



Review Paper

## Methane Mitigation in the Livestock Industry - Using Integrated Approach: A Review

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### Abstract

Agriculture is a primary source of methane (CH<sub>4</sub>), which contributes to global warming. Globally, there is a significant increase in methane emissions due to the expansion of the livestock industry. Reducing methane emissions is necessary to avert a climatic catastrophe. This article compiled and reviewed 136 published articles and online database information on greenhouse gas management from 2017 to 2024. The objective was to ascertain which technology reduces methane to the bare minimum to mitigate climate change. Mitigation systems assessed included manure acidification, animal housing systems, manure storage systems, temperature, filtration, vermicomposting, composting, biochar addition, feed additives, feeding technology, digester technology, and breed selection. It turned out that no single abatement technology can eliminate methane. Methane emissions will continue to increase if one-factor abatement is the main focus. An integrated strategy that incorporates economic and environmental assessment of livestock trade-offs, nutrition, feed quality, source, type, and breed, and feed conversion efficiency can significantly reduce methane emissions. Simulating the Earth's carrying capacity and human demand for livestock products can reduce methane.

### Keywords

*Climate change; Greenhouse gas; Global warming; Animal production*

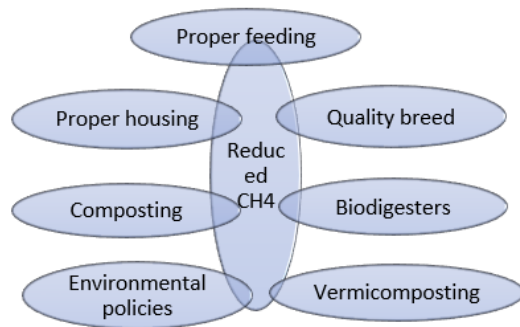
## 1. INTRODUCTION

According to the Climate Watch's Climate Analysis Indicators Tool, the USA, China, and India are the three largest emitters of greenhouse gases contributing heavily to global warming (La et al., 2018; Bačėninaitė et al., 2022; Climate Analysis Indicators Tool (CAIT), 2020). Wetlands, livestock, paddy fields, biomass burning, coal mining, oil exploration, landfills, industrial waste burning, waste-water disposal, and biogas for energy are the industries in these nations that release the highest methane (Duren et al., 2019; Nisbet et al., 2020). Livestock production is a significant contributor to the several global environmental challenges faced because of the escalating greenhouse gas (GHG) emissions from the production systems (Yoro and Daramola, 2020; Canadell et al., 2021). Fulfilling the demand for animal products and services across the world escalates greenhouse gas emissions and should be tackled by all nations and institutions. This review discusses the mitigation strategies of methane emission to avert the current trend of global warming from surpassing the Intergovernmental Panel on Climate Change target of 1.5°C. A schematic diagram (Figure 1) encompassing proper feeding and housing of animals, selection of and efficient feed conversion bred, the use of biodigesters, com-

posting and vermicomposting, and strict environmental regulations would support mitigate methane to the least.

### 1.1 Consequences of high methane emission

The repercussion of huge animal demand can lead to economic expansion for the actors but environmentally dangerous circumstances in return due to the emission of greenhouse gases. An estimated 1.5 billion cattle worldwide produce 87 million metric tons of methane annually (Nibedita et al., 2021). For instance, in the year 2020, cattle methane emissions alone represented 67% of agricultural methane emissions (United States Environmental Protection Agency (USEPA), 2022). This should be minimized by 24 to 47% by 2050 to meet the Intergovernmental Panel on Climate Change (IPCC) target (Arndt et al., 2022). The emission of methane from biological processes in the livestock digestive systems and in manure and feed is huge and needs to be addressed (Misiukiewicz et al., 2021; Khusro et al., 2022). Therefore, it is undoubtedly clear that an improvement in animal feed digestibility, source, and quality would help mitigate methane emission. Over 40 – 70% of all GHG emissions before the farm gate come with enteric methane (Holtshausen et al., 2021; Tedeschi et al., 2022).



