REVIEW OF ZOOTECHNICAL PARAMETERS USED IN THE MANAGEMENT OF GHG EMISSIONS AND ATMOSPHERIC POLLUTANTS ASSOCIATED WITH BEEF CATTLE FARM

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Abstract
Beef cattle production represents an important source of food security, but at the same time a major source of greenhouse gases (GHG) and atmospheric pollutants, primarily methane (CH_4) from enteric fermentation, nitrous oxide (N_2O) from manure management and soils, and ammonia (NH_3) as a precursor of secondary particulate matter. Accurate quantification and mitigation of these emissions require a comprehensive evaluation of zootechnical parameters that directly influence emission factors and farm-level inventories. This review examines core parameters including dry matter intake, feed conversion ratio, average daily gain, reproductive performance, and herd structure, as well as manure output and management practices. The analysis highlights the variability induced by breed-specific characteristics, production systems, nutritional strategies, microclimate parameters and discusses methodological approaches used for integrating zootechnical indicators into emission models and prognosis frameworks. Current evidence emphasizes the critical role of standardized data collection and harmonized modeling protocols in reducing uncertainties in emission estimates. Strengthening the linkage between zootechnical performance metrics and environmental impact assessment is essential for the development of science-based mitigation practices and for supporting policy frameworks targeting sustainable beef cattle production.

Key words: *GHG emissions, beef cattle, atmospheric pollutants*

INTRODUCTION

Beef cattle production remains one of the most important sectors in global agriculture, ensuring food security through the provision of nutrient-dense protein and by-products that support rural economies [1]. However, the sector is simultaneously a major source of greenhouse gas (GHG) emissions and atmospheric pollutants. The principal gases include methane (CH_4) from enteric fermentation, nitrous oxide (N_2O) originating from manure and soils, and ammonia (NH_3), which acts as a precursor of secondary particulate matter [2]. Together, these emissions account for a substantial share of livestock's carbon footprint and are recognized drivers of climate change [3]. In the United States, enteric methane alone constitutes nearly half of the beef sector's carbon footprint, underscoring its centrality in sustainability debates [4].

Enteric methane is a natural byproduct of rumen microbial fermentation, where carbohydrates such as cellulose and starch are degraded to volatile fatty acids, CO_2, and hydrogen, with methanogenesis serving as a hydrogen sink [5]. Although essential

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for rumen stability, methane emissions represent both an environmental burden and an energetic loss for the animal, estimated at 2–12% of gross energy intake [6]. Studies consistently demonstrate a strong positive association between dry matter intake (DMI) and methane production, both at phenotypic and genetic levels [7]. Increased intake supplies more substrate for microbial fermentation, thereby enhancing methane release. Body weight and average daily gain (ADG) show similar correlations, as heavier and faster-growing animals consume more feed and consequently emit greater absolute quantities of methane [7,8].

Feed conversion ratio (FCR) and residual feed intake (RFI) are additional parameters that shape emission intensity. Animals with lower FCR or RFI values exhibit improved efficiency, requiring less feed per unit of weight gain, and consequently generate lower methane per unit of product [9]. Research has confirmed that efficient bulls with superior FCR or RFI had reduced DMI and lower CH_4 and CO_2 emissions compared to inefficient cohorts [10]. Reproductive performance also exerts a significant influence: fertility decline increases the proportion of non-productive animals, raising emissions per kilogram of beef, while improvements in conception rate or reproductive management can yield measurable reductions in annual GHG output [11]. Herd structure similarly determines emissions at farm and system levels. Models such as COHORTS illustrate that variation in herd age, sex, and genetic composition alter feed requirements and emission intensity, with crossbred calves often demonstrating improved efficiency and reduced emissions compared to purebred beef herds [12].

Beyond enteric fermentation, manure output and management practices represent a major source of CH_4 and N_2O. Studies in Nebraska found that emission factors ranged from 0.98–3.05 kg CH_4/head/year in solid storage to over 45 kg CH_4/head/year in uncovered anaerobic lagoons, highlighting the importance of storage type and moisture content [13]. In grazing systems, nitrogen-rich urine patches are hotspots for N_2O, whereas fecal deposits under anaerobic conditions contribute more CH_4 [14]. Diet composition, particularly concentrate-to-roughage ratios, modulates excreta characteristics and associated emissions [15].

