

Review

Net Zero Dairy Farming—Advancing Climate Goals with Big Data and Artificial Intelligence

Suresh Neethirajan 

Faculty of Agriculture and Computer Science, Dalhousie University, Halifax, NS B3H 1W5, Canada; sureshraja@dal.ca

Abstract: This paper explores the transformative potential of Big Data and Artificial Intelligence (AI) in propelling the dairy industry toward net zero emissions, a critical objective in the global fight against climate change. Employing the Canadian dairy sector as a case study, the study extrapolates its findings to demonstrate the global applicability of these technologies in enhancing environmental sustainability across the agricultural spectrum. We begin by delineating the environmental challenges confronting the dairy industry worldwide, with an emphasis on greenhouse gas (GHG) emissions, including methane from enteric fermentation and nitrous oxide from manure management. The pressing need for innovative approaches in light of the accelerating climate crisis forms the crux of our argument. Our analysis delves into the role of Big Data and AI in revolutionizing emission management in dairy farming. This includes applications in optimizing feed efficiency, refining manure management, and improving energy utilization. Technological solutions such as predictive analytics for feed optimization, AI in herd health management, and sensor networks for real-time monitoring are thoroughly examined. Crucially, the paper addresses the wider implications of integrating these technologies in dairy farming. We discuss the development of benchmarking standards for emissions, the importance of data privacy, and the essential role of policy in promoting sustainable practices. These aspects are vital in supporting the adoption of technology, ensuring ethical use, and aligning with international climate commitments. Concluding, our comprehensive study not only suggests a pathway for the dairy industry towards environmental sustainability but also provides insights into the role of digital technologies in broader agricultural practices, aligning with global environmental sustainability efforts.



Citation: Neethirajan, S. Net Zero Dairy Farming—Advancing Climate Goals with Big Data and Artificial Intelligence. *Climate* **2024**, *12*, 15. <https://doi.org/10.3390/cli12020015>

Academic Editors: Cheng Li, Fei Zhang, Mou Leong Tan and Kwok Pan Chun

Received: 16 November 2023

Revised: 22 January 2024

Accepted: 22 January 2024

Published: 25 January 2024



Copyright: © 2024 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Keywords: climate change; net zero emissions; dairy farming; Big Data; Artificial Intelligence (AI); greenhouse gas emissions; sustainable agriculture; technological innovation; policy framework; environmental sustainability

1. Climate Change and the Drive for Net Zero Emissions

1.1. Global Climate Crisis and its Impacts

The global climate crisis, driven by anthropogenic activities, has precipitated a series of environmental upheavals with dire consequences. The Intergovernmental Panel on Climate Change (IPCC) reports indicate a substantial increase in global temperatures, attributable to the amplified concentration of greenhouse gases (GHGs) such as carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) in the atmosphere [1,2]. The primary sources of these emissions include fossil fuel combustion, deforestation, and industrial processes. The resulting global warming is not a distant threat but a present reality, manifesting in melting polar ice caps, rising sea levels, and increases in the frequency and severity of extreme weather events. These environmental changes have a cascading effect on ecosystems and biodiversity. The alterations in temperature and precipitation patterns disrupt natural habitats, leading to species migration and extinction [3]. Additionally, the acidification of oceans due to increased CO₂ levels poses a significant threat to marine life [4]. For humanity, these changes entail dire consequences, ranging from health risks due

to heatwaves and pollution to economic losses in agriculture, fisheries, and other sectors crucial for livelihoods.

1.2. The Concept and Importance of Achieving Net Zero Emissions

Net zero emissions represent a state where the amount of GHGs emitted into the atmosphere is balanced by an equivalent amount removed [5]. Achieving this balance is crucial for stabilizing global temperatures. The concept hinges on the principle of carbon neutrality, where every ton of anthropogenic GHG emitted is counterbalanced by a ton removed or sequestered from the atmosphere [6].

Achieving net zero emissions necessitates a twofold strategy: reducing the existing emissions and enhancing carbon sinks. The former involves transitioning to renewable energy sources, boosting energy efficiency, and altering land use practices [7]. Simultaneously, enhancing natural carbon sinks like forests and oceans, alongside technological solutions such as carbon capture and storage (CCS), is imperative. CCS, for instance, involves capturing CO₂ emissions at their source (like power plants) and sequestering them underground or using them in various applications [8]. This balance is not just an environmental imperative but also a socio-economic necessity. The transition to a low-carbon economy promises innovation, job creation, and energy security, fostering sustainable development [9]. However, achieving net zero is a monumental task that requires concerted global action and significant investment in technology and infrastructure.

1.3. The Role of International Commitments in Climate Change Mitigation

International commitments are pivotal in the fight against climate change. The Paris Agreement, a landmark international treaty adopted in 2015, exemplifies global efforts to combat climate change [10]. The agreement's central aim is to limit global warming to well below 2 degrees Celsius, preferably to 1.5 degrees Celsius, compared to pre-industrial levels [11]. This goal is grounded in scientific evidence suggesting that surpassing this threshold could lead to catastrophic climate impacts.

Under the Paris Agreement, countries have committed to nationally determined contributions (NDCs), which are plans to outline each country's efforts to reduce national emissions and adapt to the impacts of climate change. The effectiveness of the Paris Agreement lies in its structure, which allows for periodic review and enhancement of these NDCs, fostering a progressive increase in global ambition. However, the challenge extends beyond mere commitment. The implementation of these NDCs requires a radical overhaul of national policies and economies. It demands a shift from fossil fuel dependence to renewable energy sources, a transformation in agricultural and industrial practices, and significant changes in consumption patterns. Furthermore, international cooperation is vital in this endeavor. Developed countries are expected to provide financial and technical support to developing nations, acknowledging the principle of common but differentiated responsibilities. This support is crucial as developing countries often lack the resources to implement substantial climate action.

The role of international commitments extends to fostering a global culture of sustainability. By setting clear targets and establishing a framework for collaboration, these commitments provide a roadmap for nations to collectively address the climate crisis. They also send a strong signal to businesses and investors, shifting financial flows towards more sustainable projects and technologies.

The drive for net zero emissions is not just an environmental goal but a comprehensive strategy for sustainable development. It requires a paradigm shift in how economies operate and societies function [12]. Achieving net zero emissions is pivotal in mitigating the global climate crisis, a task that demands unwavering commitment, innovative solutions, and robust international cooperation. As we stand at the crossroads of a climatic emergency, the path we choose today will determine the future of our planet and the generations to come.

2. Environmental Footprint of the Canadian Dairy Industry

The Canadian dairy industry, a significant contributor to the national economy, also plays a pivotal role in the environmental landscape, particularly concerning greenhouse gas (GHG) emissions. The sector's environmental footprint is predominantly characterized by emissions arising from enteric fermentation in dairy cattle and manure management [13,14]. These emissions are critical factors in the broader context of climate change and environmental sustainability.

2.1. The Economic and Environmental Significance of Dairy Farming in Canada

The dairy sector in Canada is a substantial segment of the nation's agricultural framework, contributing to both the economy and food security. According to Agriculture and Agri-Food Canada, the industry provides significant economic benefits, encompassing over 9000 dairy farms and a considerable contribution to the national GDP [15,16]. This economic importance, however, is juxtaposed against the sector's environmental impacts, chiefly its contribution to GHG emissions.

The environmental footprint of dairy farming extends beyond GHG emissions. It includes land use for feed production, water consumption, and the impact on biodiversity [17–19]. Nevertheless, the emission of GHGs remains the most pressing environmental issue associated with dairy farming, directly influencing climate change.

2.2. Main Sources of GHG Emissions in Dairy Farming: Enteric Fermentation and Manure Management

2.2.1. Enteric Fermentation

Enteric fermentation is a natural digestive process in ruminants, where microbes in the stomach break down food, producing methane (CH₄) as a byproduct [20,21]. This methane, a potent greenhouse gas, is then released into the atmosphere, predominantly through belching. The global warming potential of methane is approximately 28 times greater than that of CO₂ over a 100-year period, as reported by the IPCC [22–24]. In the context of the Canadian dairy industry, enteric fermentation represents a significant portion of its GHG emissions. Strategies to mitigate these emissions include dietary modifications to reduce fermentable substrates in the rumen and the use of feed additives like lipids or nitrates that can decrease methanogenesis [25,26].

2.2.2. Manure Management

The management of manure on dairy farms is another major source of GHG emissions, particularly methane and nitrous oxide (N₂O) [27]. Methane emissions occur during the storage and handling of manure under anaerobic conditions. Nitrous oxide, with a global warming potential 265 times that of CO₂, is emitted primarily during the storage and application of manure to fields [28,29]. N₂O emissions are linked to the nitrification and denitrification processes in soil, exacerbated by the application of nitrogen-rich manure. The mitigation of these emissions can be achieved through improved manure management practices, such as the adoption of aerobic composting techniques, and the utilization of anaerobic digesters that convert manure into biogas, a renewable energy source [30].

2.2.3. Synthetic Fertilizers

The use of synthetic fertilizers in feed crop production for dairy cattle is a notable source of N₂O emissions. When applied to soil, these fertilizers undergo microbial transformations, leading to N₂O release. The extent of these emissions is influenced by factors such as soil type, climate, and application method. Precision agriculture techniques, which optimize fertilizer application based on soil needs and environmental conditions, are effective in reducing N₂O emissions from synthetic fertilizers.

2.2.4. Fossil Fuel Use

Dairy farming operations, including machinery for fieldwork, transportation, and dairy processing, contribute to CO₂ emissions through the combustion of fossil fuels [31,32]. The energy-intensive nature of these activities necessitates a shift towards more sustainable energy sources and the adoption of energy-efficient technologies.

2.3. Environmental Impact of Dairy Farming Emissions

The environmental impact of emissions from dairy farming is multifaceted. Methane and nitrous oxide, due to their high global warming potentials, significantly contribute to the greenhouse effect and climate change. These emissions are a concern not only for their contribution to global warming but also for their role in altering weather patterns, impacting ecosystems and biodiversity. Furthermore, the emission of N₂O presents an additional environmental challenge due to its role in ozone layer depletion [33,34]. This aspect underscores the need for effective strategies to manage N₂O emissions from both manure and fertilizer applications.

