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Review Article

Role of Improved Forages in Mitigating Greenhouse Gas Emissions from Ruminant Livestock: A Review

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Abstract

Livestock production is a significant contributor to global greenhouse gas (GHG) emissions, particularly methane (CH_4) and nitrous oxide (N_2O), which are primarily generated through enteric fermentation and manure management. Methane alone is over 23 times more potent than carbon dioxide (CO_2) in terms of global warming potential, making its reduction a critical target for climate change mitigation. This review explores the role of improved forage management as a sustainable strategy to reduce GHG emissions from ruminant livestock. Enhanced forage quality through the use of high-protein species, digestible silage, and legumes rich in plant secondary compounds such as tannins, saponins, essential oils, and flavonoids has demonstrated potential in mitigating CH_4 production by altering rumen fermentation and reducing methanogenic activity. Additionally, incorporating alternative forage crops like Medicago sativa (lucerne), Plantago lanceolata (plantain), and Brachiaria spp. can improve nitrogen use efficiency and reduce N_2O emissions from excreta. Improved forage systems also contribute significantly to soil carbon sequestration, enhancing soil fertility and water retention while offsetting atmospheric CO_2. By integrating these climate-smart forage practices, livestock systems can increase productivity and resilience while lowering their environmental footprint. The findings of this review highlight the critical importance of forage-based strategies in supporting global efforts to achieve methane reduction targets and promote sustainable livestock development.

Keywords

Greenhouse Gas Emissions, Improved Forage Management, Methane Mitigation Sustainable Livestock Development

1. Introduction

Greenhouse gases are gases that trap heat in the atmosphere, including carbon dioxide, methane, water vapor, and nitrous oxide, as well as synthetic gases like chlorofluorocarbons, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride (SF_6) [38]. Among these, the primary GHGs are CO_2, CH_4, and N_2O [39]. Globally, livestock production systems including feed production, enteric fermentation, and animal waste management are major sources of GHGs, contributing 37% of all human-induced methane emissions [40]. Specifically, livestock contribute approximately 5–9% of CO_2, 35–44% of CH_4, and 53–65% of N_2O emissions [17, 27, 50].

Feed quality is a key factor influencing GHG emissions from livestock, particularly affecting enteric methane (CH_4) production [46]. Enteric fermentation accounts for more than 90% of CH_4 emissions from livestock [10] and contributes approximately 40% of total agricultural GHG emissions [57], making it the largest single source of agricultural GHGs [50]. In addition to its role in global warming, CH_4 emissions rep-

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resent an energy loss of 8–12% in ruminant animals [44].

The livestock sector is expanding more rapidly than any other agricultural sector, driven by population growth (from 7.2 billion in 2010 to a projected 9.6 billion by 2050), rising incomes, and urbanization. As a result, global demand for meat and milk is expected to increase by 73% and 58%, respectively, by 2050 compared to 2010 levels [17]. While eliminating emissions from livestock is not feasible, reducing methane (CH_4) emissions from ruminants is considered a critical mitigation strategy [33]. To support global methane reduction efforts across all sectors, the livestock industry must be effectively integrated into national climate action plans.

Researchers have proposed several strategies to mitigate GHG emissions from livestock. These include adopting improved management practices and technologies such as enhancing diet quality, ensuring animal health, implementing genetic improvement programs [10, 14], and increasing carbon stocks in soil and biomass, which could reduce global GHG emissions by 5.5-5.9Gt CO_2-equivalent per year. Numerous dietary CH_4 mitigation strategies have also been identified and extensively reviewed [24], such as feeding forages that contain plant secondary metabolites. Among these mitigation strategies, cultivating improved multipurpose forage species particularly forage legumes and selected grasses stands out as one of the most effective approaches. This practice enhances environmental quality, maintains soil fertility, increases carbon sequestration in both plants and soils, reduces N_2O emissions, improves animal productivity, and lowers GHG emissions per unit of animal product. Therefore, this review aims to review how improved forages contribute to the reduction of greenhouse gas emissions from ruminant animals.

2. Literature Review

2.1. Overview Greenhouse Gases

Nowadays, the emission of GHGs is a major global concern, with human activities across all sectors contributing. Among these, agriculture contributes emission from livestock and crop production. Therefore different intervention of GHG emissions across various sectors is crucial to protect atmospheric air quality and global warming. Without these efforts, the survival of all living beings on Earth will be at risk.

Agriculture, forestry, and other land use activities accounted for about 13% of CO_2, 44% of CH_4 and 81% of N_2O emissions from human activities globally between 2007 and 2016, which accounted for 23% of total net anthropogenic GHG emissions [26]. According to [17], in agricultural the two sectors that create the greatest greenhouse gases are crop production and enteric fermentation from livestock, which account for 45 and 39% of total sector emissions, respectively and manure storage and processing, and the transportation of animal products contribute 10 and 6%.

The livestock sector globally is responsible for about 14.5% of the world's greenhouse gas emissions [31]. Large differences in emission intensities and/or quantities are observed between species, regions and production systems. When considering total supply chain emissions, cattle (beef and dairy) production generates 4.6 Gt, the largest share of global livestock emissions by some margin. This figure drops to a still significant 3.3 Gt when only the direct CH_4 and N_2O emissions from enteric fermentation and manure are considered [12]. Other livestock species have much lower and similar levels of emissions, even when considering the full lifecycle of emissions: pigs (0.7Gt CO_2-eq), poultry (0.7Gt CO_2-eq), buffalo (0.6 Gt CO_2-eq) and small ruminants (0.5Gt CO_2-eq) [11, 12]. Decreasing this emission is accomplished by the use of a number of mitigation techniques vital important. Nutritional strategies to mitigate enteric CH_4 have been studied and developed so far [24] and other GHGs mitigation option [10].

