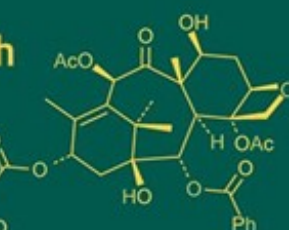
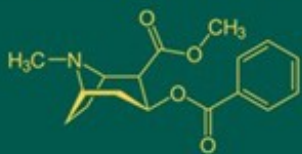


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Carbon footprint of livestock production and strategies for reduction in India: A review

Prashant Mohanrao Sathe¹, Sakshi Vijay Tirpude²DOI: <https://www.doi.org/10.33545/26174693.2026.v10.i10e.10396>**ABSTRACT**

Livestock production is an important component of India's agricultural economy, food security and rural livelihoods, but it is also a significant source of greenhouse gas emissions. The carbon footprint of livestock production arises from enteric fermentation, manure management, feed production, fertilizer use, energy consumption, transportation and land-use changes. Enteric methane from ruminants is a major emission source in Indian livestock systems. This review examines the principal sources of greenhouse gas emissions from Indian livestock production and evaluates practical and emerging strategies for reducing emission intensity. Major approaches include ration balancing, improvement of feed quality and digestibility, enhanced animal productivity, genetic improvement, feed additives, rumen manipulation, improved manure management, anaerobic digestion, biogas production, efficient fertilizer use, fodder development, integrated crop-livestock systems, renewable energy and carbon sequestration. Indian life-cycle assessment studies show considerable variation in carbon footprint among species, regions and production systems because of differences in productivity, feed resources, manure management and methodological assumptions. Ration balancing has reduced methane emission and emission intensity under field conditions, while manure management can reduce methane emissions and provide renewable energy. However, mitigation measures must be compatible with farm size, feed availability, cost, climate, infrastructure and farmer adoption capacity. A combination of improved productivity, efficient feeding, better manure management, renewable energy, nutrient recycling and region-specific interventions is therefore required. Future research should emphasize farm-level measurements, India-specific emission factors, standardized life-cycle assessment, long-term field validation and integration of mitigation technologies with farmer economics.

Keywords: Carbon footprint, Livestock, Greenhouse gases, Methane, Enteric fermentation, Manure management, Life-cycle assessment, India, Mitigation, Dairy production

Introduction

Livestock production occupies an important position in the Indian agricultural system. Cattle, buffaloes, sheep, goats, pigs and poultry contribute to milk, meat, eggs, manure, employment and household income. Livestock are particularly important to small and marginal farmers because animals provide regular income and can utilize crop residues and agricultural by-products that are unsuitable for direct human consumption. However, the expansion and intensification of livestock production have increased concerns about greenhouse gas emissions and environmental sustainability.

Livestock production contributes to climate change through methane, nitrous oxide and carbon dioxide. Methane is primarily associated with enteric fermentation in ruminants and anaerobic decomposition of manure, whereas nitrous oxide is associated mainly with nitrogen excretion, manure management, fertilizer application and soil processes. Carbon dioxide emissions are associated with feed production, fossil-fuel use, electricity, transportation and other activities throughout the livestock production chain. Consequently, the carbon footprint of livestock products cannot be assessed solely on animal methane production; the complete production system must be considered (Patra, 2012; Dixit *et al.*, 2016; Patra, 2017; Rojas-Downing *et al.*, 2017) [1, 2, 3, 4].

At the global level, livestock has been estimated to account for approximately 14.5% of anthropogenic greenhouse gas emissions, although estimates vary according to system boundaries, years, emission factors and accounting approaches (Grossi *et al.*, 2019) [5]. Livestock-related emissions arise from land-use change, feed production, animal production, manure management, processing and transportation. Life-cycle assessment is therefore increasingly used to quantify environmental burdens associated with livestock products (de Vries *et al.*, 2010) [6].

