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Integrating Feed Efficiency and Waste Management for Climate-resilient Farming: A Review

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ABSTRACT

Livestock production plays a pivotal role in global food security, providing essential protein and vitamins to billions of people. However, conventional intensive farming practices have come under scrutiny due to their significant environmental consequences. The role of cattle production in global warming is a complex and multifaceted issue, subject to ongoing scientific research and robust public discussion. The three primary environmental challenges associated with animal husbandry are land degradation, water pollution and the release of greenhouse gases (GHG). To ensure the sustainability of future food chains, a transition to more environmentally friendly practices is imperative. Reducing excess phosphorus and nitrogen is crucial for optimal animal health and environmental well-being. This review underscores the significance of dietary alterations as a key strategy to mitigate these issues. By optimizing nutrient utilization, lowering enteric methane (CH_4) emissions and minimizing waste excretion, dietary changes can contribute to a more sustainable cattle industry. Additionally, effective waste management is essential for reducing gaseous emissions.

Key words: Feeding strategies, GHG, Livestock, Waste management.

As the world's population expands, the requirement for livestock-based goods such as milk, eggs and meat and their by-products are likely to increase dramatically. However, conventional livestock production practices frequently provide significant environmental issues, such as high emissions of GHG, a depletion of water and soil resources and degradation of biodiversity (Henchion *et al.,* 2021). Integrating feed efficiency and waste management is crucial for building climate-resilient livestock production systems. By optimizing feed utilization, we minimize resource inputs like land and water, reducing the sector's environmental footprint. Simultaneously, effective waste management strategies, such as anaerobic digestion or composting, transform animal waste into valuable resources like biogas or fertilizer, mitigating GHG emissions and enhancing soil fertility. This integrated approach not only promotes sustainable practices but also enhances the resilience of livestock systems to climate change impacts, ensuring food security and economic stability for both producers and consumers (Alary *et al.,* 2022; Chen *et al.,* 2022). The rapid increase of GHG emissions triggered global awareness over the last decade to climate change and how important it is for all human beings.. Specific to the list of GHG, CH_4 and nitrous oxide (N_2O) have been mostly produced by dairy industry and industries have had a significant impact releasing climate-warming gases by their many large-scale livestock operations, feeds production and trucking prior to stores. The dairy industry is under growing scrutiny around the world as it tries to become more environmentally friendly due to climate change (Muetzel *et al.,* 2024). Moreover, the pursuit of higher efficiency in milk production has led to a remarkable global expansion of modern dairy farming practices. This growth has been driven by technological advancements and improved management techniques, aiming to increase milk yields while minimizing production costs. In response to these concerns, there has been a coordinated effort worldwide to develop and implement more sustainable dairy production systems that reduce the sector's carbon footprints (Abdelbagi *et al.,* 2023).

At the 26th Conference of the Parties (COP26) to the United Nations Framework Convention on Climate Change (UNFCCC) held in Glasgow, a significant milestone was achieved. Over 120 countries pledged to reach net-zero emissions by mid-century, with target dates ranging from 2050 to 2070. This ambitious commitment represents a major step forward in the global effort to combat climate change and limit global warming to 1.5°C (Soliman *et al.,* 2023). Between 1980 and 2018, GHG emissions from the agriculture sector experienced a concerning 34% increase. This trend is projected to continue, with estimates indicating a further 33% rise in emissions by 2060. The growing demand for food, coupled with the expansion of intensive

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agricultural practices, are major drivers of this upward trajectory (UNEP, 2021). In 2020, China made a bold declaration of its intention to achieve carbon neutrality by 2060. This ambitious goal signifies a significant commitment from the world's largest emitter of GHG to transition to a low-carbon economy. By setting this target, China aims to play a leading role in addressing the global climate crisis and promoting sustainable development (Chen *et al.,* 2022). It has been discovered that epidemics exacerbate the effects of GHG emissions by reducing efficiency and productivity and by increasing the amount of resources required to treat the illness (Ezenwa *et al.,* 2020). The raising of livestock is the foundation of the world's food systems, giving billions of people access to essential micronutrients and protein.

