decarbonizing the supply chain of dairy industry: current practice and emerging strategies

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Abstract

The food supply chain is currently challenged by the imperative to sustainably feed the increasingly expanding population while simultaneously striving to meet global net-zero emission targets. The dairy sector is widely considered as a carbon-intensive industry, contributing to significant greenhouse gas (GHG) emissions thereby exacerbating global warming. Here, we first summarize recent studies on determining GHG emissions of various dairy products, which suggests that farms are the primary emission hotspots in the dairy supply chain. Next, the vital role of novel techniques and emerging strategies to reduce carbon emissions in the dairy industry is emphasized at both local- and systematic levels. The implementation of targeted techniques at each stage, along with policy initiatives such as carbon pricing, plant-based alternatives, international standards and clean air act, play a vital role in establishing global optimization to mitigate climate warming. Despite these progresses, standards and guidelines of emission reduction for the dairy industry are currently lacking, which calls for continuous efforts to fill the gap.

Keywords Dairy supply chain, Carbon emission, Greenhouse gas, Life cycle assessment, Sustainability, Climate change

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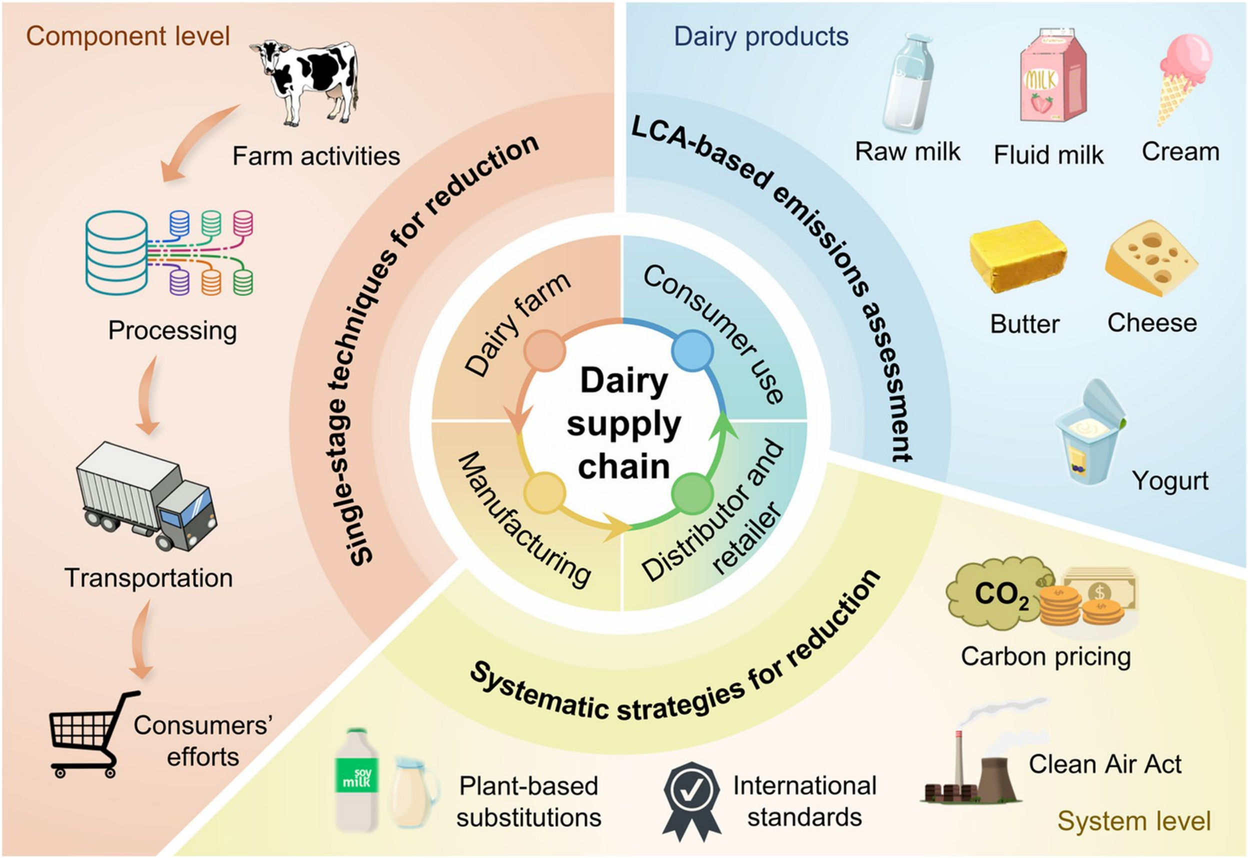
Graphical Abstract



1 Introduction

The sustainability of current food industry stands at a critical juncture, facing unprecedented environmental challenges driven by population growth, dwindling arable land, escalating food and energy demand, and the burgeoning aspirations for nutritional well-being [1]. Strikingly, it is predicted that an additional 70% of the food production will be required to feed the projected global population of 9 billion by 2050 [2, 3]. The anticipated growth in food demand inevitably leads to a significant increase in energy consumption as well as carbon emissions in the food industry. Meanwhile, the increase in resource-intensive and animal-based diets is likely to further strain the global carbon budget [4]. Previous studies have suggested that without effective measures to achieve near "net-zero" emissions, global climate change will be further worsened, leading to multiple climate disasters and severe challenges to food security, even to human survival [5, 6]. Thus, mitigating emissions across the food supply chain from production to consumption is imperative to curbing global warming and achieving climate targets.

The dairy sector, as one of the most carbon-intensive industries, plays a pivotal role in environmental impact worldwide. Dairy products have historically been recognized as a valuable nutritional resource with proteins, fatty acids and micronutrients, which are deemed essential for maintaining a well-balanced diet [7]. In 2022, world milk production increased to 937.3 million tonnes and the exports were 84.7 million tonnes (9% of milk produced) [8]. Consequently, the ongoing growth in production and trade has raised apprehensions about the accompanying higher greenhouse gas (GHG) emissions [9]. Specifically, milk exhibits a higher carbon footprint (CF), with the highest number of global warming potentials (GWP) values ($n=262$) identified from all food categories [10, 11]. It had been reported that dairy accounted for 36% of the increase in global animal-based emissions, amounting to 2.8 Gt CO_2 equivalents (CO_2-eq) in 2019 [4]. Moreover, ruminant production systems employed in milk production have been pinpointed as significant sources of anthropogenic GHG emissions and major drivers of global warming and climate change [12]. Besides, the production of dairy products impacts the environment in various ways, including global warming, water eutrophication, land use and biodiversity loss [13]. Facing local and global pressures, how to meet the growing global demand for dairy products while minimizing irreversible environmental damage is thus one of the urgent issues for the dairy industry.

In this review, we comprehensively overview important work on decarbonization of the dairy supply chain. We first identify key emission spots at each stage across the supply chain from a life cycle perspective. Further, we present effective techniques as well as current practice and emerging strategies for reducing carbon emissions in the dairy industry. Finally, we put forward and highlight future research directions towards a more sustainable, resilient, extensive and low-carbon global dairy supply chain. While extensive studies have been conducted on carbon emissions from the dairy industry, to our knowledge, holistic reviews on current efforts aimed at reducing carbon emissions in the dairy industry are lacking yet. This review addresses this gap by emphasizing the role of innovative single-stage techniques and emerging systematic practices for emission reduction. It also offers an integrative view of the challenges and opportunities in reducing emissions across the dairy supply chain, thereby promoting a deeper understanding of decarbonization towards the dairy industry.

2 Systematic review methodology

A systematic search strategy was conducted by accessing data from the electronic database Web of Science. The aim of this systematic search is to identify the carbon emission hotspots within the dairy supply chain. The combinations of the following keywords were used: ("dairy industry" AND "life cycle assessment") OR ("dairy supply chain" AND "life cycle assessment"). In addition, the articles were selected following the criteria including being consistently in English, available as open access, and recently published (from 2014 to 2025). The article screening and selection process was shown in Fig. 1.