India presents a distinctive situation because of its very large livestock population and predominance of smallholder production. The 20th Livestock Census recorded approximately 536.76 million livestock in

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2019 [7], including 193.46 million cattle, 109.85 million buffaloes, 74.26 million sheep and 148.88 million goats, while the poultry population was approximately 851.81 million (Department of Animal Husbandry and Dairying, 2019) [7]. Earlier Indian estimates demonstrated the importance of livestock methane. Patra estimated that enteric fermentation accounted for approximately 89.2% of livestock greenhouse gas emissions in the 2007 assessment, while manure methane contributed approximately 9.5% (Patra, 2012) [8]. A later assessment estimated total livestock emissions at approximately 339 Tg carbon dioxide equivalents, with enteric methane contributing 89.7% (Patra, 2017) [9].

The magnitude of the carbon footprint varies considerably among production systems. A smallholder dairy study from Anand, Gujarat, reported a cradle-to-farm-gate carbon footprint of approximately 2.2 kg carbon dioxide equivalents per kilogram of fat- and protein-corrected milk (Garg *et al.*, 2016) [10]. More recent research from Karnataka reported an average carbon footprint of 1.45–1.81 kg carbon dioxide equivalents per kilogram of fat- and protein-corrected milk, with enteric methane and feed production identified as major hotspots (Mech *et al.*, 2023) [11].

The objective of this review was to examine the major sources of carbon footprint in Indian livestock production and critically discuss practical and emerging strategies for reducing emissions while maintaining productivity, farmer income and food security.

2. Materials and methods

This manuscript was prepared as a narrative review of published literature concerning greenhouse gas emissions, carbon footprint, life-cycle assessment and mitigation strategies in livestock production, with particular emphasis on Indian production systems. The reviewed literature included research articles, review articles and relevant reports addressing enteric methane, manure management, feed production, animal productivity, nutrition, reproductive efficiency, genetic improvement, feed additives, renewable energy and integrated crop-livestock systems. Particular attention was given to studies reporting Indian farm-level measurements and life-cycle assessments. Life-cycle assessment concepts and methodological limitations were interpreted in accordance with established literature (de Vries *et al.*, 2010; Mohini *et al.*, 2018) [6, 12].

The evidence was organized into the following themes: (i) concept and assessment of carbon footprint; (ii) major emission sources; (iii) carbon footprint of major Indian livestock production systems; (iv) mitigation strategies; (v) challenges to adoption; and (vi) research gaps and future directions. Because this was a narrative review rather than a systematic review or meta-analysis, no pooled effect estimate was calculated. Reported values were retained with their original units and study context to avoid inappropriate direct comparison among studies using different system boundaries, functional units and emission factors.

3. Results

3.1 Concept of carbon footprint in livestock production

Carbon footprint refers to the total greenhouse gas emissions associated with a product, activity or production system, generally expressed as carbon dioxide equivalents. For livestock, it is commonly expressed per unit of milk, meat, eggs or live-weight production. A typical livestock carbon footprint includes feed production and processing, enteric fermentation, manure storage and management, fertilizer production and application, farm energy consumption, transportation, processing and other post-farm activities, and land-use change. Carbon sequestration may be considered where it is appropriately measured (de Vries *et al.*, 2010; Mohini *et al.*, 2018) [6, 12].

Life-cycle assessment provides a systematic approach for assessing these emissions and generally includes goal and scope definition, life-cycle inventory, life-cycle impact assessment and interpretation (de Vries *et al.*, 2010) [6]. The functional unit is important because carbon footprint may be reported per kilogram of live weight, kilogram of

meat, litre of milk or kilogram of fat- and protein-corrected milk. Direct comparison among studies therefore requires caution because studies may use different system boundaries, allocation procedures, emission factors and global warming potentials (de Vries *et al.*, 2010; Mohini *et al.*, 2018; Dağlıoğlu *et al.*, 2024) [6, 12, 13].

3.2 Major sources of carbon footprint in Indian livestock production

3.2.1 Enteric methane

Enteric fermentation is a major source of livestock methane in India. Methane is produced by methanogenic microorganisms in the rumen as a consequence of microbial fermentation and is primarily released through eructation. It represents both an environmental burden and an energy loss to the animal. Poor-quality, highly fibrous diets generally increase methane production per unit of animal product because of lower feed conversion efficiency (Patra, 2012; Patra, 2017; Malik *et al.*, 2012; Eckard *et al.*, 2010; Hristov *et al.*, 2013; Martin *et al.*, 2010) [8, 9, 14, 15, 16, 17]. In Karnataka smallholder dairies, enteric methane accounted for approximately 66.8% of total greenhouse gas emissions associated with milk production (Mech *et al.*, 2023) [11].