2.2. Methane and Methanogenesis

Comparing CH_4, to CO_2, its potential for global warming is 23 times greater [48]. Naturally occurring in the atmosphere is CH_4 which has a specific gravity of 0.554 and is lighter than air. The melting and boiling points of methane gas are -187°C and -161°C, respectively, and its density is 0.717m^{-3}/kg. Dissolves in organic solvents, but it is insoluble in water. Methane is produced during rotting and fermentation processes under anaerobic conditions. Preferred habitats for methanogenic bacteria and thus natural methane sources are the stomachs of ruminants. The primary mechanism that produces naturally occurring CH_4 is methanogenesis in this reaction, $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ [22]. Photochemical oxidation processes in the atmosphere produce carbon monoxide (CO) and ozone (O_3) from methane. Due to its relatively short atmospheric residence time (less than 20 years), methane is one of the short lived climate pollutants.

Enteric Methanogenesis in Ruminants:

Methanogenesis is a process of CH_4 production in the rumen where H_2 reduced the CO_2 with the help of methanogenic archaea. This is a dynamic process, in which methanogens strongly influence the metabolism of fermentative and acetogenic bacteria via interspecies hydrogen transfer [49]. Enteric CH_4 emission is produced as a result of microbial fermentation of feed components. CH_4 is a colorless, odorless, inflammable, and tasteless gas, which is produced predominantly in the rumen (87%) and to a small extent (13%) in the large intestines [56]. See Figure 1. Thus, any mitigation strategy aimed at reducing methanogen populations must include an alternative pathway for H_2 removal from the rumen as well.

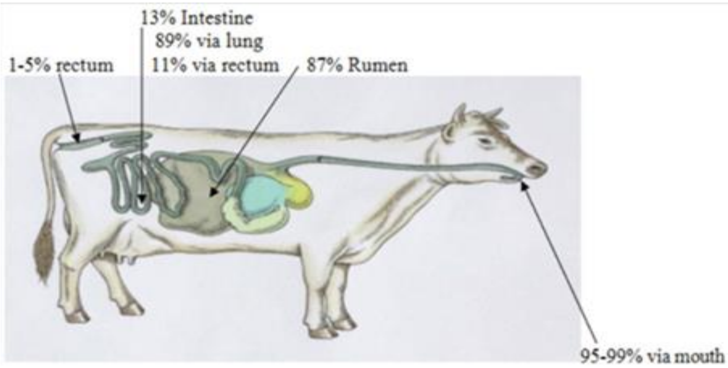

Figure 1. *Emission of methane from ruminants.*

2.3. Type of Feed to Reduce Methane Emission from Large Ruminants

2.3.1. Role of Concentrate in Reducing Methane Emission

The type of feed allowed to a ruminant can have a major effect on methane production. Forage to concentrate ratio of the ration has an impact on the rumen fermentation and hence the acetate to propionate ratio [8]. It would therefore be expected that methane production would be less when high concentrate diets are fed. For example, a six-fold decrease in CH_4 emission was observed when grazing cattle were switched to a high-quality feedlot diet in Canada observed that a reduction in forage in vitro organic matter digestibility (i.e., decline in forage quality) also resulted in an increase in CH_4 emissions when animals were fed ad libitum [7]. The same is true, according to [61], a high grain diet and/or the addition of soluble carbohydrates gave as shift in fermentation pattern in the rumen which give rise to a more hostile environment for the methanogenic bacteria in which passage rates are increased, ruminal PH is lowered and certain populations of protozoa, ruminal ciliates and methanogenic bacteria may be eliminated or inhibited. Dietary manipulation can reduce CH_4 emission up to 40% depend on the degree of change and the nature of the intervention [5]. Another study also indicated that CH_4 emissions can possibly be reduced up to 75% through better nutrition [36].

2.3.2. Role of Improved Forage in Reducing Methane Emission

Improved forages play a significant role in climate change mitigation, primarily by enhancing feed digestibility and thereby reducing methane (CH_4) emissions from livestock [25]. Ruminants consuming grass forages typically emit more CH_4 per unit of dry matter intake (DMI) than those grazing on legumes. This difference is largely attributed to the higher digestibility and altered ruminal fermentation patterns of legume forages, which lead to faster passage rates through the rumen and less time for methane production. However, some studies [59] have found no significant differences in methane emissions between grasses and legumes, suggesting that the effect may depend on forage type, quality, and animal diet.

Forage legumes such as lucerne (*Medicago sativa L.*), red clover, and white clover (*Trifolium repens L.*) are rich in degradable proteins and organic matter. While these characteristics support better animal nutrition, they can also increase the risk of bloat, which may discourage farmers from using them as the sole feed source [44]. To overcome this challenge, mixing legumes with grasses is recommended as an effective feeding strategy to balance nutritional benefits while minimizing bloat risks. Overall, feeding improved forage species provides multiple advantages: it enhances animal productivity, improves nutrient utilization, and reduces greenhouse gas emissions (including CH_4, N_2O, and ammonia). This makes improved forages an important and sustainable strategy for mitigating the environmental impacts of livestock production.