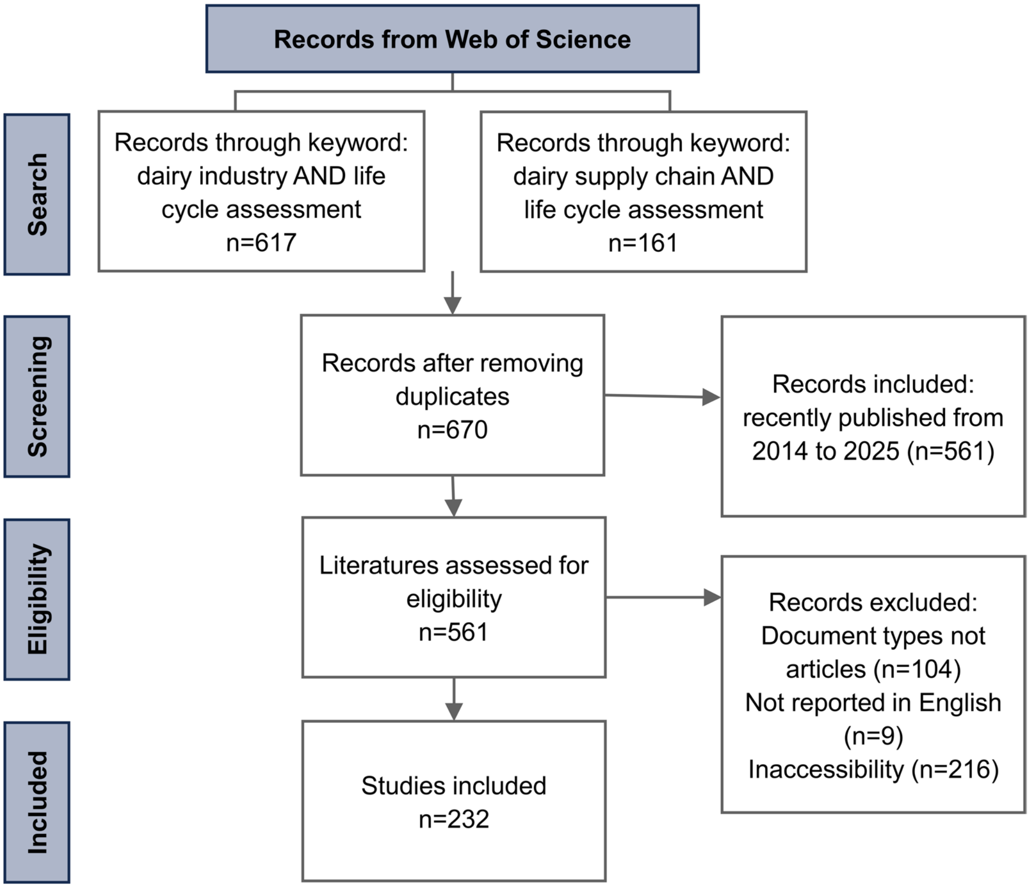


Fig. 1 PRISMA flow diagram summarizing the literature search strategy used in this review

3 Carbon emissions in dairy supply chain

Multiple studies have been conducted in the last years to investigate the decarbonization processes of different foods based on their supply chains, such as fresh vegetables [14], fresh fruits [15], staples [16], dairy [17], non-ruminant and ruminant livestock [18]. Among them, dairy products, standing as one of the most common and valuable agricultural commodities, exhibit a high GHG emission and therefore are of significance to be comprehensively discussed.

3.1 Dairy supply chain

The dairy supply chain encompasses a series of interrelated stages from farm (where raw milk is produced) to fork (where dairy products are used), which can be divided into four major stages: dairy farm, manufacturing, distributor and retailer and consumer use. As shown in Fig. 2, specific processes that took place in these four stages are summarized, and the carbon emissions that can be generated in dairy life cycle are further outlined.

Carbon or GHG emissions often strongly correlate with energy consumption. Thus, considering dairy as an important energy consumer, the carbon emissions at each stage of dairy supply chain can be speculated from the energy consumption levels. For instance, Malliaroudaki et al. provided an energy map for broadly estimating energy use along the dairy supply chain [19]. The average energy use on conventional dairy farms was estimated as high as 4.1 MJ/kg of energy-corrected milk (standardizes any milk to the caloric equivalent of milk with 3.5% fat and 3.2% protein content), which indicates that the dairy farm may be the hot emission spot. They also developed a flexible energy use model for sustainable dairy manufacturing and distribution, highlighting transportation, heat treatment, and cleaning-in-place processes as energy hotspots in the comprehensive net-zero roadmap analysis [20]. Nevertheless, there are significant carbon emissions not associated with energy usage (e.g., gases emitted by cattle), which should not be overlooked. It is estimated that enteric methane (CH_4) contributes approximately 70% of total GHG emissions from livestock [21]. However, there is currently a lack of research focusing on carbon emissions unrelated to energy usage. For this purpose, more scientific and applicable approaches for calculating dairy carbon emissions are urgently needed.

3.2 Carbon emissions assessments of dairy supply chain

Assessing carbon emissions in the dairy supply chain is crucial for identifying opportunities to reduce environmental impact. In the dairy industry, the primary gases targeted for emission reduction include methane (CH_4), nitrous oxide (N_2O), carbon dioxide (CO_2), and fluorinated gases, which trap heat in the atmosphere. Generally, CO_2-eq is commonly used as the metric for measuring carbon emissions, which combines the warming potential of various GHG into a standardized unit based on the GWP values. Several methods have been employed to evaluate GHG emissions in dairy sector, such as life cycle assessment (LCA) [22], multi-regional input–output analysis [23], and physical trade flow accounting [4]. Particularly, LCA is the most commonly used method for environmental assessment typically recommended by international institutions, such as the European Commission and the United Nations Environment Programme, to support policy-making for

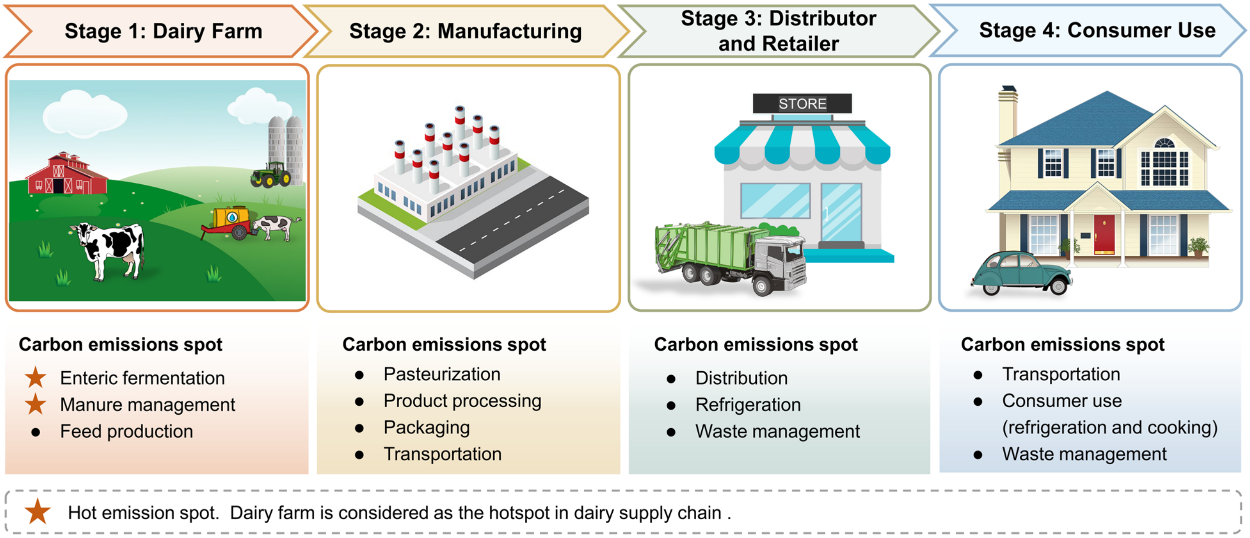


Fig. 2 Illustration of carbon emission spots across the dairy supply chain

sustainability by quantitatively assessing the environmental impacts during the entire life cycle of a product. As a result of systematic searching, the publications of the included studies on the period from 2014 to 2025 (February) contain 232 publications. There has been a growing trend in the number of publications over the years, primarily published on the JOURNAL OF CLEANER PRODUCTION and SUSTAINABILITY (Fig. 3). In the following, the recent LCA studies in the dairy industry are summarized in detail. Recent studies on the assessment approaches for GHG emissions of dairy production and their key findings are summarized in Table 1.

3.2.1 LCA analysis for raw milk

As reported, raw milk production is the most significant contributor to the overall environmental impact associated with dairy products [24, 29]. Approximately 90% of GHG emissions within the dairy product supply chain originate from cradle-to-farm gate subprocess [30]. It can be stated that the level of carbon emissions from raw milk determines that of derived dairy products. Wherein, dairy farm activities serve as the carbon emission hotspots in the supply chain of raw milk. This common consensus has been reached irrespective of the diverse raw milk production systems (organic/non-organic/mixed, confined/semi-confined feedlot or pasture-based grazing), the dairy farm characteristics and the methodological choices made by LCA practitioners [31–33]. In this respect, farm-related processes such as animal-related activities (enteric fermentation, manure management) and feed production (fertilization, transport and processing) represent hotspots for improvement as previously mentioned [34–36]. In detail, around 55% of GHG emissions come from enteric fermentation, 20% from manure management and 15% from feed production [37].

