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Review

Sustainable Livestock Solutions: Addressing Carbon Footprint Challenges from Indian and Global Perspectives

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Highlights

What are the main finding?

- India is one of the largest livestock systems based GHG contributors, due to large livestock population.
- Numerous GHG emission quantifying and mitigating methodologies were highlighted.

What is the implication of the main findings

- The scaling up of GHG emission mitigations options can help mitigate the GHG footprint of Indian Livestock Systems.
- Artificial Intelligence backed mathematical modelling for devising favourable government policies, can help Indian Livestock systems achieve their 2070 GHG emission benchmarks.

Abstract: The rising environmental temperatures and growing global demand for animal protein pose major challenges to sustainable livestock production, highlighting the urgent need for climate change mitigation strategies. The livestock system in different parts of the world, especially in developing and underdeveloped nations, holds a significant role in supporting the livelihoods and nutritional security of millions, yet climate change is jeopardizing its efficiency and exacerbating its carbon footprint. This increase in carbon footprint is an alarming challenge for global sustainability, which needs to be addressed meticulously with fruitful outcomes. As the world's largest livestock hub, the Indian livestock system can be adopted as a model for understanding the challenges and opportunities within the livestock system to develop sustainable approaches. In 2022, India accounted for approximately 7% of global greenhouse gas emissions (GHGEs), with a total of 3.9 billion metric tons of CO_2e. This review provides updated insights on the livestock-related carbon footprint, sustainability-enhancing technologies, GHG estimation models, and strategies for climate-neutral livestock production. Emission estimation models are categorized into

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source-based and whole-farm models for a comprehensive assessment of emissions. Mitigation strategies for cattle include rumen modification, nutritional approaches, efficient manure management, and precision livestock farming. India's commitment to achieving net-zero emissions by 2070 is reflected in various initiatives aimed at promoting sustainable livestock systems. Future perspectives emphasize decision modeling and climate-resilient technologies to address environmental challenges in alignment with the UN's sustainable development goals.

Keywords: carbon footprint; global warming; greenhouse effect; lifecycle assessment; methane; sustainable development

1. Introduction

Livestock production plays a critical role in food security, providing a substantial source of protein, essential nutrients, and livelihoods for millions of people worldwide. In many developing countries, livestock is a key asset for rural communities, contributing to food diversity and the safety net during times of economic hardship [1,2]. As the global population continues to rise, the demand for animal-based products—such as meat, dairy, and eggs—has surged, placing significant pressure on agricultural systems. However, the sustainability of livestock-based food systems is under threat in this era of climate change with rising temperatures, altered precipitation patterns, and increased frequency of extreme weather events. These changes can lead to decreased productivity, as livestock may suffer from heat stress, reduced forage quality, and increased disease prevalence. Consequently, this affects the availability of animal products, threatening food security for populations that rely heavily on these sources of nutrition. Additionally, the livestock sector is also one of the major contributors to greenhouse gas (GHG) emissions, which exacerbate climate change and further jeopardize food security [3,4].

The relationship between livestock production and climate change creates a feedback loop that complicates efforts to achieve food security. Vulnerable communities, especially those in developing nations, may find it increasingly difficult to secure sufficient and nutritious food; this widens existing inequalities. Hence, prioritizing sustainability in livestock production is crucial for nutritional and livelihood security and long-term environmental, societal, and animal well-being [5,6]. On the other hand, increased livestock numbers to meet growing demand can lead to higher GHG emissions, which in turn contribute to the carbon foot print and its associated impacts on food production and the ecosystem. This cycle highlights the need for sustainable and carbon neutral practices in livestock management that ensure climate-smart livestock practices from the farm to fork. Sustainable livestock farming seeks to minimize adverse impacts on ecosystems, animal welfare, and human health while fostering long-term resilience and resource efficiency. Climate-smart production refers to adopting practices and technologies to mitigate both the impact of the environment on livestock and the environmental impact of livestock farming [7]. Resilience and adaptability in livestock systems are essential for safeguarding food security in an era of rapid climate change [8]. Addressing the challenges in climate change and livestock-based food production requires a multifaceted approach, wherein policymakers, producers, and consumers work collaboratively to foster sustainable practices for a healthy world [9]. This approach emphasizes sustainable and environmentally friendly methods to reduce greenhouse gas emissions (GHGEs), conserve natural resources, and adapt to changing climatic conditions while maintaining or improving productivity and profitability.

Anthropogenic GHGs, such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), emerge as significant sources of emissions, with the agriculture sector primarily responsible for the majority of the latter two GHGs [10,11]. In 2022, India's GHGEs amounted to 3.9 billion metric tons (BMTs) of carbon dioxide equivalent (CO_2e) emissions, representing about seven percent of the global total. Livestock, a significant contributor to climate change due to emissions like CH_4 and N_2O, poses challenges to worldwide ecological balance [12]. The Global Methane Tracker 2022 reveals that agriculture is responsible for 61% of total CH_4 emissions, with the energy sector at 16.4% and waste at 19.8%. India notably leads in total livestock methane emissions despite lower emission rates per animal than developed countries [13], because of a significantly higher head of cattle population. With the world's largest bovine population, at around 303.76 million in 2019 [14], and ranked as the second-largest rice producer, India's methane emissions in 2016, excluding Land Use, Land-Use Change, and Forestry (LULUCF), reached 409 million metric tons (MMTs) of CO_2e, of which 73.96% was from the agriculture sector, as per India's third Biennial Update Report. In the upcoming decades, addressing this issue will be crucial to curbing GHGEs from the livestock sector and promoting sustainable economic food services [15,16].

The term 'ecological footprint' was introduced by the researchers Mathis Wackernagel and William Rees in the early 1990s, and is a measure of human impact on the Earth's ecosystems, considering the total amount of biologically productive land and sea area required to support a particular population's lifestyle and consumption patterns. The concept of the "carbon footprint" was rooted in the ecological footprint and, being a subset of it, serves as a crucial indicator for measuring the environmental impact of human activities focusing exclusively on the amount of GHGEs associated with a particular activity, individual, organization, or product. It provides a valuable framework for understanding and promoting global sustainable development [17]. As we grapple with the consequences of livestock production, scaling up sustainable livestock practices becomes imperative. Optimizing feed, managing enteric fermentation, implementing efficient manure handling, and improving livestock productivity and profitability while escalating soil carbon sequestration are key climate-smart agriculture techniques that can help reduce GHGEs [3,18].

This manuscript aims to thoroughly examine and emphasize crucial aspects of a climate-smart livestock management system, focusing on optimizing resources, implementing strategies to reduce emissions, and analyzing the changing emissions landscape in India. The paper draws on established frameworks like the Greenhouse Gas Protocol and the global agenda for sustainable livestock research perspectives, covering topics such as GHG assessments, innovative methods for monitoring CH_4 emissions, and the importance of understanding carbon footprints in livestock farming. Our goal is to provide a refined understanding of sustainable livestock practices implementable by the Indian Livestock System while being aligned with the sustainability objectives set by IPCC/COP28. Additionally, we explore mathematical models for estimating GHGEs in livestock and scalable strategies for Indian livestock GHGE reduction. Hence, our overarching objective is to be a comprehensive guide offering valuable insights for future initiatives that can contribute to a more sustainable and environmentally conscious global livestock farming system with a special emphasis on India.

2. Search Strategy

For this narrative review, a comprehensive literature search was conducted using two major databases, Scopus and PubMed, to ensure the inclusion of relevant publications. The search was performed using a combination of keywords and Boolean operators to identify articles related to the carbon footprint of livestock systems and sustainable livestock production. The following keywords were used in various combinations: “carbon footprint”, “livestock”, “greenhouse gases”, “methane”, “sustainable development”, “emission models”, “manure management”, “precision farming”, and “India”. Filters were applied to limit results. The search yielded a wide range of articles that were screened for relevance based on their title, abstract, and full text. The final selection of references focused on those providing insights into the topic under review. This search strategy ensured the inclusion of diverse perspectives and comprehensive coverage of the topic while maintaining methodological rigor.

3. Sustainable Livestock Systems: The Need of the Hour for Environmental Resilience and Climate Mitigation

Ensuring the sustainability of livestock production is essential for optimizing resource utilization, enhancing food security, and preserving the environment. This becomes especially crucial in low-income countries and marginal areas with complex and dynamic animal production systems. Adopting sustainable practices not only helps efficiently manage resources and reduce costs but also contributes to increased profitability [18].

Greenhouse gases like CO_2, CH_4, and N_2O are essential for sustaining a habitable climate. However, human activities such as fossil fuel combustion, deforestation, industrial processes, and specific agricultural practices have significantly increased their atmospheric concentrations, amplifying the greenhouse effect. With its methane emissions, deforestation for feed production, and fertilizer use, livestock farming emerges as a significant contributor to GHGEs, thereby influencing climate change [19].

In 2015, global animal products, encompassing milk, eggs, and meat, reached substantial quantities with significant environmental implications. The associated carbon dioxide equivalent emissions amounted to approximately 6.2 gigatons, contributing about 12 percent to the total anthropogenic emissions in 2015 [20]. Cattle are the largest contributors among livestock species, accounting for around 3.8 gigatons of emissions annually, or 62 percent of the total emissions from the livestock sector. Other species such as pigs, chickens, and small ruminants, make up the remaining share. Direct emissions from the global livestock sector, which include CH_4 from enteric fermentation and CH_4 and N_2O from manure management, amounted to 3.7 gigatons of CO_2e, making up approximately 60 percent of the sector’s total emissions. Of these, 54 percent were attributed to methane, while carbon dioxide and nitrous oxide accounted for 31 percent and 15 percent, respectively.

With the growing global population and urbanization, there is an increased demand for meat and dairy products. It is imperative to implement sustainable practices in livestock farming, including improving feed efficiency, reducing methane emissions, and adopting better land use management practices, to mitigate the sector’s impact on climate change [21]. Furthermore, climate change poses challenges to livestock production such as rising heat stress levels, changing disease patterns, and alterations in feed availability. Farmers can effectively address these challenges by adopting climate-smart farming methods that aim to reduce GHGE from livestock [22].