Given these complexities, accurate quantification of GHG emissions requires integrating zootechnical parameters into emission models and inventories. Whole-farm assessments demonstrate that emission intensity can vary widely, from 22.5 to 50.8 kg CO_2e/kg carcass, depending on management practices, reproductive performance, and slaughter age [16]. Improving forage quality, optimizing feeding strategies, and adopting best management practices can significantly reduce methane yield, while genetic selection and reproductive technologies provide complementary mitigation avenues [17,18]. Strengthening the linkage between performance metrics and environmental assessment is therefore essential to designing evidence-based mitigation strategies and policy frameworks aimed at climate neutrality in beef cattle production.

MATERIAL AND METHOD

This review was conducted through a structured analysis of peer-reviewed literature addressing parameters that influence greenhouse gas (GHG) emissions in beef cattle production. Scientific articles were sourced from internationally recognized journals and publishers, including Frontiers in Animal Science, Frontiers in Sustainable Food Systems, Animals (MDPI), Livestock Science (Elsevier), Agricultural Systems (Elsevier), Journal of Animal Science (Oxford Academic), Italian Journal of Animal Science (Taylor & Francis), and Environmental Research Communications (IOP Publishing). Reports from institutional sources such as the National Cattlemen's Beef Association and the Publications Office of the European Union were also included.

The literature was retrieved using academic databases such as Web of Science, Scopus, PubMed, ScienceDirect, and MDPI Open Access, ensuring broad coverage of animal science and environmental research. Search terms combined production and environmental keywords, including "beef cattle greenhouse gas emissions," "enteric methane," "dry matter intake," "feed conversion ratio," "average daily gain," "reproductive performance," "herd structure," and "manure management." Boolean operators (AND, OR) were applied to refine the results.

The inclusion criteria focused on peer-reviewed studies published between 2010 and 2025, covering both experimental trials (e.g., feed efficiency, manure management) and modeling approaches (e.g., whole-farm systems, life cycle assessments). Studies unrelated to beef production or lacking methodological rigor were excluded. This approach ensured a comprehensive yet targeted synthesis of the most relevant knowledge on zootechnical parameters and their link to GHG emissions.

RESULTS AND DISCUSSIONS

Dry matter intake (DMI) is consistently identified as the most influential parameter affecting enteric methane emissions in beef cattle. Numerous studies demonstrate a strong positive correlation between DMI and methane production, both at phenotypic and genetic levels, with reported correlation coefficients ranging from 0.36 to 0.96 (table 1) [7].

Table 1 Reported correlations between DMI and greenhouse gas emissions in beef cattle (Lakamp et al., 2022)

Parameter	Correlation with CH_4	Correlation with CO_2
DMI	r = 0.36–0.96	–
DMI	r = 0.25	r = 0.36

This relationship is biologically intuitive, as higher feed intake provides more fermentable substrates for the rumen microbiome, thereby intensifying microbial activity and methanogenesis [6].

Meta-analyses confirm that methane output increases proportionally with DMI. For instance, regression models revealed that DMI explained up to 44% of the variability in daily methane production, outperforming other animal or dietary parameters [8]. Similarly, studies in pasture-fed systems indicated that, while bodyweight, sex, and physiological stage had modulating effects, methane production was mostly explained by DMI, whereas pasture quality or concentrate supplementation had little additional predictive value [19]. These findings emphasize that methane yield (g CH_4/kg DMI) remains relatively constant across diets, supporting the use of DMI-based coefficients in national GHG inventories [5].

The interaction between DMI and dietary composition further refines emission predictions. Recent models demonstrated that methane per unit DMI is significantly influenced by the ratio of dietary starch to neutral detergent fiber (NDF) and ether extract levels. Incorporating these variables improved predictive accuracy (R^2 up to 0.74) compared with using DMI alone [18]. These results highlight that while DMI remains the core determinant of methane production, diet structure modulates emission intensity per unit of intake.

At the individual animal level, DMI is also linked with feeding behavior and efficiency traits. Studies on finishing steers found that animals with higher feeding times and greater DMI produced more methane, whereas animals with lower residual feed intake (RFI) emitted less methane relative to their intake [13]. Correlations between DMI and greenhouse gases extended beyond methane, with Holstein bull trials reporting coefficients of 0.25 for CH_4 and 0.36 for CO_2 [10].

In summary, evidence across production systems and breeds confirms that DMI is the single most robust predictor of enteric methane emissions. Its inclusion as a central parameter in emission models and farm-level inventories is therefore critical to improving the accuracy of GHG accounting and guiding targeted mitigation strategies.