In addressing these emissions, the dairy industry faces several challenges. Technological barriers include the development and implementation of effective mitigation strategies that are economically viable and scalable [35]. Economic constraints, particularly the cost of adopting new technologies and practices, pose significant hurdles for many dairy farmers. Additionally, policy and regulatory challenges can impact the pace and extent of emission reduction efforts.

In the realm of dairy farming, quantifying and understanding emissions is vital for crafting sustainable practices. This sector, integral to global agriculture, faces the dual challenge of maintaining productivity while mitigating its environmental footprint [36]. Key emission sources include enteric fermentation, manure management, synthetic fertilizers, and fossil fuel use. Each of these sources contributes uniquely to the overall environmental impact of dairy farming.

The environmental footprint of dairy farming, notably its GHG emissions, poses significant challenges to sustainability goals. Enteric fermentation and manure management are the main contributors to these emissions, necessitating targeted mitigation strategies. The Canadian dairy industry's approach to addressing its environmental impact involves a multifaceted strategy, incorporating technological innovations, farm management practices, and policy interventions.

Technological innovations, such as precision agriculture, can optimize feed efficiency and manure management, thereby reducing emissions. Precision agriculture utilizes data-driven insights to tailor feed formulations and application rates of manure, minimizing excess nutrient application and optimizing digestion processes [37]. In addition to technological solutions, farm management practices play a crucial role. Strategies such as altering feed composition to reduce enteric fermentation, improving manure storage and treatment facilities, and adopting nutrient management plans are integral to reducing the dairy industry's environmental footprint.

Policy interventions and incentives are also critical. Regulations and guidelines that promote sustainable practices, alongside financial incentives for farmers who adopt emission-reducing technologies, can significantly contribute to mitigating the environmental impact of dairy farming. The environmental footprint of the Canadian dairy industry, particularly its contribution to GHG emissions, is a complex issue that requires a holistic approach. The mitigation of emissions from enteric fermentation and manure management necessitates a combination of technological innovations, effective farm management practices, and supportive policy frameworks. As the dairy industry continues to evolve, the integration of these strategies will be key in ensuring its sustainability and alignment with broader environmental objectives.

3. Sustainability Challenges and Industry Efforts in Dairy Farming

The dairy industry, a vital component of global agriculture, faces significant sustainability challenges, particularly in mitigating its environmental impact. Central to these challenges are the greenhouse gas (GHG) emissions from dairy farms, primarily methane emissions from enteric fermentation, the environmental implications of manure management, and energy use in dairy processing. These factors significantly contribute to climate change, necessitating urgent and innovative responses from the industry.

3.1. Addressing Methane Emissions from Enteric Fermentation

The dairy industry has been exploring various strategies to mitigate these emissions. One approach is dietary manipulation, where the feed composition is adjusted to reduce fermentable substrates in the rumen that contribute to methane production. This includes incorporating lipids, nitrates, or certain enzymes that can decrease methanogenesis. Another method is the use of feed additives like 3-nitrooxypropanol (3-NOP), which directly inhibits the enzyme (methyl coenzyme M reductase) responsible for methane production in the rumen [38,39].

3.2. Innovations in Manure Management

Innovative manure management practices are being developed to mitigate these emissions. These include the adoption of aerobic composting techniques, which reduce methane production by promoting aerobic conditions. Anaerobic digesters are another solution, converting manure into biogas, a renewable energy source, while significantly reducing methane emissions [40]. Additionally, precision agriculture tools are being utilized to optimize the application rates of manure, ensuring nutrients are used efficiently and minimizing excess nitrogen application, which contributes to nitrous oxide emissions.

3.3. Energy Use in Dairy Processing and its Environmental Implications

Dairy processing, encompassing pasteurizing, homogenizing, and packaging milk, is an energy-intensive process. The reliance on fossil fuels in dairy processing contributes significantly to GHG emissions [41,42]. Reducing the energy footprint of dairy processing is crucial for the overall sustainability of the industry.

Efforts to mitigate energy use in dairy processing include transitioning to renewable energy sources, such as solar or wind power [43]. Energy efficiency measures, such as the use of energy-efficient equipment and the optimization of processing operations, are also being implemented. These measures not only reduce GHG emissions but also decrease operational costs. Another innovative approach is the recovery and utilization of waste heat generated during processing. Heat recovery systems can repurpose this waste heat for other processing steps or for heating purposes within the facility, thereby improving overall energy efficiency.

Continuous research and development, coupled with industry-wide adoption of these practices, are essential for achieving substantial reductions in GHG emissions. The integration of these strategies, supported by policy frameworks and incentives, will be key in ensuring the dairy industry's progress towards sustainability. As the industry evolves, the continuous refinement and implementation of these approaches will play a critical role in mitigating its environmental footprint and contributing to global efforts to combat climate change.

4. The Transformative Impact of Big Data and AI in Dairy Farming

The advent of Big Data and Artificial Intelligence (AI) has revolutionized dairy farming, introducing enhanced efficiency, improved sustainability, and innovative management practices. These technologies address key challenges in dairy farming, such as optimizing resource usage, improving herd health, and benchmarking for sustainability [44].

Big Data in dairy farming involves collecting and analyzing extensive data from various sources, like sensor networks and animal health monitoring systems. This compre-

hensive approach enables farmers to make data-driven decisions, optimizing productivity and sustainability. Big Data analytics play a crucial role in resource management, particularly in optimizing feed and water usage, and in analyzing a farm’s climate impact, especially concerning greenhouse gas emissions [45].

AI technologies bring sophistication to herd management and resource optimization. Predictive analytics in herd health, powered by AI, revolutionize animal care by anticipating health issues, thereby enhancing preventive care [46]. AI also optimizes feed composition and energy management, integrating renewable energy sources like solar or biogas into operations, reducing reliance on fossil fuels.

4.1. Benchmarking for Performance and Sustainability

Benchmarking is a critical process in dairy farming, enabling the comparison of farm performance against industry standards [47]. It identifies areas for improvement in resource utilization, animal health management [Figure 1], and environmental sustainability. Benchmarking also helps in the adoption of best practices, tracking progress over time, and ensuring compliance with environmental standards [48]. The process of benchmarking emissions in the dairy industry is comprehensive, involving identification and quantification of emissions sources such as enteric fermentation, manure management, and fossil fuel usage. It entails comparing emission levels with industry standards and best practices, setting reduction targets, and regular monitoring and reporting.

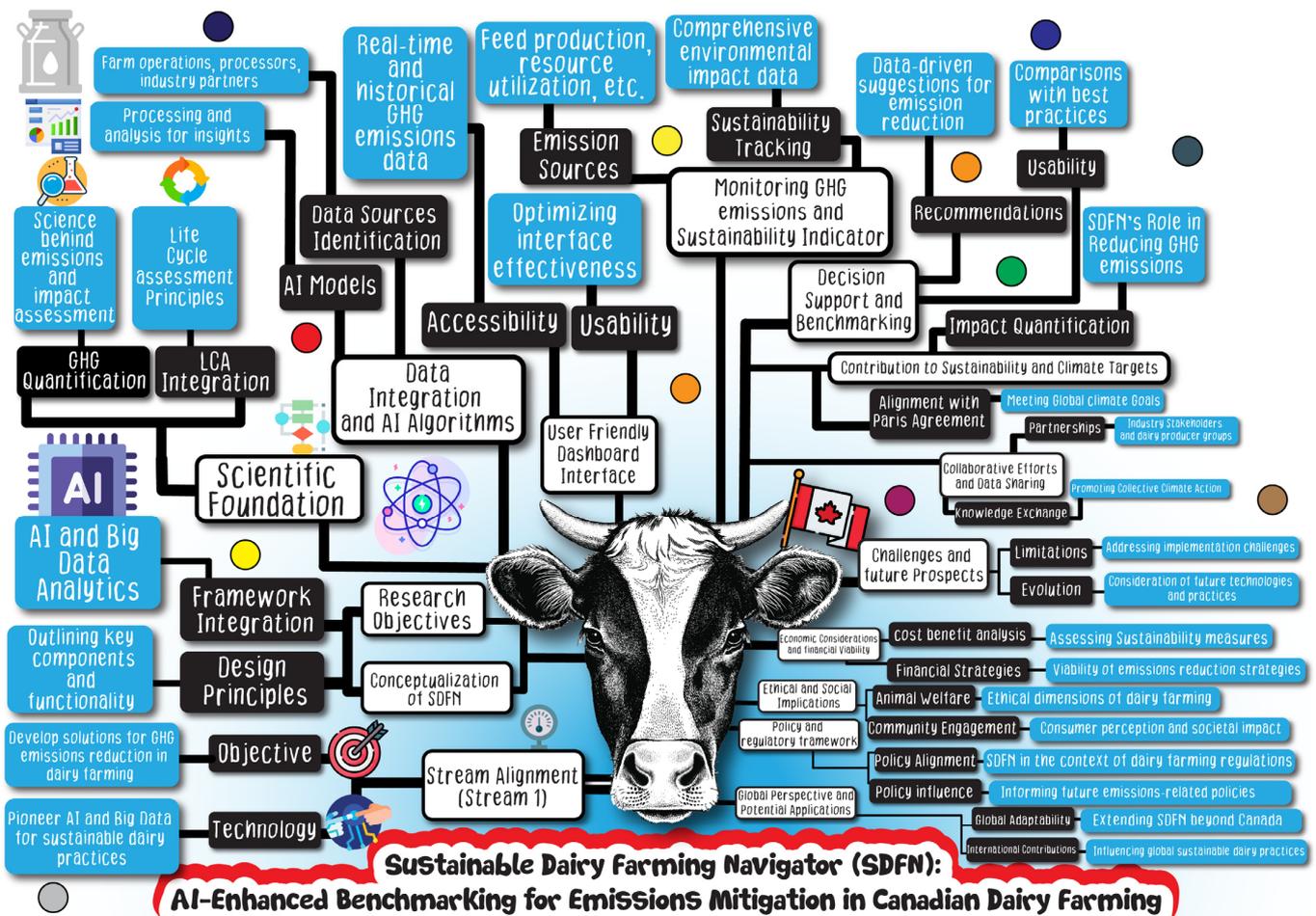


Figure 1. AI-enhanced benchmarking for emissions in Canadian dairy farming.