2.3.3. Preparation of Silage

Another interesting strategy from an environmental perspective is the use of legume silage (e.g., red clover) [23] or mixtures of grasses and legumes such as white or red clover, birdsfoot trefoil, and sainfoin [43]. These feeding strategies are particularly effective for dairy cattle, and to a lesser extent for beef cattle, while no significant effects have been observed in sheep [60]. Although the magnitude of the response can vary, methane (CH_4) emissions are generally reduced when grass silage is included in the diet. The inclusion of legume silage contributes to lower methane production due to its lower fiber content, which increases the passage rate of digesta through the rumen, thereby reducing the time available for methanogenesis.

In addition, improving the quality of silage enhances feed digestibility and nutrient utilization, leading to better production efficiency and consequently lower methane emissions per unit of product [30]. Silage also allows for the preservation of forages during periods of surplus, ensuring a consistent supply of high-quality feed throughout the year. This stability supports more balanced diets, minimizes feed shortages that can lead to inefficient rumen fermentation, and ultimately contributes to mitigating greenhouse gas emissions from ruminant livestock systems.

2.4. Plant Secondary Compounds on Enteric Methane Mitigation

The wide range of chemical compounds produced by plants in addition to major metabolic products that are not engaged in the main biochemical processes of growth and reproduction are known as plant secondary metabolites. Forages rich in secondary plant compounds, such as tannins, have been studied both for their nutritional effects on animal productivity and for their anti- methanogenic properties, as thoroughly described by [28]. A significant amount of the diversity in CH_4 generation in legumes can be linked to the availability of secondary metabolites in certain legume species, which can impede CH_4 creation, according to in vitro studies [29]. Choosing fodder plants that contain secondary chemicals help to reduce methane emissions from ruminant animals.

Although they are some anti nutritional effect, metabolites have drawn more attention in the field of animal nutrition because of their positive effects on rumen fermentation, parasite management, and the reduction of methane emission. There are several phytochemicals from a variety of plant sources that have the potential to reduce methane emissions, including saponins, tannins, essential oils, and numerous additional unidentified metabolites [42]. Their impact on the microbial population in the rumen is often indirect rather than direct. Feeding forage contain plant secondary metabolites like leucaena (*Leucaena leucocephala*), Sainfoin (*Onobrychis viciifolia*), Birdsfoot trefoil (*Lotus corniculatus*), Sericea lespedeza (*Lespedeza cuneata*) or incorporating forages rich in secondary plant compounds into ruminant diets plays a vital role in mitigating greenhouse gas emissions.

2.4.1. Tannins

Tannins are naturally occurring plant compounds that exist in two main forms: hydrolysable tannins and condensed tannins (CT). These two types differ in their molecular structures, which influence how they interact with rumen microbes and affect methane (CH_4) production. Several mechanisms have been proposed to explain how tannins reduce enteric methane emissions. One mechanism involves the direct inhibition of rumen methanogenic archaea. Condensed tannins can bind to protein components of the methanogens' cell envelope, disrupting the formation of methanogen–protozoa complexes, reducing interspecies hydrogen transfer, and inhibiting methanogen growth [55].

Another mechanism is indirect inhibition, which occurs when tannins form complexes with nutrients such as carbohydrates and proteins. This binding reduces the availability of these nutrients to rumen microorganisms, thereby limiting fermentation substrates and methane formation. When these tannin–protein complexes reach the abomasum (pH ≈ 7), the protein is released and digested, meaning less fermentation occurs in the rumen but nutrient digestion continues post-ruminally [36]. This can, however, also lower overall feed digestibility and alter the rumen microbial population.

Tannins can also act as hydrogen sinks, diverting hydrogen away from methanogenesis, thus reducing the conversion of carbon dioxide to methane. Empirical studies support these mechanisms. For example, condensed tannins present in *Leucaena leucocephala* have been shown to lower methane emissions in dairy cows [34]. Similarly, tropical pastures containing *Desmanthus spp*., which are rich in condensed tannins, have been found to reduce CH_4 emissions in grazing cattle systems [53]. However, not all tannin sources are equally effective. For instance, supplementing diets with up to 2% DM quebracho tannin extract did not significantly reduce methane emissions in growing cattle [4]. Overall, tannins—especially condensed tannins—show considerable potential in mitigating enteric methane emissions. Nevertheless, the effectiveness varies depending on the plant source, the type and concentration of tannins, and dietary context. Further research is needed to identify the optimal levels and sources of tannins that can reduce CH_4 emissions without negatively impacting feed intake and digestibility.

2.4.2. Saponins

Saponins are high molecular weight glycosides composed of sugars and sometimes exhibit steroid-like properties. In water, they produce stable, soap-like foam. They are commonly found in leaves, tubers, bark, roots, seeds, and fruits [18]. Overall, saponins from different plant sources have shown inconsistent effects as methane inhibitors. In one study using fenugreek and sesbania extracts (in water, 50% methanol, and 95% methanol), no significant in vitro methane reduction was observed, even though protozoa counts decreased by about 50% in both concentrate- and roughage-based diets [18]. However, when these extracts were added to hay, concentrate, or mixed substrates, methane production was reduced by 5.1% to 11.9%. Another study found that soap nut (Sapindus mukorossi) extracts prepared with water, ethanol, and methanol reduced methane production in vitro, with the highest reduction (96%) observed with the ethanol extract [1]. Similarly, Sapindus saponaria saponins reduced methane by up to 20% without affecting methanogen numbers [20].