3.2.2 LCA analysis for dairy products

The downstream of raw milk are dairy products. Since the 1990s, various LCA case studies have been conducted on them, including fluid milk [38], cheese [39], yogurts [40], butter [41], and milk powder [42]. As previously mentioned, dairy farms are widely recognized as the primary source of GHG emissions throughout the entire dairy supply chain. For instance, around 80% of the CF for full-fat cheese occurs from raw milk production in a cradle-to-retail store study [26]. Systematically, Clune et al. reviewed the GHG emissions of 90 LCA studies in dairy category that generated 341 GWP values [10]. Among them, yogurt, cream, cheese and butter showed ascending median values, reaching 1.31, 5.64, 8.55, and 9.25 kg CO_2-eq/kg, respectively. Interestingly, it also stated that almond and soy milk, as two plant-based milk alternatives, demonstrated lower median GWP values (0.42 and 0.75 kg CO_2-eq/kg) than animal-based milk (1.29 kg CO_2-eq/kg). This may serve as evidence supporting the debate whether plant-based dairy alternatives would be potentially superior to traditional animal-based dairy products from the “low-carbon” aspect.

4 Single-stage techniques and strategies for reducing GHG in dairy industry

Since climate change is the most paramount global concern currently [43], substantial efforts have been devoted to mitigating carbon emissions in the dairy industry, which can be delineated into two facets: i) at the component level, novel techniques and strategies that can reduce emissions at individual stages of the dairy supply chain and ii) at the system level, focusing on holistic improvements throughout the entire dairy supply chain (i.e. global optimization). Herein, novel techniques and

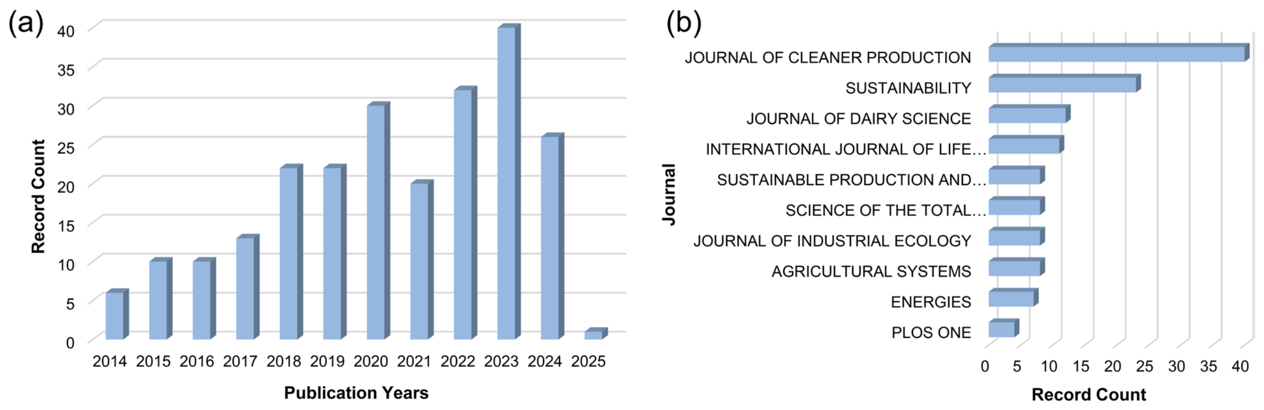


Fig. 3 **a** Year-wise distribution and (**b**) the top 10 journals with the most publications in the past decade

Table 1 Recent studies on carbon emission assessment of dairy products

Product	Geographical location	System boundaries	Data sources/LCA tools	Key findings	Reference
Raw milk	Asturias (Spain)	Cradle to farm gate	Real data/SimaPro	The CF of milk is mainly influenced by the cattle feeding system and cow emissions, while it is 1.22 and 0.99 kg CO_2-eq kg_{FPCM}^{-1} in semi-confinement and pasture-based dairy farms	[24]
Yogurt, butter and cheese	the Eastern Alps	Cradle to dairy gate	Real data/CML-IA and SimaPro	Yogurt, cheese and butter show ascending mean GWP values, reaching 1.5, 4.3–11.7, and 15 kg CO2-eq/kg. Dairy farm phase is the emissions hotspot. Milk yield、stocking rate and concentrate percentages are the key farm management features	[25]
Cheese	NW Spanish region	Cradle to retail stores	Real data and reference data/SimaPro	The CF of 1 kg cheese is 10.2 kg CO_2-eq. Raw milk production and cheese composition are the main factors influencing CF, while the scale of production has a negligible effect	[26]
Cheese, high-quality milk and UHT milk	Po Valley-Northern Italy	Cradle to distribution center gate	Real data /PMT_01	PMT _ 01 is developed, and it is found that most of the environmental impacts are mainly related to raw milk production, while only a few of the impact categories are significant in the dairy factory process	[13]
Dulce de leche, yogurt, milk, butter, cheese, cheese spread	Minas Gerais (Brazil)	Cradle to farm gate	Real data and reference data /SimaPro	The production of cheese has the greatest impact on the environment, and the production of raw milk is identified as the most critical part of the environmental impact in dairy production, followed by energy and packaging	[27]
Reggiano and soft cheese	Emilia Romagna (Italian)	Cradle to farm gate	Real data and reference data /Simapro	The diesel consumption of agricultural machinery and the production of plastic packaging have the most prominent impact on the environmental impact of dairy production, rather than the energy consumption, packaging and animal feed	[28]

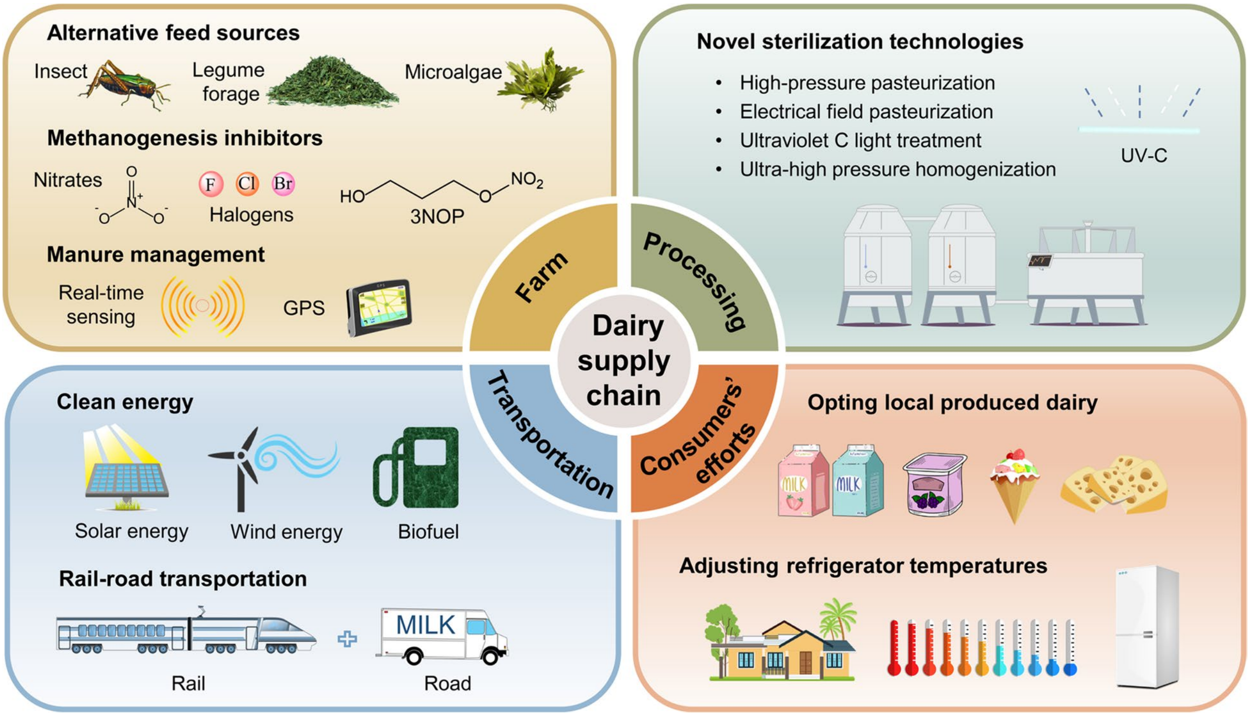


Fig. 4 Carbon reduction techniques for different dairy supply chain stages

recommended practices at the component level, namely at each stage of the dairy supply chain, will be first discussed (Fig. 4).

4.1 Farm stage

The farm stage has long been regarded as a hotspot for carbon emissions in the dairy supply chain, which contributes approximately 80%~90% of the total carbon emissions across the dairy supply chain [44]. In this respect, targeted efforts can be employed to reduce both feed production and animal-related emissions.