Despite the advancements in modern dairy farming, the environmental impact of livestock production remains a significant concern. The industry's reliance on natural resources, such as land, water and feed, can contribute to deforestation, water pollution and biodiversity loss. These negative effects highlight the need for sustainable practices that minimize the industry's footprint and ensure the long-term health of our planet (Van-Heurck *et al.,* 2020). Feed management, which includes acquiring, arranging and distributing feed to animals, is an essential component of livestock production. The sustainability of the environment can be impacted by the feed category, nutritional value and feed conversion efficiency. For instance, animal production's ecological footprint can be lowered by using more sustainably obtained feed components, such as indigenous fodder or food processing wastes (Beldman *et al.,* 2021). Globally, countries like Brazil, India and China are leading emitters due to large livestock populations and extensive agricultural practices. Developed nations, despite smaller livestock populations, contribute signifi-cantly due to high per capita meat consumption. On a global scale, cattle are the largest contributors to livestock-related GHG emissions, primarily driven by beef production. Pigs follow as the second-largest contributors, mainly from manure management. Poultry, while having relatively low per-animal emissions, contribute significantly due to their massive global populations (Shi *et al.,* 2022). Beef production stands out as a major driver of livestock-related GHG emissions. The combination of factors such as the CH_4 produced by ruminant animals, the land and water resources required for feed cultivation and the energy-intensive processes involved in beef production contribute to its significant carbon footprint (Rotz, 2020). Addressing the environmental impact of livestock production requires a multi-pronged approach. This includes reducing global meat consumption, particularly beef, improving feed efficiency and reducing enteric fermentation in livestock, adopting sustainable manure management practices and implementing regulations and incentives to promote sustainable livestock production. By understanding the magnitude and sources of livestock-related GHG emissions, we can work towards more sustainable and environmentally friendly food systems (Wanapat *et al.,* 2024). In response to this, some have suggested that replacing beef with chicken could be a more sustainable option. The industrial nature of chicken production often involves higher efficiency and lower emissions per unit of meat compared to beef. However, it's important to note that the overall environmental impact of chicken production also depends on factors such as feed sources, transportation and waste management (Yan *et al.,* 2024). This review aims to account significant variables such as feed management and waste disposal strategies to support the development of healthy and sustainable livestock. It seeks to give a thorough summary of recent studies and cutting-edge tactics that might lessen livestock farming's negative environmental effects while enhancing animal welfare and output.

Enhancing feed efficiency

The efficiency with which animals convert feed into meat, milk, or eggs can significantly influence the environmental impact of livestock production. Variations in feed efficiency can affect productivity levels, resource utilization and the rate at which GHG are released from animal products. For example, animals that are more efficient at converting feed into meat or milk will require less feed to produce the same amount of product, reducing the overall land and water resources needed. Additionally, more efficient animals may produce less methane, a potent GHG, per unit of output (Herrero *et al.,* 2013). To minimize emissions and the overall consumption of resources, livestock producers often select animals with a higher feed conversion ratio (FCR). This means that these animals are more efficient at converting feed into meat, milk, or eggs. By choosing animals with superior feed conversion, producers can reduce the amount of feed required to produce a given quantity of product, thereby decreasing the demand for land, water and other resources. Additionally, higher FCR can lead to lower emissions of GHG, such as methane, which is produced by ruminant animals (Prakash *et al.,* 2020). Rapid changes in food production, preservation and distribution, driven by scientific and technological advancements, are significantly impacting livestock production systems, particularly in developing regions. These changes, while potentially beneficial, must be carefully managed to ensure sustainability, environmental protection and the well-being of both humans and animals, while considering the unique socio-economic contexts of different regions (Boyazoglu, 1998). N_2O CH_4 carbon dioxide (CO_2) and ammonia (NH_3) are the primary gases emitted by poultry farms. Even though N_2O and CH_4 are emitted relatively little, they are important gases to research. The impact of CH_4 and N_2O is 25 and 298 times greater than CO_2, respectively (Sugiharto *et al.,* 2023). When compared to other animal production systems, poultry farming methods have the lowest emissions of NH_3 and other GHG and the amount of emissions will go down as