3.2.2 Feed production

Feed production contributes to carbon footprint through fertilizer manufacture and application, irrigation, farm machinery, electricity, crop production, transportation and processing. Feed ingredient choice can strongly influence the footprint. Fodder crops may require fertilizer, irrigation, pesticides and diesel, whereas crop residues and agro-industrial by-products can reduce environmental burdens when appropriate allocation procedures are used. In the Karnataka study, feed production represented approximately 23% of total greenhouse gas emissions from milk production (Mech *et al.*, 2023) [11].

3.2.3 Manure management

Manure is an important source of methane and nitrous oxide. Methane is generated when organic matter decomposes under anaerobic conditions, particularly during storage of slurry or manure, while nitrous oxide is associated with nitrification and denitrification of nitrogen in manure and soil. Indian measurements have demonstrated substantial seasonal variation in manure emissions and have highlighted the value of India-specific emission factors (Gupta *et al.*, 2007) [18]. Recent modelling has further indicated considerable mitigation potential through alternative cattle-manure management, including anaerobic digestion, biogas utilization and improved digestate management (Lama *et al.*, 2025) [19].

3.2.4 Nitrous oxide from manure and fertilizer

Nitrogen inefficiency increases environmental emissions. When dietary nitrogen exceeds animal requirements, excess nitrogen is excreted through urine and faeces. During manure storage and land application, part of this nitrogen can be converted to nitrous oxide. Feed production also contributes to nitrous oxide emissions because synthetic nitrogen fertilizer generates direct and indirect emissions. Improving nitrogen-use efficiency at both animal and crop levels is therefore important.

3.2.5 Energy and fuel use

Electricity and fossil fuels are consumed for milking, pumping, cooling, feed processing, transportation and other activities. Although these emissions may be smaller than enteric methane in many Indian ruminant systems, they become increasingly important as farms become mechanized.

3.2.6 Land use and carbon sequestration

Livestock systems interact strongly with land through feed crops, grazing systems and grasslands. Improved pasture management can increase soil organic carbon, although estimates of sequestration vary with climate, soil, vegetation and management. Carbon sequestration should therefore not simply be subtracted from livestock emissions without appropriate measurement and consideration of permanence.

3.3 Carbon footprint of major Indian livestock production systems

3.3.1 Dairy cattle and buffaloes

Dairy production is particularly important in India because of the large milk-producing population and predominance of smallholder farms. A cradle-to-farm-gate life-cycle assessment of smallholder dairy farms in Anand, Gujarat, demonstrated the importance of feed production, enteric fermentation and manure management in determining milk carbon footprint (Garg *et al.*, 2016) [10]. Ration balancing reduced lifetime greenhouse gas emission intensity by increasing productivity and distributing environmental burdens over greater milk production (Garg *et al.*, 2016) [20]. A field experiment reported a 10.1% reduction in methane emission following ration balancing in crossbred cows (Garg *et al.*, 2013) [21]. Smallholder dairy research from Karnataka similarly identified enteric methane and feed production as major hotspots (Mech *et al.*, 2023) [11]. Buffalo production also contributes substantially to India's livestock carbon footprint; differences have been reported between smallholder and organized buffalo farms (Garg *et al.*, 2014) [22], while feed composition has been shown to influence carbon footprint, water use and nutrient losses in tropical dairy buffalo production (Pordhiya *et al.*, 2023) [23].

3.3.2 Sheep production

Sheep are important in arid and semi-arid regions of India. Life-cycle assessment has identified enteric methane as a major contributor to the environmental footprint of sheep production, with reported contributions varying by breed and production system (Reddy *et al.*, 2019) [24]. A comparison of intensive, semi-intensive and extensive sheep farming systems reported carbon footprints of approximately 16.9, 15.8 and 17.1 kg carbon dioxide equivalents, respectively, and highlighted the importance of enteric fermentation and feed-related emissions (Lal *et al.*, 2022) [25].