4.2. Leveraging Cross-Industry Insights for Dairy Farming

The dairy industry can learn from methodologies and sustainability practices from sectors like food processing, biomedicine, and industrial manufacturing. Techniques from industrial manufacturing for process optimization, energy management systems from other industries, and waste-to-resource models from food processing can be adapted to enhance sustainability in dairy farming. The implementation of Big Data, AI, and benchmarking in dairy farming represents a transformative leap towards sustainability and efficiency [49]. By leveraging these technologies, the dairy industry can achieve significant gains in environmental stewardship, resource optimization, and overall farm management. The critical role of benchmarking, particularly in emissions reduction, provides a roadmap (Table 1) for the dairy industry to align with global sustainability goals and environmental regulations. The integration of these technologies, coupled with lessons learned from other industries, paves the way for a more sustainable, efficient, and innovative future in dairy farming.

Table 1. Benchmarking of emissions in dairy industry.

Aspect of Benchmarking	Enteric Fermentation	Manure Management	Energy Use	Feed Efficiency	Water Usage
Emission Source	Methane from digestion	Methane and nitrous oxide from storage	CO ₂ from fossil fuel use	Methane from digestion	Water management related energy use
Quantification Method	CH ₄ measurements, LCA	Gas capture and analysis, LCA	Energy audits, carbon footprinting	Feed analysis, LCA	Water usage metering, energy audits
Industry Average	X kg CH ₄ /cow/year	Y kg N ₂ O/ton manure	Z kWh/liter of milk	A kg CH ₄ /ton feed	B liters/milk liter
Best Practice Standard	Low-methane feed	Aerobic composting, digesters	Renewable energy use	High-efficiency feed	Water recycling systems
Improvement Strategy	Feed additives, diet optimization	Manure treatment, efficient application	Solar, biogas energy	Precision feeding	Irrigation management, leak repairs
Monitoring Frequency	Bi-annually	Annually	Quarterly	Annually	Bi-annually
Compliance Requirement	Voluntary industry standards	Environmental regulations	Energy conservation laws	Sustainable farming certifications	Water management regulations
Technology Used	Rumen sensors, data analytics	Emission capturing systems	Smart energy meters	AI-driven feeding systems	Automated irrigation
Training Required	Feed management	Manure handling, system operation	Energy management	Nutritional management	Water conservation techniques
Cost Implication	Moderate investment	High investment	High investment for renewables	Moderate investment	Moderate investment
Potential Emission Reduction	Significant CH ₄ reduction	CH ₄ and N ₂ O reduction	Significant CO ₂ reduction	CH ₄ reduction	Energy-related emission reduction

In our comprehensive benchmarking analysis of emissions in the dairy industry, as detailed in Table 1, we systematically evaluate various aspects such as enteric fermentation, manure management, and energy use. This includes a thorough examination of emission sources, ranging from methane from digestion to CO₂ from fossil fuel use, and strategies for their quantification, like CH₄ measurements and energy audits. The industry averages for these emissions provide a baseline for setting best practice standards, which include low-methane feed and renewable energy use. Our study also outlines improvement strategies, such as diet optimization and efficient manure application, and underscores the importance of regular monitoring, compliance with environmental regulations, and the use of advanced technologies like AI-driven feeding systems for effective emission reduction.

5. The Economic and Structural Landscape of Canadian Dairy Industry

The Canadian dairy industry, integral to the country's agriculture, epitomizes a complex interplay of economic impact, diverse farm structures, and a stringent regulatory framework, all of which align to create a unique economic and structural landscape.

5.1. Industry Size and Economic Impact

As of recent data, Canada's dairy sector is a substantial component of the agricultural economy. It is not only a significant contributor to the national GDP but also a pivotal player in the rural economy. The industry is characterized by its extensive production capacity, involving thousands of dairy farms and processing facilities across the country. These farms collectively contribute billions to the national economy, underscoring the sector's economic significance. The dairy industry's impact extends beyond direct production. It encompasses a wide range of associated industries, including feed production, veterinary services, equipment supply, and transportation. This extensive value chain [50,51] amplifies the sector's economic influence, providing employment and stimulating local economies in rural and urban areas alike.

5.2. Global Market Presence

Despite its robust domestic market, the Canadian dairy industry has a relatively modest footprint in the global dairy trade. This is primarily due to the country's supply management system, which focuses on balancing domestic supply with demand, thus limiting export volumes [52,53]. However, the industry still contributes significantly to the global dairy market through specialized products and niche markets. Its reputation for quality and safety standards positions Canadian dairy products favorably in the international arena, where they command a premium.

5.3. Diversity in Farm Structures and Operations

Canadian dairy farms exhibit a diverse range of structures and operational scales. This diversity is reflective of the country's vast geographical and climatic variations. From small family-owned farms to large corporate-run facilities, the industry encompasses a wide spectrum of farming models. This structural diversity is underpinned by a common commitment to high-quality milk production, animal welfare, and sustainable farming practices. Technological integration varies across these farms, with some employing cutting-edge technologies for milking, feeding, and herd management, while others adhere to more traditional farming methods. This variation is indicative of the sector's adaptability and its ability to cater to different market needs and preferences.

5.4. Regulatory Framework Governing Canadian Dairy Farming

The Canadian dairy sector operates under a unique regulatory framework known as supply management [54]. This system, characterized by production quotas, price setting, and import controls, ensures stable income for producers and processors. It balances supply with domestic demand, protecting the industry from market volatilities and ensuring consistent quality of dairy products. Additionally, the industry adheres to strict standards regarding animal welfare and environmental sustainability. These regulations, coupled with initiatives like the ProAction program, underscore the sector's commitment to responsible farming practices. The ProAction program, in particular, sets benchmarks [55,56] in areas such as milk quality, animal health, and environmental stewardship.

5.5. Economic and Policy Challenges

Despite its strengths, the Canadian dairy industry faces several economic and policy challenges. These include adapting to changing market demands, both domestically and globally, and responding to pressures from international trade agreements. The sector also grapples with the need for continuous innovation and sustainability improvements, particularly in the face of global environmental concerns. Emerging trends, such as the

growing demand for plant-based alternatives and the increasing importance of sustainable practices, are set to shape the industry's future. Adapting to these trends while maintaining its core values and economic viability will be crucial for the sector's continued success.

6. Strategies for GHG Emission Reduction in Dairy Farming

In the pursuit of reducing greenhouse gas (GHG) emissions in dairy farming, a combination of innovative practices, technological advancements, and supportive policy initiatives plays a pivotal role. Addressing the emissions from this sector is crucial for mitigating climate change impacts given the significant contribution of dairy farming to global GHG emissions, particularly methane (CH₄) and nitrous oxide (N₂O).

6.1. Innovative Farming Practices for Emission Reduction

6.1.1. Optimized Feed Efficiency

One of the primary strategies in emission reduction is optimizing feed efficiency. Research has shown that improved feed quality and dietary adjustments can significantly reduce methane emissions from enteric fermentation. Feed additives, such as lipids, tannins, and certain enzymes, have been studied for their potential to reduce methane production during digestion [57–59]. Furthermore, precision feeding techniques, ensuring each animal receives a diet tailored to its specific needs, not only improve the feed conversion efficiency but also reduce the overall carbon footprint of the dairy operation.

6.1.2. Advanced Manure Management

Manure management represents a substantial opportunity for emission reduction. Traditional manure storage and treatment methods often lead to significant methane and nitrous oxide emissions. Implementing advanced techniques, such as anaerobic digestion, can convert manure into biogas, a renewable energy source, while significantly reducing emissions [60,61]. Moreover, innovative practices like composting and improved storage and application methods can minimize emissions from manure handling.

6.1.3. Pasture-Based Farming

Transitioning to pasture-based systems can also contribute to lowering GHG emissions. Grazing systems promote better manure distribution and can enhance soil carbon sequestration, reducing the overall carbon footprint compared to conventional confinement systems [62,63].

6.1.4. Precision Agriculture

The application of precision agriculture technologies is a game-changer in reducing emissions. Using tools such as GPS, sensors, and data analytics, dairy farmers can optimize resource use, thereby reducing emissions [64,65]. For instance, sensor-based technologies can monitor soil health and moisture levels, enabling more efficient use of fertilizers and irrigation, thereby reducing nitrous oxide emissions from synthetic fertilizers.

6.1.5. Biogas Systems

The adoption of biogas systems for energy production from dairy waste not only provides a sustainable energy source but also plays a critical role in methane emission reduction. These systems capture methane from manure and convert it into bioenergy, effectively reducing the methane emissions associated with manure management practices. The biogas produced can be used for heating, electricity generation, or even as a vehicle fuel, contributing to the overall energy sustainability of the dairy farm.

6.1.6. Carbon Capture and Storage (CCS) Technologies

Emerging CCS technologies offer potential in mitigating the climatic impact of dairy operations [66]. While still in development, these technologies aim to capture carbon emissions directly from various sources within dairy farms, including manure management

systems and energy consumption processes. Implementing CCS could play a significant role in reducing the carbon footprint of dairy farming.

6.2. Role of Policy Initiatives and Incentives in Emission Reduction

6.2.1. Federal and Provincial Incentives

Government incentives are crucial in supporting emission reduction efforts in the dairy sector [67]. These incentives can take various forms, such as funding for adopting sustainable practices, tax breaks for implementing green technologies, or technical support for transitioning to low-emission practices. For example, programs like the Sustainable Canadian Agricultural Partnership (CAP) offer financial assistance for projects aimed at improving environmental sustainability [68].

6.2.2. Carbon Pricing and Trading Systems

Implementing carbon pricing mechanisms, like carbon taxes or cap-and-trade systems, encourages emission reductions by attributing a cost to carbon emissions [69,70]. Such mechanisms can incentivize dairy farmers to adopt sustainable practices by making emission-intensive operations more costly. This economic approach can drive significant changes in the industry towards more sustainable and low-emission practices.