**Figure 1.** Schematic Methane Mitigation

## 2. RESEARCH PROGRESS ON SUGGESTED PRACTICES TO MITIGATE GREENHOUSE GAS EMISSIONS FROM THE LIVESTOCK INDUSTRY

### 2.1 Modelling methane emission

Methane concentrations have increased over the past few decades, from 722 parts per billion (ppb) in pre-industrial times to 1907 ppb recently (Wei et al., 2020; Global Monitoring Laboratory (GML), 2021). By absorbing electromagnetic radiation between 3.5 and 8  $\mu\text{m}$ , methane's global warming potential (GWP) is predicted to be 28 times more effective in a century at regulating climate change (Intergovernmental Panel on Climate Change (IPCC), 2022). Methane directly causes global warming by releasing a large amount of  $\text{CO}_2$  and  $\text{H}_2\text{O}$ , and it is a powerful precursor of tropospheric ozone (Lu et al., 2019; Francoeur et al., 2021).

Strongly suggested practices to mitigate methane emissions include but are not limited to closing the gaps in nutrient cycling in the agricultural systems through the combined use of animal manure as a soil amendment in crop production (Hendriks et al., 2022; Goldan et al., 2023). Enteric methane emissions, among other variables, can be predicted by models, though their specificity and accuracy vary depending on the species and production environment (Tedeschi, 2019; Hansen et al., 2021).

Current implementation technology options can minimize global warming by up to 30% in the next decade (Warszawski et al., 2021; Ocko et al., 2021; United States Environmental Protection Agency (USEPA), 2022). Techniques and strategies to cut greenhouse gas emissions from human activity by up to 50% in the next years are possible and can be achieved. Thus, to maximize the technology goal, the different strategies suggested to reduce methane emissions—such as direct inhibition of methanogens with chemical inhibitors, feed manipulation to lower hydrogen production, and hydrogen consumption maximization—must be combined. Effective nutrient management in the food production value chain can reduce methane emissions, which is critical to climate change and global warming. Methane reduction can be achieved in a combined methodology by integrating the tested research technologies.

## 3. METHANE REDUCTION THROUGH MANURE ACIDIFICATION

### 3.1 Limiting stock numbers and acidifying the little manure

The solid, semisolid, and liquid waste products known as animal manures are produced by animals that are raised for their milk, eggs, meat, and other agricultural products that humans can consume (Janni and Cortus, 2020; Haider et al., 2024). Growing livestock populations are expected to increase global manure production, which would have a significant impact on the GHG balance in terrestrial ecosystems (Cai et al., 2021). This implies that the increase in livestock production could lead to environmental pollution and therefore should be monitored, regulated, and limited. For example, Germany reduced methane emissions to 20% or 10.4 Mt  $\text{CO}_2\text{-eq}$  from 1990 to 2017 by limiting livestock numbers (Cárdenas et al., 2021).

Acidification of manure demonstrates a potential remedy for mitigating methane emissions from manure even though it can also increase  $\text{N}_2\text{O}$  emissions (Sokolov et al., 2019, 2020; Esteves et al., 2024). Methanogenic communities are susceptible to pH ranges outside the neutral range, hence low to medium reduces emissions (Sokolov et al., 2019; Qiu et al., 2023). Neutralization of the acidity content in manure will significantly lower methane emissions. The intensification of the livestock industry and manipulation of manure should be critically examined to avoid emission trade-offs when manure is to be acidified to mitigate methane emissions. Using effective manure management principles that comply with the IPCC Tier 2 approach in the livestock production system would facilitate the reduction of methane emissions while adhering to pH and acidification principles.

## 4. PROPER HOUSING AND STORAGE TEMPERATURE

### 4.1 Animal housing systems in methane mitigation

The type of housing, when manure is removed, the conditions and length of storage, and manure management systems all have an impact on the nutrient contents and emissions of methane (Petersen, 2018; Amon et al., 2021). To minimize emissions from livestock houses, reducing the losses of the conserved nitrogen during the downstream handling of the manure, storage, and temperature management would significantly maximize emission mitigation. Whether the manure is kept in the pit beneath the slated floor for an extended period of time determines the methane emission rates (Qu et al., 2021; Varma et al., 2021).

Due to the longer retention period of manure in barns and the decreased removal frequency of the slurry from the pit beneath the floor, several studies showed that the methane emission rate from a slated floor with pit storage was higher than the emission from a solid floor. Housing structures for animals that offer a conducive and cool environment are suitable for reducing methane emissions.

Housing structure and temperature affect manure management, hence greenhouse gas emissions, therefore, a realistic temperature range that is ideal for minimizing methane emissions is still confusing and needs to be researched. Housing structures for animals that offer a conducive and cool environment are suitable for reducing methane emissions.