These results indicate that the effects of saponins vary widely, even when using the same plant species or similar animals. Saponins are thought to act mainly through their anti-protozoal activity, as methanogenic archaea are often symbiotically associated with rumen protozoa [43]. By reducing protozoa, saponins can suppress methane production and also offer nutritional benefits. They may enhance microbial protein synthesis, increase fiber-degrading bacteria and fungi, and improve feed utilization, especially in low-quality diets.

2.4.3. Essential Oils

Aromatic and mostly volatile, essential oils are found in medicinal, herbal, and inedible plants. Special cells in various plant parts, such as roots, seeds, fruit, leaves, flowers, bark, petals, and stems, create them [58]. By preventing gram-positive bacteria from growing, essential oils have the same effect as monensin (ionophore antibiotic). Essential oil may decrease methanogen abundance, certain protozoa species, and methane production by up to 37% and alter the organization of the archaeal community [54]. Lipids rich in unsaturated fatty acids (FA), act as a hydrogen sink through the hydrogenation of FA. These microbial changes favor a shift in ruminal fermentation towards propionate, and thus, to a potential reduction in CH_4 production.

2.4.4. Flavonoids

Flavonoids are well known for their antibacterial properties, which rely on their chemical structure, specifically on the substitutions on the aromatic rings, reducing inflammation in high grain diets, balancing rumen pH in subacute acidosis, and helping animals during times of stress [39]. Incorporating flavonoids into ruminant diets has been suggested as a way to improve productivity by increasing the synthesis of propionate as opposed to acetate. In vitro, the flavonoid quercetin and naringin decreased hydrogenotrophic methanogens, ciliate protozoa, and methane production [41]. Flavonoids can suppress the growth or activity and modifying rumen microbial populations.

2.5. Chemical Composition of Forage Vs CH_4 Production

2.5.1. Effect of Forage Digestibility on Methane Emission

As forages become more digestible, less manure is produced and enteric fermentation occurs, which lowers CH_4. Research has examined the impact of digestibility of forage organic matter (OM) on the intensity of CH_4 emissions for a variety of forages, including fresh herbage and silage, as well as forage types such as grass, legume, and maize, and animal groups (cattle, sheep) [44, 60]. Though large efforts have been made, the response in CH_4 emission is not consistent and depends on the unit as well as the animal category considered [60]. Increased forage digestibility resulted in increased dry-matter intake (DMI, kg/day) and consequently increased CH_4 emission (g/day) for dairy and beef cattle, but not for sheep. When intake or production is considered, both CH_4 yield (g/kg DMI) and CH_4 intensity (g/kg milk) are decreased with increased digestibility for dairy cattle, but no difference in CH_4 yield (g/ kg DMI) was observed for beef cattle. For sheep CH_4 yield decreased with increased forage digestibility [60].

2.5.2. Crude Protein Content of Forage on Mitigation Potential of Methane

According to [2] ruminal fermentation of forages may be restricted and animal protein needs may not be satisfied below a threshold value of 7% CP for sufficient forage quality. However, [62] contend that forage CP concentrations need to be higher than 10% of DM for livestock maintenance needs and roughly 19% for young growing stock or high-producing dairy cows. [62] Propose that enhanced digestibility for forage can reduce CH_4 intensity (g/kg milk/meat) in dairy cow while decrease CH_4 emission in sheep. Therefore, having forage with the highest CP%, improved digestibility, a healthy nutrient supply, and the capacity to reduce the rate or intensity of methane emission in ruminant animals. According to [6], ruminate feed source*, Crotalaria juncea, M. stenopetala, and L. leucocephala*, have comparatively greater CP concentrations and a consistently lower CH_4 percentage, making them ideal species to minimize CH_4 production in ruminants. Feeding ruminant animals with forages that have high crude protein content enhances digestibility, shortens rumen retention time, and improves nutrient absorption. This not only boosts animal performance but also plays a significant role in reducing the amount of CH_4 produced during rumen fermentation.

2.5.3. Fiber Fraction Content of Forage Vs Methane Production

Methane mitigation in ruminate animals we can determines NDF, ADF, and ADL content of forage. An NDF level of less than 35.5% would be regarded as high quality, whereas one exceeding 46% would be regarded as bad quality [19]. Tropical forages are frequently characterized by their greater levels of lignin, a characteristic that might change the feed's voluntary intake and digestibility [16], leading to higher energy loss and an increase in CH_4 output per unit of product through a drop in animal production efficiency [47]. Because of the rate at which the rumen passes is slowed down, which restricts the intake of dry materials [16, 35], and lignin is linked to fiber and represents an undigested fraction of the feed. As a result the more lignin a plant contains, the less digestible the feed is and the less dry matter an animal can ingest [35].

The effect of ADL on CH_4 mitigation has been a subject of contrasting views among researchers. Some studies have reported a consistent decrease in CH_4 production with increasing ADL content [6]. This reduction is likely because lignin protects plant fibers from ruminal degradation, thereby limiting methanogenesis [21]. The decreased availability of nutrients for rumen microbes involved in methanogenesis, could also explain this effect. Despite some disagreement in the literature, number of researchers and nutritionists acknowledge the potential role of lignin in mitigating methane emissions, suggesting that higher ADL content may contribute positively increase CH_4 production in ruminant livestock systems.

Improving forage quality generally provides better nutritional value for ruminant animals due to its higher crude protein content and lower lignin levels. As a result, it enhances daily production per animal and also contributing to the reduction of global warming and helping maintain atmospheric quality. We can maximizing the chemical composition of ruminate feed quality either purchase concentrate feed, mixing with other forage, or treatment roughage (crop residue), but the high cost of purchasing concentrate feed or material and equipment, skill required during treatment process is not easy and accessible in all farmer as well in business farm. Therefore, one potentially effective strategy to boost ruminant productivity in a sustainable manner is to use easily adapted multipurpose forages produced by small-scale farmers [15].