3.3.3 Goat production

Goats contribute substantially to meat, milk and household income, particularly in resource-poor areas. Compared with dairy cattle and buffaloes, fewer Indian studies have quantified the complete carbon footprint of goat production. Mitigation should focus on improved nutrition and forage quality, strategic supplementation, reproductive performance and reduced mortality. Increasing productivity per breeding female can reduce emissions per unit of meat or milk by distributing maintenance emissions over greater output.

3.3.4 Poultry and pigs

Poultry and pigs differ from ruminants because enteric methane is relatively unimportant. Their environmental footprint is more strongly influenced by feed production, energy use and manure management. Improvements in feed conversion ratio, feed ingredient selection, energy efficiency and manure management are therefore particularly relevant in intensive poultry and pig systems.

3.4 Strategies for reducing carbon footprint

3.4.1 Ration balancing

Ration balancing is one of the most practical mitigation strategies for Indian dairy systems. Many smallholder animals receive diets based on locally available crop residues, green fodder and concentrates without precise balancing of energy, protein, minerals and vitamins. Nutritional imbalance can reduce milk production and increase methane emission intensity. Balanced feeding improves nutrient synchronization, microbial protein synthesis, feed utilization and animal productivity (Garg *et al.*, 2016; Sarkar *et al.*, 2024; Sherasia *et al.*, 2016; Kannan *et al.*, 2010) [20, 26, 27, 28].

3.4.2 Improving feed quality and digestibility

Improving forage quality through appropriate harvesting stage, processing, conservation and supplementation can increase digestibility and animal productivity. Measures include cultivation of high-quality perennial grasses, inclusion of suitable legumes, treatment of poor-

quality crop residues, silage production, appropriate concentrate supplementation, chopping and processing of roughages, and balanced mineral supplementation. However, intensification of fodder production should itself be assessed through life-cycle approaches because fertilizer, irrigation and machinery can introduce additional emissions (Reddy *et al.*, 2019; Lal *et al.*, 2022) [24, 25].

3.4.3 Improving animal productivity

Higher productivity per animal can reduce emission intensity because maintenance requirements are distributed over greater quantities of milk or meat. Productivity improvement can be achieved through improved nutrition, genetic improvement, disease control, reproductive efficiency, reduced mortality, improved calf management, heat-stress management and better housing. Productivity improvement should not be pursued at the expense of animal health or welfare (Mech *et al.*, 2023) [11].

3.4.4

Feed additives and rumen manipulation

Feed additives can modify rumen fermentation and reduce methane formation. Potential approaches include vegetable oils, tannins, saponins, nitrates, essential oils, probiotics, direct-fed microbial products and specific antimethanogenic compounds (Malik *et al.*, 2012; Eckard *et al.*, 2010; Hristov *et al.*, 2013; Martin *et al.*, 2010; Sherasia *et al.*, 2018) [14, 15, 16, 17, 29]. Their effectiveness depends on dose, diet composition, animal species and duration of feeding. Indian studies have investigated tannin-rich plant materials as locally available mitigation options (Sidhu *et al.*, 2024) [30]. Recent work has also explored biowaste-derived microbial feed additives, although wider field validation is required before broad extrapolation (Asediya *et al.*, 2026) [31].

3.4.5 3-Nitrooxypropanol

3-Nitrooxypropanol inhibits methyl-coenzyme M reductase, an enzyme involved in the final step of methanogenesis. International studies have demonstrated substantial reductions in enteric methane in dairy cattle, although the response depends on dose, dietary fibre content, basal diet composition and cattle type (Dijkstra *et al.*, 2018; van Gastelen *et al.*, 2022) [32, 33]. Large-scale application in Indian smallholder systems requires assessment of cost, availability, delivery mechanism, regulatory requirements, long-term animal performance and farmer acceptance.

3.4.6 Tannin-containing feeds

Condensed tannins can reduce methane formation through effects on rumen microorganisms and protein degradation. Tropical tree leaves and pods containing tannins may therefore have relevance to Indian systems. Excessive tannin concentrations, however, can reduce feed intake, digestibility and nutrient availability. Appropriate inclusion levels are therefore essential (Sidhu *et al.*, 2024) [30].