4. An Assessment of India’s Evolving Carbon Landscape

Over the past two decades, India has seen a substantial rise in emissions primarily fueled by its growing population and rapidly expanding economy (Figure 1). This surge propelled India to become the world’s third-largest GHG emitter in 2021, with a GHG footprint of 3.78 BMTs, following China and the U.S. [23]. Despite this, India’s per capita GHGEs are significantly lower than the global average, standing at just 2.7 tons of CO_2e, consistent with the nation’s per capita GDP. China and the U.S. report per capita emissions of 9.4 and 17.7 tons of CO_2e, respectively [24]. India’s economic expansion has been predominantly driven by coal, the most carbon-intensive fossil fuel. With coal constituting over 70 percent of India's power mix, coal combustion in 2021 alone produced 1.8 gigatons of CO_2 [25]. The substantial volume of CO_2 emissions from coal-fired power plants positions the electric power sector as the primary contributor to GHGEs in India. This is followed by the agriculture sector, which significantly contributes to CH_4 emissions from rice fields and cattle [26].

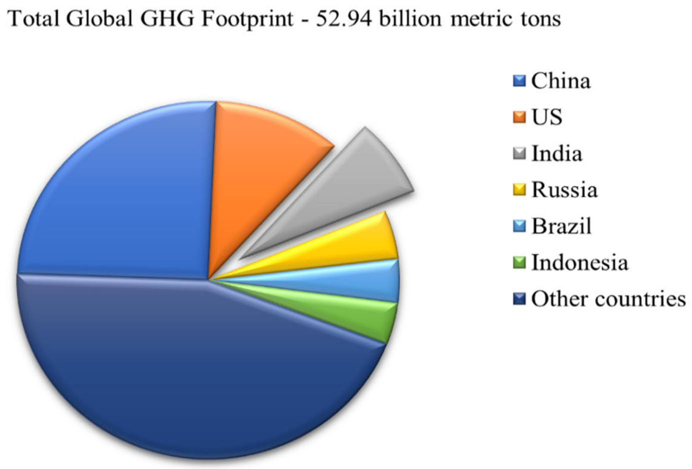

Figure 1. A comparison of the greenhouse gas footprint of India compared to other major global economies in 2021. GHG footprints shown are in billion metric tons. Source: [24].

Moreover, India's historical cumulative CO_2 emissions contribution from 1850 to 2019 is relatively modest, accounting for less than four percent compared to other major economies. In 2020, the global agriculture sector contributed 5.87 billion metric tons (BMTs) of CO_2e, with the Indian agriculture sector contributing 741.92 MMTs [27]. In the same year, India's per capita emissions from the agriculture sector amounted to 0.53 tons of CO_2e. These data provide insights into India's evolving carbon landscape, emphasizing its substantial growth rate for emissions and the comparatively restrained per capita emissions contributions. India's global GHGE escalated from around 3.52 BMTs of CO_2e in 2020 to approximately 3.78BMTs in 2021 (Figure 1), reflecting a significant increase in its overall environmental footprint within a single calendar year.

5. Assessing the Greenhouse Gas Emissions from Indian Livestock and Their Contribution to Global Warming

Climate change in India is primarily driven by fossil fuel combustion, nitrogen fertilizer use, and large ruminant husbandry. According to the FAO, CO_2, CH_4, and N_2O are the major greenhouse gases (GHGs) emitted during agricultural activities. Livestock accounts for 80% of agricultural GHG emissions globally [21], contributing 9% of CO_2, 36% of CH_4, and 64% of N_2O. In India, ruminants produce 75% of livestock-related CO_2 emissions. In 2003, CH_4 emissions from Indian livestock were estimated at 11.75 MMTs, with enteric fermentation responsible for 91% of methane emissions. This process releases 212.10 million tons of CO_2e annually, including 10.1 million tons of CH_4, while manure handling contributes 0.115 million tons of CH_4 and 70 tons of N_2O [28–30].

The Global Warming Potential (GWP) of GHGs measures their heat-trapping ability over a century, with CO_2 as the baseline (GWP = 1). CH_4 has a GWP 30 times higher, while N_2O is 298 times more potent [31] than a unit of CO_2. Ruminant livestock in India contributes 214.53 million tons of CO_2e [30], emitting 80–115 MMTs of CH_4 annually, accounting for 15–20% of global anthropogenic methane emissions [32,33]. Based on the sixth IPCC assessment, CH_4 has a revised GWP of 27.9, and N_2O has a GWP of 273 [34].

India, home to the world's largest livestock population (16.1% of cattle, 57.9% of buffaloes, and significant goat and sheep populations) [35], emits 9.10 MMTs of CH_4 from enteric fermentation (Figure 2) and animal waste yearly. Projections estimate total enteric CH_4 emissions will reach 19 MMTs by 2050, with CH_4 from manure and N_2O emissions rising to 22 MMTs [36]. Figure 2 presents the estimated and projected enteric methane emissions (in kg $\pm 10^9$) from different livestock species and poultry in India, highlights the trends and potential future impact of these emissions.

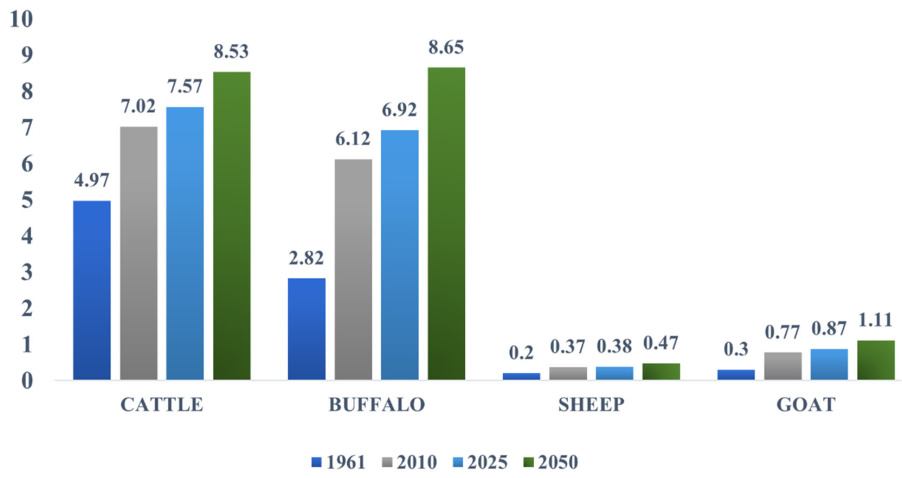

Figure 2. Estimated and projected trends of enteric methane emissions (in kg $\pm 10^9$) from ruminants.

Ruminant microorganisms drive 73% of livestock CH_4 emissions, with poor-quality tropical diets causing 10–12% of gross energy loss as CH_4 [37]. Enteric fermentation accounts for 30–40% of agricultural CH_4 emissions [38]. Developing improved feeding strategies is essential for long-term GHG mitigation and immediate economic benefits [39].

6. The Role of the Carbon Footprint in Agro-Environmental Sustainability and Livestock Management

The carbon footprint (CF) represents the total GHGE from human activities, measured in CO_2e emissions. In agro-environmental sciences, CF assessment is essential for evaluating the environmental impact of agricultural practices and developing strategies to mitigate climate change [40]. By quantifying emissions, CF serves as a critical tool for promoting sustainability and guiding informed decisions on resource use and emissions reduction [41].

In livestock management, CF assessment is crucial for understanding how different production systems influence GHGE. Livestock contributes significantly to global GHGE, but quantifying its impact is complex due to variations in emissions across species, breeds, production stages, and management practices [42]. Given the substantial role of livestock in climate change, developing effective mitigation strategies is imperative [43]. Measuring CF not only enhances our understanding of livestock-related emissions but also supports the implementation of sustainable and climate-resilient solutions to reduce the environmental footprint of animal agriculture [44].

7. Strategic Estimation and Management of the Carbon Footprint in Livestock Production for Sustainability

Accurate estimation of the CF in livestock production is essential for enhancing sustainability in agriculture. To assess CF, precise GHGEs, such as CO_2, CH_4, and N_2O, is required. This involves detailed data collection on animal numbers, feed intake, and waste management practices, with emission factors applied to determine the gases produced per unit of activity [45]. The total CF is derived by aggregating emissions across all stages of the livestock system [46]. The total GWP or CF is calculated as the CF or GWPtot (kg CO_2e).

$$GWP_{tot}\ (\text{kg } CO_2e) = \text{amount of } CO_2 \times 1 + \text{amount of } CH_4 \times GWP_{CH4} + \text{amount of } N_2O \times GWP_{N2O}$$

where GWP_{CH4} is the attribution factor for CH_4 and GWP_{N2O} is the attribution factor for N_2O.

This process provides a comprehensive view of the environmental impact of livestock farming. Additionally, the GHG Protocol offers a standardized framework for measuring and managing emissions, especially Scope 3 emissions in livestock production, which include the following:

(a) Upstream sources: emissions from feed production, including land use, fertilizer and energy consumption.
(b) Midstream sources, which include emissions from livestock transportation and processing of livestock products.
(c) Downstream sources: emissions from the use of livestock products, including food processing and waste [47].