6.2.3. Research and Development Support

Governmental support for research and development is essential in advancing new technologies and practices for emission reduction. This includes funding for research into low-emission animal diets, manure management technologies, and precision farming tools. Partnerships between the government, academia, and the dairy industry are vital for fostering innovation and developing practical, scalable solutions for emission reduction.

6.2.4. Extension Services and Education

Providing extension services and education about sustainable practices and technologies is critical for enabling dairy farmers to effectively implement emission reduction strategies. These services can offer technical advice, training, and support, helping farmers to understand the benefits of sustainable practices and how to integrate them into their operations.

Reducing GHG emissions in dairy farming requires a multifaceted approach that incorporates innovative farming practices, technological advancements, and supportive policy frameworks [71,72]. The adoption of these strategies not only contributes to climate change mitigation but also enhances the overall sustainability and resilience of the dairy sector. Collaboration between farmers, industry stakeholders, researchers, and policymakers is essential in driving these changes and achieving substantial emission reductions in dairy farming.

7. The Future of Dairy Farming with Big Data

The integration of Big Data into dairy farming is not merely an incremental change but represents a fundamental shift in agricultural practices. By harnessing the power of vast datasets, dairy farmers can optimize various aspects of their operations, from herd management to resource utilization, ushering in a new era of efficiency and sustainability.

7.1. Emerging Technologies in Big Data for Dairy Farming

Big Data in dairy farming involves the collection, analysis, and utilization of large and complex datasets from various sources, including sensor networks, farm equipment, and environmental data inputs. These extensive data encompass information ranging from milk yield and quality metrics to animal feeding patterns, health indicators, and environmental conditions.

7.1.1. Advanced Sensors and Monitoring Systems

The deployment of advanced sensor technologies in dairy farming is reshaping the management of herd health and environmental monitoring. Sensors that track animal health indicators, such as body temperature and activity levels, along with environmental sensors measuring factors like air quality and humidity, are generating vast amounts of data. These sensors provide critical insights into the well-being of the herd and the optimization of the farm environment.

7.1.2. Data Analytics for Enhanced Decision Making

The analysis of collected data enables farmers to gain comprehensive insights into their operations. This involves using sophisticated algorithms and machine learning techniques to process and interpret complex datasets, leading to informed decision making. For instance, data-driven insights can guide feed composition adjustments, resulting in improved feed efficiency and reduced waste.

7.1.3. Predictive Modeling for Proactive Management

Utilizing predictive analytics, farmers can forecast future scenarios based on historical data trends. This proactive approach allows for early intervention in potential issues such as health problems in the herd or environmental stressors, minimizing risks and enhancing productivity.

7.2. Integration with Other Technologies: IoT and Robotics

The convergence of Big Data with the Internet of Things (IoT) and robotics is driving significant advancements in dairy farming. IoT in Dairy Farming: Integrating Big Data with IoT devices facilitates a more connected and automated farm environment [73,74]. Connected devices such as milking robots, feed dispensers, and climate control systems can generate real-time data, enhancing precision in farming operations. The integration of these devices through IoT platforms allows for seamless data flow and analytics, leading to more efficient and sustainable farm management.

Robotics and Automation

The incorporation of robotics in dairy farming, coupled with Big Data, is revolutionizing traditional practices. Automated systems for milking, feeding, and cleaning not only improve efficiency but also reduce the physical labor required. The data generated by these robotic systems contribute to a deeper understanding of farm operations, enabling continuous improvement and innovation.

7.3. Policy and Industry Implications of Technological Advancements

The advancements in Big Data and its integration with other technologies have significant implications for both policy and the dairy industry. Sustainability and Environmental Impact—Big Data technologies contribute to the environmental sustainability of dairy farms by optimizing resource use and reducing waste. This aligns with global efforts to minimize agriculture's environmental footprint, particularly concerning greenhouse gas emissions. Policies encouraging the adoption of such technologies can support the industry's transition towards more sustainable practices.

7.3.1. Regulatory Frameworks for Data Use and Privacy

The use of Big Data raises important considerations regarding data privacy and security. Regulatory frameworks need to be established to protect sensitive farm data, ensure their ethical use, and clarify issues around data ownership and control [75,76]. Policymakers must balance the need for data protection with the potential benefits of data sharing and utilization in the industry.

7.3.2. Industry Adaptation and Skill Development

As dairy farming becomes increasingly data-driven, there is a growing need for skills development in this area. Training and educational programs focusing on data analytics, IoT, and robotics are essential for preparing the current and future workforce. The industry must adapt to these technological changes by fostering a culture of continuous learning and innovation.

7.3.3. Economic Considerations and Market Adaptation

The economic implications of adopting Big Data technologies in dairy farming cannot be overlooked. While the initial investment may be substantial, the long-term benefits in terms of efficiency, productivity, and sustainability can offer a significant return on investment. The market readiness to accept and integrate these technologies is also a crucial factor, influencing their widespread adoption and economic viability.

7.4. Digital Technology's Role in Enhancing Dairy Farm Emission Efficiency

In their 2023 study, Liu et al. [77] provide a comprehensive analysis of how digital technology applications enhance carbon emission efficiency in dairy farms. Utilizing a robust methodology involving the Undesirable Outputs-SBM model, Tobit model, propensity score matching, quantile regression model, and an instrumental variable approach, the study examines 136 Chinese dairy farms. The focus is on the impact of digital technology, particularly precision feeding, on carbon emission efficiency, and how environmental regulations modulate this relationship.

The key findings reveal that digital technology significantly improves carbon emission efficiency, with the most substantial impact observed in farms with lower initial efficiency levels. Precision feeding technology emerges as the most effective, followed by manure treatment, environmental monitoring, and cow monitoring technologies. The study also highlights the critical role of environmental regulations in enhancing this effect; more stringent regulations amplify the positive impact of digital technology on emission efficiency.

Further, the study underscores the influence of factors such as farmers' educational background and technical training in adopting digital technologies. It notes that implementation of digital technology could potentially increase carbon emission efficiency by 11.61% in dairy farms. This finding emphasizes the need for enhanced educational and policy initiatives to promote digital technology use in dairy farming, aligning with low-carbon and efficient production goals.

The research by Liu et al., (2023) [77] provides empirical evidence on the pivotal role of digital technologies in reducing carbon emissions in the dairy industry, highlighting the need for supportive educational and regulatory environments to maximize these technologies' benefits.

8. Artificial Intelligence in Emission Management and Energy Efficiency in Dairy Farming

Artificial Intelligence (AI) has emerged as a pivotal tool in the agricultural sector, particularly in dairy farming, where it offers substantial potential for improving emission management and enhancing energy efficiency. The deployment of AI in this context addresses two critical areas: predictive analytics for optimizing feed and manure management, and monitoring of and reduction in energy use. AI's role in emission management and energy efficiency in dairy farming is multidimensional and highly impactful. As AI technology advances, its integration into dairy farming practices promises to drive significant improvements in environmental sustainability, operational efficiency, and economic viability. The key to realizing these benefits lies in overcoming the current challenges and continuing innovation and development in AI applications specific to the dairy industry. This evolution of AI in dairy farming not only contributes to reducing the environmental footprint of the sector but also aligns with the broader goals of sustainable agriculture and climate change mitigation.

The application of Artificial Intelligence (AI) in feed optimization for dairy farming involves the development and implementation of algorithms capable of analyzing extensive datasets. These algorithms are designed to predict the most efficient feed compositions and schedules, taking into account individual animal health, milk production, and varying environmental conditions [78,79]. This data analysis is critical in understanding how different feeds impact milk yield, quality, and the overall health of the herd.

A significant focus of feed optimization using AI is the reduction in methane emissions produced during enteric fermentation. AI models are equipped to suggest dietary adjustments that minimize methane production, considering breed-specific responses and the diverse nutritional needs of the herd. Optimizing feed through AI not only contributes to reducing methane emissions but also enhances feed efficiency. This leads to lower production costs and a reduced environmental impact while simultaneously improving animal health and productivity.

In the realm of manure management, another critical area for reducing greenhouse gas emissions in dairy farming, AI systems offer significant benefits. They can predict optimal times and methods for manure application, storage, and processing, taking into account external factors such as weather patterns and soil conditions. This guidance helps farmers make decisions that not only reduce emissions but also enhance soil quality.

AI's role extends to optimizing anaerobic digestion processes, where it can improve the conversion of manure into biogas, thereby reducing methane emissions. By determining the optimal mix of manure and other organic wastes, AI models ensure maximum biogas production with minimum greenhouse gas emissions. This optimization is a testament to AI's growing significance in enhancing environmental sustainability in dairy farming practices.

AI in Monitoring and Reducing Energy Use

Energy management is a critical aspect where AI can make a significant impact. The application of AI in energy use within dairy farms entails:

AI-driven smart energy systems are increasingly pivotal in managing and optimizing energy consumption on dairy farms. These sophisticated systems utilize AI algorithms to forecast energy needs and effectively integrate renewable energy sources. For example, AI can optimize the use of solar panels or biogas, a renewable energy source generated from manure, enhancing the energy efficiency of dairy farming operations.

In the realm of energy consumption, AI algorithms excel in monitoring and analyzing patterns across various dairy farm operations, including milking, cooling, and processing [80]. This monitoring is instrumental in identifying areas where energy consumption can be reduced and more efficient practices can be implemented. By pinpointing these areas, dairy farms can significantly cut down on energy usage, contributing to both economic and environmental sustainability.

Another crucial aspect of AI in dairy farming is predictive maintenance. AI can accurately predict when machinery or equipment requires maintenance, thereby avoiding energy wastage due to inefficient operation. This predictive maintenance ensures that farm equipment operates at optimal energy efficiency, leading to a reduction in unnecessary energy consumption and associated costs.