3.4.7 Genetic selection for efficient animals

Genetic improvement can reduce emission intensity by increasing productivity and feed efficiency. Selection for lower residual methane or improved residual feed intake is being investigated internationally (Herrero *et al.*, 2016) [34]. For India, breeding programmes should consider local breeds, crossbreds and buffaloes rather than directly applying results from temperate dairy cattle. Individual-animal methane measurement remains technically demanding.

3.4.8 Improving reproductive efficiency and animal health

Poor reproductive performance increases nonproductive days and lifetime maintenance emissions. Reducing age at first calving, calving interval and days open can therefore reduce emissions per unit of milk over the animal's lifetime. Disease prevention also contributes indirectly to climate mitigation by increasing productive efficiency and reducing premature culling. These measures should be integrated with nutrition, health management and genetic improvement (Gupta *et al.*, 2007) [35].

3.4.9 Manure management and anaerobic digestion

Manure management provides opportunities for reducing greenhouse gas emissions through frequent manure removal, improved storage, covered manure pits, solid-liquid separation, composting where appropriate, anaerobic digestion, biogas recovery, efficient digestate application and reduction of nitrogen losses (Montes *et al.*, 2013) [36]. Anaerobic digestion can convert livestock manure into biogas while reducing uncontrolled methane release. Biogas can be used for cooking or electricity generation, and purified biomethane can be used as a renewable fuel. Digestate can be returned to land as a nutrient source (Lama *et al.*, 2025) [19].

3.4.10 Improved fertilizer and nitrogen management

Nitrogen-use efficiency should be improved in both crop and livestock components of integrated farming. Important measures include matching fertilizer application with crop requirements, avoiding excessive nitrogen application, improving manure utilization, synchronizing nitrogen and energy supply in animal diets, reducing unnecessary dietary protein and using precision fertilizer application. These measures can reduce nitrous oxide emissions while improving economic efficiency.

3.4.11 Improved fodder production and integrated crop-livestock systems

Year-round availability of high-quality fodder can improve livestock productivity and reduce dependence on low-quality crop residues. Perennial grasses, suitable legumes, fodder trees and silage can improve feed availability, although fodder systems should be selected according to local climate, soil and water availability (Reddy *et al.*, 2019; Lal *et al.*, 2022) [24, 25]. Integrated crop-livestock systems can recycle nutrients: crop residues can be used as animal feed and manure can return nutrients to agricultural soils. Transparent allocation procedures are required when environmental burdens are divided among crop and livestock outputs (de Vries *et al.*, 2010) [6].

3.4.12 Renewable energy and precision livestock technologies

Solar energy can replace fossil-fuel electricity for water pumping, milking, lighting, cooling and fodder processing. Energy-efficient equipment and local renewable energy generation can reduce indirect carbon dioxide emissions. Precision livestock technologies can contribute indirectly by improving feed efficiency, health monitoring, reproduction and environmental control. Sensors can monitor feeding behaviour, activity, rumination and environmental parameters, while early detection of disease and reproductive events can reduce productivity losses (Udharwar *et al.*, 2025) [37]. Adoption in smallholder systems requires assessment of cost-effectiveness, connectivity and technical capacity.

3.5 Challenges to carbon-footprint reduction in India

Smallholder dominance

A large proportion of Indian livestock production occurs on small and fragmented farms. Technologies designed for large commercial farms may not be economically suitable for smallholders.

Feed shortage and seasonal variation

Shortages of green fodder and quality feed can restrict implementation of nutrition-based mitigation.

Cost of mitigation technologies

Advanced feed additives, sensors, methane-measurement equipment and biogas systems may require substantial investment.

Lack of farm-level emission data

More direct measurements of methane and nitrous oxide are required across breeds, climates, feeding systems and manure-management practices.

Variation in life-cycle assessment methodology

Differences in functional unit, allocation procedure, system boundary, emission factors and global warming potentials make comparisons among studies difficult (de Vries *et al.*, 2010; Mohini *et al.*, 2018) [6, 12].