#### 4.2 Temperature and pH regulation in mitigating methane

Methanogenesis is slowed in cool temperatures and low pH hence, cooling is a potential technology for mitigating methane emission (Hilgert et al., 2022; Rama et al., 2024). Temperature influences microbial activities in manure and affects methane emissions (Getabalew et al., 2019). Methane emissions from liquid manure storage facilities are substantial, particularly when retention periods are extended and temperatures are warm (Cárdenas et al., 2021). Temperature and methane emission strongly depend on the temperature interval (Hempel et al., 2020). As the temperature rises, methane emission rates tend to rise as well, from -3.2°C to 30.3°C (Poteko et al., 2019; Qu et al., 2021).

Dean et al. (2018) and Comer-Warner et al. (2018) found that higher temperatures significantly increased methane emissions. Therefore, reducing the storage time and temperature of storage structures would mitigate substantially methane emissions. Cows that are exposed to high temperatures (heat stress) spend less time ruminating and feeding, which may result in less methane being produced (Ramón-Moragues et al., 2021). Higher temperatures increased methane production by promoting the transcription of *mcrA* rather than by increasing methanogen cell numbers (Guo et al., 2020).

### 5. VERMICOMPOSTING AND FILTRATION

#### 5.1 Earthworms and microorganisms use in methane mitigation

Earthworms and microorganisms work together to bio-oxidize and stabilize organic materials in a process known as vermicomposting (Ansari et al., 2020; Arutselvan and Nedunchezhiyan, 2022). An easier and less expensive alternative to waste management is the use of earthworms to treat solid organic waste (Liu et al., 2021). This should be applied to all intensive livestock production systems. Earthworms, microorganisms, and other degradable communities interact in this bio-oxidative process to speed up the breakdown of organic waste (Patwa et al., 2020). Vermicomposting reduces and facilitates the handling of solid waste. By incorporating earthworms into traditional composting, vermicomposting improves the process of stabilizing organic waste and produces higher-quality organic matter and soluble nutrient levels (Lv et al., 2020; Mupambwa and Mnkeni, 2018; Kaur, 2020). The amount of nutrients in the converted waste is increased by the earthworms' metabolic activity during this process (Zziwa et al., 2021; Gómez-Brandón et al., 2022) and creates more available nutrients

per weight for agricultural use (Sanchez-Hernandez and Domínguez, 2019; Liu et al., 2021).

Therefore, vermicomposting can facilitate, and improve waste management, sustain the livestock industry, and reduce methane emissions. Biols, composts, vermicompost, and compost teas are examples of organic fertilizers that can be biotransformed from methane emissions associated with large waste and pollution from the application of manure (Giménez et al., 2020; Ros et al., 2020). Vermicomposting is regarded as one of the greatest substitutes for treating waste that has been contaminated by pathogens, for instance, wastewater from livestock production systems (Karimi et al., 2024). Vermicomposting could be an environmentally sustainable technology in the management of waste in the livestock industry.

#### 5.2 Vermifiltration

Therefore, digestate from low-tech digesters may be suitable for vermifiltration as a post-treatment option to reduce methane emissions (Dore et al., 2022; Cucina et al., 2024). A natural method of treating wastewater, vermifiltration combines the sand filtration and vermicomposting processes (Gutiérrez et al., 2023; Kumar and Khwairakpam, 2024). Vermifiltration has recently been highlighted as an inexpensive and sustainable digestate post-treatment technology and has proven to be effective in livestock waste management (Juanpera et al., 2022; Ziegler-Rodriguez et al., 2023). For instance, it was shown that organic matter, solids, nutrients, and pathogens could be effectively removed for a variety of feedstock and proven to be effective in livestock waste management (Miito et al., 2021; Gutiérrez et al., 2023; Kumar and Khwairakpam, 2024).

### 6. COMPOSTING

Composting provides the option to recover valuable nutrient resources, thus reducing environmental pollution (Zhang et al., 2020; Fan et al., 2021). Ex-situ and in-situ technologies can help reduce nitrogen losses during composting (Zhao et al., 2020). One benefit of composting is that it is an inexpensive technology that is widely available and yields stable products and manages volatile solids that facilitate methane emissions (Lin et al., 2018). By controlling the matrix's initial C/N ratio, it effectively lowers GHG emissions and nitrogen loss (He et al., 2019). Composting ought to be applied and integrated into the waste management stream of the livestock industry to mitigate GHG emissions. One important factor in reducing greenhouse gas emissions from the livestock sector is the advancement of low-carbon emission technology for managing livestock manure.