The integration of AI with renewable energy sources on dairy farms offers a promising pathway toward reducing dependence on fossil fuels. AI can skillfully balance the use of renewable energy sources with traditional energy sources. This balance is essential for maintaining a consistent energy supply and minimizing the carbon footprint of dairy farming operations. Additionally, AI systems are adept at forecasting weather conditions and energy requirements. This capability aids in planning and optimizing the use of renewable energy sources, such as solar and wind energy, on dairy farms. This integration not only enhances energy efficiency but also supports the broader goal of sustainable and environmentally responsible dairy farming.

9. Future Pathways—Implementing AI and Big Data in Dairy Farming for Climate Change Mitigation and Emissions Reduction

In envisioning a roadmap for future research and application of AI and Big Data in dairy farming (Figure 2), particularly in addressing climate change challenges and emissions reduction, a strategic and methodical approach is required. This roadmap should encompass both immediate and long-term strategies, integrating the latest advancements in technology with practical on-the-ground farming practices.

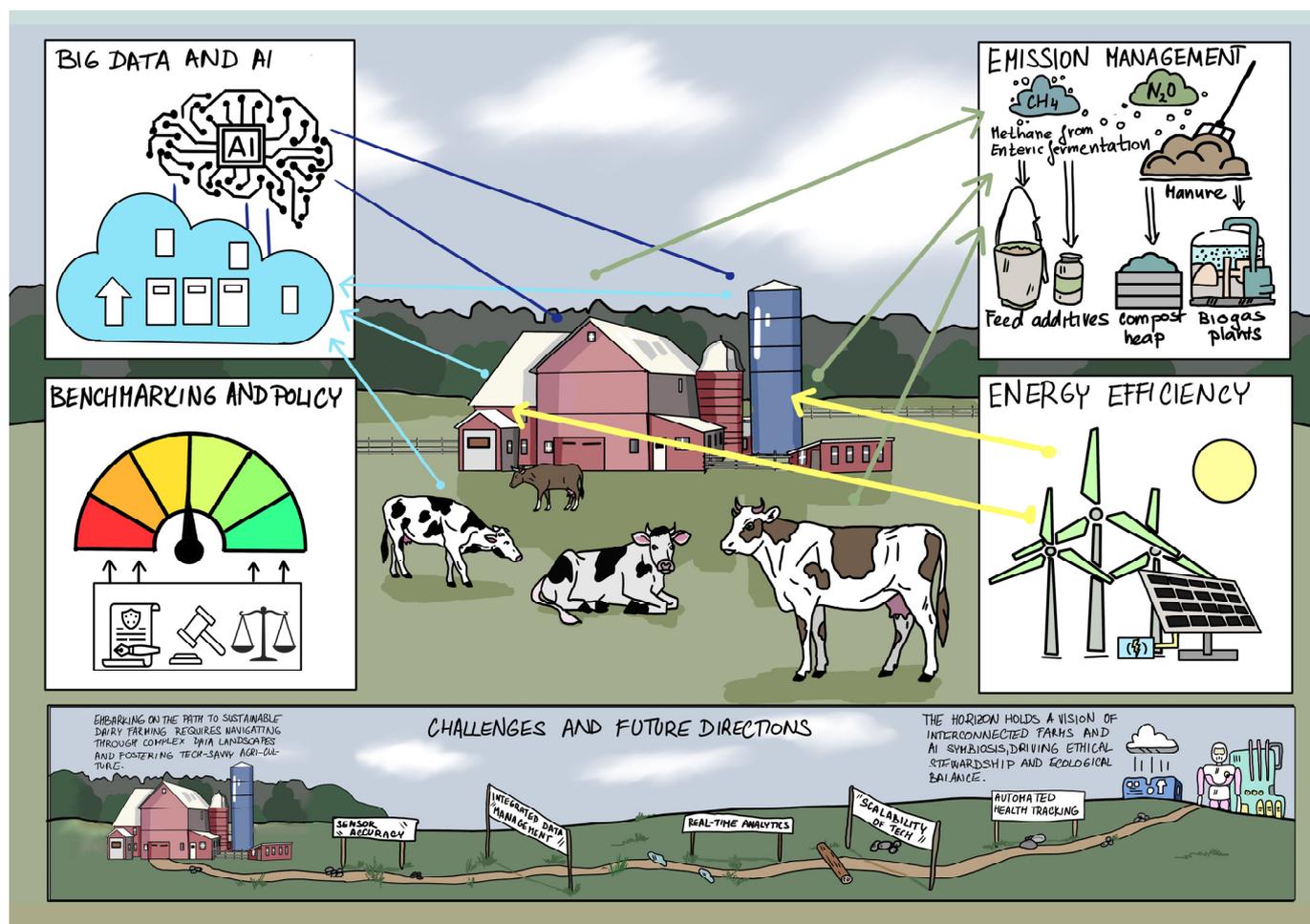


Figure 2. Harnessing Big Data and AI for sustainable dairy farming—a visual guide to emission reduction and benchmarking.

9.1. Immediate Strategies

9.1.1. Enhanced Data Collection and Analysis

- Invest in sensor technologies and IoT devices to collect comprehensive data on various aspects of dairy farming, including feed intake, animal health, and manure management.
- Utilize advanced data analytics and machine learning algorithms to process these data, identifying patterns and correlations that can inform more sustainable farming practices.

9.1.2. Predictive Analytics for Resource Optimization

- Develop AI models that can predict optimal feeding strategies, reducing waste and improving the efficiency of resource use.
- Implement systems that can forecast environmental impacts and provide recommendations for minimizing carbon footprints.

9.2. Long-Term Strategies

9.2.1. Integration of Climate Models with Farm Management Systems

- Collaborate with climate scientists to integrate global and regional climate models into AI-driven farm management systems.
- Use these integrated models to anticipate and mitigate the impacts of climate variability on dairy farming operations.

9.2.2. Development of AI-Driven Sustainable Practices

- Focus on AI innovations that promote sustainable practices, such as precision agriculture techniques to optimize the use of water, fertilizers, and energy.
- Explore AI-based solutions for managing waste and manure in environmentally friendly ways, such as converting waste into renewable energy sources.

9.3. Cross-Disciplinary Collaboration and Knowledge Sharing

Fostering Industry–Academia Partnerships

- Encourage partnerships between dairy farmers, technology companies, and academic institutions to drive innovation and research in AI and Big Data applications.
- Facilitate knowledge sharing and technology transfer through workshops, conferences, and joint research projects.

9.4. Policy Advocacy and Support for Technological Adoption

- Engage with policymakers to advocate for support and funding for the adoption of AI and Big Data technologies in dairy farming.
- Work towards the development of regulatory frameworks that encourage innovation while ensuring ethical and sustainable use of technology.

9.5. Adaptive and Evolving Methodologies

Continuous Improvement and Adaptation

- Establish a culture of continuous improvement, where technologies and methodologies are regularly reviewed and updated based on new research and changing climate conditions.
- Embrace adaptive management approaches that allow for flexibility and responsiveness to new challenges and opportunities.

9.6. Monitoring and Evaluation

- Implement robust monitoring and evaluation systems to assess the effectiveness of AI and Big Data applications in reducing emissions and addressing climate change.
- Use these assessments to refine and improve strategies over time, ensuring that the dairy farming industry can effectively contribute to global climate change mitigation efforts.

By following this roadmap, the dairy farming industry can not only significantly reduce its environmental impact but also enhance productivity and resilience in the face of climate change. This comprehensive approach, blending cutting-edge technology with practical farming practices and policy support, paves the way for a more sustainable and environmentally responsible future in dairy farming.

10. Challenges and Future Directions

The integration of Artificial Intelligence (AI) in dairy farming, while holding immense potential, faces several challenges that need to be addressed for wider adoption and effective utilization. One of the primary challenges is the complexity of integrating AI with existing farming systems. This integration is not just a matter of software compatibility; it requires the systems to effectively process and analyze diverse data types, which is essential for the AI to function optimally.

Another critical issue involves the quality and availability of data, which are foundational for the effectiveness of AI. The performance of AI systems can be significantly hindered by inconsistent data recording practices and the limited availability of comprehensive data. This challenge underscores the need for standardized, high-quality data collection practices in the dairy farming sector.

Moreover, the successful implementation of AI in dairy farming hinges on the training and adaptation of farmers. It is imperative for farmers to receive adequate training to understand and manage AI systems effectively. This aspect involves overcoming potential resistance to new technologies and facilitating a smooth transition from traditional farming practices to more technologically advanced methods.

Looking towards future advancements, several key developments are anticipated to enhance the role of AI in dairy farming. One such advancement is the continuous improvement in the accuracy of AI algorithms, which will lead to more efficient and effective farm management practices. Additionally, the integration of AI with Internet of Things (IoT) devices is expected to play a significant role. This integration will provide more detailed and granular data, further optimizing farm operations and energy usage.

Furthermore, the development of customized AI solutions tailored to the specific needs of different farming operations will greatly enhance the applicability and effectiveness of AI in the dairy industry. These customized solutions will address the unique challenges and requirements of various farming setups, thereby maximizing the benefits of AI in dairy farming.

While the integration of AI in dairy farming presents challenges, the future holds promising advancements that will likely overcome these hurdles. Continuous improvements in AI technology, coupled with better integration and customization, are poised to transform dairy farming into a more efficient, sustainable, and economically viable sector.

Addressing Challenges and Enhancing Policies for Sustainable Transformation

Addressing the multifaceted challenges and enhancing policies for a sustainable transformation in dairy farming involves navigating through technological, economic, and policy barriers. These barriers need to be methodically addressed to facilitate the transition to more sustainable practices. Simultaneously, it is crucial to ensure that technological advancements are harmonized with ethical farming practices.

Table 2 presents a comprehensive policy framework essential for sustainable transformation in the dairy farming industry. It details various policy focuses, from establishing benchmarking standards to promoting Big Data utilization and integrating AI technologies, which collectively aim to enhance farm efficiency and achieve significant reductions in greenhouse gas emissions. The table also highlights the key components of each policy, the stakeholders involved, the challenges faced, and the potential outcomes. This framework serves as a roadmap for stakeholders at various levels, including farmers, industry regulators, tech companies, and government bodies, guiding the industry towards a sustainable and environmentally responsible future while balancing economic viability.