feed efficiency increases (Ferreira *et al.,* 2019). Animals with higher FCR tend to produce lower emissions of CH_4 and N_2O. This is primarily due to a reduction in enteric fermentation, the process by which microorganisms in the animals' digestive systems break down plant material and produce these GHG. When animals are more efficient at converting feed into products, they require less feed, which in turn leads to less enteric fermentation and lower emissions (Wang and Huang, 2005). In addition to reducing GHG emissions from enteric fermentation, higher feed efficiency can also lead to a decrease in waste production. When animals are more efficient at converting feed into products, they produce less waste, such as manure and urine. This reduction in waste can lower emissions of GHG associated with waste decomposition and storage (Hill and Azain, 2009). In a study conducted by De Verdal *et al.* (2010), a broiler strain selected for improved FCR was found to produce significantly lower emissions compared to a control group. The study demonstrated that this strain emitted 67.5% fewer GHG than the control, highlighting the potential of genetic selection to reduce the environmental impact of poultry production.

In the context of dairy cows, residual feed intake (RFI) is also known as net feed efficiency. This parameter was first introduced by Koch *et al*. (1963) as a way to evaluate the efficiency with which an animal utilizes feed. RFI is calculated by subtracting an animal's expected feed intake, based on its growth, weight gain and production, from its actual feed intake. A negative RFI indicates that the animal is consuming less feed than expected for its level of performance, suggesting that it is more efficient in utilizing its feed resources (Rius *et al.,* 2012). Animals with a low RFI are those that require less feed to maintain a similar body condition score and growth rate compared to animals with a higher RFI. This suggests that these animals have a lower maintenance energy requirement and are therefore more efficient in utilizing their feed. Studies have shown that cattle with a low RFI emit 15-25% less gastric methane than those with a higher RFI. This reduction in CH_4 emissions is directly linked to the lower dry matter intake of animals with a low RFI. Since CH_4 production is influenced by the amount of feed consumed, animals that eat less will naturally produce less CH_4 (Basarab *et al.,* 2013). According to a study by Aboagye *et al.* (2022), three widely used feed additives *i.e*. tylosin, monensin and beta-adrenergic agonists (βAA) can enhance animal performance and reduce the environmental impact of beef production. However, restricting the use of these additives could lead to a larger environmental footprint for beef produced both domestically and for export markets. This is because these additives can improve feed efficiency, reduce CH_4 emissions and enhance animal growth, ultimately contributing to a more sustainable beef production system.

Some of the strategies for enhancing feed efficiency and reduction in GHG are explained in Table 1.

Livestock waste management

Enhancing animal manure management practices is essential for addressing multiple environmental challenges. By improving the handling, storage and utilization of manure, we can significantly reduce air pollution, mitigate the effects of global warming and promote sustainable agriculture. This involves implementing strategies such as proper storage to minimize odor emissions, anaerobic digestion to produce biogas and reduce GHG and the use of manure as a nutrient-rich fertilizer to enhance soil health and reduce reliance on synthetic inputs (Grassauer *et al.,* 2023).

By implementing a range of mitigation strategies at different stages of the manure management cycle, it's possible to significantly reduce the harmful effects of GHG emissions and air pollutants associated with livestock production. These strategies can include proper storage and handling practices to minimize odor and emissions, anaerobic digestion to convert manure into biogas and biofertilizers and the use of manure as a nutrient-rich soil amendment to reduce reliance on synthetic fertilizers.

A study conducted in the Ampara district of Sri Lanka revealed that cattle farmers primarily utilize farm waste as fertilizer, highlighting the potential for sustainable manure management practices. However, the study also emphasized the critical need for government support to further enhance the efficiency and sustainability of these practices (Dissanayakaa *et al.,* 2022).

By adopting a comprehensive approach to manure management, we can contribute to a more sustainable and environmentally friendly livestock industry (Ershadi *et al.,* 2020). To achieve agricultural sustainability and protect the environment, it is imperative to reduce GHG emissions from the livestock sector. Effective manure management practices can play a crucial role in achieving this goal. By implementing strategies such as regular manure removal, manure covering and manure composting at various stages of the manure management process, GHG emissions can be significantly reduced (Yan *et al.,* 2024).