4.1.1 Exploring alternative feed sources

Feed production is a primary driver of environmental impact in traditional livestock systems, and replacing conventional feed with more environmentally friendly ingredients is an effective method for improving feed quality. In this respect, novel insect feed is a high-quality protein and energy source, which can provide environmental benefits including land use reduction, waste valorization, and mitigation of resource depletion [45]. For example, larval meals from black soldier fly (BSF) offer a promising alternative protein supplement for cattle [46], boasting a protein content comparable to soybean meal. It has been found that 1 kg of BSF protein meal had an average GHG reduction effect of 1.19 kg CO_2-eq/kg during production [47]. Additionally, a GWP decreases by 61% when comparing housefly meal to a 50:50 mixture of fish and soybean meal [48]. Regarding the financial aspect, insect-based feed is reported more costly to procure compared to soybean meal [49]. However, Abro Zewdu et al. highlighted the considerable potential economic benefits of insect-based feed, with a benefit–cost ratio estimated at 28:1 under optimal conditions and still maintaining a high ratio of 8:1 in the worst-case scenario [50]. Currently, some insects are already being authorized for the production of animal feed (Regulation (EU) 2017/893 and Regulation (EU) 2021/1372) but only restricted to feed for aquaculture, pigs, and poultry. With increasing scientific evidence supporting the safety of insect-based feed, there is potential to further ease current restrictions on its use in ruminant diets. In other aspects, a nutritionally equivalent mixture of sunflower seed and faba beans replaced solvent-extracted soybean meal can result in an average reduction of 42% in GHG emissions [51]. The addition of dietary fats to silage and the utilization of legume forage can also reduce methane emissions from livestock [52–54]. Recently, microalgal-based feed has been employed in dairy ruminant nutrition owing to the environmental benefits and shows the capacity to improve milk quality and production yield [55]. It exhibits lower production costs and wider applicability as a feed additive in ruminant farming compared to insect-based feed [56]. Numerous studies have demonstrated the positive impact of microalgal-based feed in reducing methane emissions from ruminants [57–59]. However, it should be considered that the supplementation of microalgae in ruminant diets may result in reduced intake due to the unfavorable flavor of feed in the practical application. Noticeably, Smetana et al. reported that the use of microalgae as concentrated protein powder for animal feed was not more environmentally friendly than plant-derived sources [60]. Given this, further comprehensive work is needed to evaluate and compare the carbon emissions and environmental benefits as well as the practical and financial constraints of microalgae feed, animal feed, and plant feed.

4.1.2 Application of methanogenesis inhibitors

Feed additives have been investigated as a practical dietary control strategy in ruminant animals, aiming to mitigate enteric methane emissions by either inhibiting methane production or altering the rumen environment [61, 62]. It acts directly on the methane generation pathway, hindering methanogenesis through the biosynthesis inhibition of methyl-coenzyme M reductase enzyme (e.g., 3-nitrooxypropanol (3NOP) and halogens), or competing with methanogens for hydrogen, thereby reducing CH_4 emissions (e.g., nitrates). In detail, it showed that feeding lactating cows 3NOP at a rate of 0.04–0.08 g/kg DM reduced methane production by 30%, with no impact on feed intake and milk production [63]. In lactating dairy cattle, Roque et al. found that the inclusion of seaweed (*Asparagopsis armata*, which contained relatively high concentrations of halogens) at a rate of 18.3 g/kg DM (10 g/kg of OM) led to a reduction in methane intensity up to 67.2% (g/kg milk produced) [64]. Besides, the addition of nitrates to ruminant diets also is an effective methane mitigation approach, but it is important to note that nitrites may accumulate in the bloodstream and be toxic to ruminants [65]. Thus, the adoption of nitrate as a methane mitigation strategy requires a careful evaluation of its environmental benefits with potential risks to animal health.

4.1.3 Efficient manure management

Manure management is identified as one of the critical hot spots for carbon emissions at the farm stage. In the USA, the choice of manure management was pointed out as a significant factor contributing to differences among five milk production regions [66]. In China, it has been reported that the implementation of a fully integrated approach, incorporating both solid and liquid animal manure recycling, led to reduced GHG emissions compared to semi-integrated approach, which solely reuses solid manure on farmlands [67]. Recently, with the development of emerging techniques for precision fertilization, manure management is entering the digital era. Noval techniques include real-time sensing of manure nutrients, measurement of solid manure density, generation of real-time soil maps, and integration with global positioning systems (GPS) and mapping systems, aiming to efficiently utilize manure nutrients and reduce excessive and inadequate applications [68]. The effectiveness and feasibility of manure management vary depending on regional contexts, farm scales, and technological capacities. In large-scale intensive farms, advanced digital techniques can greatly improve nutrient utilization efficiency and mitigate GHG emissions. However, the high initial investment and operational costs of these digital techniques may pose economic challenges for small-scale farms or resource-limited regions. In contrast, small-scale farms may rely on low-cost and easily implementable semi-integrated methods, although their emission reduction potential remains relatively limited. Therefore, developing region-specific manure management strategies that strike the balance between technological feasibility and economic viability is essential for achieving effective mitigation in the dairy industry.

4.2 Dairy processing stage

Dairy processing is an important stage within the dairy system. It is noteworthy that there exists a significant issue of milk wastage in the dairy supply chain, directly attributable to the total waste generated from milk processing and handling, which amounts to approximately 330,000 tonnes per year, with a value exceeding 150 million [69]. Interestingly, the "separator desludge" waste generated during milk processing is considered as a potential protein-rich resource by the Waste and Resources Action Programme (WRAP). It can be further processed into food or animal feed, thereby reducing waste by 10,000 tonnes and disposal costs by £1 million annually.

Additionally, novel emerging techniques in the dairy processing stage are offering environmental benefits owing to the improvement of energy efficiency, optimization of production processes, and implementation of renewable energy sources. Commercially sterilized milk employing novel nonthermal sterilization techniques, gained shorter processing durations, enhanced energy efficiency, elevated safety standards, and prolonged food shelf-life [70]. For instance, high-pressure pasteurization (HPP) can reduce cheese coagulation time and increase yield in cheese manufacturing, but may lead to whey protein denaturation at pressure levels between 200 and 600 MPa and higher capital investment [71]. In addition, electrical field pasteurization consumes significantly less energy (63%) than high temperature short time with a potential increase in milk shelf life by up to

15 days [72], which is energy-efficient and environmentally friendly but costly compared to thermal techniques [73, 74]. Meanwhile, ultraviolet C (UV-C) light treatment, another emerging method, involves exposing milk to short-wave light spanning from 200 to 280 nm to inactivate pathogenic microorganisms [75]. It can extend the shelf life of dairy products and maintain nutritional content and sensory characteristics [76, 77]. Moreover, ultra-high pressure homogenization (UHPH) utilizes dynamic pressures up to 400 MPa to reduce particle size in fluids and achieve microbial inactivation [78]. This technique enhances the quality and extends the shelf life of commercially sterile milk, with the added benefit of reduced energy consumption (achieving a CF reduction of up to 88%). It is important to note that emerging dairy processing techniques should account for the impact on the sensory properties and nutritional composition of dairy products to ensure the market acceptance facilitates practical application.

4.3 Transportation of dairy products

Transportation plays a crucial role in the life cycle of dairy products, particularly for perishable fresh dairy items that require controlled temperature conditions during transportation [19]. For this aspect, selecting appropriate transportation measures, such as utilizing clean energy, adopting higher-efficiency vehicles, and optimizing the distribution routes, will be an advantageous approach to emissions reduction [79]. Wherein, the innovative approach of intermodal rail-road transportation in milk delivery [80], exemplifying reduced carbon emissions potential, is gaining increasing advocacy. This method, typified by combining rail and road transport in the same unit, is considered one of the most effective tools to help reduce the environmental impact of the cold chain. It has been demonstrated to reduce pollution connected to CO_2, CO, NO_x, CH_4, and hydrocarbons by up to 77.4%, as compared to the use of road transport alone [81].

4.4 Consumers' efforts: adopting sustainable milk consumption practices

Finally, it should not be discounted that the milk supply chain involves over 6 billion consumers globally, highlighting the crucial role of consumer efforts in reducing carbon emissions. It is necessary to increase public environmental consciousness and encourage consumers to adopt sustainable milk consumption behaviors [73]. On the one hand, consumers can contribute to reducing carbon emissions associated with dairy products by opting for locally produced milk, which minimizes transport emissions and fossil fuel usage. On the other hand, adjusting refrigerator temperatures from 6.6 °C to below 5 °C at home can help mitigate milk waste. According to WRAP statistics [69], lowering refrigerator temperatures to below 5 °C could prevent over 50,000 tonnes/year of milk waste, leading to savings of £25 million. Although it may require more energy to run the fridge, the GHG savings from waste reduction could approximately offset the additional energy usage.

5 Systematic techniques and strategies for reducing GHG in dairy industry

Apart from controlling CF generated at individual stages of the dairy supply chain, holistic approaches and strategies for mitigating emissions across the entire dairy supply chain at the system level are also essential. In this regard, a series of policies and regulations have been enacted subsequently in the past three years to better support the application of these new techniques, further ensuring the successful implementation of emerging energy and/or emission reduction innovations.

5.1 Carbon pricing

Carbon pricing acts as a pivotal adjustment lever for reducing global carbon emissions. Specifically, it is a policy instrument used to capture the external costs of GHG emissions in the market, commonly in the form of a price on CO_2 [82]. The significance of carbon pricing is to help align economic incentives with environmental goals, driving the transition to a low-carbon economy. Generally, carbon pricing manifests in various forms, including direct mechanisms such as carbon taxes [83] and emissions trading systems (ETS) [84], as well as indirect methods like fuel taxes and commodity taxes. As of 2023, there were 73 carbon pricing mechanisms in operation globally, covering 23% of global GHG emissions according to the World Bank Group report [85]. As shown in Fig. 5, it can be found that most developed countries have implemented carbon pricing (especially carbon tax) at relatively high rates, while many developing countries have just begun to implement or are in planning.