Table 2. Policy framework for sustainable transformation in dairy farming.

Policy Focus	Objective	Key Components	Stakeholders Involved	Challenges	Potential Outcomes
Benchmarking Standards	Establish industry-wide benchmarking standards for emissions and efficiency	Comparative analysis, Best practices, Performance metrics	Farmers, Industry regulators, Environmental agencies	Standardization across diverse farm operations	Consistent quality and sustainability metrics across the industry

Table 2. Cont.

Policy Focus	Objective	Key Components	Stakeholders Involved	Challenges	Potential Outcomes
Big Data Utilization	Promote the use of Big Data for farm management optimization	Data collection, Analysis tools, Real-time monitoring	Farmers, Tech companies, Data analysts	Managing large datasets, Interpreting complex information.	Optimized farm operations, Enhanced decision making
Emission Reduction Targets	Set clear and achievable emission reduction targets	Methane and N ₂ O reduction, Carbon footprint assessment	Government, Environmental groups, Dairy producers	Balancing economic viability with environmental goals.	Significant reduction in greenhouse gas emissions
AI Integration in Farming	Facilitate the integration of AI technologies in dairy farming	Predictive analytics, Herd management, Resource optimization	Tech developers, Farmers, AI experts	Adapting to new technologies, Overcoming resistance	Increased farm efficiency and reduced labor costs
Data Privacy and Security	Ensure the security and privacy of farm data collected via digital means.	Data encryption, User consent, Ethical use guidelines	Farmers, Data protection agencies, Legal experts	Risk of data breaches, Maintaining farmer trust	Protected farmer data, Ethical technology usage
Renewable Energy Incentives	Encourage the use of renewable energy sources through incentives.	Subsidies, Tax breaks, Green energy solutions	Energy companies, Farmers, Government bodies	Initial investment costs, Long-term sustainability	Reduced carbon footprint, Energy self-sufficiency
Education and Training	Enhance farmer knowledge and skills in advanced technologies	Workshops, Online courses, Technical assistance	Educational institutions, Dairy farmers, Industry experts	Varied technological proficiency among farmers	Improved adoption of advanced farming technologies
Public-Private Partnerships	Foster collaboration between government, industry, and academia	Joint funding, Knowledge exchange, Innovation incubators	Government, Corporates, Research institutions	Aligning goals and resources of different entities	Synergy in innovation, Accelerated technology transfer
Environmental Regulation	Implement stringent environmental regulations to control emissions.	Compliance standards, Monitoring, Penalties for non-compliance	Regulatory bodies, Dairy farmers, Environmentalists	Ensuring regulations are effective yet feasible	Enhanced environmental protection, Sustainable dairy practices.
Innovation and R&D Support	Support research and development in sustainable dairy farming technologies.	Innovative feed solutions, Waste management, Energy-efficient practices	Scientists, Dairy industry, Government funders	Translating research into practical, scalable solutions	Breakthroughs in sustainable farming techniques

11. Overcoming Technological, Economic, and Policy Barriers

Technological barriers in dairy farming often stem from the complexity of integrating new technologies with existing systems. This includes ensuring compatibility with current hardware and software and effectively processing diverse data types. To overcome these challenges, there is a need for technologies that are adaptable, user-friendly, and can seamlessly integrate with various farming operations. Additionally, addressing data quality and availability is crucial. Inconsistent data recording practices and limited data availability can impede AI systems’ performance. Establishing standardized data collection methods and ensuring the availability of high-quality, comprehensive datasets are imperative.

Economic barriers, primarily the high costs associated with adopting new technologies, pose a significant hurdle. This is particularly challenging for small- and medium-sized

farms. Addressing these barriers requires the implementation of financial incentives such as subsidies, grants, or tax breaks to make investments more feasible for farmers. Moreover, demonstrating the long-term economic benefits of these technologies through case studies and pilot projects can encourage broader adoption.

Policy barriers often involve existing regulations that are not adapted to new technologies, hindering their implementation. To address this, regulatory frameworks need regular review and reform to keep pace with technological advancements. This includes relaxing certain regulatory barriers and developing standards that encourage innovation while ensuring safety and sustainability.

11.1. Enhancing Policies for Emission Reduction and Sustainable Practices

Enhancing policies to support emission reduction and sustainable practices in dairy farming is essential. This can be achieved by developing and implementing policies that support the transition to sustainable dairy farming, providing a regulatory environment that encourages the adoption of sustainable practices. Governments can play a pivotal role by offering financial incentives and investing in research and development of sustainable dairy farming technologies.

Creating sustainability guidelines is also critical. Policymakers should establish guidelines that promote sustainability and environmental responsibility in dairy farming, ensuring that the industry's growth aligns with environmental conservation goals. This could involve setting clear, measurable emission reduction targets specific to the dairy sector, aligning with broader sustainability goals.

11.2. Balancing Technological Advancement with Ethical Farming Practices

The integration of technology in dairy farming should complement, not replace, traditional farming practices. It should respect the cultural heritage of farming communities and adapt to fit within their existing cultural framework. This includes developing technologies that enhance rather than overhaul existing practices and ensuring that technological development involves farmers in the design process.

Ensuring equity and inclusivity in technological advancement is crucial. Technologies must be accessible to all farmers, including smallholders and family-owned farms, and training and support must be provided to ensure that farmers have the knowledge and skills to effectively utilize these tools.

Regulatory and policy frameworks should establish clear guidelines for the ethical use of technology in dairy farming. These guidelines could cover aspects such as data privacy, animal welfare, and labor rights. Effective regulatory frameworks should also include mechanisms for monitoring the implementation of technology and enforcing compliance with ethical standards.

Addressing challenges and enhancing policies for sustainable transformation in dairy farming requires a multifaceted approach. By overcoming technological, economic, and policy barriers, enhancing policies for emission reduction and sustainable practices, and ensuring that technological advancements are balanced with ethical farming practices, the dairy industry can move towards a more sustainable and environmentally responsible future. This transition not only aligns with environmental imperatives but also ensures the economic viability and cultural sustainability of the dairy farming sector.

12. Summary and Conclusions

Dairy processing, an energy-intensive process, significantly contributes to GHG emissions. Mitigating these emissions involves transitioning to renewable energy sources and implementing energy efficiency measures. Innovations like waste heat recovery and the use of energy-efficient equipment can reduce the energy footprint of dairy processing, decreasing operational costs and GHG emissions.

The advent of Big Data and AI has revolutionized dairy farming, offering enhanced efficiency, improved sustainability, and innovative management practices. These tech-

nologies address challenges in resource optimization and herd health management. Big Data analytics, involving collecting and analyzing extensive data, enables farmers to make informed decisions for productivity and sustainability. AI brings sophistication to herd management and resource optimization, with applications in predictive analytics for feed optimization and manure management. Benchmarking for performance and sustainability, involving comparing farm performance against industry standards, helps in identifying improvement areas and ensuring compliance with environmental standards.

The implementation of Big Data and AI in dairy farming marks a transformative leap towards sustainability and efficiency. By leveraging these technologies, the dairy industry can make significant gains in environmental stewardship, resource optimization, and overall farm management. However, this transformation also brings challenges, including integrating AI with existing farming systems, ensuring data quality, and farmer training. Addressing these challenges involves developing adaptable, user-friendly technologies, standardized data collection methods, and comprehensive farmer training programs.

Policies play a crucial role in supporting this transformation. Governments can offer financial incentives, invest in research and development, and implement sustainability guidelines. Creating a regulatory environment that encourages the adoption of sustainable practices and aligns industry growth with environmental conservation goals is essential. The study concludes that a multifaceted approach is needed to address technological, economic, and policy barriers and enhance policies for emission reduction and sustainable practices. The integration of technology in dairy farming should complement traditional practices and respect the cultural heritage of farming communities. Ensuring equity and inclusivity in technological advancement is crucial, as is establishing guidelines for the ethical use of technology in dairy farming.

By overcoming these challenges and enhancing policies for sustainable transformation, the dairy industry can progress towards a more sustainable and environmentally responsible future. This transition not only aligns with environmental imperatives but also ensures the economic viability and cultural sustainability of the dairy farming sector. The integration of Big Data and AI emerges as a crucial factor in this journey towards sustainability, offering innovative solutions to reduce GHG emissions and optimize resource use, thereby contributing significantly to global efforts in environmental sustainability.

Funding: This research received no external funding.

Conflicts of Interest: The author declares no conflicts of interest.

References

1. Easterling, D.R.; Kunkel, K.E. Climate Change in the Earth System. In *Climate Change and Estuaries*; CRC Press: Boca Raton, FL, USA, 2023; pp. 23–42.
2. Sudo, K. Atmospheric Mixing Ratios of Ozone and Radiative Forcing. In *Handbook of Air Quality and Climate Change*; Springer Nature Singapore: Singapore, 2023; pp. 997–1029.
3. Pouresmaeily, M. Ecological Responses to Climate Change. In *Climate Change: The Social and Scientific Construct*; Springer International Publishing: Cham, Switzerland, 2022; pp. 133–149.
4. Falkenberg, L.J.; Bellerby, R.G.; Connell, S.D.; Fleming, L.E.; Maycock, B.; Russell, B.D.; Sullivan, F.J.; Dupont, S. Ocean acidification and human health. *Int. J. Environ. Res. Public Health* **2020**, *17*, 4563. [[CrossRef](#)]
5. Rogelj, J.; Geden, O.; Cowie, A.; Reisinger, A. Three ways to improve net-zero emissions targets. *Nature* **2021**, *591*, 365–368. [[CrossRef](#)]
6. McLaren, D.P.; Tyfield, D.P.; Willis, R.; Szerszynski, B.; Markusson, N.O. Beyond “net-zero”: A case for separate targets for emissions reduction and negative emissions. *Front. Clim.* **2019**, *1*, 4. [[CrossRef](#)]
7. Huang, M.T.; Zhai, P.M. Achieving Paris Agreement temperature goals requires carbon neutrality by middle century with far-reaching transitions in the whole society. *Adv. Clim. Change Res.* **2021**, *12*, 281–286. [[CrossRef](#)]
8. Wilberforce, T.; Olabi, A.G.; Sayed, E.T.; Elsaid, K.; Abdelkareem, M.A. Progress in carbon capture technologies. *Sci. Total Environ.* **2021**, *761*, 143203. [[CrossRef](#)]
9. Mentes, M. Sustainable development economy and the development of green economy in the European Union. *Energy Sustain. Soc.* **2023**, *13*, 32. [[CrossRef](#)]
10. Petri, F.; Biedenkopf, K. “United we stand, divided we fall”: The effects of US contestation on EU foreign climate policy ambition. *Glob. Aff.* **2020**, *6*, 381–397. [[CrossRef](#)]