Feed conversion ratio (FCR), defined as the amount of feed required to produce a unit of weight gain, is a central indicator of production efficiency in beef cattle. Its importance extends beyond economic outcomes, as efficiency in feed utilization is directly related to greenhouse gas (GHG) emission intensity. Animals with improved FCR require less dry matter intake (DMI) to achieve the same growth, thereby diluting maintenance requirements and reducing methane (CH_4) and carbon dioxide (CO_2) emissions per kilogram of carcass [20].

FCR showed weak to moderate correlations with CH_4 (r = 0.25) and CO_2 (r = 0.36), but animals with lower FCR values consistently emitted less GHG per unit of product [10]. Similarly, efficiency-related traits such as residual feed intake (RFI) are closely associated with FCR. Studies demonstrated that cattle with low RFI (more efficient) produced significantly less CH_4 relative to intake than their high-RFI counterparts, confirming feed efficiency as a viable selection criterion for mitigation (table 2) [8].

At the system level, improvements in FCR translate into shorter finishing periods and reduced slaughter age. Life cycle assessments revealed that calf-fed beef systems, which generally display superior feed efficiency compared to yearling-fed systems, achieved a 6–7.5% lower carbon footprint [21].

Table 2 Reported correlations between FCR and greenhouse gas emissions (Callegaro et al., 2022)

Parameter	Correlation with CH_4	Correlation with CO_2
FCR	r = 0.25	r = 0.36
Efficiency traits (RFI)	Negative	–

Moreover, when growth promotants were applied in feedlot diets, FCR improvements contributed to an additional 4.9–5.1% reduction in GHG intensity (table 3) [21].

Table 3 Production systems, FCR efficiency, and carbon footprint (Basarab et al., 2012)

Production system	FCR efficiency	Carbon footprint	Notes
Calf-fed	Higher efficiency	6–7.5% lower CF	Earlier slaughter age
Yearling-fed	Lower efficiency	Higher CF	More days on feed
Calf-fed + growth promotants	Improved FCR	–5% CF	Use of implants

Genetic improvement programs have also highlighted the role of FCR in emission reduction. Simulation models indicate that multiple-trait selection incorporating feed efficiency can reduce emissions intensity by up to 2.6% per generation, especially when carbon pricing is factored into breeding objectives [9]. This evidence underscores that FCR, both as a direct trait and as a proxy for efficiency, is a key determinant in linking productivity with environmental sustainability.

FCR is not only an economic benchmark but also a powerful predictor of emission efficiency. Selection for improved FCR, whether through management, nutrition, or genetics, has the potential to simultaneously enhance productivity and reduce the carbon footprint of beef cattle systems.

The composition of the dietary ration is a major determinant of greenhouse gas (GHG) emissions in beef cattle. Diets rich in low-digestibility forage increase acetate production in the rumen, thereby elevating methane (CH_4) yield per unit of dry matter intake (DMI). In contrast, concentrate-rich rations promote propionate formation and reduce CH_4 intensity, although they may increase nitrous oxide (N_2O) emissions from manure due to greater nitrogen excretion, table 4 [5,6].

Table 4 Reported effects of dietary ration on greenhouse gas emissions (Hristov et al., 2013)

Dietary strategy	Effect on CH_4	Effect on N_2O	Notes
High-forage (low quality grass)	Increase	Moderate	Higher acetate, lower digestibility
High-concentrate diets	Decrease	Increase	More propionate, higher N excretion
Grass–clover silage	Decrease	Neutral	Better digestibility, lower fiber

Breed × diet interactions further influence outcomes. In Brazilian feedlots, Nellore × Angus bulls on high-concentrate diets produced more CH_4 and N_2O from manure compared to purebred Nellore [15]. Similarly, grass–clover silage reduced methane yield relative to grass-only silage, owing to improved digestibility and lower fiber content [22].

Advanced models confirm that methane per unit DMI depends not only on intake but also on chemical composition of the diet. Incorporating starch: neutral detergent fiber (NDF) ratio and ether extract (EE) improved predictive accuracy (R^2 = 0.74), highlighting the role of ration structure [18]. At the system level, strategies such as corn silage substitution, legume inclusion, and supplementation with lipids, tannins, nitrates, or 3-nitrooxypropanol (3-NOP) can reduce methane by 10–60%, depending on conditions [5].

Ration formulation strongly shapes both enteric and manure-derived emissions. Optimizing forage quality, adjusting forage-to-concentrate ratios, and adopting targeted supplementation are effective strategies to mitigate the carbon footprint of beef cattle.