Adoption and extension

Economic benefits, ease of application and compatibility with existing farming practices are critical because technically effective interventions may have limited climate benefits if farmers do not adopt them.

Environmental trade-offs

Reducing one emission source may increase another. For example, increasing concentrate feeding may reduce methane intensity but increase emissions associated with feed cultivation. Anaerobic digestion reduces manure methane but requires infrastructure and careful digestate management. Whole-farm or life-cycle approaches are therefore preferable.

3.6 Research gaps and future directions

India requires more country-specific emission factors for cattle, buffaloes, sheep, goats and other livestock. Farm-level life-cycle assessment databases should be developed for different agro-climatic regions because breeds, feed resources, climate and manure management vary considerably. Greater attention should be given to buffaloes and to sheep and goat production systems. Mitigation strategies, especially feed additives, phytochemicals, microbial products and novel methane inhibitors, should be tested under long-term field conditions. Future research should combine environmental and economic assessment because farmers are more likely to adopt practices that improve productivity or reduce production costs. Climate mitigation should also be integrated with animal welfare and climate adaptation. Digital technologies such as sensors, artificial intelligence and precision feeding may improve farm-level carbon accounting, but their feasibility for smallholder farms requires dedicated research (Udharwar *et al.*, 2025) [37].

3.7 Recommended framework for low-carbon livestock production in India

A practical Indian strategy should follow a hierarchical approach:

(1) improve animal productivity through nutrition, genetics, health, reproduction and calf management; (2) improve feed efficiency through ration balancing and better forage quality; (3) reduce enteric methane using validated feed additives and rumen-modifying technologies; (4) improve manure management through covered storage, composting or anaerobic digestion where feasible; (5) recover energy through biogas or upgraded biomethane; (6) improve nutrient recycling and reduce nitrogen losses; (7) increase renewable energy use; (8) monitor carbon footprint using standardized life-cycle assessment and region-specific emission factors; (9) link mitigation with farmer income; and (10) develop region-specific climate-smart livestock models for different production systems.

4. Discussion

The reviewed evidence indicates that carbon footprint reduction in Indian livestock production requires a whole-system approach rather than reliance on a single mitigation technology. Enteric methane remains particularly important in ruminant systems, while feed production and manure management represent additional major hotspots (Patra, 2012; Patra, 2017; Garg *et al.*, 2016; Mech *et al.*, 2023) [8, 9, 10, 11]. The relatively high contribution of enteric methane in Indian ruminant systems makes nutritional interventions especially relevant. Field evidence from ration-balancing programmes indicates that improved feeding can reduce methane emission while increasing productivity, thereby lowering emission intensity (Garg *et al.*, 2016; Garg *et al.*, 2013; Sarkar *et al.*, 2024; Sherasia *et al.*, 2016; Kannan *et al.*, 2010) [20, 21, 26, 27, 28].

The results also indicate that productivity and environmental efficiency are closely linked. Improving milk yield, reproductive efficiency, disease control and feed conversion can distribute maintenance emissions over greater animal output. Nevertheless, productivity gains should not be evaluated independently of feed-related emissions. Greater concentrate or fodder inputs can shift the environmental burden to crop production, fertilizer use or transport. Life-cycle assessment is therefore necessary to identify such trade-offs (de Vries *et al.*, 2010; Mech *et al.*, 2023) [6, 11].

Manure management provides a second major opportunity. Covered storage, composting and anaerobic digestion can reduce uncontrolled methane release, while biogas recovery can displace fossil-fuel use and provide an additional farm benefit (Gupta *et al.*, 2007; Lama *et al.*, 2025; Montes *et al.*, 2013) [18, 19, 36]. However, the feasibility of these systems depends on manure collection, farm size, capital investment, infrastructure and appropriate digestate management. Similarly, novel feed additives and methane inhibitors are promising but require validation under Indian field conditions, particularly in smallholder systems (Sidhu *et al.*, 2024; Asediya *et al.*, 2026; Dijkstra *et al.*, 2018; van Gastelen *et al.*, 2022) [30, 31, 32, 33].