11. Hughes, L. Warming of 1.5 °C What we do now matters more than ever. *ReNew Technol. Sustain. Future* **2019**, *146*, 24–27.
12. Stern, N.; Valero, A. Innovation, growth and the transition to net-zero emissions. *Res. Policy* **2021**, *50*, 104293. [[CrossRef](#)]
13. Wattiaux, M.A.; Uddin, M.E.; Letelier, P.; Jackson, R.D.; Larson, R.A. Invited Review: Emission and mitigation of greenhouse gases from dairy farms: The cow, the manure, and the field. *Appl. Anim. Sci.* **2019**, *35*, 238–254. [[CrossRef](#)]
14. Gavrilova, O.; Leip, A.; Dong, H.; MacDonald, J.D.; Gomez Bravo, C.A.; Amon, B.; Barahona Rosales, R.; Prado, A.D.; de Lima, M.A.; Oyhantcabal, W.; et al. *Emissions from Livestock and Manure Management*; IPCC: Geneva, Switzerland, 2019.
15. Windfeld, E.; Lhermie, G. The value of Canadian agriculture: Direct, indirect, and induced economic impacts. *Front. Sustain. Food Syst.* **2022**, *6*, 940968. [[CrossRef](#)]
16. Biden, S.; Ker, A.P.; Duff, S. Impacts of trade liberalization in Canada’s supply managed dairy industry. *Agric. Econ.* **2020**, *51*, 535–552. [[CrossRef](#)]
17. Berton, M.; Bovolenta, S.; Corazzin, M.; Gallo, L.; Pinterits, S.; Ramanzin, M.; Ressi, W.; Spigarelli, C.; Zuliani, A.; Sturaro, E. Environmental impacts of milk production and processing in the Eastern Alps: A “cradle-to-dairy gate” LCA approach. *J. Clean. Prod.* **2021**, *303*, 127056. [[CrossRef](#)]
18. Clay, N.; Garnett, T.; Lorimer, J. Dairy intensification: Drivers, impacts and alternatives. *Ambio* **2020**, *49*, 35–48. [[CrossRef](#)]
19. Biagetti, E.; Gislou, G.; Martella, A.; Zucali, M.; Bava, L.; Franco, S.; Sandrucci, A. Comparison of the use of life cycle assessment and ecological footprint methods for evaluating environmental performances in dairy production. *Sci. Total Environ.* **2023**, *905*, 166845. [[CrossRef](#)]
20. Cholewińska, P.; Czyż, K.; Nowakowski, P.; Wyrstek, A. The microbiome of the digestive system of ruminants—A review. *Anim. Health Res. Rev.* **2020**, *21*, 3–14. [[CrossRef](#)]
21. Ungerfeld, E.M.; Cancino-Padilla, N.; Vera-Aguilera, N. Fermentation in the rumen. In *Microbial Fermentations in Nature and as Designed Processes*; Hurst, C.J., Ed.; Wiley: Hoboken, NJ, USA, 2023; pp. 133–165.
22. Liu, S.; Proudman, J.; Mitloehner, F.M. Rethinking methane from animal agriculture. *CABI Agric. Biosci.* **2021**, *2*, 1–13. [[CrossRef](#)]
23. Dobson, S.; Goodday, V.; Winter, J. If it matters, measure it: A review of methane sources and mitigation policy in Canada. *Int. Rev. Environ. Resour. Econ.* **2023**, *16*, 309–429. [[CrossRef](#)]
24. Parker, K. “Cow-nting down”: Regulatory measures to reduce New Zealand’s biogenic methane emissions. *N. Z. J. Environ. Law* **2021**, *25*, 191–215.
25. Beauchemin, K.A.; Ungerfeld, E.M.; Eckard, R.J.; Wang, M. Fifty years of research on rumen methanogenesis: Lessons learned and future challenges for mitigation. *Animal* **2020**, *14*, s2–s16. [[CrossRef](#)]
26. Honan, M.; Feng, X.; Tricarico, J.M.; Kebreab, E. Feed additives as a strategic approach to reduce enteric methane production in cattle: Modes of action, effectiveness and safety. *Anim. Prod. Sci.* **2022**, *62*, 1303–1317. [[CrossRef](#)]
27. Rivera, J.E.; Chará, J. CH₄ and N₂O emissions from cattle excreta: A review of main drivers and mitigation strategies in grazing systems. *Front. Sustain. Food Syst.* **2021**, *5*, 657936. [[CrossRef](#)]
28. Costa, C.; Wironen, M.; Racette, K.; Wollenberg, E.K. *Global Warming Potential*(GWP*): Understanding the Implications for Mitigating Methane Emissions in Agriculture*; CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS); Wageningen, The Netherlands, 2021.
29. Rotz, A.; Stout, R.; Leytem, A.; Feyereisen, G.; Waldrip, H.; Thoma, G.; Holly, M.; Bjerneberg, D.; Baker, J.; Vadas, P.; et al. Environmental assessment of United States dairy farms. *J. Clean. Prod.* **2021**, *315*, 128153. [[CrossRef](#)]
30. Khoshnevisan, B.; Duan, N.; Tsapekos, P.; Awasthi, M.K.; Liu, Z.; Mohammadi, A.; Angelidaki, I.; Tsang, D.C.; Zhang, Z.; Pan, J.; et al. A critical review on livestock manure biorefinery technologies: Sustainability, challenges, and future perspectives. *Renew. Sustain. Energy Rev.* **2021**, *135*, 110033. [[CrossRef](#)]
31. O’Brien, P.L.; Hatfield, J.L. Dairy Manure and Synthetic Fertilizer: A Meta-Analysis of Crop Production and Environmental Quality. *Agrosyst. Geosci. Environ.* **2019**, *2*, 1–12. [[CrossRef](#)]
32. Woolery, S.; Osei, E.; Yu, M.; Guney, S.; Lovell, A.; Jafri, H. The Carbon Footprint of a 5000-Milking-Head Dairy Operation in Central Texas. *Agriculture* **2023**, *13*, 2109. [[CrossRef](#)]
33. Arvidsson Segerkvist, K.; Hansson, H.; Sonesson, U.; Gunnarsson, S. Research on environmental, economic, and social sustainability in dairy farming: A systematic mapping of current literature. *Sustainability* **2020**, *12*, 5502. [[CrossRef](#)]
34. Ravishankara, A.R.; Daniel, J.S.; Portmann, R.W. Nitrous oxide (N₂O): The dominant ozone-depleting substance emitted in the 21st century. *Science* **2009**, *326*, 123–125. [[CrossRef](#)]
35. Neethirajan, S. Artificial Intelligence and Sensor Technologies in Dairy Livestock Export: Charting a Digital Transformation. *Sensors* **2023**, *23*, 7045. [[CrossRef](#)]
36. Neethirajan, S. The role of sensors, big data and machine learning in modern animal farming. *Sens. Bio-Sens. Res.* **2020**, *29*, 100367. [[CrossRef](#)]
37. Neethirajan, S. AI-Driven Climate Neutrality in Dairy Farming: Benchmarking Emissions for Sustainable Transformation. 2023. Available online: <https://osf.io/preprints/osf/4znq5> (accessed on 15 December 2023).
38. Pitta, D.W.; Indugu, N.; Melgar, A.; Hristov, A.; Challa, K.; Vecchiarelli, B.; Hennessy, M.; Narayan, K.; Duval, S.; Kindermann, M.; et al. The effect of 3-nitrooxypropanol, a potent methane inhibitor, on ruminal microbial gene expression profiles in dairy cows. *Microbiome* **2022**, *10*, 1–21. [[CrossRef](#)]
39. Fouts, J.Q.; Honan, M.C.; Roque, B.M.; Tricarico, J.M.; Kebreab, E. Enteric methane mitigation interventions. *Transl. Anim. Sci.* **2022**, *6*, txac041. [[CrossRef](#)]