The Emission Factor Method plays a crucial role in quantifying GHGEs from livestock, where emission factors, representing the average emissions linked to specific farming activities, are multiplied by activity data. For instance, methane production from cattle is significantly influenced by feed quality and animal characteristics, with cattle losing approximately 6% of consumed energy through CH_4 emissions during digestion [48,49]. These approaches enable effective management of livestock's environmental impact, supporting the transition towards more sustainable farming practices

8. An Overview of the Different Methods Available for Assessing Livestock CH_4 Emissions

Precise and accurate repetitive measurement of CH_4 emissions from Indian livestock systems is crucial for understanding and mitigating their impact on climate change. Below we discuss few commonly used methods that Indian livestock reseachers have access to:

1. Respiration Chambers: These are considered the gold standard for measuring CH_4 emissions. Animals are placed in enclosed chambers where their gas exchange is monitored. This method provides high-resolution data but is labor-intensive and may not reflect typical animal behavior (Table 1, Figure 3).
2. GreenFeed Systems: These systems measure gas exchange when animals visit a feeding station. They are less intrusive than respiration chambers and can be used in a more natural setting, making them suitable for long-term studies (Table 1, Figure 3).
3. Sulfur Hexafluoride (SF_6) Tracer Technique: This method involves placing a small permeation tube of SF_6 in the animal's rumen. The emitted SF_6 serves as a tracer to estimate CH_4 emissions. It is less invasive than respiration chambers but requires careful calibration and handling (Table 1, Figure 3).
4. Portable Accumulation Chambers: These are smaller, mobile chambers that can be used in the field. They are less accurate than respiration chambers but offer more flexibility and lower costs (Table 1, Figure 3).
5. In Vitro Fermentation: This laboratory method simulates the digestive process of ruminants using rumen fluid and feed samples. It helps in understanding the potential CH_4 production from different feeds but may not fully replicate in vivo conditions (Table 1, Figure 3).
6. Mathematical Modeling and AI Technologies: Advanced models and AI can predict CH_4 emissions based on various inputs like diet, animal type, and management prac-

tices. These methods are becoming increasingly important for large-scale assessments and mitigation strategies (Table 1, Figure 3).

Each method has its advantages and limitations as discussed in Table 1, and the choice often depends on the specific research goals, available resources, and the scale of the study.

Table 1. Different methods available for assessing livestock CH_4 emissions.

Method	Description	Key Features	Advantages	Limitations	References
Respiration chamber	Collects exhaled breath and analyzes CH_4 concentration using open- or closed-circuit indirect calorimetry.	Measures CH_4 by analyzing airflow difference at inlet and outlet. Chambers may have insulation and controlled temperature/humidity.	Considered the "gold standard" for accuracy.	Artificial environment may alter dry matter intake (DMI) and affect emissions.	[50]
SF_6 tracer technique	Uses SF_6, an inert gas, as a tracer to estimate CH_4 emissions. SF_6 is released from a surgically implanted cannula in the rumen.	Uses an internal tracer release system with a gas collection tube affixed to the animal's neck. Gas chromatography measures CH_4/SF_6 ratio.	Allows for CH_4 measurement in free-ranging animals. No need for a controlled environment.	Requires surgical insertion of SF_6 capsule. Regular sample collection needed.	[51,52]
In vitro gas production technique (IVGPT)	Simulates rumen fermentation outside the animal's body using rumen fluid and various substrates.	Incubation at ~39 °C in sealed bottles to mimic the rumen. Gas production is monitored to estimate CH_4 emissions.	Enables controlled feedstuff testing. Useful for evaluating dietary strategies to reduce CH_4.	May not fully replicate in vivo conditions. Dependent on donor animal rumen fluid.	[53–56]
CO_2 technique	Uses CO_2 as a natural tracer to estimate CH_4 emissions.	CH_4/CO_2 ratio is measured, and CH_4 emissions are estimated.	Avoids external tracer gases. More natural than SF_6 method.	Requires accurate feed intake and heat production data for precise CH_4 estimation.	[55,57]
Laser technique	Uses a laser CH_4 detector (LMD) to measure methane concentrations in exhaled air.	Employs infrared absorption spectroscopy. Portable equipment allows non-invasive measurement.	Enables real-time CH_4 monitoring in natural settings. Non-invasive.	Accuracy depends on correct positioning and distance of the device.	[58–60]
Proxy methods	Uses biological samples (e.g., milk or feces) to estimate CH_4 emissions based on fatty acid composition.	Links specific milk or fecal components (fatty acids or lipids) to methanogenic activity and diet composition.	Simple and non-invasive. Can be integrated into routine milk or fecal analysis.	Indirect method; requires further validation for precise CH_4 estimation.	[61,62]
Mathematical models	Estimates CH_4 emissions based on variables like species, age, weight, and diet using statistical and dynamic mechanistic models.	Uses observed animal data or biochemical simulations of rumen fermentation. Models include MANNER (Methane and Nitrous Oxide Emissions from National cattle), CNCPS (Cornell Net Carbohydrate and Protein System), Ruminant, Ruminant Nutrition System, IPCC Tiers 1 and 2, AD-GENIE, DEEPMODEL, RumiGas, GRAZPLAN, and CoolFarmTool.	Allows for CH_4 prediction based on various parameters. Useful for policy-making and farm-level emissions tracking. Can simulate dietary changes.	Requires detailed input data. Some models are complex and computationally demanding.	[63–71]

Table 1. *Cont.*

Method	Description	Key Features	Advantages	Limitations	References
Green feed system	Uses an automated feeder with sensors to measure CH_4 and CO_2 emissions from non-confined cattle and sheep.	Animals are attracted using a pelleted concentrate. Sensors detect CH_4 released during short feeding periods.	Cost-effective compared to SF_6 and respiration chamber techniques. Works indoors and in pastures.	Requires repeated visits from the animal to collect sufficient data.	[50,58,72–75]
Blood methane detection	Measures CH_4 absorbed into the bloodstream via a jugular blood sample.	Uses SF_6 injection (intra ruminal bolus) into the rumen to track methane absorption and exhalation.	Provides a continuous measure rather than a one-time sample.	Invasive and requires blood sampling.	[50]
Infrared (IR) thermography	Detects CH_4 emissions by measuring temperature differences between an animal's flanks.	Uses thermal imaging to assess fermentation heat in the rumen, which correlates with CH_4 production.	Non-invasive and simple to implement.	Accuracy depends on timing (most effective postprandial). External temperature variations may affect readings.	[76]
Eddy covariance (EC) technique	A micrometeoro-logical approach that tracks gas exchange between ecosystems and the atmosphere.	Evaluates the link between computed flux and emission rate of point sources.	Effective for large-scale CH_4 tracking in grazing systems.	Complex setup and modeling required.	[77,78]

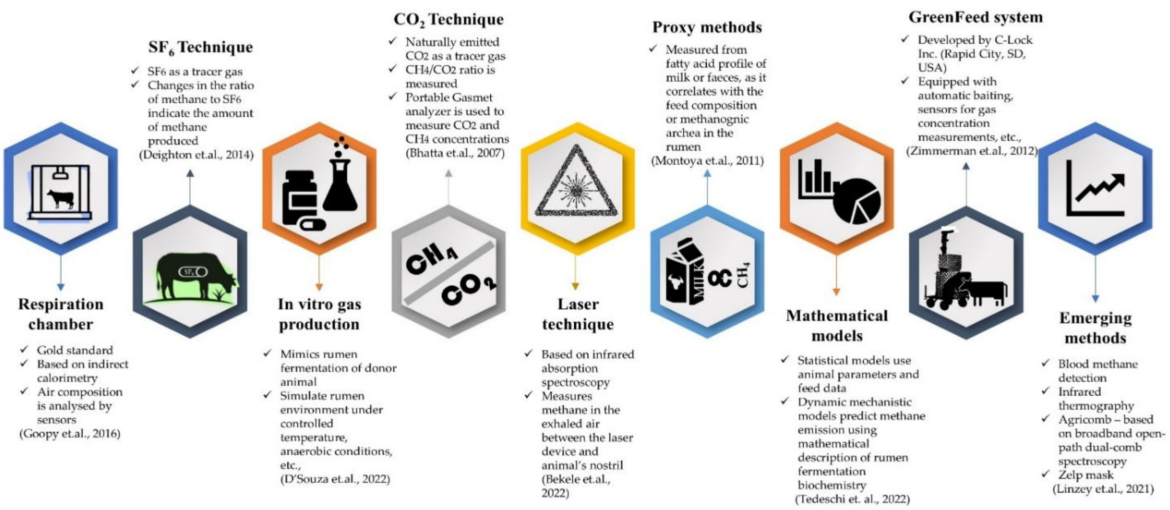

Figure 3. Numerous historical and modern methane emissions measurement techniques are available to Indian livestock systems [50,51,54,56,60,61,67,72,79].

9. Life Cycle Assessment of Greenhouse Gas Emissions

A life cycle assessment (LCA) measures GHGEs from animals throughout their life cycle, as depicted in Figure 4. This encompasses feed cultivation, processing, livestock feeding, gastrointestinal fermentation, manure fermentation, and slaughter [43]. The International Organization of Standardization (ISO) defines LCA as a four-phase process that includes an aim and scope definition, inventory analysis, life cycle impact assessment, and interpretation [80].

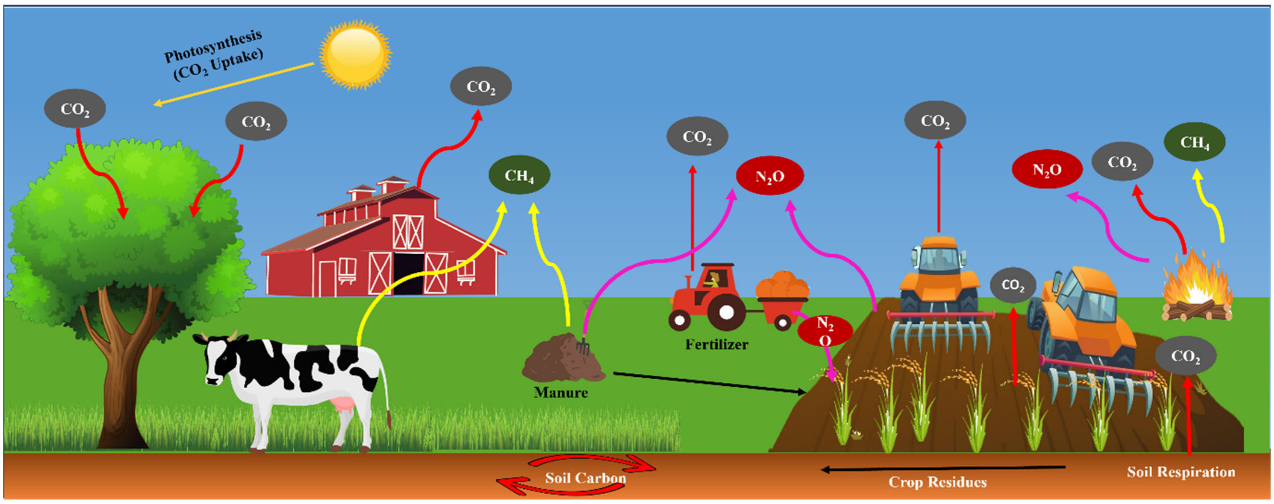

Figure 4. Visual representation of sources of GHG emissions and sequestration that need to be accounted for during inventory data collection.