#### 6.1 Electric-assisted and hyperthermophilic composting

Many composting methods, including electric-assisted composting and hyperthermophilic composting, have been developed to improve the composting process, lower greenhouse gas emissions, and improve the decomposition of

organic waste. According to (Cui et al., 2019), hyperthermophilic composting has a good potential to reduce N<sub>2</sub>O and CH<sub>4</sub> emissions, while also decomposing organic matter quickly.

By encouraging microbial activity, electric-assisted composting has also been shown to increase organic conversion and lower CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O emissions (Tang et al., 2019). Additionally, recent studies by (Xing et al., 2022; Wang et al., 2022; Sun et al., 2023) discovered that a considerable quantity of reactive oxygen species (ROS), including hydroxyl radicals (-OH), are produced throughout the composting process, which encourages the humification process and improves the effectiveness of organic pollutants and heavy metal removal.

## 7. MANURE AMENDMENTS

### 7.1 Biochar amendments in manure

Applying organic amendments such as biochar in compost can reduce manure (GHG) emissions. When added externally to manure, biochar improves composting efficiency and lowers greenhouse gas emissions (Awasthi et al., 2020; Wang et al., 2018), because of its high porosity and large surface area (Das et al., 2023; Kumar et al., 2021). Biochar can accelerate the startup of composting, shorten the composting period, and significantly reduce the emissions of methane and other greenhouse gases (Li et al., 2020; Chung et al., 2021). A substantial 58% reduction in methane emissions and a roughly 67%, 61%, and 70% reduction in air pollutants like hydrogen sulfide (H<sub>2</sub>S), volatile organic compounds (VOCs), and nitrogen oxides (NO<sub>x</sub>) are achieved by composting dairy manure with biochar (Haider et al., 2024). This study suggests that biochar addition to manure composting provides an option for methane emissions mitigation.

### 7.2 Lignite amendments in manure

Lignite addition to manure can reduce greenhouse gas emissions during the composting process, N<sub>2</sub>O (58–72%), CO<sub>2</sub> (12–23%), and CH<sub>4</sub> (52–59%) (Impraim et al., 2020). Nevertheless, lignite's impact on gaseous emissions in windrow composting under open field conditions increased total N<sub>2</sub>O and CH<sub>4</sub> emissions by 2.6 times while reducing NH<sub>3</sub> emissions by 54% when compared to manure alone (Bai et al., 2020).

Further research on lignite reactions in controlled temperatures and environments and methane gas emissions needs to be conducted to support the greenhouse gas abatement struggle.

## 8. METHANE MITIGATION THROUGH FEED ADDITIVES

### 8.1 Feed supplements

Methane-reducing feed additives could have a key role to play in achieving methane emissions reduction targets

of -24 to -47% by 2050 concerning 2010 (McCauley et al., 2020; Arndt et al., 2021). This should be properly integrated with other reducing strategies for effective methane mitigation. Many feed additives are designed to reduce ruminal methanogens, 3-nitroxypropanol (3-NOP), a novel methane inhibitor that has gained popularity recently, and has been demonstrated to cut methane emissions in dairy cattle by 20% to 40% (Melgar et al., 2020, 2021). The inhibitor 3-nitroxypropanol (3-NOP) performs better in methane mitigation in dairy cows, hence increasing the 3-NOP dose reduces methane emissions; however, dietary factors, such as the amount of dietary fiber, counteract this effect (Dijkstra et al., 2018). This implies that 3-NOP could significantly help in reducing enteric methane emissions when fully exploited.

### 8.2 Methane inhibitors

Methane inhibitors can also be found in plant-based products like essential oils, saponins, and condensed tannins (Tedeschi et al., 2021).