2.6. Potential of Using Alternative Forage and Pasture to Mitigate Nitrous Oxide Emission

Manure deposition on pastures and its use as fertilizer for feed crops produce significant amounts of nitrous oxide emissions, accounting for around half of these emissions [17]. Livestock responsible for 18% of greenhouse gas emissions (CO_2 equivalent) and accounts for 65% of the anthropogenic nitrous oxide (N_2O) emissions, with most of the N_2O emitted from animal excreta or manure [13]. This Microbial processes of nitrification and denitrification transform NH_4^+ in soil and release N_2O, most produced from the N returned to the soil in animal excreta, particularly in the urine. Mitigation technologies that have been developed include reducing N content of ruminate urine, using high N use efficiency forage, and the use of nitrification inhibitors. While the use of nitrification inhibitors awaits the establishment of an international standard for food for the active ingredient and restricted grazing management may require capital investments, alterative cost-effective options are now being investigated. The critical issue with animal urine-N is the high N concentration in the urine, leading to high N loading rates under the urine patch in a single urination. One possible approach that has been considered to reduce N_2O emissions (and nitrate (NO_3^-) leaching) from animal urine patches is to reduce the N concentration by using alternative pastures and improved forage.

Growing forage exhibit high N use efficiency is mechanism to mitigate N_2O. According to research, the plant forage lucerne (*Medicago sativa L.),* which resembles feed, has a considerably deeper root system forages. This forage enhances its capacity to draw water and nitrogen from a deeper soil depth, lowering the possibility of N loss [45]. In addition, some forage plants have been shown to release biological nitrification inhibitors, thus affecting the nitrification rate and potentially N_2O emissions like, tropical grass *Brachiaria spp* [51]. Tropical forage grasses, cereals and crop legumes show a wide range in biological nitrification inhibition ability. In grazed pastoral incorporating alternative forages such as plantains and lucerne are being utilized more frequently in place of the traditional perennial like ryegrass/white clover pasture better control and decrease in agricultural N_2O emissions through increased N use efficiency would be possible with a better understanding of these forages' vulnerability to N_2O emissions after urine deposition.

2.7. Role of Forage Crops for Soil Carbon Sequestration

Soil carbon sequestration is the process by which atmospheric CO_2 is taken up by plants through photosynthesis and stored as carbon in biomass and soils. Sequestering carbon either into soil or into the vegetation is one of the effective means for mitigation of greenhouse gas (GHG) emissions. Reducing agriculture's GHGs emissions and increasing carbon stock in the soil and biomass could reduce global GHG emissions. The capacity of agriculture lands to store or sequester carbon depends on several factors, including climate, soil type, type of crop or vegetation cover and different management practices. Results from several field experiments under various climatic conditions revealed that farming forage crops has a remarkable capacity to sequester carbon in soil. [3] conducted an experiment with three different forage crops and four different types of nutrient management. They found that after three years of experimentation Cumbu napier cultivated soil stored more carbon of 18.63 t/ha compared with fodder sorghum (17.62 t/ha) and lucerne (15.19 t/ha) cultivated soil. [32] reported that cultivation of perennial forages could store 50.16, 49.16 and 48.34 Mg/ha soil organic carbon after two years of study by setaria grass, signal grass and guinea grass as against initial value of 41.75, 41.28 and 40.27 Mg/ha, respectively. [37] conducted an experiment during 2010-11 and reported that the total organic carbon present in the soil ranged from 0.65 to 0.89% before cultivation i.e. 57.67 t carbon/ha. After harvesting of crops, the calculated tonnes of carbon/hectare were 95.90 for hedge lucerne, 93.96 for hybrid napier, 86.83 for fodder maize and 85.54 for fodder cowpea. [52] Conducted an experiment to quantify the impact of changing soil organic carbon (SOC) storage with farming forage crops during 2010-11. They found that the amount of carbon sequestered in the soil varied from 1.09% by fodder maize, 1.12% by fodder cowpea, 1.33% by hybrid napier and 1.31% by hedge lucerne after harvesting was accomplished.

Importance of soil carbon sequestration in agriculture in addition to significant reduction of carbon dioxide the atmospheric air also vital role include, carbon sequestration builds soil fertility and improves soil quality, improves agronomic productivity, protect soil from compaction and nurture soil biodiversity, increased organic matter in soil, improves soil aggregation which in turn improves soil aeration, water holding capacity, reduces soil erosion and improves infiltration, producing high biomass yield of forage method of minimizing feed scarcity, Supply nutrient for growth of both plants and soil micro-organisms [9].

3. Conclusion

Greenhouse gases like CO_2, CH_4, and N_2O contribute to climate change, with methane from livestock being especially potent. The livestock sector is a major emitter due to enteric fermentation and manure management. As demand for animal products grows, so does the environmental impact—unless climate-smart practices are adopted. Key mitigation strategies include improving herd productivity, diet quality, animal health, and incorporating forages rich in beneficial secondary metabolites. Nitrous oxide emissions can be reduced through better manure and fertilizer management and the use of nitrogen-efficient forages. Carbon sequestration via perennial forages also helps mitigate emissions while improving soil health and feed availability.