9.1. Define the Goal and Scope

This involves defining the LCA study of emissions for a given livestock operation, kind of livestock (e.g., cattle, poultry), or region-wide livestock industry. Next, we evaluate the population and establish boundaries for various stages of the cattle life cycle, such as feed production, enteric fermentation, and waste management.

9.2. Inventory Data Collection

This involves collecting data on all aspects of livestock production (Figure 4, including feed composition and methods, livestock population and characteristics, feed conversion ratios, manure management practices, energy use on farm and in processing facilities, fuel consumption for transportation, and emission factors for nitrous oxide, methane, and carbon dioxide associated with various activities.

9.3. Emission Calculations

This involves using emission factors and activity data to estimate GHGEs throughout the cattle life cycle. Then, we estimate methane emissions from enteric fermentation based on animal type, nutrition, and emission parameters. Subsequently, we evaluate methane and nitrous oxide emissions from manure management, taking into account handling, storage, and treatment strategies. Feed production emissions can be approximated based on crop type, growing practices, and transportation modes.

9.4. Impact Assessment

This involves evaluating the GWP of emissions by converting CH_4 and N_2O emissions into CO_2e using appropriate attribution values.

9.5. Interpreting and Reporting Results

This involves using life cycle interpretation to systematically find, measure, check, and assess information from the life cycle impact assessment. Then, we evaluate the environmental impact of the cattle system using analysis. The outputs of this effort are vital for assessing the comprehensiveness, sensitivity, and consistency of the LCA research. After analysis, we create a concise and orderly report to document the study's findings. ISO 14040-14044 [80,81] provides comprehensive standards and requirements for life cycle assessment (LCA). The Global Livestock Environmental Assessment Model (GLEAM) is a GIS framework that simulates biophysical processes and activities in livestock supply chains using the life cycle assessment (LCA) approach. Tyagi et al. [82] conducted a comprehensive LCA to evaluate the GHGEs and assess the carbon footprint from cradle to farm gate for dairy animals, specifically quantifying emissions per kilogram of milk produced. In a study conducted by Sarkar et al. [83] on sheep, a comprehensive life cycle assessment (LCA) was performed to evaluate three different sheep farming systems—intensive (stall-fed only), semi-intensive (grazing with supplementation), and extensive (grazing only)—in the semi-arid region of India, aiming to assess the carbon cost of sheep rearing. The findings revealed that for the production of 1 kg of mutton in semi-intensive and intensive systems, approximately 30% and 24% of carbon footprints (CFs) were attributed to enteric fermentation and feed, respectively. In contrast, in the extensive system, the contribution of enteric fermentation increased to 50%.

10. Models for Livestock Greenhouse Gas Estimation

Models for estimating GHGEs from livestock can be broadly categorized into source-based models and whole-farm models.

10.1. Source-Based Models

Source-based livestock GHG emissions are estimated using models based on emission factors. This simple approach uses a single value to represent the entire production system. Process-driven emission factors involve quantifying individual processes within a system and are also used to calculate GHG emissions from livestock. For instance, livestock's enteric methane emissions might be expressed as a function of the animals' gross energy intake. This provides a more detailed representation than a single value and is classified as Tier 2 according to the IPCC guidelines. Empirical or statistical models describe a process as a function of multiple variables. These models rely on observed data and may not require a deep understanding of the underlying processes. Relationships may be developed using linear or nonlinear functions. Empirical relationships offer a more detailed representation than simple emission factors, relying on statistical patterns observed in data. One such mathematical model was developed to predict enteric methane emission from cattle by Benaouda et al. [84]. The most detailed modeling approach involves mechanistic process simulation, where multiple relationships represent the dynamics within a process [67,85]. This model offers a thorough insight into the underlying mechanisms and interactions. Mechanistic process simulations are complex and resource-intensive but offer the highest level of detail, making them valuable for in-depth analysis and understanding of the system dynamics, but demand extensive data and resources. The application of machine learning indicates a contemporary trend in utilizing advanced computational techniques to enhance the accuracy and efficiency of predicting greenhouse gas outputs but may face challenges in generalization across varying systems. Ensemble machine learning techniques, such as gradient boosting and random forests, are utilized to construct models to deliver more accurate GHGE predictions [86]. In summary, the choice of modeling approach depends on the level of detail required, data availability, and the specific goals of the analysis. While simple emission factors provide quick estimates, more detailed models, such as process-driven factors, empirical relationships, or mechanistic simulations, offer increased accuracy and insight into the underlying processes within agricultural systems but lack specificity for diverse systems.

10.2. Whole-Farm Models

The statement "the whole is not equal to the sum of the parts" implies that the overall emissions from the entire production system cannot be simply calculated by adding up the emissions from individual sources [87]. Complex interactions and feedback loops affect the overall emissions. For example, carbon (C) and nitrogen (N) emissions from the housing system can influence the amounts of these compounds that move on to storage and field application [88]. To effectively assess and quantify total farm emissions, it is essential to model and understand the interactions among individual emission sources and to take into account the cumulative impacts of feeding and management practices on the entire production system. For this purpose, approaches like whole-farm models and life cycle assessment (LCA) tools fall into this category, as they thoroughly investigate all processes linked to livestock-related activities [89]. Whole-farm tools integrate LCA concepts into resource-based models, providing a comprehensive approach to estimating farm-level emissions. Such tools include GLEAM, Cool Farm Tool, AgRECalc, COMET-Farm, Holos, etc. [90]. These tools vary in modeling techniques, with some employing simpler models such as IPCC Tier 1, requiring minimal information, and others utilizing more detailed Tier 3 models that demand extensive input data. Complex models are often employed for in-depth research on the intricate interactions between livestock emission sources yet their effectiveness relies on high-quality input data and region-specific considerations.

The Global Livestock Environmental Assessment Model (GLEAM) is a robust tool developed by the FAO to evaluate the ecological footprint of livestock value chains. GLEAM aims to quantify the utilization of natural resources throughout the livestock sector by employing a life cycle assessment approach. GLEAM provides estimates of CH_4, CO_2, and N_2O emissions at various stages of production. The model categorizes emissions into three groups: upstream emissions related to feed production, processing, and transportation; animal production emissions encompassing enteric fermentation, manure management, and on-farm energy use; and downstream emissions resulting from the processing and post-farm transport of livestock commodities. The model plays a crucial role in identifying environmental effects associated with livestock, contributing to evaluating adaptation and reduction strategies for a more sustainable livestock sector [91].

Decision support tools incorporate simple models based on emission factors that can be adjusted to accommodate various production practices [92]. Examples like Cool Farm Tool, COMET-Farm, and AgRECalc are versatile, functioning across diverse production systems, including dairy farming. While these models offer practical guidance for strategic planning and day-to-day management when accurately calibrated or validated with empirical data, they may not fully represent individual farm processes under all conditions or capture source interactions as efficiently as more intricate models.

Scientists developed farm-scale process simulation models like DairyMod, MELODIE, FASSET, SIMS(Dairy), IFSM, and Manure DNDC (Table 2) to gain a deeper understanding of processes and predict their interactions [90]. These models, while less flexible than simpler ones, provide comprehensive insights into the effects of changes in farm management. For example, DairyMod concentrates on pasture-based dairy operations in Australia, while SIMS (dairy) and MELODIE were created in Europe for pasture-based dairy production. FASSET and IFSM, designed for confinement production systems, also include elements of pasture and grazing [88]. DairyGEM, FarmAC, DairyWise, and Holos fall into the intermediate range of model complexity. These models strike a balance, relying more on empirical relationships and process-related emission factors to describe emission processes. They offer moderate detail and flexibility compared to the simpler decision support tools and the more complex process simulation models, providing valuable insights into emissions and environmental impacts associated with dairy farming. Thus, whole-farm tools play a crucial role in aiding decision-makers by providing insights into the ecological footprint of farms and facilitating the development of effective mitigation strategies.

Table 2. Whole-farm models for estimating GHGEs.