Asparagopsis taxiformis (seaweed), is noted to reduce methane emissions by up to 98% in ruminants when added to animal feed (Kinley et al., 2020). This is a significant reduction and should be integrated with other technologies to its full potential. Gram-positive methanogens, which provide the substrate for methanogenesis, are decreased by monensins (Wingard et al., 2018), suggesting that because nitrate competes with methanogens for hydrogen in the rumen, reducing the production of methane, its use in ruminant diets can also be an effective methane mitigation strategy (Villar et al., 2020). Supplementary cottonseed oil with feed reduces approximately 42% reduction in enteric methane production (Nogueira et al., 2020), antimicrobial essential oil blends, such as geranyl acetate, coriander extract, and eugenol, cut methane production by almost 20% (Hart et al., 2019). Nitrates, ionophores, secondary plant compounds, and direct-fed microbes indirectly inhibit methanogenesis by altering the rumen environment, thereby reducing methane formation (Kelly and Kebreab, 2023).

## 9. REDUCTION OF METHANE THROUGH PROPER FEEDING TECHNOLOGY

### 9.1 Rumen microbial manipulation

Global estimates indicate that livestock methane emissions are high and rising. About 95% of the methane released during enteric fermentation passes through the buccal cavity, while 5% passes through the anal canal (EPA, 2023; Samal et al., 2024). To reduce this fermentation and release of methane, manipulation of the feed and the animal's digestive system is crucial by adding antacids. The amount of methane generated is determined by the fermentation of carbohydrates and the ratio of propionic to acetic acid produced (Li et al., 2021). A significant contributor to GHG is the metabolic hydrogen produced during rumen fermenta-

tation and can be minimized by neutralization reaction. Evidence exists that Prevotella and other associated bacteria are responsible for methane production in the rumen, thereby increasing the emission of methane (Shinkai et al., 2024). Manipulating the bacterial content and quantity by introducing antibacterial compounds in the rumen will alter their activities and reduce enteric emissions. Rumen microbiota is thought to have a significant impact on feed efficiency and methane production (Auffret et al., 2018; Li et al., 2019).

According to Wallace et al. (2019), microbial information may encourage rumen manipulation for environmentally friendly methane mitigation. Microbiota and methane emission are connected, this suggests that changes in microbiota could influence methane emission (Beauchemin et al., 2020). Clarifying the microbial and functional traits of animals, and thus methane emissions, requires precise datasets, such as those for methane production, digestibility, composition, and fermentation (Hristov et al., 2018; Uemoto et al., 2020). An environmentally friendly approach in ruminant production while mitigating methane emissions through advanced knowledge of feeding and bacterial behavior could mitigate methane emissions.

## 9.2 Feed manipulation

Change and manipulative feeding that make varying quantities and types of feed available at varying times could influence microbiota load, hence methane emission. An in-depth comprehension of ruminal digestion and its role of microbiota in different feeds and different regimes will facilitate the development of a mitigation option, further research needs to be conducted.

Dry feeding and diet composition are responsible for ruminal methanogens and are critically important in ruminant production and methane management. One important factor influencing the variation in methane production in lactating cows is the amount of digested dry matter (Grešáková et al., 2021; Li et al., 2021). Enteric methane yield and intensity can be decreased by increasing concentration feed inclusion and starch concentration in lactating dairy cows. Low methane-emitting cows have been associated with the Prevotellaceae, Succinivibrionaceae, and Lachnospiraceae taxonomic units, whereas some breeds of the same genus emit high methane (Tapio et al., 2018; Daugaliyeva et al., 2022; Lee et al., 2023).

Methane can be reduced by incorporating a high-cereal diet, biohydrating unsaturated fatty acids, increasing the production of propionic acid, inhibiting protozoa, or supplementing with ionophores, fats, organic acid, probiotics, acetogens, and bacteriocins (Nibedita et al., 2021). Therefore, a specific choice of feed combined with specific feed additives has been proven to reduce methane in the rumen of animals (Hristov, 2024). In relation to energy intake, methane emissions are decreased when a ratio's concentration fraction increases (Haque, 2018; Delveaux Araujo Batalha et al.,

2020). Therefore, the ability of the feed to be easily digested and the dry matter intake of the animal affect the amount of methane produced and should be manipulated. Vitro works and sole diet can decrease total gas production and methane concentration by-products (Melesse et al., 2018; Della Rosa et al., 2022). The ability of the animal to effectively convert feed, whether mixed or whole, are effective options for mitigating enteric methane emissions.