Abbreviations

CH_4	Methane
CO_2	Carbon dioxide
CP	Crud Protein
DM	Dry Matter
DMI	Dry Matter Intake
FAO	Food and Agricultural Organization
GHG	Greenhouse Gases
IPCC	Intergovernmental Panel on Climatic Change
N	Nitrogen
N_2O	Nitrous Oxide
NOAA	National Oceanic and Atmospheric Administration
OM	Organic Matter

Author Contributions

Abebe Mosneh Wudu is the sole author. The author read and approved the final manuscript.

Conflicts of Interest

The author declares no conflicts of interest.

References

[1] Agarwal, N., Kamra, D. N., Chaudhary, L. C., & Patra, A. K. Effect of Sapindus mukorossi Extracts on in vitro Methanogenesis and Fermentation Characteristics in Buffalo Rumen Liquor. *Journal of Applied Animal Research*. 2006, 30(1), 1–4. https://doi.org/10.1080/09712119.2006.9706814

[2] Arelovich, H. M., Abney, C. S., Vizcarra, J. A., & Galyean, M. L. Effects of dietary neutral detergent fiber on intakes of dry matter and net energy by dairy and beef cattle: Analysis of published data, *The Professional Animal Scientist*. 2008, 24(5), 375–383. https://doi.org/10.15232/S1080-7446(15)30882-2

[3] Bama, K. S. and Babu. Perennial forages as a tool for sequestering atmospheric carbon by best management practices for better soil quality and environmental safety. *Forage Research.* 2016, 42(3): 149-157.

[4] Beauchemin, K. A., McGinn, S. M., Martinez, T. F. & McAll ister, T. A. Use of condensed tannin extract from quebracho trees to reduce methane emissions from cattle. *Journal of Animal Science*. 2007. 85(8), 1990 1996. https://doi.org/10.2527/jas.2006-686

[5] Benchaar C, Pomar C, Chiquette J. Evaluation of dietary strategies to reduce methane production in ruminants: a modelling approach. Canadian Journal of Animal Science. 2001. 81(4): 563-574. https://doi.org/10.4141/A00-119

[6] Berhanu, Y., Olav, L., Nurfeta, A., Angassa, A. and Aune, J. B.. Methane emissions from ruminant livestock in Ethiopia: Promising forage species to reduce CH_4 emissions. *Agriculture*. 2019. 9(6), 1-16. http://dx.doi.org/10.3390/agriculture9060130

[7] Boadi, D. A. and Wittenberg, K. M. (2002) Methane Production from Dairy and Beef Heifers Fed Forages Differing in Nutrient Density Using the Sulphur Hexafluoride (SF_6) Tracer Gas Technique. *Canadian Journal of Animal Science*. 2002, 82, 201-206. http://dx.doi.org/10.4141/A01-017

[8] Dana Olijhoek, Peter Lund. (2017). Methane production by ruminants. Department of Animal science AU-Foulum. Aarhus University, Denmark.

[9] Das, H., & Rai, A. K. Forage crops hold potential for soil carbon sequestration: A measure for mitigating climate change. Indian Farmer. 2002, 7(05), 389–391.

[10] FAO (2016). Greenhouse gas emissions and fossil energy demand from small ruminant supply chains: Guidelines for assessment. Livestock environmental assessment and performance partnership. Draft public Rev. Rome, Italy.

[11] FAO. (2006). Livestock's long shadow, environmental issues and options. Food and Agriculture Organization of the United Nations, Rome.

[12] FAO. (2013a). Greenhouse gas emissions from pork and chicken supply chains, a global life cycle assessment. FAO, Rome. Italy.

[13] FAO. (2013b). Greenhouse gas emissions from ruminant supply chains, a global life cycle assessment. FAO, Rome.

[14] FAO-New Zealand Agricultural Greenhouse Gas Research Centre. (2017). Supporting low emissions development in the Ethiopian dairy cattle sector—reducing enteric methane for food security and livelihoods. Rome, Italy: Food and Agriculture Organization of the United Nations.

[15] Faurès, J. M., Bartley, D., Bazza, M., Burke, J., Hoogeveen, J., Soto, D., & Steduto, P. (2013). Climate Smart Agriculture: Sourcebook; Food and Agriculture Organization of the United Nations (FAO): Rome, Italy.

[16] Frei, M. Lignin: Characterization of a multifaceted crop component: Review Article. The *Scientific World Journal*. 2013, 25. https://doi.org/10.1155/2013/436517

[17] Gerber, P. J., Hristov, A. N., Henderson, B., Makkar, H., Oh, J., Lee, C., Meinen, R., Montes, F., Ott, T., Firkins, J., Rotz, A., Dell, C., Adesogan, A. T., Yang, W. Z., Tricarico, J. M., Kebreab, E., Waghorn, G., Dijkstra, J., & Oosting, S). Technical options for the mitigation of direct methane and nitrous oxide emissions from livestock: A review. *Animal.* 2013, 7, 220–234. https://doi.org/10.1017/S1751731113000876

[18] Goel G, Makkar HPS., & Becker K. Changes in micro bial community structure, methanogenesis and rumen fermentation in response to saponin-rich fractions from different plant materials. *Journal of Applied Microbiology*. 2008, 105(3): 770-7. https://doi.org/10.1111/j.1365-2672.2008.03818.x

[19] Harper, K. J.; McNeill, D. M. The Role iNDF in the Regulation of Feed Intake and the Importance of Its Assessment in Subtropical Ruminant Systems (the Role of iNDF in the Regulation of Forage Intake). *Agriculture*. 2015, 5, 778-790. https://doi.org/10.3390/agriculture5030778