5.1.1 Carbon pricing in major dairy producers

According to FAO statistics on the production of milk and milk products, India, the European Union (EU), the United States (US), China, Brazil, Russia, and New Zealand can be considered the major dairy-producing countries and organizations. For developed countries and organizations, the EU is the second-largest dairy producer as well as the largest exporter in the world. On the other hand, carbon pricing policies in the US vary significantly across states and local governments. The federal and state levels both implemented initiatives and programs aimed at reducing GHG emissions from agriculture, which indirectly influence carbon pricing in the

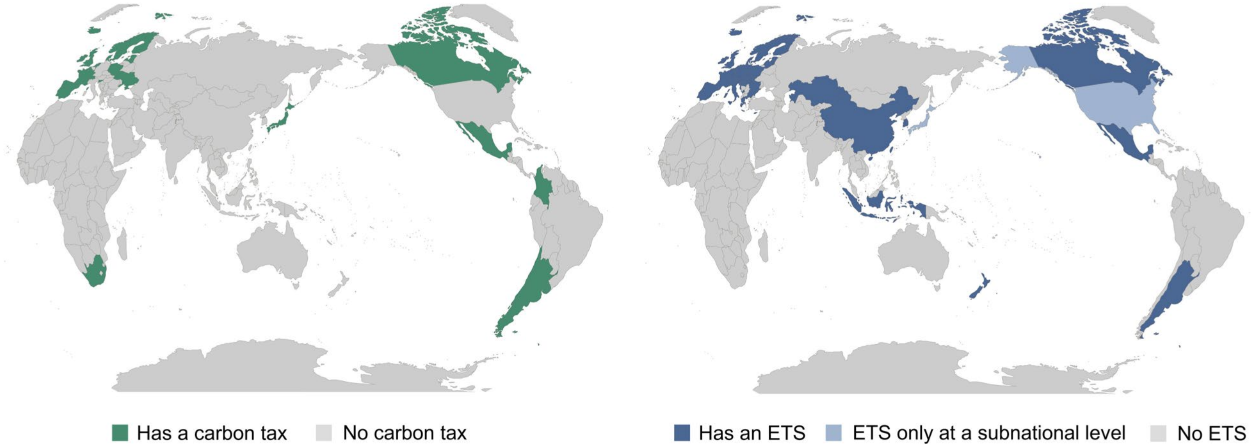


Fig. 5 Implementation of carbon tax (left) and ETS (right) in different countries. The data were obtained from the World Bank Group (last updated March, 31 2023) [86]

dairy sector. Besides, the Inflation Reduction Act was signed into law, incorporating the implementation of a methane emissions charge. For developing countries like India, being the largest dairy producer in the world, carbon pricing is a relatively novel idea, not yet widely adopted as a national policy. However, discussions and proposals have emerged regarding its potential implementation to tackle GHG emissions. China, as the largest dairy importer worldwide, launched its national ETS in 2021. In Brazil, the government created the National Greenhouse Gas Emissions Reduction System (Sinare). Concurrently, the Brazilian Congress discussed legislative proposals for an ETS, including a monitoring system for GHG emissions and a centralized registry for Brazilian GHG mitigation projects and their resulting carbon credits. In Russia, the approaches to carbon pricing have primarily focused on voluntary initiatives and pilot projects rather than comprehensive nationwide policies.

5.1.2 Impact of carbon pricing on dairy industry

Despite its short history, carbon pricing has already been shown to induce changes and reduce GHG levels in agricultural and food production systems [87]. Moreover, it creates a financial incentive for dairy industries and stakeholders to reduce their emissions. Higher carbon prices make carbon-intensive activities more expensive, prompting dairy businesses to invest in cleaner techniques, improve energy efficiency, and shift towards low-carbon alternatives. For consumers, higher carbon costs may drive individuals to reduce their emissions by selecting low CF dairy products and transportation, adopting energy-efficient smart refrigerators, and minimizing dairy consumption waste as much as possible. Nonetheless, related research has shown a low impact of carbon pricing on consumption changes [88]. Although increasing consumer environmental awareness is considered more challenging, positive changes in consumer behavior can make significant contributions to reducing emissions in the dairy supply chain.

5.2 Plant-based substitutions

In recent years, there has been an interesting debate about whether plant-based dairy products are better than traditional animal-derived dairy products. Emerging evidence has indicated that plant-based foods are more environmentally friendly as they require less water and land for production, resulting in a significantly reduced CF [89–91]. For example, Coluccia et al. evaluated the CF of the entire supply chain for both cow milk and soy beverages [17]. The results revealed that the CF of milk ranged from 0.99 to 1.08 kg CO_2-eq/L, whereas that of soy milk ranged from 0.51 to 0.52 kg CO_2-eq/L. Therefore, from an environmental perspective, soy beverages can serve as an effective low-carbon alternative to cow milk.

Nevertheless, the risks associated with plant-based milk alternatives should not be overlooked, particularly affecting dairy farmers and end consumers [92]. For the economic challenges, the rise of plant-based dairy alternatives may reduce the demand for traditional dairy products, leading to job losses and business closures among dairy farmers while negatively impacting local and national economies. For the health challenges, for now, plant-based milk alternatives still cannot provide the same nutritional values as animal milk [93], which may increase the risk of osteoporosis and thyroid dysfunction among younger generations if advocating abandonment of animal-dairy products.

5.3 International standards

International process standards, defined by the International Organization for Standardization (ISO) in collaboration with national standard bodies and government agriculture departments, are essential for optimizing techniques and strategies to mitigate GHG emissions, ensuring safety and regulatory compliance [73]. Biochar is one manure amendment strategy that can reduce GHG emissions by transforming waste biomass from dairy farms to a carbon-rich product [94, 95]. The International Biochar Initiative biochar standard in the US and the European Biochar Certificate are widely acknowledged as the most prevalent standards globally, all operating as voluntary industry standards [96]. Since 2018, the Australian New Zealand Biochar Initiative has been developing a biochar standard at the behest of industry and government regulators. Moreover, carbon labelling is voluntarily employed by dairy firms and companies to inform consumers about the CF of the products they consume [73]. Examples of such labels include the UK and Australian Carbon Trust labels, as well as the Japan national carbon label. These labels facilitate consumers in identifying and selecting low CF products, concurrently incentivizing producers to reduce emissions. For the dairy industry, there is currently a lack of global standards for emission reduction. However, some international organizations are striving to promote low-carbon development in the dairy industry. For instance, the International Dairy Federation has introduced a common CF methodology for the global dairy sector, intending to provide guidelines for the implementation of comprehensive measures throughout the entire dairy value chain to mitigate emissions.

5.4 Clean air act

The Clean Air Act (CAA), established by the United States Congress and administered by the Environmental Protection Agency (EPA), is a comprehensive regulatory statute aimed at preventing air pollution and protecting the environment. In this regard, dairy farms and processing facilities are required to comply with emission standards set under National Ambient Air Quality Standards. Additionally, GHG Reporting Program which is implemented under the authority of the CAA, mandates large emission sources to report their GHG emissions. Under the indirect influence of the CAA and the increasing focus on methane regulation, several state-level policies targeting dairy farms have been progressively implemented to reduce methane and other pollutant emissions. It has been reported that the CAA has significantly improved air quality, achieving greater emission reductions at a lower cost than conventional mandates [97].

6 Conclusion and future prospect

In the context of net-zero targets, it is necessary to establish new emission reduction strategies and development models for the dairy industry (a significant energy-intensive food sector) in response to global climate change and other environmental challenges. This Review scrutinizes the GHG emissions sources across the dairy supply chain and presents current emission mitigation strategies of the dairy industry. LCA serves as a standardized method for calculating GHG emissions to achieve carbon verification. As dairy farm has been identified the hot emission spot within dairy supply chain by LCA analysis, animal-related activities and feed production on farms represent key directions for improvement. In this regard, targeted efforts focused on the farm stage, such as feed optimization, manure management, and precision farming techniques, can be highly effective in mitigating carbon emissions. It is worth noting that there are also potential contradictions in the effectiveness of target reduction strategies depending on different regions and farm scales. Additionally, effective strategies for environmental sustainability can also be formulated at each stage. Furthermore, policy initiatives including carbon pricing and the Clean Air Act, also play pivotal roles in globally optimizing the decarbonization across the dairy supply chain, contributing to the reduction of overall carbon emissions. However, the dairy industry currently lacks global standards and a set of guidelines for emission reduction, therefore needs additional endeavors to comprehensively address sustainability issues.