Model	Description	Reference	Developed in
DairyMod	Simulating the biophysical processes of pasture-based dairy systems to predict the dynamics of greenhouse gas emissions, encompassing both primary and secondary emissions, while also assessing the soil carbon balance.	[93]	IMJ Consultants, Dairy Australia, University of Melbourne, Australia.
MELODIE	Conducting a dynamic simulation of the movement of carbon, nitrogen, phosphorus, copper, zinc, and water within components such as animals, pastures, crops, and manure.	[94]	French National Institute for Agricultural Research, INRA, France
SIMS (dairy)	Simulating the impact of management practices, climate conditions, and soil properties on the losses of nitrogen, phosphorus, and carbon, as well as evaluating effects on profitability, biodiversity, soil quality, and animal welfare.	[95]	BC3-Basque Centre for Climate Change, Spain
FASSET	Utilizing process simulation to assess the impacts of alterations in regulations, management strategies, pricing, and subsidies on farm output, profitability, nitrogen runoff, energy usage, and GHG emissions.	[96]	Aarhus University, Denmark
IFSM	Conducting process simulation for all crucial farm components, depicting their performance, economic aspects, and environmental impacts, encompassing both direct and indirect GHGEs and the carbon footprint.	[97]	USDA-Agricultural Research Service, University Park, PA, USA
DairyGEM	A tool for estimating GHGs, ammonia (NH_3), and other gaseous emissions, as well as the carbon footprint, through the utilization of emission factors and process simulation in dairy production systems.	[98]	USDA-Agricultural Research Service, University Park, PA, USA
DairyWise	An empirical model designed to simulate the technical, environmental, and financial processes in a dairy farm, encompassing nitrogen and phosphorus cycling and losses, GHG emissions, and energy consumption.	[99]	Wageningen UR, the Netherlands
FarmAC	Emission factors related to processes depict the carbon and nitrogen flow in both arable and livestock farms, quantifying GHGEs, soil carbon sequestration, and nitrogen losses to the environment.	[100]	Aarhus University, Denmark
Holos	Emission factors based on processes estimate all significant direct and indirect sources of GHGEs from livestock operations.	[101]	Agriculture and Agri-Food Canada

11. Comparative Assessment of Carbon Footprints

Meat and dairy production are major contributors to GHGEs within the food supply chain. Annually, the food supply chain generates 13.7 BMTs of carbon dioxide equivalents (CO_2es), constituting 26% of total anthropogenic GHGEs (Figure 5) [102]. Notably, beef possesses the largest carbon footprint among various types of meat, trailed by lamb. At the same time, pork and poultry production collectively emit less than half the GHGs produced by beef and lamb combined (Figure 6). The key sources of emissions in beef production arise from cattle methane emissions and manure [103].

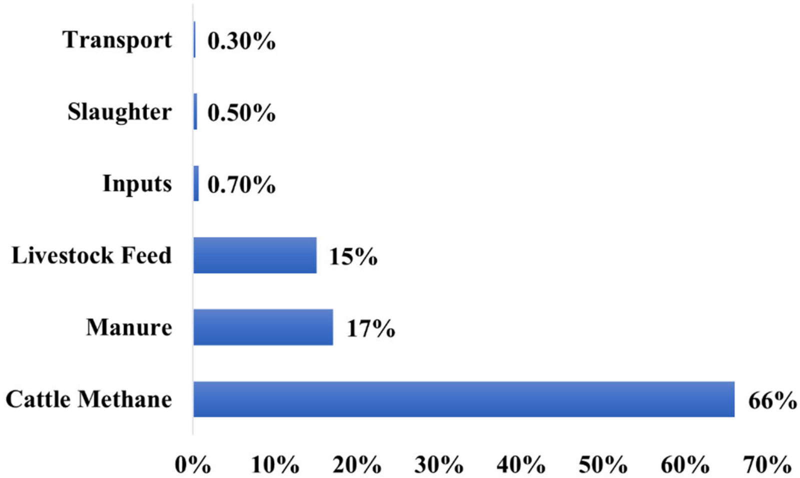

Figure 5. Beef production emission sources (% of total). Source: [102].

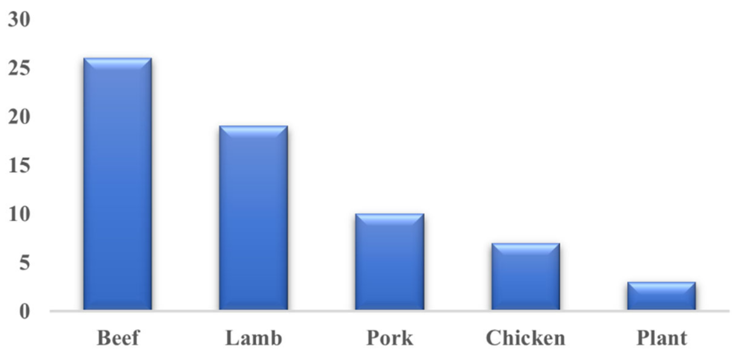

Figure 6. Supply chain greenhouse gas emissions by food type (kg-CO_2e/kg).

Foods with similar protein content, like different types of meat, show substantial variations in their CF/g of protein. These differences are mainly due to the varying carbon footprints per gram of edible food, which range from 17–36 g CO_2e/g for chicken, duck, and rabbit, to 129–293 g CO_2e/g of protein for beef (Figure 7) [104]. The ruminant nature of beef, sheep, and veal contributes significantly to their emissions, while non-ruminant animals like pig, chicken, rabbit, and duck show lower carbon footprints. Larger animals typically generate a greater CF/g of protein. A notable comparison is between milk and beef: milk, despite having the lowest carbon footprint per gram of edible food, demonstrates a relatively high footprint of 38–79 g CO_2e/g protein, surpassing the average value for beef [104]. Cheese, closely aligned with milk in protein-related CF, suggests that lacto-ovo-vegetarian diets might be less effective at lowering CF compared to alternative diets that include protein sources like chicken while excluding carbon-intensive meats like beef. Additionally, the discussion touches on game meat, which, despite being excluded from national carbon assessments, emits significant greenhouse gases comparable to mass-produced ruminant meats. Notably, the study emphasized that larger animals generally generate a greater CF/g of protein. The findings, therefore, underscore the importance of considering both total food weight and protein content when assessing the ecological effects of various foods, emphasizing the need for diversified dietary choices to mitigate carbon footprints in the food supply chain.

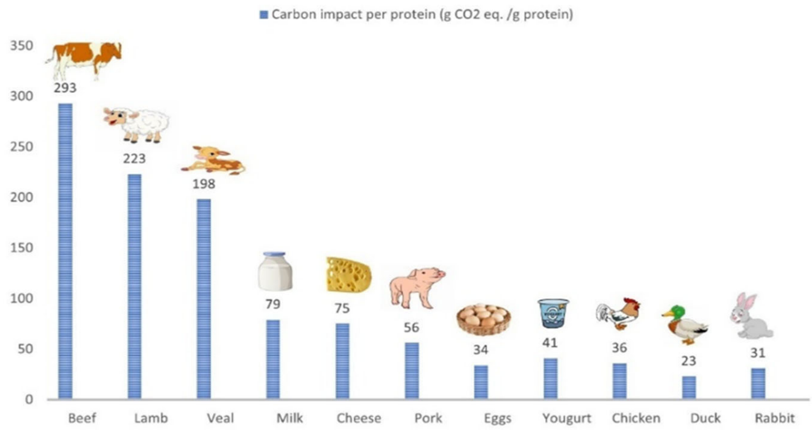

Figure 7. Carbon intensity of protein in common meat and dairy products measured in g CO_2e/g protein. Source: [104].

12. Strategies to Mitigate Livestock GHG Emissions

Livestock, especially cattle, play a major role in GHGEs, mainly via methane released during digestion (enteric fermentation) and manure management. The primary factors contributing to the CF from livestock are associated with feed utilization and manure handling. To address this environmental challenge, strategies to reduce CF in livestock systems focus on mitigating enteric emissions and emissions from manure. Combating these emissions involves a combination of technological, nutritional, and management approaches. As livestock farming poses complex challenges to environmental sustainability, a holistic and integrated strategy is essential. At the same time, carbon sequestration refers to the sustained storage of carbon in different ecosystems and presents an opportunity for mitigating climate change by offering the potential to offset CO_2 levels in the atmosphere. Given the urgency of climate concerns, a comprehensive approach that incorporates multiple strategies, like improved livestock management, dietary adjustments, and sustainable land use practices, emerges as a comprehensive and efficient method to mitigate GHGEs from livestock farming while promoting long-term carbon sequestration.

12.1. Reducing Enteric Emissions in Livestock

Many mitigation strategies have been proposed, each demonstrating a different level of effectiveness in reducing enteric methane emissions (e.g., modification of diet, vaccinations, chemical additives, genetic selection, etc.). Enteric methane production is affected by forage quality and digestibility. Another successful mitigation technique involves increasing concentrate feeding, which reduces methane emissions per unit of fat-protein-adjusted milk by 15% [105]. Nutritional techniques like high cereal diets, biohydrogenation of unsaturated fatty acids, increased production of propionic acid, protozoal inhibition, and supplementation with ionophores, fats, organic acid, probiotics, adaptogens, and bacteriocins have been suggested to reduce livestock CH_4 emissions [106,107]. Additionally, research is being done on vaccinations against rumen methanogens and animal breeding and selection to lower CH_4 production. By reducing the amount of energy obtained from fermentable carbohydrates and altering the microbial community of the rumen, the addition of lipids or fatty acids to the diets of ruminants can reduce enteric methane emissions [108]. It is also reported that a few agro-products, such as brewer's grains, cottonseed, cold-pressed canola meal, etc., are useful in lowering enteric fermentation.

12.1.1. Use of Anti-Methanogenic Agents

In ruminants, CH_4 production is considered an efficiency loss. Strategies that reduce CH_4 emissions may also benefit energy efficiency [109]. Dietary supplements to reduce methane production in ruminants include chemical inhibitors, nitrate, ionophores, and lipids. While these compounds are effective in reducing CH_4 emissions and may enhance production efficiency, they can also adversely impact ruminal health, function, and metabolism. Disrupting methanogenesis (CH_4 production) might lead to the accumulation of hydrogen gas (H_2) in the rumen, potentially impairing rumen fermentation [110]. If these supplements are to be utilized, it is crucial to determine appropriate dosage levels based on factors such as animals' weight, production stage, and nutritional status. Additionally, strategies should be employed to introduce these supplements into ruminant diets gradually.