[20] Hess, H. D., Beuret, R. A., Lotscher, M., HindrichsenI, K., & Machmüller, A. Ruminal fermentation, methanogenesis and nitrogen utilization of sheep receiving tropical grass hay-concentrate diets offered with Sapindus Saponaria fruits and Cratylia argentea foliage. *Journal of Animal Science*. 2004, 79(1), 177-189. https://doi.org/10.1017/S1357729800054643

[21] Hindrichsen, I. K., Wettstein, H. R., Machmuller, A., Jorg, B., Kreuzer, M. E. (2005). Effect of the carbohydrate composition of feed concentrates on methane emission from dairy cows and their slurry. *Environmental Monitoring and Assessment.* 2005, 107(1-3): 329-50. https://doi.org/10.1007/s10661-005-3008-3

[22] Hook S. E., Wright, Andre denis, G., & McBride, Brian. W. (2010). Methanogens: Methane Producers of the Rumen and Mitigation Strategies. Archaea. 2010, 30: 2010: 945785. https://doi.org/10.1155/2010/945785

[23] Hristov, A. N., Oh, J., Firkins, J. L., Dijkstra, J., Kebreab, E., Waghorn, G., Makkar, H. P., Adesogan, A. T., Yang, W., Lee, C., Gerber, P. J., Henderson, B., & Tricarico, J. M. Special topics–Mitigation of methane and nitrous oxide emissions from animal operations: I. A review of enteric methane mitigation options. *Journal of Animal Science*. 2013, 91(11), 5045–5069. https://doi.org/10.2527/jas.2013-6583

[24] Hristov, A. N., Oh, J., Lee, C., Meinen, R., Montes, F., Ott, T., Firkins, J., Rotz, A., Dell, C., Adesogan, A., Yang, W., Tricarico, J., Kebreab, E., Waghorn, G., Dijkstra, J. & Oosting, S. Mitigation of greenhouse gas emissions in livestock production – A review of technical options for non-CO_2 emissions. Edited by Pierre J. Gerber, Benjamin Henderson and Harinder P. S. Makkar. *FAO Animal Production and Health. 2013,* 177-226. FAO, Rome, Italy.

[25] Idupulapati, R., Peters, M., Van der Hoek, R., Castro, A., Subbarao, G., Cadisch, G., & Rincón, A. Tropical forage-based systems for climate-smart livestock production in Latin America. *Rural 2. 2014, 4*: 12-15. https://hdl.handle.net/10568/56951

[26] IPCC. Summary for policymakers. In Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems; Shukla, P. R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H. O., Roberts, D. C., Zhai, P., Slade, R., Connors, S., van Diemen, R., Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Portugal Pereira, J., Vyas, P., Huntley, E., Kissick, K., Belkacemi, M., Malley, J., Eds.; IPCC: Geneva, Switzerland; 2019. Available from: https://www.ipcc.ch/srccl/chapter/summary-for-policymakers/ Accessed 5 October 2023.

[27] IPCC. Climate Change: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland: Intergovernmental Panel on Climate Change (IPCC); 2007.

[28] Jayanegara, A., Goel, G., Makkar, H. P. S., & Becker, K. (2015). Divergence between purified hydrolysable and condensed tannin effects on methane emission, rumen fermentation and microbial population in vitro. *Animal Feed Science and Technology,* 209, 60-68. https://doi.org/10.1016/j.anifeedsci.2015.08.002

[29] Jayanegara, A., Leiber, F., & Kreuzer, M. (2012). Meta- analysis of the relationship between dietary tannin level and methane formation in ruminants from in vivo and in vitro experiments. *Journal of Animal Physiology and Animal Nutrition*, 96(3), 365–375. https://doi.org/10.1111/j.1439-0396.2011.01172.x

[30] Keady, T. W. J., Marley, C. M., Scollan, N. D. Grass and alternative forage silages for beef cattle and sheep: Effects on animal performance. In Proceedings of the 16th International Silage Conference, Hämeenlinna, Finland, 2012; pp. 210–228.

[31] Kristiansen, S., Painter, J., & Shea, M. Animal agriculture and climate change in the US and UK elite media: volume, responsibilities, causes and solutions. *Environmental Communication*. 2021, 15(2): 153-172. https://doi.org/10.1080/17524032.2020.1805344

[32] Kundu, C. K., Das, H. and Ghosh, P. K. 2019. Soil organic carbon sequestration potential and economic profitability of perennial forage crops under different mulching environments. *Range Management and Agroforestry.* 40(1): 83-88.

[33] Makkar, H. P. S., Vercoe, P. E. Measuring Methane Production from Ruminants. 15 editions. *Springer*. 2007. Berlin, Germany.

[34] Molina, I. C., Angarita, E. A., Mayorga, O. L., Chará, J., & Barahona-Rosales, R. Effect of Leucaena leucocephala on methane production of Lucerna heifers fed a diet based on Cynodon plectostachyus. Livestock Science. 2016, 185: 24-9. https://doi.org/10.1016/j.livsci.2016.01.009

[35] Moore, K. J., & Jung, H. J. G. Lignin and fiber digestion. *Rangeland Ecology & Management/Journal of Range Management Archives.* 2001, 54(4), 420-430.