In the future, the following aspects can be taken into consideration to accelerate positive changes. Firstly, it is encouraged to design low-carbon dairy alternatives such as sustainable animal-free foods in the wave of future food development to alleviate the environmental issues associated with traditional livestock. Simultaneously, there is a necessity to enhance the utilization of a low-carbon energy system in the dairy industry. Currently, solar energy has been successfully utilized in dairy farms, and more efforts can be made to improve the energy-use efficiency of other renewable energy at emission hotspots of the supply chain. Eventually, big data has great potential to contribute to global emissions optimization. Artificial intelligence (AI) algorithms and models can be developed to enhance logistics, monitor energy consumption, and predict emissions. AI-aided techniques will be a promising approach for optimizing emissions reduction within dairy supply chain and thus mitigating the impacts of climate change.

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None.

Authors' contributions

Haojie Ni: Conceptualization, Writing-original draft, Visualization. Hong Zeng: Conceptualization, Writing-original draft, Funding acquisition. Zihao Liu: Investigation, Methodology. Wenlu Li: Investigation, Visualization. Song Miao: Writing-review & editing, Project administration, Supervision. Aidong Yang: Conceptualization, Writing-review & editing, Project administration, Supervision. Yanbo Wang: Conceptualization, Writing-review & editing, Project administration.

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Data availability

No data was used for the research described in the article.

Declarations

Competing interest

The authors declare no competing interests.

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References

1. Pandey V, Pant M, Snasel V (2022) Blockchain technology in food supply chains: Review and bibliometric analysis. Technol Soc 69:101954. https://doi.org/10.1016/j.techsoc.2022.101954
2. FAO (2009) How to feed the world in 2050. https://www.fao.org/fileadmin/templates/wsfs/docs/expert_paper/How_to_Feed_the_World_in_2050.pdf. Accessed 29 Jan 2024
3. Sovacool BK, Bazilian M, Griffiths S, Kim J, Foley A, Rooney D (2021) Decarbonizing the food and beverages industry: A critical and systematic review of developments, sociotechnical systems and policy options. Renew Sustain Energy Rev 143:110856. https://doi.org/10.1016/j.rser.2021.110856
4. Li Y, Zhong H, Shan Y, Hang Y, Wang D, Zhou Y et al (2023) Changes in global food consumption increase GHG emissions despite efficiency gains along global supply chains. Nat Food 4(6):483–495. https://doi.org/10.1038/s43016-023-00768-z
5. Cheng P, Tang H, Lin F, Kong X (2023) Bibliometrics of the nexus between food security and carbon emissions: hotspots and trends. Environ Sci Pollut Res 30(10):25981–25998. https://doi.org/10.1007/s11356-022-23970-1
6. Lam S, Dodd W, Berrang-Ford L, Ford J, Skinner K, Papadopoulos A et al (2021) How are climate actions evaluated? A review of United Nations food security evaluations. Glob Food Sec 28:100509. https://doi.org/10.1016/j.gfs.2021.100509
7. Soulat J, Andueza D, Graulet B, Girard CL, Labonne C, Aït-Kaddour A et al (2020) Comparison of the potential abilities of three spectroscopy methods: near-infrared, mid-infrared, and molecular fluorescence, to predict carotenoid. Vitamin and fatty acid contents in cow milk. Foods 9(5):259. https://doi.org/10.3390/foods9050592
8. FAO (2023) Dairy market review – overview of global dairy market and policy developments in 2022. Food and Agriculture Organization of the United Nations, Rome. https://www.fao.org/3/cc8217en/cc8217en.pdf. Accessed 29 Jan 2024
9. Du Y, Ge Y, Ren Y, Fan X, Pan K, Lin L et al (2018) A global strategy to mitigate the environmental impact of China's ruminant consumption boom. Nat Commun 9(1):4133. https://doi.org/10.1038/s41467-018-06381-0
10. Clune S, Crossin E, Verghese K (2017) Systematic review of greenhouse gas emissions for different fresh food categories. J Cleaner Prod 140:766–783. https://doi.org/10.1016/j.jclepro.2016.04.082
11. Wu Y, Mao X, Lu J, Wang M, Zhang Q, Song P et al (2022) Dairy Trade Helps to Alleviate Global Carbon Emission Pressure. Environ Sci Technol 56(17):12656–12666. https://doi.org/10.1021/acs.est.2c00623
12. Herron J, O'Brien D, Shalloo L (2022) Life cycle assessment of pasture-based dairy production systems: Current and future performance. J Dairy Sci 105(7):5849–5869. https://doi.org/10.3168/jds.2021-21499
13. Famiglietti J, Guerci M, Proserpio C, Ravaglia P, Motta M (2019) Development and testing of the Product Environmental Footprint Milk Tool: A comprehensive LCA tool for dairy products. Sci Total Environ 648:1614–1626. https://doi.org/10.1016/j.scitotenv.2018.08.142
14. Rasines L, Castillejo N, San Miguel G, Aguayo E (2023) Can household storage conditions reduce food waste and environmental impact? A broccoli case study. Sci Total Environ 892:164779. https://doi.org/10.1016/j.scitotenv.2023.164779
15. Alkaabneh FM, Lee J, Gómez MI, Gao HO (2021) A systems approach to carbon policy for fruit supply chains: Carbon tax, technology innovation, or land sparing? Sci Total Environ 767:144211. https://doi.org/10.1016/j.scitotenv.2020.144211
16. Liu B, Gu W, Yang Y, Lu B, Wang F, Zhang B et al (2021) Promoting potato as staple food can reduce the carbon–land–water impacts of crops in China. Nat Food 2(8):570–577. https://doi.org/10.1038/s43016-021-00337-2
17. Coluccia B, Agnusdei GP, De Leo F, Vecchio Y, La Fata CM, Miglietta PP (2022) Assessing the carbon footprint across the supply chain: Cow milk vs soy drink. Sci Total Environ 806:151200. https://doi.org/10.1016/j.scitotenv.2021.151200
18. Xue L, Prass N, Gollnow S, Davis J, Scherhaufer S, Östergren K et al (2019) Efficiency and Carbon Footprint of the German Meat Supply Chain. Environ Sci Technol 53(9):5133–5142. https://doi.org/10.1021/acs.est.8b06079
19. Malliaroudaki MI, Watson NJ, Ferrari R, Nchari LN, Gomes RL (2022) Energy management for a net zero dairy supply chain under climate change. Trends Food Sci Technol 126:153–167. https://doi.org/10.1016/j.tifs.2022.01.015
20. Malliaroudaki MI, Watson NJ, Glover ZJ, Nchari LN, Gomes RL (2023) Net zero roadmap modelling for sustainable dairy manufacturing and distribution. Chem Eng J 475:145734. https://doi.org/10.1016/j.cej.2023.145734
21. Uddin ME, Tricarico JM, Kebreab E (2022) Impact of nitrate and 3-nitrooxypropanol on the carbon footprints of milk from cattle produced in confined-feeding systems across regions in the United States: A life cycle analysis. J Dairy Sci 105(6):5074–5083. https://doi.org/10.3168/jds.2021-20988
22. Singaravadivelan A, Sachin PB, Harikumar S, Vijayakumar P, Vindhya MV, Farhana FMB et al (2023) Life cycle assessment of greenhouse gas emission from the dairy production system — review. Trop Anim Health Prod 55(5):320. https://doi.org/10.1007/s11250-023-03748-4
23. Hitaj C, Rehkamp S, Canning P, Peters CJ (2019) Greenhouse Gas Emissions in the United States Food System: Current and Healthy Diet Scenarios. Environ Sci Technol 53(9):5493–5503. https://doi.org/10.1021/acs.est.8b06828
24. Laca A, Gómez N, Laca A, Díaz M (2020) Overview on GHG emissions of raw milk production and a comparison of milk and cheese carbon footprints of two different systems from northern Spain. Environ Sci Pollut Res 27(2):1650–1666. https://doi.org/10.1007/s11356-019-06857-6
25. Berton M, Bovolenta S, Corazzin M, Gallo L, Pinterits S, Ramanzin M et al (2021) Environmental impacts of milk production and processing in the Eastern Alps: A "cradle-to-dairy gate" LCA approach. J Cleaner Prod 303:127056. https://doi.org/10.1016/j.jclepro.2021.127056
26. Canellada F, Laca A, Laca A, Díaz M (2018) Environmental impact of cheese production: A case study of a small-scale factory in southern Europe and global overview of carbon footprint. Sci Total Environ 635:167–177. https://doi.org/10.1016/j.scitotenv.2018.04.045
27. Santos LdLCd, Renato NdS, Florindo TJ, Rosa AP, Borges AC (2022) Life cycle assessment of dairy products: a case study of a dairy factory in Brazil. Sustainability, 2022;14(15):9646. https://doi.org/10.3390/su14159646
28. Zanni S, Roccaro M, Bocedi F, Peli A, Bonoli A (2022) LCA to Estimate the Environmental Impact of Dairy Farms: A Case Study. Sustainability 14(10):6028. https://doi.org/10.3390/su14106028