Average daily gain (ADG) is a critical zootechnical parameter that links animal performance to greenhouse gas (GHG) emissions. Higher ADG is generally associated with greater dry matter intake (DMI), which results in higher absolute methane (CH_4) emissions due to the greater amount of fermentable substrate available for ruminal fermentation, figure 1 [7].

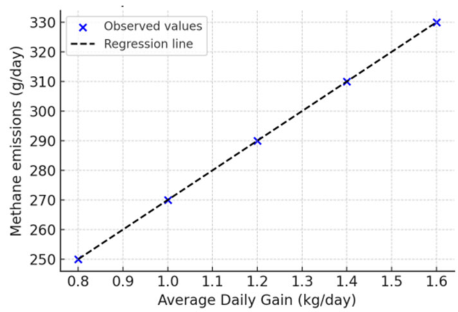

Figure 1 Relationship between ADG and methane emissions (Lakamp et. al., 2022)

Regression models demonstrated that ADG showed significant, though weaker, correlations with methane production compared to DMI (R^2 = 0.19), but it remains an important driver of variation in emission outputs [6].

At the same time, higher ADG shortens the number of days required to reach slaughter weight, thereby reducing the lifetime emissions of each animal. Comparative life-cycle assessments (LCA) confirmed that calf-fed beef systems, which typically achieve higher ADG than yearling-fed systems, exhibited 6.3–7.5% lower carbon footprints per kilogram of carcass weight [21]. When hormonal implants were applied to further enhance growth, emissions intensity decreased by an additional 4.9–5.1% [21]. These findings underscore that while faster growth leads to greater daily emissions, it dilutes emissions per unit of product through improved efficiency.

Breed and genetic background also influence ADG–emission relationships. Crossbred calves (dairy × beef) achieved superior ADG compared to purebred beef animals, and when modeled through herd dynamics, these differences translated into lower GHG intensities at the system level [12]. Conversely, animals with poor reproductive performance or slower ADG remain longer in the herd, increasing the number of unproductive days and consequently raising emission intensity [11].

Experimental studies in finishing systems provide additional evidence. Trials with Holstein bulls demonstrated that animals with higher ADG displayed greater absolute methane emissions, yet when expressed per kilogram of gain, methane yield was reduced [10]. Similarly, studies across different feeding regimes confirmed that although high-ADG cattle produce more methane daily, their shorter finishing periods result in lower emissions per kilogram of carcass [16].

ADG plays a dual role: it elevates absolute methane production but reduces emission intensity when considered relative to animal productivity. Strategies that improve ADG, including genetic selection, nutritional optimization, and growth promotants, therefore represent effective approaches for mitigating the carbon footprint of beef cattle production.

Quantitative modeling highlights the environmental gains from fertility improvements. A 10% increase in conception rates has been shown to reduce herd-level GHG emissions by approximately 3% annually [11]. In Norwegian beef production, whole-farm modeling demonstrated that enhanced calf survival and fertility reduced emission intensity by 3% [23]. Similarly, European assessments concluded that reproduction traits represent one of the most effective levers for lowering emission intensity at herd level, due to their system-wide effects on productivity [12].

Reproductive performance exerts a profound influence on greenhouse gas (GHG) emissions from beef cattle systems because fertility determines herd replacement rates, calving intervals, and the proportion of productive versus non-productive animals. Poor reproductive efficiency results in longer inter-calving intervals and a higher number of unproductive days, thereby increasing maintenance-related methane (CH_4) emissions and nitrous oxide (N_2O) from manure (figure 2) [6,20]. This effect is particularly evident in suckler cow systems, where reproductive success dictates both calf output and herd emission intensity [16].

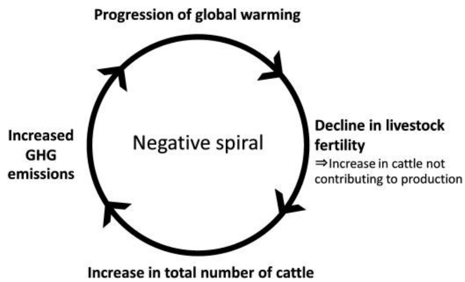

Figure 2 Diagram of global warming caused by cattle (Sakatani et. al., 2022)

Environmental stressors exacerbate reproductive inefficiency. Heat stress is among the most critical factors: in tropical and subtropical regions, pregnancy rates may fall by 20–25% during hot seasons compared to cooler periods [11]. This not only extends animal lifespan before slaughter but also amplifies methane and nitrous oxide outputs relative to product yield. Climate change projections suggest that without mitigation, heat stress will increasingly compromise reproductive success, undermining both animal welfare and environmental sustainability [3].