Chemical Inhibitors

Chemical inhibitors such as halomethanes, including bromochloromethane and chloroform, can markedly decrease the direct production of CH_4 by a considerable percentage, reaching up to 50% [111]. However, prolonged incorporation of these inhibitors into the ruminants' diet has been linked with adverse effects such as hepatotoxicity, nephrotoxicity, and the potential for carcinogenic outcomes. According to Patra [112], there is a reported risk of toxicity linked to halomethane supplementation, with observed effects ranging from liver damage to death. In contrast to the above chemical inhibitors, supplementation of the compound 3NP (3-nitrooxypropanol) is a prominent approach for reducing CH_4 emissions in ruminants without any potential side effects. During in vivo trials with sheep [113], 3-nitrooxypropanol (3NP) led to a notable 24% decrease in CH_4 emissions. For cattle, the reductions varied from 7% [114] to a remarkable 60% [115]. These results indicate that 3NP is highly promising in mitigating CH_4 emissions and appears to be a safe dietary strategy for ruminants.

Nitrates

Nitrates can serve as an electron acceptor instead of CO_2, producing ammonia instead of CH_4 [116]. This represents an alternative hydrogen utilization pathway in the rumen. In the unadapted rumen, the nitrate reduction rate surpasses nitrite reduction, leading to nitrite accumulation in the rumen and subsequent absorption [117]. When nitrite is available in the blood, it binds strongly to hemoglobin, forming methemoglobin, which is unable to transport oxygen. Gradually acclimating animals to a diet that includes nitrate results in an increased abundance of nitrite-reducing bacteria, thereby enhancing the ability to reduce nitrite. This adaptation is crucial in preventing the harmful effects of nitrite on oxygen transport in the blood.

Antibiotic Ionophores

Monensin is the most commonly used antibiotic ionophore for reducing methane emissions in ruminants. Monensin induces a significant initial reduction of 27% to 30% in enteric methane emissions in beef cattle within the first month [118]. Nevertheless, the effectiveness diminishes over time as the ruminal microflora adapt to monensin. Thus, the impact is reduced, even to a 9% decrease in CH_4 emissions in cattle, as Appuhamy et al. [119] noted. Ionophores possess the ability to enhance feed efficiency, resulting in a decreased amount of feed intake needed to sustain production. This, in turn, contributes to a decrease in CH_4 emissions per unit of product produced.

Lipid Supplementation

Medium-chain fatty acids have been recognized for decreasing methanogenesis through various mechanisms. These include reducing the reliance on fermentable carbohydrates for energy supply, altering the composition of rumen microbiota with a notable inhibition of methanogens, and participating in the microbial hydrogenation of unsaturated fatty acids, serving as a hydrogen acceptor. The cumulative effect of these mechanisms can lead to a reduction in methane production of up to 5.4% for every 1% increase in lipid content (up to 6% lipid supplementation on a dry matter basis)(Table 3) [120]. Higher lipid supplementation in the diet can affect gastrointestinal function in ruminants, so it is crucial to avoid exceeding 3% to 4% of total dry matter intake [121], especially in diets rich in fiber. Nevertheless, lipid supplementation should be utilized as a tactic to reduce methane emissions. In that case, adding fats may be required at levels ranging from 5% to 8% of the dry matter in the diet [122]. Additionally, supplementation with ALA has been shown to enhance cellular antioxidant status and stabilize the transient heat shock response, extending thermo-tolerance from a short-lived phase to long-term acclimatization [123]. This dual benefit suggests that strategic lipid supplementation not only mitigates methane emissions but may also contribute to improved cellular resilience under heat stress conditions.

Table 3. Strategies to mitigate enteric methane emissions with advantages and limitations.

Types	Compounds	Advantages	Limitations
Chemical inhibitors	Halomethanes (bromochloromethane, chloroform)	CH_4 emission reduction by up to 50% [111]; improved energy efficiency	Hepatotoxic, nephrotoxic, and carcinogenic
	3-nitrooxypropanol	CH_4 emission reduction by up to 60% [115]	
Electron acceptors	Nitrate	CH_4 emission reduction by up to 50% [124]	Methemoglobinemia and carcinogenic; ammonia pollution
Ionophores	Monensin	CH_4 emission reduction by up to 9% [119]; increased feed efficiency	Antibiotic resistance
Lipids	Medium-chain fatty acids	CH_4 emission reduction by up to 5.4% [120]	Impaired gastrointestinal function

12.1.2. Commercial Feed Solutions for Methane Mitigation

Various feed supplements have been developed and commercialized to mitigate methane emissions from ruminants such as cattle, sheep, and goats. These supplements are specifically designed to influence the digestive processes occurring in the rumen, where CH_4 is generated as a byproduct of microbial fermentation. The effectiveness of these supplements may differ based on factors such as livestock, diet, and management practices.

Rumin8

After CO_2, CH_4 is the second most prevalent anthropogenic GHG, responsible for approximately 20% of global emissions. Over 20 years, CH_4 exhibits a warming potency 80 times greater than CO_2. Rumin8, an Australian startup, is developing a dietary supplement to curb methane production. The supplement utilizes a pure form of nature's anti-methanogenic compound, tribromo-methane (TBM), sourced from red seaweed as a synthetic material. Continuous experiments consistently demonstrate significant appeal to animals, productivity increases of up to 9%, and remarkable effectiveness in reducing methane emissions (ranging from 50–90% in grain-fed cattle and 24–50% in grass-fed cattle) [125].

Bovaer

Bovaer, a feed supplement created by Dutch State Mines, is designed to diminish enteric CH_4 emissions from ruminant animals like beef cattle and dairy cows. It incorporates a compound known as 3-NOP (3-nitrooxypropanol), which hinders the final stage of methane production in these animals. The active component in Bovaer undergoes natural breakdown during the digestion process. Research has shown that Bovaer can decrease methane emissions by 30% in dairy cows and 45% in beef cattle [126].

Tamarind Seed Husk

The husk of tamarind seeds can be efficiently utilized for obtaining condensed tannin, constituting up to 5% of the diet while having no impact on feed intake or digestibility. Incorporating tamarind seed husk into the diet could significantly reduce enteric methane emissions by 15–17%. This reduction is attributed to the direct suppression of rumen methanogens, reduction in rumen protozoa, and alteration in the rumen fermentation process. In addition to reducing methane emissions, the appropriate supplementation of tamarind seed husk improves the efficiency of protein utilization in ruminants by reducing protein degradability [127]. A complete feed block enriched with tamarind seed husk has been developed by the Institute ICAR-NIANP and shown to have decreased methane production up to 20% with inclusion in the livestock feed [128].

HaritDhara

HaritDhara is a dietary additive intended for buffalo, cattle, and sheep, specifically designed to decrease CH_4 production by targeting rumen methanogens responsible for its production. Its effectiveness lies in the presence of saponins, which induce defaunation by binding to sterols on protozoal surfaces, and tannins that can deactivate ruminal enzymes [129]. Studies indicate that HaritDhara's partial inhibition of enteric methanogenesis results in a 20–25% reduction in methane production [130]. This reduction increases milk production with more lactose content and weight gain. The recommended daily consumption for adult cattle is 150–200 g and it varies based on the animal and its age. Developed by ICAR-NIANP, HaritDhara is a cost-effective solution that reduces methane emissions, addresses environmental concerns, and provides economic benefits by promoting increased milk production and improved body weight in livestock. The adoption of climate-smart technologies is more likely when they offer economic benefits.

12.1.3. Genetic Selection

Livestock methane emissions are closely linked to their body weight, productivity, and dietary factors. Indian dairy livestock exhibit lower milk yield per animal than developed countries like the USA, Netherlands, Denmark, etc. [131]. It is possible to lower methane production per unit of milk by switching out low-yielding and non-productive breeds with higher-yielding ones. Genetic selection focused on enhanced feed efficiency can result in animals with improved energy ratios, ultimately leading to lower methane emissions [132]. Prioritizing the selection of dairy cows with high milk production and energy utilization efficiency effectively mitigates methane emissions. Indigenous cattle breeds such as the Tharparkar, Kankrej, Gir, and Sahiwal demonstrate better adaptation to challenging climates, particularly regarding heat tolerance and disease resistance, than cross-bred and exotic breeds. Emphasizing the conservation of indigenous livestock breeds and implementing genetic improvement programs geared towards climate resilience is crucial for the future.

12.1.4. Microalgae Cultivation

Microalgae can convert CO_2 into organic carbon (biomass) through photosynthesis, utilizing light energy [133]. The high presence of lipids and carbohydrates in microalgae biomass makes it a valuable resource for biofuel production [134]. The biodiesel production process from microalgae biomass is environmentally friendly, emitting no toxic compounds into the atmosphere [135]. Biofuels derived from microalgae could contribute to lower carbon dioxide emissions than other commercial fuels, potentially playing a crucial role in reducing global warming [136]. Livestock farms generate organic waste, such as manure, which contains nutrients that microalgae can utilize for growth. Microalgae cultivation in photo-bioreactors allows for the efficient utilization of nutrients in livestock waste, contributing to waste management practices on the farm. The microalgae that have been harvested can be added to animal feed to improve its nutritional value. Proteins, important fatty acids, and other nutrients found in microalgae can improve the overall nutritional profile of animal feed. Additionally, microalgae can also aid in the removal of toxic compounds, such as nitric and sulfur oxides, from flue gases [137]. This cultivation process as an alternative CO_2 fixation technology could enhance biomass productivity, promoting increased carbon biofixation. Cultivating microalgae not only aids in the remediation of nutrient-rich livestock waste but also yields microalgae biomass that can serve as a valuable resource.

12.1.5. Grassland Management

A number of techniques, such as managing grazing, introducing suitable forage species, applying fertilizer sparingly, irrigating grasslands, and restoring degraded areas, can improve the sequestration of carbon in grasslands (Figure 8). Around the world, soils hold three times as much carbon as vegetation and roughly twice as much as the atmosphere. Consequently, soil serves as both a source and a sink for greenhouse gases, and maintaining a delicate balance between these functions is crucial. Gases continuously move between different pools of the ecosystem to sustain equilibrium [138]. Rates of carbon sequestration and soil organic carbon (SOC) values exhibit variations among grassland systems. However, grassland systems play a vital role in storing carbon. Increasing SOC storage through land use changes and effective land management presents a low-cost and environmentally beneficial method for sequestering significant amounts of atmospheric CO_2, emphasizing the need for its widespread adoption. Implementing these strategies contributes to mitigating climate change by sequestering carbon effectively within grassland ecosystems [139].