29. Finnegan W, Yan M, Holden NM, Goggins J (2018) A review of environmental life cycle assessment studies examining cheese production. Int J Life Cycle Assess 23(9):1773–1787. https://doi.org/10.1007/s11367-017-1407-7
30. FAO (2010) Greenhouse gas emissions from the dairy sector. Food and Agriculture Organization of the United Nations, Rome. https://milk.procon.org/wp-content/uploads/sites/44/ghg-emissions-from-dairy-sector-fao-2010.pdf. Accessed 4 Feb 2024.
31. de Léis CM, Cherubini E, Ruviaro CF, Prudêncio da Silva V, do Nascimento Lampert V, Spies A, et al (2015) Carbon footprint of milk production in Brazil: a comparative case study. Int J Life Cycle Assess 20(1):46-60. https://doi.org/10.1007/s11367-014-0813-3
32. Egas D, Ponsá S, Colon J (2020) CalcPEFDairy: A Product Environmental Footprint compliant tool for a tailored assessment of raw milk and dairy products. J Environ Manage 260:110049. https://doi.org/10.1016/j.jenvman.2019.110049
33. Noya I, González-García S, Berzosa J, Baucells F, Feijoo G, Moreira MT (2018) Environmental and water sustainability of milk production in Northeast Spain. Sci Total Environ 616–617:1317–1329. https://doi.org/10.1016/j.scitotenv.2017.10.186
34. Dalla Riva A, Burek J, Kim D, Thoma G, Cassandro M, De Marchi M (2017) Environmental life cycle assessment of Italian mozzarella cheese: Hotspots and improvement opportunities. J Dairy Sci 100(10):7933–7952. https://doi.org/10.3168/jds.2016-12396
35. Gollnow S, Lundie S, Moore AD, McLaren J, van Buuren N, Stahle P et al (2014) Carbon footprint of milk production from dairy cows in Australia. Int Dairy J 37(1):31–38. https://doi.org/10.1016/j.idairyj.2014.02.005
36. Thoma G, Popp J, Nutter D, Shonnard D, Ulrich R, Matlock M et al (2013) Greenhouse gas emissions from milk production and consumption in the United States: A cradle-to-grave life cycle assessment circa 2008. Int Dairy J 31:S3–S14. https://doi.org/10.1016/j.idairyj.2012.08.013
37. Australia D (2020) Greenhouse gases on dairy farms Where do emissions come from? https://cdn-prod.dairyaustralia.com.au/-/media/project/dairy-australia-sites/national-home/resources/2020/07/08/greenhouse-gases-on-dairy-farms-factsheet/greenhouse-gases-on-dairy-farms-factsheet.pdf?rev=48dad81b12014ed6b1ffe5606b9a7916. Accessed 5 Mar 2024
38. Eide MH (2002) Life cycle assessment (LCA) of industrial milk production. Int J Life Cycle Assess 7(2):115–126. https://doi.org/10.1007/BF02978855
39. Berlin J (2002) Environmental life cycle assessment (LCA) of Swedish semi-hard cheese. Int Dairy J 12(11):939–953. https://doi.org/10.1016/S0958-6946(02)00112-7
40. Berlin J, Sonesson U (2008) Minimising environmental impact by sequencing cultured dairy products: two case studies. J Cleaner Prod 16(4):483–498. https://doi.org/10.1016/j.jclepro.2006.10.001
41. Masoni P, Scartozzi D, Tarantini M, Sra B, Raggi A (1998) A life cycle assessment pilot study in an Italian Dairy Company
42. Blonk T, Lafleur M, Zeijts H (1997) Towards an environmental infrastructure for the Dutch Food Industry: exploring the environmental information conversion of five food commodities. Universiteit Amsterdam-IVAM (Environmental Research), Amsterdam
43. Chen W, Jafarzadeh S, Thakur M, Ólafsdóttir G, Mehta S, Bogason S et al (2021) Environmental impacts of animal-based food supply chains with market characteristics. Sci Total Environ 783:147077. https://doi.org/10.1016/j.scitotenv.2021.147077
44. IDF (2021) Dairy sustainability outlook. https://fil-idf.org/wp-content/uploads/woocommerce_uploads/2021/07/IDF-Dairy-Sustainability-Outlook-2021-web1-j06u5f.pdf. Accessed 31 Jan 2025
45. Smetana S, Palanisamy M, Mathys A, Heinz V (2016) Sustainability of insect use for feed and food: Life Cycle Assessment perspective. J Clean Prod 137:741–751. https://doi.org/10.1016/j.jclepro.2016.07.148
46. Jayanegara A, Novandri B, Yantina N, Ridla M (2017) Use of black soldier fly larvae (Hermetia illucens) to substitute soybean meal in ruminant diet: An in vitro rumen fermentation study. Vet World 10(12):1439–1446. https://doi.org/10.14202/vetworld.2017.1439-1446
47. Salomone R, Saija G, Mondello G, Giannetto A, Fasulo S, Savastano D (2017) Environmental impact of food waste bioconversion by insects: Application of Life Cycle Assessment to process using Hermetia illucens. J Cleaner Prod 140:890–905. https://doi.org/10.1016/j.jclepro.2016.06.154
48. van Huis A, Oonincx DGAB (2017) The environmental sustainability of insects as food and feed. A review. Agron Sustain Dev 37(5):43. https://doi.org/10.1007/s13593-017-0452-8
49. Sogari G, Amato M, Palmieri R, Hadj Saadoun J, Formici G, Verneau F et al (2023) The future is crawling: Evaluating the potential of insects for food and feed security. Curr Res Food Sci 6:100504. https://doi.org/10.1016/j.crfs.2023.100504
50. Abro Z, Macharia I, Mulungu K, Subramanian S, Tanga CM, Kassie M (2022) The potential economic benefits of insect-based feed in Uganda. Front Insect Sci 2:968042. https://doi.org/10.3389/finsc.2022.968042
51. Hörtenhuber SJ, Lindenthal T, Zollitsch W (2011) Reduction of greenhouse gas emissions from feed supply chains by utilizing regionally produced protein sources: the case of Austrian dairy production. J Sci Food Agric 91(6):1118–1127. https://doi.org/10.1002/jsfa.4293
52. Machmüller A, Ossowski DA, Kreuzer M (2000) Comparative evaluation of the effects of coconut oil, oilseeds and crystalline fat on methane release, digestion and energy balance in lambs. Anim Feed Sci Technol 85(1):41–60. https://doi.org/10.1016/S0377-8401(00)00126-7
53. Shields S, Orme-Evans G (2015) The Impacts of Climate Change Mitigation Strategies on Animal Welfare. Animals 5(2):361–394. https://doi.org/10.3390/ani5020361
54. Benchaar C, Pomar C, Chiquette J (2001) Evaluation of dietary strategies to reduce methane production in ruminants: A modelling approach. Can J Anim Sci 81(4):563–574. https://doi.org/10.4141/A00-119
55. Saadaoui I, Rasheed R, Aguilar A, Cherif M, Al Jabri H, Sayadi S et al (2021) Microalgal-based feed: promising alternative feedstocks for livestock and poultry production. J Anim Sci Biotechnol 12(1):76. https://doi.org/10.1186/s40104-021-00593-z
56. Nagappan S, Das P, AbdulQuadir M, Thaher M, Khan S, Mahata C et al (2021) Potential of microalgae as a sustainable feed ingredient for aquaculture. J Biotechnol 341:1–20. https://doi.org/10.1016/j.jbiotec.2021.09.003
57. Gomaa AS, Kholif AE, Kholif AM, Salama R, El-Alamy HA, Olafadehan OA (2018) Sunflower Oil and Nannochloropsis oculata Microalgae as Sources of Unsaturated Fatty Acids for Mitigation of Methane Production and Enhancing Diets' Nutritive Value. J Agric Food Chem 66(8):1751–1759. https://doi.org/10.1021/acs.jafc.7b04704
58. Lobo RR, Almeida E, Monteiro A, da Silva SS, Salas-Solis G, Coronella CJ et al (2024) Replacing soybean meal with microalgae biomass in diets with contrasting carbohydrate profiles can reduce in vitro methane production and improve short-chain fatty acid production. J Dairy Sci 107(8):5542–5555. https://doi.org/10.3168/jds.2023-24025
59. Sato Y, Shioya H, Uda Y, Asano H, Nagao Y, Kuno H et al (2024) Effects of two types of Coccomyxa sp. KJ on in vitro ruminal fermentation, methane production, and the rumen microbiota. PLoS One 19(8):e0308646. https://doi.org/10.1371/journal.pone.0308646
60. Smetana S, Sandmann M, Rohn S, Pleissner D, Heinz V (2017) Autotrophic and heterotrophic microalgae and cyanobacteria cultivation for food and feed: life cycle assessment. Bioresour Technol 245:162–170. https://doi.org/10.1016/j.biortech.2017.08.113
61. Cottle DJ, Nolan JV (2011) Wiedemann SG, Ruminant enteric methane mitigation: a review. Anim Prod Sci 51(6):491–514. https://doi.org/10.1071/AN10163
62. Honan M, Feng X, Tricarico JM, Kebreab E (2022) Feed additives as a strategic approach to reduce enteric methane production in cattle: modes of action, effectiveness and safety. Anim Prod Sci 62(14):1303–1317. https://doi.org/10.1071/AN20295
63. Hristov AN, Oh J, Giallongo F, Frederick TW, Harper MT, Weeks HL et al (2015) An inhibitor persistently decreased enteric methane emission from dairy cows with no negative effect on milk production. Proc Natl Acad Sci 112(34):10663–10668. https://doi.org/10.1073/pnas.1504124112
64. Roque BM, Salwen JK, Kinley R, Kebreab E (2019) Inclusion of Asparagopsis armata in lactating dairy cows' diet reduces enteric methane emission by over 50 percent. J Clean Prod 234:132–138. https://doi.org/10.1016/j.jclepro.2019.06.193
65. Latham EA, Anderson RC, Pinchak WE, Nisbet DJ (2016) Insights on alterations to the rumen ecosystem by nitrate and nitrocompounds. Front Microbiol 7. https://doi.org/10.3389/fmicb.2016.00228
66. Thoma G, Popp J, Shonnard D, Nutter D, Matlock M, Ulrich R et al (2008) Regional analysis of greenhouse gas emissions from USA dairy farms: A