Technological and management interventions offer solutions. Estrus synchronization, artificial insemination, embryo transfer, and reproductive monitoring tools (such as activity sensors and ultrasound) have all been shown to increase fertility and reduce inter-calving intervals [5]. Nutritional management, including energy-balanced diets and micronutrient supplementation, further supports reproductive outcomes while avoiding excessive nitrogen excretion [6].

When combined with genetic selection for fertility traits and feed efficiency, these interventions provide synergies that enhance productivity and reduce emission intensity [9,12]. Overall, reproductive performance represents a critical leverage point in achieving climate-neutral beef systems. By improving conception rates, reducing calving intervals, and mitigating heat stress, beef cattle systems can simultaneously increase productivity and lower their environmental footprint.

Manure output and its management are major contributors to greenhouse gas (GHG) emissions in beef cattle systems. Methane (CH_4) is primarily produced under anaerobic conditions during storage, while nitrous oxide (N_2O) arises through nitrification and denitrification processes once manure is applied to soils [6]. Emission intensity is highly dependent on both the quantity of manure excreted and the management practices employed [3, 20].

Quantitative estimates demonstrate large differences between manure management systems. In Nebraska, solid storage systems generated only 0.98–3.05 kg CH_4/head/year, while uncovered anaerobic lagoons produced up to 45.7 kg CH_4/head/year, with higher emissions during summer months (figure 2) [4]. Composting and daily spreading also resulted in substantially lower emissions than lagoons, emphasizing the strong role of storage method and moisture content [13, 23].

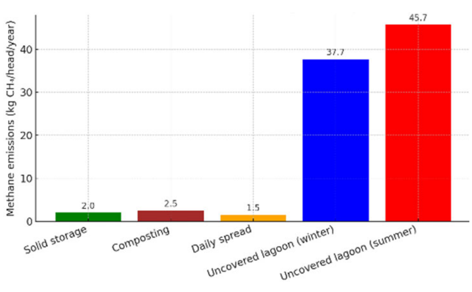

Figure 3 Emission factors for beef cattle manure management systems (Hernandez, 2022)

Excreta type also determines emission pathways. Urine patches are recognized as hotspots for N_2O, while feces deposited under anaerobic soil conditions are associated with CH_4 release [14]. Environmental conditions such as soil moisture, rainfall, and temperature further modulate emissions, creating high variability across grazing systems [17].

Whole-farm modeling highlights the mitigation potential of manure management strategies. The adoption of dietary interventions to lower nitrogen excretion, silvopastoral systems, nitrification inhibitors, and optimized pasture management have been shown to reduce manure-related CH_4 and N_2O emissions by 15–55% depending on region and production system [16]. However, trade-offs are evident: while concentrate-rich diets lower enteric CH_4 yield, they may increase N_2O losses from manure [18]. Integrated strategies that consider both enteric and manure emissions are therefore essential.

Manure output and management practices substantially shape the carbon footprint of beef systems. Mitigation options such as shifting from lagoon storage to solid or composting systems, improving ration formulation, and adopting integrated manure–pasture management are crucial for reducing CH_4 and N_2O while sustaining animal productivity.

CONCLUSIONS

This review highlights that greenhouse gas (GHG) emissions from beef cattle production are tightly linked to core zootechnical parameters such as dry matter intake, feed conversion ratio, average daily gain, reproductive performance, herd structure, and manure management. The evidence demonstrates that these parameters act both individually and interactively to shape emission intensity across breeds, production systems, and feeding strategies.

From a practical perspective, monitoring and optimizing these indicators provides opportunities to improve production efficiency while reducing environmental impact. Enhanced reproductive efficiency, balanced rations, improved feed conversion, and optimized manure handling can all deliver tangible reductions in CH_4 and N_2O emissions. At the same time, genetic selection and innovative management practices offer long-term pathways toward climate-neutral beef systems.

The scientific importance of this study lies in integrating zootechnical performance metrics with environmental assessments, thereby reducing uncertainties in emission estimates. Such integration supports the development of robust mitigation models and informs science-based policies. By strengthening the linkage between productivity and sustainability, this review underscores that sustainable beef production is achievable through targeted management and evidence-driven decision-making.

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