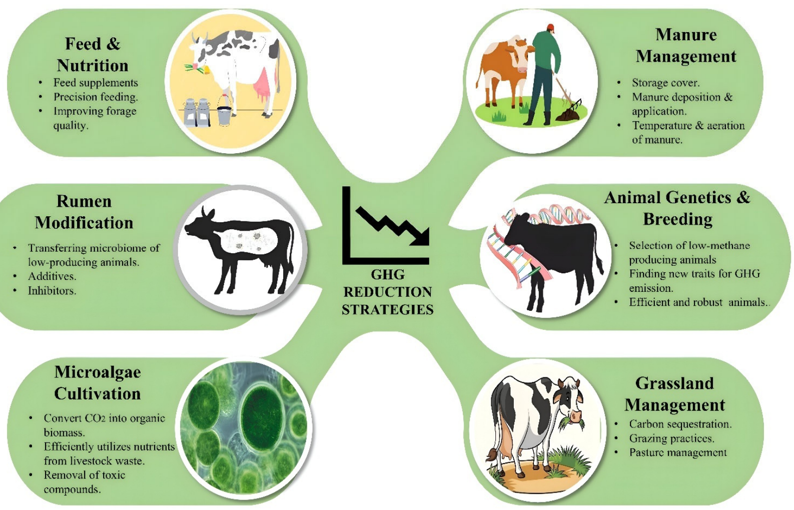

Figure 8. Strategies for mitigating GHG emissions from livestock.

12.1.6. Precision Livestock Farming (PLF)

Precision livestock farming (PLF) integrates sensor technology, algorithms, interfaces, and applications in animal husbandry, and is predominantly observed in dairy farming [140]. It regularly collects data from animals using data modeling techniques and Internet of Things (IoT) devices. It analyzes these data to inform decisions concerning the animals and the surrounding environment. PLF technologies, integrated into various processes, such as those contributing to the greenhouse effect (e.g., feed efficiency and fertility management), are gaining widespread acceptance in the agricultural sector. Incorporating sensors to identify early signs of animal illnesses benefits animal health and reduces environmental impact by minimizing the need for antibiotics and preventing disease spread [141]. Furthermore, PLF not only presents opportunities for objective data collection and risk prediction, but also raises concerns such as technological dependency and shifts in human–animal relationships.

12.1.7. AI for Monitoring and Scouting Natural Resources

Machine learning has become more popular for soil analysis, including soil carbon assessment, as a result of easier access to soil data and openly available algorithms. AI applications in soil carbon include digital mapping of carbon fractions, carbon stock estimation using satellite images, climate-sensitive soil carbon mapping with field samples, modeling organic carbon changes, and estimating soil health indicators using spectroscopic data [142].

Recent exploration into deep learning algorithms, particularly deep neural networks (DNNs), has focused on predicting water quality (WQ) parameters and harmful algal blooms (HABs) using remote sensing (RS) data. Pyo et al. [143] trained a convolutional neural network (CNN) to predict phycocyanin (PC) and chlorophyll-a (Chl) concentrations from airborne hyperspectral imagery. Yim et al. [144] investigated a fully connected DNN model for PC prediction and found that unsupervised pre-training improved prediction accuracy by 3%. Peterson et al. [145] compared a DNN with conventional machine learning (ML) methods for estimating WQ parameters from Landsat-8/Sentinel-2 satellite imagery, showing the DNN outperforming ML methods. Further studies by Sagan et al. [146] utilizing various spectral data sources corroborated these findings. Despite advancements in optically active WQ parameter estimation, non-optically active WQ estimation continues to be challenging. DNN-based multimodal spatiotemporal analysis, as demonstrated by Hill et al. [147] in HABNet, combines a CNN with long short-term memory (LSTM) to achieve high detection accuracy for HAB events, showcasing the DNN's capability in processing complex spatiotemporal data.

To further enhance sustainability in agricultural and water resource management, recent advancements in machine learning and deep learning technologies have shown significant promise in analyzing and optimizing soil and water parameters. The global population boom and the increasing per capita demand for freshwater are amplifying the strain on natural resources. The water footprint (WF) serves as a crucial metric to assess both direct and indirect water use in various processes. In agriculture, WF modeling helps highlight the impacts and limitations of current crop production systems, allowing for targeted actions to improve water productivity and promote sustainable water use [148]. With the rising consumption of animal products, the pressure on the world's freshwater resources is poised to escalate further. Nearly one-third of the total agricultural water footprint globally is linked to the production of animal products. The WF of animal products significantly exceeds that of crop products with equivalent nutritional value, highlighting inefficiencies within the livestock sector [149]. Livestock and poultry production consume considerable water resources, posing substantial challenges to global freshwater reserves. For instance, sheep meat has the second-highest water footprint among livestock meats. As the demand for sheep meat grows annually, so does water consumption for its production. Estimating the WF of animal husbandry is essential for making informed water management decisions. The water footprint for sheep and goats was calculated to be 6.03 m^3/kg and 5.05 m^3/kg, respectively [150].

A case study on the water footprint in dairy processing units in India found that the average total WF, encompassing both direct and indirect water use, was 9.0 L of water per kg of milk processed. Indirect water use, primarily due to electricity consumption, accounted for a significant share (~89%) of this total. Additionally, the dairy plant's processing capacity and product mix contributed to seasonal and annual variations in the WF. An inverse relationship was observed between the average total WF and the average monthly milk processed in the study plants [151]. These studies underscore the importance of sustainable water management practices in agriculture and livestock production. By adopting more efficient water use practices, enhancing water productivity, and promoting sustainable water use, we can mitigate the environmental impact of livestock farming and ensure the long-term availability of freshwater resources. Continuous monitoring and WF assessment are essential for making data-driven decisions to achieve sustainable agriculture and livestock production.

12.2. Steps to Cut Down Manure-Related Emissions

After enteric methane, manure constitutes the second largest source of GHGEs from dairy farms. It accounts for 7% of both methane and nitrous oxide emissions in agriculture [152]. Livestock manure should be stored and applied properly as it releases GHGs (CO_2, N_2O, and CH_4), in addition to NH_3 and NO_3. Aerating the stockpile, engaging in composting, and employing a durable plastic film cover for the stockpile are all methods that can reduce methane emissions [74]. Methane and nitrous oxide may result from the breakdown of animal manure in environments with limited oxygen [153]. This commonly occurs in concentrated animal feeding operations, including swine and poultry farms, dairy farms, and beef feedlots. In these settings, manure is frequently amassed in substantial heaps or managed in lagoons, and various manure disposal systems favor an anaerobic environment. Dung beetles belonging to *Scarabaeidae* (Scarabaeinae, Aphodiinae, and Geotrupidae) play a crucial role in decomposing dung in both temperate and tropical agricultural grasslands [154]. These beetles contribute to lessening the environmental impact by promoting dung aeration and burial. Penttila et al. [155] found that dung beetles decreased methane (CH_4) emissions from cattle dung pats by reducing anaerobic decomposition and methanogenesis. Urease inhibitors can be added to manure stockpiles to slow down or stop the rate at which urea in animal urine and manure transforms to N_2O.

Biofilters effectively reduce methane and ammonia in animal housing that is mechanically ventilated. Still, managing nitrification and denitrification processes is crucial for controlling nitrous oxide emissions and enhancing overall efficiency in mitigating GHGEs. Manure digestion under anaerobic conditions is another method for lowering GHGEs. By capturing and eliminating the majority of CH_4 from manure, generating renewable energy, and assisting with sanitation in developing nations, anaerobic manure digesters offer a significant method for reducing GHGEs. Manure digestion causes a net neutral effect on air emissions, increasing direct N_2O emissions while decreasing NH_3 emissions [21]. Acidifying manure to lower its pH is a promising way to lower NH_3 and CH_4 during storage, but it may also increase N_2O emissions when applied to land. Emission of N_2O can be reduced by applying manure at the right time (avoiding applying it right before it rains) and keeping the pH of the soil above 6.5 [156].

13. Strategies Implemented by India for Methane Reduction

13.1. India Greenhouse Gas Program (Launched in 2012)

The India Greenhouse Gas (GHG) Program is a voluntary initiative spearheaded by the industry and intended to assist Indian companies in tracking their progress towards measuring and controlling GHGEs. WRI India, The Energy and Resources Institute (TERI), and the Confederation of Indian Industry (CII) are collaborating on this effort. The program's primary goal is to formulate inclusive approaches for emissions reduction, thereby enhancing the profitability, competitiveness, and sustainability of businesses and organizations in India. Participating companies have the opportunity to gauge and regulate their GHGEs using tools and methodologies provided by WRI's GHG Protocol [157].

13.2. The National Livestock Mission (NLM) (Since 2014)

The Department of Animal Husbandry and Dairying (DAHD) in India actively executes the National Livestock Mission (NLM), incorporating efforts like breed improvement and balanced rationing. A key focus is on feeding livestock high-quality, balanced rations to help mitigate methane emissions from these animals. The Indian government, through the NLM, is promoting practices like production of green fodder, silage, chaff cutting, and total mixed rations. These efforts aim to not only enhance livestock nutrition but also contribute to reducing methane emissions [158].

13.3. The Galvanizing Organic Bio-Agro Resources (Gobar-Dhan) Scheme

The Indian government has launched programs such as 'The Gobar (Galvanizing Organic Bio-Agro Resources)-Dhan' scheme (implemented in 2018) [159] and the New National Biogas and Organic Manure Programme (in operation since 2017). These programs incentivize the utilization of cattle waste, promoting the efficient conversion of waste into valuable resources and the generation of clean energy in rural areas [160]. The Gobar-Dhan scheme specifically supports the recovery of biodegradable waste, emphasizing the reduction of methane emissions and the transformation of waste into resources.