The evidence further demonstrates that mitigation potential cannot be separated from farmer economics. Smallholder farmers operate under constraints of land, fodder, labour, capital and market access. Consequently, practices that simultaneously improve productivity, reduce input costs or generate energy are more likely to be adopted. Region-specific combinations of nutrition, fodder development, manure management, renewable energy and digital monitoring are likely to be more appropriate than a uniform national intervention package. Differences in life-cycle assessment methodology remain a major limitation to cross-study comparison. Functional units, system boundaries, allocation methods, emission factors and global warming potentials can substantially influence calculated carbon footprints (de Vries *et al.*, 2010; Mohini *et al.*, 2018; Dağlıoğlu *et al.*, 2024) [6, 12, 13]. Greater standardization and development of India-specific emission factors are therefore essential for reliable assessment of mitigation progress.

5. Conclusion

Livestock production is essential to India's agricultural economy, food security and rural livelihoods, but it also contributes substantially to greenhouse gas emissions. The reviewed evidence indicates that enteric methane is a principal contributor to the carbon footprint of ruminant production, while feed production and manure management are other major hotspots. Carbon footprint varies among species, breeds, regions and production systems because of differences in productivity, feeding practices, manure management and life-cycle assessment methodology. Ration balancing, improved feed quality, enhanced productivity, better reproductive and health management, efficient fodder production and improved manure management have strong relevance to Indian conditions. Anaerobic digestion and biogas production provide an additional opportunity to convert manure from an emission source into an energy resource. Novel feed additives, methane inhibitors, genetic selection and precision livestock technologies are promising but require further field validation and economic assessment. An integrated strategy combining better nutrition, higher productivity, animal health, efficient manure management, renewable energy, circular nutrient management and region-specific life-cycle assessment is more appropriate for India, particularly for smallholder systems.

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Conflict of interest: The authors declare no conflict of interest related to this work.

Units and Symbols

The manuscript uses International System of Units where applicable. Chemical and greenhouse-gas expressions are presented using standard scientific symbols, including CH₄, N₂O and CO₂. Ranges are expressed with an en dash, and a space is placed between numerical values and unit symbols.

Tables

Table 1. Relative importance of selected mitigation strategies for reducing livestock carbon footprint in India

Mitigation strategy	Main emission target	Relevance to India	Major limitation
Ration balancing	Enteric methane; emission intensity	Very high	Extension and adoption
Better-quality forage	Enteric methane	High	Fodder availability
Improved animal productivity	Methane per unit product	Very high	Genetic and management constraints
Tannin-rich feeds	Enteric methane	Moderate–high	Dose and animal-response variation
3-Nitrooxypropanol	Enteric methane	Potentially high	Cost, delivery and field validation
Genetic selection	Methane intensity	Long-term high	Measurement and breeding infrastructure
Better reproduction	Emission intensity	High	Requires integrated management
Anaerobic digestion	Manure methane	Very high	Capital and infrastructure
Biogas/biomethane	Manure methane and fossil-fuel displacement	Very high	Collection and processing
Improved fertilizer management	Nitrous oxide	High	Farmer awareness
Fodder improvement	Feed-related emissions	Very high	Land and water availability
Renewable energy	Carbon dioxide	Moderate–high	Initial investment
Precision livestock farming	Multiple sources	Emerging	Cost and digital access
Soil carbon sequestration	Net greenhouse gas balance	Potentially high	Measurement and permanence

(continued on next page)

Table 2. Major sources of greenhouse gas emissions associated with livestock production

Source	Principal greenhouse gas	Major contributing activities
Enteric fermentation	Methane	Rumen fermentation in cattle, buffaloes, sheep and goats
Manure management	Methane, nitrous oxide	Storage, anaerobic decomposition, handling and land application
Feed production	Carbon dioxide, nitrous oxide	Fertilizer, irrigation, machinery, processing and transport
Energy and fuel use	Carbon dioxide	Milking, pumping, cooling, feed processing and transport
Land-use change	Carbon dioxide	Conversion or alteration of land associated with livestock/feed systems
Fertilizer use	Nitrous oxide	Nitrogen fertilizer manufacture and field application

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