cradle to farm-gate assessment of the American dairy industry circa 2008. Int Dairy J 31:S29–S40. https://doi.org/10.1016/j.idairyj.2012.09.010
67. Fan X, Chang J, Ren Y, Wu X, Du Y, Xu R et al (2018) Recoupling Industrial Dairy Feedlots and Industrial Farmlands Mitigates the Environmental Impacts of Milk Production in China. Environ Sci Technol 52(7):3917–3925. https://doi.org/10.1021/acs.est.7b04829
68. Trojan C (2021) Bringing manure application to the digital age. https://water.unl.edu/article/animal-manure-management/bringing-manure-application-digital-age. Accessed 4 Feb 2024
69. Karen Fisher, Whittaker D (2018) Opportunities to reduce waste along the journey of milk, from dairy to home, https://wrap.org.uk/sites/default/files/2020-10/WRAP-Report%20-%20Opportunities%20to%20reduce%20waste%20along%20the%20journey%20of%20milk%20PUB%2011.2018.pdf. Accessed 4 February 2024
70. Zhang Z-H, Wang L-H, Zeng X-A, Han Z, Brennan CS (2019) Non-thermal technologies and its current and future application in the food industry: a review. Int J Food Sci Technol 54(1):1–13. https://doi.org/10.1111/ijfs.13903
71. Hokmollahi F, Ehsani MR (2017) High pressure processing and its application in cheese manufacturing: a review. J Food Biosci Technol 7:57–66
72. Al-Hilphy AR, Abdulstar AR, Gavahian M (2021) Moderate electric field pasteurization of milk in a continuous flow unit: Effects of process parameters, energy consumption, and shelf-life determination. Innov Food Sci Emerg Technol 67:102568. https://doi.org/10.1016/j.ifset.2020.102568
73. Grandsir C, Falagán N, Alamar MC (2023) Application of novel technologies to reach net-zero greenhouse gas emissions in the fresh pasteurised milk supply chain: A review. Int J Dairy Technol 76(1):38–50. https://doi.org/10.1111/1471-0307.12926
74. Alirezalu K, Munekata PES, Parniakov O, Barba FJ, Witt J, Toepfl S et al (2020) Pulsed electric field and mild heating for milk processing: a review on recent advances. J Sci Food Agric 100(1):16–24. https://doi.org/10.1002/jsfa.9942
75. Nurcan K, Müge U, Turkuaz Ecem S (2018) Ultraviolet light applications in dairy processing. In: K. Nurcan (ed.). Technological approaches for novel applications in dairy processing. IntechOpen, Rijeka, p. Ch. 1. https://doi.org/10.5772/intechopen.74291
76. Delorme MM, Guimarães JT, Coutinho NM, Balthazar CF, Rocha RS, Silva R et al (2020) Ultraviolet radiation: An interesting technology to preserve quality and safety of milk and dairy foods. Trends Food Sci Technol 102:146–154. https://doi.org/10.1016/j.tifs.2020.06.001
77. Koutchma T, Barnes G (2013) Shelf Life Enhancement of Milk Products. Food Technol 67:68–70
78. Valsasina L, Pizzol M, Smetana S, Georget E, Mathys A, Heinz V (2017) Life cycle assessment of emerging technologies: The case of milk ultra-high pressure homogenisation. J Clean Prod 142:2209–2217. https://doi.org/10.1016/j.jclepro.2016.11.059
79. Xu Z, Sun D-W, Zeng X-A, Liu D, Pu H (2015) Research Developments in Methods to Reduce the Carbon Footprint of the Food System: A Review. Crit Rev Food Sci Nutr 55(9):1270–1286. https://doi.org/10.1080/10408398.2013.821593
80. Cannas VG, Ciccullo F, Pero M, Cigolini R (2020) Sustainable innovation in the dairy supply chain: enabling factors for intermodal transportation. Int Int J Prod Res 58(24):7314–7333. https://doi.org/10.1080/00207543.2020.1809731
81. Pinto JTdM, Mistage O, Bilotta P, Helmers E (2018) Road-rail intermodal freight transport as a strategy for climate change mitigation. Environ Dev 25:100–110. https://doi.org/10.1016/j.envdev.2017.07.005
82. Le H, Azhgaliyeva D (2023) Carbon pricing and firms' GHG emissions: Firm-level empirical evidence from East Asia. J Clean Prod 429:139504. https://doi.org/10.1016/j.jclepro.2023.139504
83. O'Mahony T (2020) State of the art in carbon taxes: a review of the global conclusions. Green Finance 2(4):409–423. https://doi.org/10.3934/GF.2020022
84. Wang X, Teng F, Wang G, Zhou S, Cai B (2018) Carbon leakage scrutiny in ETS and non-ETS industrial sectors in China. Resour Conserv Recycl 129:424–431. https://doi.org/10.1016/j.resconrec.2016.09.017
85. World Bank (2023) State and trends of carbon pricing. https://carbonpricingdashboard.worldbank.org/map_data. Accessed 4 Feb 2024
86. World Bank (2023) Carbon pricing dashboard. https://carbonpricingdashboard.worldbank.org/map_data. Accessed 5 Mar 2024
87. Alvim AM, Sanguinet ER (2021) Climate Change Policies and the Carbon Tax Effect on Meat and Dairy Industries in Brazil. Sustainability 13(16):9026. https://doi.org/10.3390/su13169026
88. Yokessa M, Marette S (2019) A Tax Coming from the IPCC Carbon Prices Cannot Change Consumption: Evidence from an Experiment. Sustainability 11(18):4834. https://doi.org/10.3390/su11184834
89. Xu X, Lan Y (2016) A comparative study on carbon footprints between plant- and animal-based foods in China. J Cleaner Prod 112:2581–2592. https://doi.org/10.1016/j.jclepro.2015.10.059
90. Bryant CJ (2022) Plant-based animal product alternatives are healthier and more environmentally sustainable than animal products. Future Foods 6:100174. https://doi.org/10.1016/j.fufo.2022.100174
91. Nelson ME, Hamm MW, Hu FB, Abrams SA, Griffin TS (2016) Alignment of Healthy Dietary Patterns and Environmental Sustainability: A Systematic Review. Adv Nutr 7(6):1005–1025. https://doi.org/10.3945/an.116.012567
92. Astbury CC, Ferguson J, Krettmann A, McGale L, Redway M (2020) The UK cross-government programme on food security research, Milking it dry? Risks and opportunities of plant-based milk alternatives. https://www.foodsecurity.ac.uk/blog/milking-it-dry-risks-and-opportunities-of-plant-based-milk-alternatives/. Accessed 4 Feb 2024.
93. Vanga SK, Raghavan V (2018) How well do plant based alternatives fare nutritionally compared to cow's milk? J Food Sci Technol 55(1):10–20. https://doi.org/10.1007/s13197-017-2915-y
94. Peterson CB, Mitloehner FM (2021) Sustainability of the Dairy Industry: Emissions and Mitigation Opportunities. Front Anim Sci 2:760310. https://doi.org/10.3389/fanim.2021.760310
95. Zhang C, Zeng G, Huang D, Lai C, Chen M, Cheng M et al (2019) Biochar for environmental management: Mitigating greenhouse gas emissions, contaminant treatment, and potential negative impacts. Chem Eng J 373:902–922. https://doi.org/10.1016/j.cej.2019.05.139
96. Hu Q, Jung J, Chen D, Leong K, Song S, Li F et al (2021) Biochar industry to circular economy. Sci Total Environ 757:143820. https://doi.org/10.1016/j.scitotenv.2020.143820
97. Aldy JE, Auffhammer M, Cropper M, Fraas A, Morgenstern R (2022) Looking Back at 50 Years of the Clean Air Act. J Econ Lit 60(1):179–232. https://doi.org/10.1257/jel.20201626

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