13.4. Seaweed-Based Animal Feed

In partnership with three prominent Indian institutes, the Central Salt & Marine Chemical Research Institute (CSMCRI), located in Bhavnagar, has created an animal feed additive derived from seaweed. This pioneering formulation serves multiple purposes, including reducing methane emissions from cattle by incorporating seaweed into their feed. Additionally, the additive enhances the immunity of both cattle and poultry [161].

13.5. Anti-Methanogenic Feed Supplement "HaritDhara"

As per a recent estimation conducted by the ICAR-National Institute of Animal Nutrition and Physiology in Bangalore, India, the country's livestock emit around 9.25 million metric tons of enteric methane annually. Following a decade of thorough and systematic research, the institute has successfully created a product named "HaritDhara" as part of an ICAR-sponsored research initiative titled "Estimation of methane emission under different feeding systems and development of mitigation strategies" [130]. India has set ambitious targets to reduce GHGEs by 33–35% by 2030 compared to 2005 levels and achieve net-zero emissions by 2070 [162].

14. Global Research Initiatives and Future Perspectives for Sustainable Livestock Management

With a commitment to limiting global warming to 1.5 °C, India has set an ambitious target of achieving net-zero carbon emissions by 2070. This commitment, officially announced at COP26 in 2021 and reinforced in the 2022 Nationally Determined Contributions (NDC), includes the Panchamrita strategy, which focuses on five key goals: generating 500 GW of non-fossil fuel electricity by 2030, sourcing half of the country's energy from renewables, cutting total carbon emissions by one billion metric tons from 2022 levels, reducing the economy's carbon intensity by at least 45% from 2005 levels, and ultimately achieving net-zero emissions by 2070, demonstrating India's commitment to global climate action [163]. Additionally, the Global Methane Pledge (GMP), launched at COP26 by the United States and the European Union, aims to reduce methane emissions by at least 30% by 2030 compared to 2020 levels, potentially lowering global warming by 0.2 °C by 2050. This pledge targets key methane-emitting sectors, including energy, agriculture, and waste management [164].

The livestock sector plays a critical role in global food security, economy, and livelihoods, yet it significantly contributes to greenhouse gas emissions (GHGEs). Climate change, driven by global warming, has heightened the vulnerability of livestock worldwide to heat stress, leading to decreased animal productivity and posing a threat to sustainability [165]. The International Livestock Research Institute (ILRI), in collaboration with the Ministry of Livestock Development (MLD) and FAO, focuses on improving livestock productivity, sustainability, and safety. ILRI initiatives aim to reduce emissions per unit of milk by increasing dairy productivity, facilitating carbon credit methodologies [166]. At COP28, nearly 200 countries reached a historic agreement to reduce fossil fuel consumption, prioritizing climate justice through financial support for low-income nations and advocating for a swift transition to renewable energy. The summit underscored the need for urgent emission reductions, biodiversity-conscious climate actions, and financial backing for climate initiatives [167]. To assess GHGE mitigation and adaptation strategies in livestock, the FAO developed the Global Livestock Environmental Assessment Model (GLEAM), which utilizes Tier 2 IPCC methodologies. Additionally, the Livestock Environmental Assessment Performance (LEAP) Partnership provides harmonized accounting rules for quantifying GHGEs from livestock supply chains [168].

Technological innovations have been instrumental in reducing methane emissions in livestock farming. The European Union-supported ZELP project developed a wearable device for cattle that captures exhaled methane and converts it into carbon dioxide and water vapor through a catalytic converter. By mitigating methane emissions in real-time, this technology significantly contributes to the decarbonization of the agricultural sector [79,169]. In the United States, the Department of Agriculture invested USD 3.1 billion in 2022 to support climate-smart agricultural projects aimed at expanding markets for low-carbon commodities and providing economic incentives for sustainable farming practices. Notable initiatives include the following:

i. The California Dairy Research Foundation's USD 85 million project promoting climate-smart dairy markets through methane-reducing manure management techniques [170];
ii. South Dakota State University's USD 80 million "The Grass is Greener on the Other Side" project, which fosters climate-smart beef and bison commodity markets through data-driven grazing and land management practices;
iii. Texas A&M AgriLife Research's USD 65 million five-year initiative to promote climate-smart agriculture and forestry practices through improved pasture management and economic tools for farmers.

As the agricultural sector evolves, Digital Livestock Farming (DLF) is emerging as a transformative approach integrating artificial intelligence (AI), the Internet of Things (IoT), and big data to enhance efficiency, animal welfare, and environmental sustainability. By 2030, real-time tracking of individual animals using sensors, cameras, and wearables will enable early detection of diseases, optimization of feed strategies, and improved reproductive management. Machine learning (ML) algorithms will predict stressors and disease outbreaks, minimizing economic losses. Looking beyond 2030, fully automated livestock farms are envisioned, where AI-driven robots perform tasks such as milking, feeding, and monitoring, reducing labor challenges and maximizing resource efficiency [171].

While technological advancements are crucial, the transition to sustainable livestock production must also consider economic viability. Sustainable intensification strategies, such as organic fertilization and cover cropping, have relatively lower costs and offer faster returns on investment. However, more capital-intensive interventions, such as biodiversity conservation zones and water sequestration landscaping, require careful economic assessments. Garcia et al. [172] estimated that sustainable cattle intensification in the Brazilian Amazon would require an investment of approximately USD 1300 per hectare, which could be financially viable for farms exceeding 400 hectares of pastureland while simultaneously reducing deforestation and environmental impact. In contrast, studies evaluating the cost–benefit analysis of climate-smart cattle production in India remain limited and warrant increased research efforts.

To further enhance sustainability, promoting small ruminants, such as tropical goats, which exhibit climate resilience and lower GHGEs, is essential, particularly in developing countries where small-scale farmers can contribute to climate change mitigation. India has pledged to increase tree cover, creating additional carbon sinks equivalent to its annual emissions. This strategy extends to afforestation and agroforestry in grazing areas, enhancing carbon sequestration and supporting sustainable land management practices aligned with India's Paris Agreement commitments [173]. Long-term strategies for 2030–2045 are being formulated to decouple carbon emissions from economic growth, with state-level climate action plans integrating renewable energy expansion, e-mobility adoption, and emission reduction policies [174].

Additionally, innovative strategies such as seaweed cultivation for biofuels and livestock feed are gaining traction in India, serving as natural carbon sinks while mitigating agricultural emissions. This initiative contributes to food security and economic empowerment, particularly for women engaged in seaweed farming. Strengthening climate policies, including carbon pricing mechanisms and financial incentives for climate-friendly livestock management, is imperative. A collaborative approach involving governments, research institutions, farmers, and the private sector is essential for achieving meaningful GHGE reductions and positioning India as a global leader in sustainable livestock practices. These efforts contribute to international climate goals while ensuring a resilient and environmentally responsible future for the livestock sector.

15. Conclusions

Achieving sustainable livestock production is crucial for meeting the growing global demand for animal-derived products while simultaneously addressing climate change challenges. The global livestock system significantly contributes to greenhouse gas emissions, with India, as the largest livestock hub, playing a pivotal role in this dynamic. Despite lower emissions per animal, India's overall contribution to emissions remains substantial, necessitating targeted interventions to reduce its carbon footprint. Strategies such as improving feed efficiency, modifying diets, and enhancing manure management are essential for mitigating emissions and promoting sustainability. Due emphasis on various carbon footprint measurement tools and AI modeling approaches can enable precise assessments and optimized management practices. The introduction of tools like the Carbon Footprint Index represents a significant advancement in assessing sustainability, enabling stakeholders to evaluate key factors such as feed efficiency, waste management, and emission reduction efforts. Such technologies provide valuable insights for decision-making and effective resource allocation, supporting the efforts to reduce the carbon footprint of livestock systems.

As the global population expands and environmental pressures intensify, implementing sustainable livestock practices becomes increasingly critical. These practices not only aim to balance demand with environmental preservation but also ensure food security for current and future generations. By adopting and implementing these measures, we not only contribute to environmental health but also enhance the long-term viability of the livestock sector amidst global challenges. Ultimately, fostering sustainability within livestock systems is not just an environmental imperative but also a pathway to resilience and stability in food production, ensuring a balanced approach for future generations.

Author Contributions: K.K. and H.A.S. conceived the study, establishing its foundational framework and objectives. The initial draft was collaboratively developed by V.K.E., S.P.M., S.K.L., H.A.S. and K.K., who contributed significantly to the structure and content. S.P.M., V.K.E. and L.S. created the tables and figures, enhancing the visual representation of key data. The references were formatted by V.K.E., S.P.M., H.A., L.K., Z.F., H.A.S. and S.K.L. Subsequent revisions and enhancements to the manuscript were conducted by K.S., M.A.P., V.S.C., S.P.M., Z.F, V.K.E., V.P.M., G.S., H.A.S. and K.K., each bringing their specialized knowledge to refine the analysis and discussion. All authors engaged in critical review of the final manuscript, ensuring a comprehensive exploration of sustainable livestock solutions and their implications for addressing carbon footprint challenges. This collaborative effort reflects the diverse expertise within the team, underscoring the interdisciplinary nature of the research. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

GHG	Greenhouse gas
GHGE	Greenhouse gas emissions
BMT	Billion metric tons
MMT	Million metric tons
CO_2e	Carbon dioxide equivalent
CF	Carbon footprint
kg	kilograms
Mg	megagrams
GWP	Global Warming Potential
AR	Assessment reports
SF_6	Sulfur hexafluoride
IVGPT	Invitro-gas production technique
LMD	Laser methane detector
MANNER	Methane and Nitrous Oxide Emissions from National cattle
CNCPS	Cornell Net Carbohydrate and Protein System
RNS	Ruminant Nutrition System
LCA	Life cycle assessment
GLEAM	Global Livestock Environmental Assessment Model
PLF	Precision livestock farming
NLM	National Livestock Mission
WF	Water footprint

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