Calcium cyanamide ($CaCN_2$) has good potential to reduce the pH of the manure and it reduces the release of NH_3. A study by Holtkamp *et al*. (2023) found that applying 300 mg/kg of $CaCN_2$ to livestock manure significantly inhibited the microbial degradation of volatile fatty acids (VFAs). This reduction in VFAs degradation led to an accumulation of VFAs in the sludge, which in turn lowered the pH. The decrease in pH had the unintended effect of reducing the release of NH_3 a potent GHG.

The partially permeable membrane-covered composting method has gained widespread popularity worldwide as a sustainable and efficient approach for the aerobic processing of biological waste. This innovative technique offers several advantages, including its superior responsiveness to environmental conditions, ease of operation and low environmental impact. By utilizing

partially permeable membranes, this method effectively controls the exchange of gases and moisture within the composting process, optimizing the breakdown of organic matter and reducing odor emissions (Soto-Herranz *et al.,* 2021).

Acidification has emerged as a promising technology for reducing CH_4 emissions from sludge storage. By lowering the pH of the sludge to 5.5, acidification can significantly inhibit the activity of methanogenic microorganisms, which are responsible for producing CH_4. Studies have demonstrated that this approach can reduce CH_4 emissions in stored cattle slurry by an impressive 65-99%, making it a highly effective mitigation

Table 1: Strategies for enhancing feed efficiency and reduction in GHG.

Species	Feeding strategy	Mechanism of action	Key findings	Reference
Cattle	Supplementation with tannins	Tannins reduce CH_4 production by inhibiting methanogens	Improved feed efficiency and reduced CH_4 emissions	(Verma *et al.,* 2024)
Goat	Condensed tannins supplementation	Tannins reduce CH_4 production by inhibiting methanogens	Shift from urinary to fecal nitrogen, reduced CH_4 emissions	(Verma *et al.,* 2024)
Ruminants (*In vitro*)	Use of prebiotic additives *i.e.* Inulin	Prebiotics enhance microbial fermentation efficiency	lessen the rumen microbiota's production of CH_4 during feed fermentation	(Paya *et al.,* 2024)
Swine	High-fiber diets (Almond hulls)	Fiber reduces fermentation rate and CH_4 emission	Both growth performance and NH_3 gas reduction were seen.	(Ahammad *et al.,* 2024)
Dairy cows	Inclusion of brown seaweed	Seaweed reduces CH_4 production through bioactive compounds	Improved DMI, energy status and milk composition and reduced NH_3 emission	(Wanapat *et al.,* 2024)
Poultry	Enzyme supplementation	Enzymes enhance nutrient digestibility and reduce waste	Increased feed efficiency and lower emission of NH_3 and hydrogen sulfide (H_2S)	(Sugiharto *et al.,* 2023)
Cattle	Adjusted protein levels	Optimal protein levels improve microbial efficiency and reduce emissions	Better feed conversion and reduced CH_4 production	(Liu *et al.,* 2024)
Goats	Essential oil supplementation	Essential oils have antimicrobial properties that reduce CH_4	Improved feed efficiency and lower enteric CH_4	(Cruz *et al.,* 2024)
Cattle	Use of novel protein sources *i.e.* Cricket meal	Novel proteins improve digestibility and reduce waste	Enhanced digestibility and decreased CH_4 and protozoal population	(Phesatcha *et al.,* 2023)
Poultry	Feeding BSF larvae	Reduce the CH_4 and CO_2 emissions in the livestock waste	Enhance feed effeciency and immune response	(Shahand Çetingül, 2022; Iqbal *et al.,* 2019)
Dairy cows	Carbohydrate sources modification *i.e.* corn silage and barley grains	Adjusted carbohydrates improve fermentation efficiency	Silage and concentrate, both high in starch produce least amount of enteric CH_4	(Giagnoni *et al.,* 2024)
Broilers	Methionine, Lysine and threonine supplementation	Amino acids improve growth efficiency and reduce nitrogen waste	Nitrogen excretion and equilibrium NH_3 concentration was reduced.	(Aderibigbe *et al.,* 2024)
Beef cattle	3-nitrooxypropanol Supplementation	Control rumen fermentation to enhance animal health.	Good inhibitor of CH_4 production	(Orzuna-Orzuna *et al.,* 2021)
Cattle	Direct-fed microbials	Microbials enhance digestion and reduce CH_4 production	Improve health and production concurrently reduction in CH_4	(Asediya, 2024)
Ewes	Probiotic supplementation *i.e. Candida tropicalis*	Probiotics improve gut health and reduce CH_4 emissions	4×10^8 CFU/d per head is appropriate dose	(Liu *et al.,* 2023)