40. Oibileke, K.; Nwokolo, N.; Makaka, G.; Mukumba, P.; Onyeaka, H. Anaerobic digestion: Technology for biogas production as a source of renewable energy—A review. *Energy Environ.* **2021**, *32*, 191–225. [[CrossRef](#)]
41. Malliaroudaki, M.I.; Watson, N.J.; Ferrari, R.; Nchari, L.N.; Gomes, R.L. Energy management for a net zero dairy supply chain under climate change. *Trends Food Sci. Technol.* **2022**, *126*, 153–167.
42. Malliaroudaki, M.I.; Watson, N.J.; Glover, Z.J.; Nchari, L.N.; Gomes, R.L. Net zero roadmap modelling for sustainable dairy manufacturing and distribution. *Chem. Eng. J.* **2023**, *475*, 145734. [[CrossRef](#)]
43. Paris, B.; Vandorou, F.; Tyris, D.; Balafoutis, A.T.; Vaiopoulos, K.; Kyriakarakos, G.; Manolakos, D.; Papadakis, G. Energy use in the EU livestock sector: A review recommending energy efficiency measures and renewable energy sources adoption. *Appl. Sci.* **2022**, *12*, 2142. [[CrossRef](#)]
44. Bertoglio, R.; Corbo, C.; Renga, F.M.; Matteucci, M. The digital agricultural revolution: A bibliometric analysis literature review. *IEEE Access* **2021**, *9*, 134762–134782. [[CrossRef](#)]
45. Neethirajan, S.; Kemp, B. Digital livestock farming. *Sens. Bio-Sens. Res.* **2021**, *32*, 100408. [[CrossRef](#)]
46. Neethirajan, S. SOLARIA-SensOr-driven resiliEnt and adaptive monitoRIng of farm Animals. *Agriculture* **2023**, *13*, 436. [[CrossRef](#)]
47. Kofler, J.; Suntinger, M.; Mayerhofer, M.; Linke, K.; Maurer, L.; Hund, A.; Fiedler, A.; Duda, J.; Egger-Danner, C. Benchmarking based on regularly recorded claw health data of Austrian dairy cattle for implementation in the Cattle Data Network (RDV). *Animals* **2022**, *12*, 808. [[CrossRef](#)]
48. Pouloupoulou, I.; Zanon, T.; Alrhoun, M.; Katzenberger, K.; Holighaus, L.; Gauly, M. Development of a benchmarking tool to assess the welfare of dairy cattle on small-scale farms. *J. Dairy Sci.* **2023**, *106*, 6464–6475. [[CrossRef](#)]
49. Kakani, V.; Nguyen, V.H.; Kumar, B.P.; Kim, H.; Pasupuleti, V.R. A critical review on computer vision and artificial intelligence in food industry. *J. Agric. Food Res.* **2020**, *2*, 100033. [[CrossRef](#)]
50. Grandsir, C.; Falagán, N.; Alamar, M.C. Application of novel technologies to reach net-zero greenhouse gas emissions in the fresh pasteurised milk supply chain: A review. *Int. J. Dairy Technol.* **2023**, *76*, 38–50. [[CrossRef](#)]
51. Snorek, J.; Cummings, W.; Hryniewicz, E.; Stevens, K.; Iannuzzi, R. Diversification strategies for the resilience of small New England dairies. *J. Agric. Food Syst. Community Dev.* **2023**, *12*, 1–21. [[CrossRef](#)]
52. Mazzetto, A.M.; Falconer, S.; Ledgard, S. Mapping the carbon footprint of milk production from cattle: A systematic review. *J. Dairy Sci.* **2022**, *105*, 9713–9725. [[CrossRef](#)]
53. Auclair, O.; Burgos, S.A. Carbon footprint of Canadian self-selected diets: Comparing intake of foods, nutrients, and diet quality between low-and high-greenhouse gas emission diets. *J. Clean. Prod.* **2021**, *316*, 128245. [[CrossRef](#)]
54. Peta, C. Canada’s Supply Management System and the Dairy Industry in the Era of Trade Liberalization: A Cultural Commodity? *Am. Rev. Can. Stud.* **2019**, *49*, 547–562. [[CrossRef](#)]
55. Ritter, C.; Mills, K.E.; Weary, D.M.; von Keyserlingk, M.A. Perspectives of western Canadian dairy farmers on the future of farming. *J. Dairy Sci.* **2020**, *103*, 10273–10282. [[CrossRef](#)]
56. Denis-Robichaud, J.; Kelton, D.F.; Bauman, C.A.; Barkema, H.W.; Keefe, G.P.; Dubuc, J. Biosecurity and herd health management practices on Canadian dairy farms. *J. Dairy Sci.* **2019**, *102*, 9536–9547. [[CrossRef](#)]
57. Beauchemin, K.A.; Ungerfeld, E.M.; Abdalla, A.L.; Alvarez, C.; Arndt, C.; Becquet, P.; Benchaar, C.; Berndt, A.; Mauricio, R.M.; McAllister, T.A.; et al. Invited review: Current enteric methane mitigation options. *J. Dairy Sci.* **2022**, *105*, 9297–9326. [[CrossRef](#)]
58. Arndt, C.; Hristov, A.N.; Price, W.J.; McClelland, S.C.; Pelaez, A.M.; Cueva, S.F.; Oh, J.; Bannink, A.; Bayat, A.R.; Crompton, L.A.; et al. Strategies to mitigate enteric methane emissions by ruminants—a way to approach the 2.0 °C target. *AgriRxiv* **2021**, AgriRxiv: 20210085288. [[CrossRef](#)]
59. Min, B.R.; Solaiman, S.; Waldrip, H.M.; Parker, D.; Todd, R.W.; Brauer, D. Dietary mitigation of enteric methane emissions from ruminants: A review of plant tannin mitigation options. *Anim. Nutr.* **2020**, *6*, 231–246. [[CrossRef](#)]
60. Bhatnagar, N.; Ryan, D.; Murphy, R.; Enright, A.M. A comprehensive review of green policy, anaerobic digestion of animal manure and chicken litter feedstock potential—Global and Irish perspective. *Renew. Sustain. Energy Rev.* **2022**, *154*, 111884. [[CrossRef](#)]
61. Yao, Y.; Huang, G.; An, C.; Chen, X.; Zhang, P.; Xin, X.; Shen, J.; Agnew, J. Anaerobic digestion of livestock manure in cold regions: Technological advancements and global impacts. *Renew. Sustain. Energy Rev.* **2020**, *119*, 109494. [[CrossRef](#)]
62. Franzluebbbers, A.J. Cattle Grazing Effects on the Environment: Greenhouse Gas Emissions and Carbon Footprint. In *Management Strategies for Sustainable Cattle Production in Southern Pastures*; Academic Press: San Diego, CA, USA, 2020; pp. 11–34.
63. Lal, R. Reducing carbon footprints of agriculture and food systems. *Carbon Footpr.* **2022**, *1*, 3. [[CrossRef](#)]
64. Niloofar, P.; Francis, D.P.; Lazarova-Molnar, S.; Vulpe, A.; Vochin, M.C.; Suci, G.; Balanescu, M.; Anestis, V.; Bartzanas, T. Data-driven decision support in livestock farming for improved animal health, welfare and greenhouse gas emissions: Overview and challenges. *Comput. Electron. Agric.* **2021**, *190*, 106406. [[CrossRef](#)]
65. Lovarelli, D.; Bacenetti, J.; Guarino, M. A review on dairy cattle farming: Is precision livestock farming the compromise for an environmental, economic and social sustainable production? *J. Clean. Prod.* **2020**, *262*, 121409. [[CrossRef](#)]
66. Vitillo, J.G.; Eisaman, M.D.; Aradóttir, E.S.; Passarini, F.; Wang, T.; Sheehan, S.W. The role of carbon capture, utilization, and storage for economic pathways that limit global warming to below 1.5 °C. *iScience* **2022**, *25*, 5. [[CrossRef](#)]
67. Winsten, J.R.; Gorman, E.; Gravitz, A. Coordinating a “basket of incentives” to facilitate resilience in the dairy sector. *J. Soil Water Conserv.* **2020**, *75*, 144A–149A. [[CrossRef](#)]

68. Cameron, G.; Rosado, F.R.P.; Mederos, D.D.D. Agricultural co-operatives in Canada and Cuba: Trends, prospects and ways forward. *Environ. Dev. Sustain.* **2020**, *22*, 643–660. [[CrossRef](#)]
69. Stavins, R.N. *Carbon Taxes vs. Cap and Trade: Theory and Practice*; Harvard Project on Climate Agreements: Cambridge, MA, USA, 2019.
70. Green, J.F. Does carbon pricing reduce emissions? A review of ex-post analyses. *Environ. Res. Lett.* **2021**, *16*, 043004. [[CrossRef](#)]
71. Henchion, M.M.; Regan, Á.; Beecher, M.; MackenWalsh, Á. Developing ‘Smart’ Dairy Farming Responsive to Farmers and Consumer-Citizens: A Review. *Animals* **2022**, *12*, 360. [[CrossRef](#)]
72. Steenwerth, K.L.; Hodson, A.K.; Bloom, A.J.; Carter, M.R.; Cattaneo, A.; Chartres, C.J.; Hatfield, J.L.; Henry, K.; Hopmans, J.W.; Horwath, W.R.; et al. Climate-smart agriculture global research agenda: Scientific basis for action. *Agric. Food Secur.* **2014**, *3*, 1–39. [[CrossRef](#)]
73. van Hilten, M.; Wolfert, S. 5G in agri-food-A review on current status, opportunities and challenges. *Comput. Electron. Agric.* **2022**, *201*, 107291. [[CrossRef](#)]
74. Tian, F.; Wang, X.; Yu, S.; Wang, R.; Song, Z.; Yan, Y.; Li, F.; Wang, Z.; Yu, Z. Research on Navigation Path Extraction and Obstacle Avoidance Strategy for Pusher Robot in Dairy Farm. *Agriculture* **2022**, *12*, 1008. [[CrossRef](#)]
75. Duzha, A.; Alexakis, E.; Kyriazis, D.; Sahi, L.F.; Kandi, M.A. From Data Governance by design to Data Governance as a Service: A transformative human-centric data governance framework. In Proceedings of the 2023 7th International Conference on Cloud and Big Data Computing, Manchester, UK, 17–19 August 2023; pp. 10–20.
76. Bibri, S.E.; Krogstie, J. A novel model for data-driven smart sustainable cities of the future: A strategic roadmap to transformational change in the era of big data. *Future Cities Environ.* **2021**, *7*, 3. [[CrossRef](#)]
77. Liu, C.; Wang, X.; Bai, Z.; Wang, H.; Li, C. Does Digital Technology Application Promote Carbon Emission Efficiency in Dairy Farms? Evidence from China. *Agriculture* **2023**, *13*, 904. [[CrossRef](#)]
78. Ji, B.; Banhazi, T.; Phillips, C.J.; Wang, C.; Li, B. A machine learning framework to predict the next month’s daily milk yield, milk composition and milking frequency for cows in a robotic dairy farm. *Biosyst. Eng.* **2022**, *216*, 186–197. [[CrossRef](#)]
79. Cockburn, M. Application and prospective discussion of machine learning for the management of dairy farms. *Animals* **2020**, *10*, 1690. [[CrossRef](#)]
80. Krupitzer, C.; Stein, A. Unleashing the Potential of Digitalization in the Agri-Food Chain for Integrated Food Systems. *Annu. Rev. Food Sci. Technol.* **2023**, *15*, 1–22. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.