## 10. REDUCTION OF METHANE GAS THROUGH GENETIC SELECTION AND BREEDING

### 10.1 Breeding and genetic selection

Apart from feeding, the impact of genetic selection and breeding in greenhouse methane mitigation is crucial. Higher feed conversion efficiency, live weight gain, fat deposit, and traits all influence the amount of methane emitted. (Cantalapiedra-Hijar et al., 2018; Pino et al., 2018; Dini et al., 2018). Genetic selection plays a direct and indirect role in reducing enteric methane emissions. Methane emissions from livestock can be attributed to gene heritability between 0.12 to 0.45 (Beauchemin et al., 2020; Souza et al., 2024), Zetouni et al. (2018) reported  $0.25 \pm 0.07$ , (Richardson et al., 2021) reported  $0.16 \pm 0.11$ , and (van Breukelen et al., 2023) reported  $0.19 \pm 0.02$ .

Methane and CH<sub>4</sub>res heritability estimate in Nellore cattle range from moderate to high magnitude ( $0.42 \pm 0.09$  and  $0.21 \pm 0.09$ , respectively) (Souza et al., 2024), and  $0.21 \pm 0.06$  and  $0.16 \pm 0.10$ , in Holstein cattle (Kamalanathan et al., 2023). Methane emission is a heritable trait (Løvendahl et al., 2018). This undoubtedly indicates that gene selection is crucial in the management of methane from livestock and indicates that there is a point in heritability at which methane emission can be mitigated. Breeding and genetic selection aimed at lowering enteric methane emissions in this context may be more effective and sustainable when incorporated with other mitigation options. In Holstein cattle, enteric methane (mL) production is linked to eight genes: TAX1BP3, EMC6, P2RX5, AP2M1, REXO2, NXPE4, NXPE2, and CADM1 (Jalil Sarghale et al., 2020). Selection by breeding and trait improvement, or heterosis for reduction are likely to be effective and novel. Thus, breeding practices and genetics are more likely to result in decreases in enteric methane emissions. The potential for gene editing to incorporate desired genetic material into individuals or epigenetic control mechanisms can also be reliable in methane mitigation in dairy production (Uemoto et al., 2020; Dressler et al., 2024).

## 11. DIGESTER TECHNOLOGY

### 11.1 Aerobic and Anaerobic digestion

Understanding the microbial ecology and diversity of manure and its characteristics is critically important for methane gas mitigation. The activities of microbial actions leading to methane emissions will depend on environmental conditions; manure environment, climate, and management

practices (Dalby et al., 2021). Anaerobic digestion can treat large volumes of livestock manure to mitigate methane emissions (Shi et al., 2018; Yao et al., 2020), even though some methane can be lost from the anaerobic system (Kvist and Aryal, 2019; Scheutz and Fredenslund, 2019; Wechselberger et al., 2023).

Methane in manure is oxidized in aerobic conditions by bacteria, therefore, limiting oxygen supply to manure could help mitigate methane production and its emission. Anaerobic digestion reduces odor and methane emissions (Zheng et al., 2022; Agga et al., 2022).

By extracting methane from anaerobic lagoons and using it to produce renewable energy, anaerobic digestion is one method that can reduce methane emissions (Satchwell et al., 2018). Capturing methane from anaerobic systems substantially reduces methane production from stored stockpiles, manure solids, and liquid manure, which continue to be a significant source of methane emission from the livestock industry (Harrison et al., 2022; Esteves et al., 2024). A deeper understanding of the activities of microorganisms in anaerobic conditions in manure digestion would facilitate the design of environment-friendly, sustainable, and cost-effective anaerobic digesters for methane emission abatement.

## 12. CONCLUSION AND SUGGESTION

Methane is produced because of the anaerobic decomposition of organic matter in the livestock production system, therefore aerobic environments are most likely to reduce emissions. Though manure acidification, manipulating storage temperature and housing, vermicomposting, composting, feed additives, breed selection, and biodigesters reduces methane to a certain level. A combined strategy of selective feed and additives, breed gene manipulation to improve feed conversion, and methane reduction should be explored. Economic prosperity and the well-being of the escalating population are the main triggers of methane gas emissions. Efforts to reduce methane gas emissions must be channeled through eco-friendly production technologies such as holistic integration of human needs and environmental tradeoffs. This can be executed by state governments and embossed by the citizens through explicit climate-smart decisions for climate-resilient pathways that reduce and improve nitrogen use, misuse, and management across all spheres of human activities. Minimizing methane footprints while meeting the demand of the world's population is a holistic technology. There should be a balance between the earth's resources exploitation to satisfy human needs and anthropogenic methane emissions. This strategy would not put too much stress on production sectors to meet global food needs.

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