Table 2: Strategies for manure management and reduction in GHG.

Strategy	Description	Effect on GHG	Implementation Techniques	Reference
Anaerobic Digestion	Uses bacteria to break down manure in an oxygen-free environment.	Reduces CH_4 emissions with high efficacy and produces biogas	Install anaerobic digesters.	(Chozhavendhan *et al.,* 2023)
Composting	Aerobic decomposition of manure, turning it into compost.	Reduces CH_4 and N_2O emissions.	Use aerated piles or windrow systems.	(Su *et al.,* 2024)
Manure Separation	Separates solids from liquids to reduce CH_4 potential.	Lowers CH_4 emissions by reducing the amount of manure that decomposes anaerobically.	Use mechanical separators or centrifuges.	(Zhang *et al.,* 2024a)
Covering manure storage	Covering the manure storage facilities to limit gas emissions.	Reduces CH_4 and NH_3 emissions.	Install solid covers or floating covers on lagoons.	(Carnell *et al.,* 2021)
Incorporating manure into soil	Placing manure into the soil immediately after application.	Reduces N_2O emissions and minimizes CH_4 release.	Use injection or incorporation techniques.	(Götze *et al.,* 2023)
Controlled release fertilizers	Use fertilizers that release nutrients slowly.	Reduces N_2O emissions from manure.	Apply controlled release or slow-release fertilizers.	(Zhang *et al.,* 2024b)
Improved feed management	Adjusting feed to reduce manure's GHG potential.	Reduces CH_4 production in manure.	Modify feed formulations and add feed additives.	(Aguirre-Villegas *et al.,* 2024)
Manure application timing	Apply manure at times when crops can utilize it effectively.	Reduces N_2O emissions through improved nutrient uptake.	Optimize application timing based on crop needs.	(Fangueiro *et al.,* 2023)
Precision manure application	Use technology to apply manure precisely where needed.	Reduces over-application and N_2O emissions.	Implement GPS and sensor-based application systems.	(Singh *et al.,* 2020)
Manure to energy systems	Convert manure into energy through combustion or other processes.	Reduces CH_4 emissions and offsets fossil fuel use.	Use systems like gasifiers or combined heat and power.	(Hoyos-Sebá *et al.,* 2024)

strategy. As a result, acidification to pH 5.5 has become a widely accepted standard for minimizing CH_4 emissions from sludge storage facilities. Some of the strategies for manure management and reduction in GHG are explained in Table 2.

CONCLUSION

Addressing the environmental challenges posed by livestock production is a critical imperative. By prioritizing feed efficiency and waste management, we can significantly reduce the industry's negative impacts on the environment. Sustainable livestock production requires optimizing FCR through precision feeding, feed additives and breeding for efficiency, while effective waste management methods like anaerobic digestion and composting can mitigate climate change impacts and create a more sustainable agricultural system. Enhancing feed efficiency not only lowers GHG emissions but also conserves land and water resources, promoting a more sustainable production system. Simultaneously, effective waste management practices mitigate pollution and recover valuable nutrients, fostering a more circular and environmentally friendly agricultural model. By synergistically implementing these strategies, cattle farming can achieve a holistic reduction in its environmental footprint, aligning with global sustainability goals and ensuring the industry's long-term viability. Continued research, innovation and widespread adoption of these approaches are essential for fostering a more resilient and sustainable food system. This will ultimately help strike a delicate balance between agricultural productivity and environmental stewardship.

Conflict of interest

The authors declare no conflict of interest with perspective to the research, authorship and publication of this article.

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