[36] Mosier AR, Duxbury JM, Freney JR, Heinemeyer O, Minami K, et al. (1998). Mitigating Agricultural Emissions of Methane. *Climatic Change. 1998,* 40, 39–80. https://doi.org/10.1023/A:1005338731269

[37] Mueller-Harvey, I. Unravelling the conundrum of tannins in animal nutrition and health. *Journal of the Science of Food and Agriculture.* 2006, 86, 13. https://doi.org/10.1002/jsfa.2577

[38] NOAA (National Oceanic and Atmospheric Administration). Greenhouse Gases. 2020. Available from: https://www.ncdc.noaa.gov/monitoring-references/faq/greenhouse-gases.php Accessed 10 September 2020.

[39] Okpara, M. O. "Methane emissions in ruminants: perspectives on measurement and estimation methods." *Russian Agricultural Sciences*. 2018, 44(3): 290-294.

[40] Olagaray, K E., & Bradford, B. J. Plant flavonoids to improve productivity of ruminants– A review. *Animal Feed Science and Technology*. 2019, 251: 21 36. https://doi.org/10.1016/j.anifeedsci.2019.02.004

[41] Oskoueian, E., Abdullah, N., & Oskoueian, A. Effects of flavonoids on rumen fermentation activity, methane production, and microbial population. *BioMed Research International*. 2013: 1–8. https://doi.org/10.1155/2013/349129

[42] Patra, A. K., Kamra, D. N., & Agarwal, N. (Effect of leaf extracts on fermentation of feds and methanogenesis with rumen liquor of buffalo. *Indian Journal Animal Science*. 2008, 78, 91–96.

[43] Patra AK, Saxena J. The effect and mode of action of saponins on the microbial populations and fermentation in the rumen and ruminant production. *Nutrition Research Reviews*. 2009, 22(2): 204-19. https://doi.org/10.1017/S0954422409990163

[44] Phelan, P., Moloney, A. P., McGeough, E. J., Humphreys, J., Bertilsson, J., O'Riordan, E. G., & O'Kiely, P. (2015). Forage legumes for grazing and conserving in ruminant production systems. *Critical Reviews in Plant Sciences*. 2015, 34(1–3), 281–326. https://doi.org/10.1080/07352 689.2014.898455

[45] Sainju, U. M., Lenssen, A. W., (2011). Soil nitrogen dynamics under dry land alfalfa and durum forage cropping sequences, Soil Science Society of America Journal. 2011, 75(2), 669–677. https://doi.org/10.2136/sssaj2010.0221

[46] Sejian, V. K., Naqvi, S. M. Livestock and climate change: mitigation strategies to reduce methane production. *In Greenhouse Gases: Capturing, Utilization and Reduction,* InTech; 2012, 09. https://doi.org/10.5772/32014

[47] Shibata M, Terada F. Factor's affecting methane production and mitigation in ruminants. *Animal Science Journal*. 2010, 81(1): 2-10. https://doi.org/10.1111/j.1740-0929.2009.00687.x

[48] Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., Miller, H. L., Eds. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the 4th Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2007, pp. 996.

[49] Stams, A., Plugge, C. Electron transfer in syntrophic communities of anaerobic bacteria and archaea. Natural Review Microbiology. 2009, 7, 568–577. https://doi.org/10.1038/nrmicro2166

[50] Steinfeld, H., Gerber, P., Wassenaar, T. D., Castel, V., Rosales, M., de Haan, C. Livestock's Long Shadow: Environmental Issues and Options. Rome, Italy: Food and Agriculture Organization; 2006. ISBN 978-9251055717.

[51] Subbarao GV, Yoshihashi T, Worthington M, Nakahara K, Ando Y, Sahrawat KL, Rao IM, Lata JC, Kishii M, Braun HJ. Suppression of soil nitrification by plants. *Plant Scince.* 2015, 233: 155-164. https://doi.org/10.1016/j.plantsci.2015.01.012 Epub 2015 Jan 28.

[52] Sundaram, S. M., Sivakumar, T., Sankaran, V. M., Rajkumar, J. S. I. and Nishanth, B. (2012). Farming forage crops for improving soil organic carbon stocks in agricultural lands. *International Journal of Research in Biological Sciences*. 2012, 2(3): 116-119.

[53] Suybeng, B., Charmley, E., Gardiner, C. P., Malau-Aduli, B. S., Malau-Aduli, A. E. Methane emissions and the use of desmanthus in beef cattle production in Northern Australia. *Animals. 2019, 9(8), 542.* https://doi.org/10.3390/ani90 80542

[54] Szumacher-Strabel, M., & Cie´ slak, A. (2010). Potential of phytofactors to mitigate rumen ammonia and methane production. *Animal Feed Science and Technology*. 2010, 19: 319 37. https://doi.org/10.22358/jafs/66296/2010

[55] Tavendale, M. H., Meagher., L. P., Pacheco, D., Walker N, Attwood G. T., & Sivakumaran, S. Methane production from in vitro rumen incubations with Lotus pedunculatus and Medicago sativa, and effects of extractable condensed tannin fractions on methanogenesis. *Animal Feed Science and Technology*. 2005, 123–124, 403–19. https://doi.org/10.1016/j.anifeedsci.2005.04.037

[56] Torrent, J., Johnson, D. E. Methane production in the large intestine of sheep. In Energy Metabolism of Farm Animals, Aguilera, J. F., Ed., EAAP Publication No. 76. Granada, Spain: Servicio de Publicaciones, Consejo Superior de Investigaciones Científicas; 1994, pp. 391–394.

[57] Tubiello, F. N., Salvatore, M., Rossi, S., Ferrara, A., Fitton, N., & Smith, P. (2013). The FAOSTAT database of greenhouse gas emissions from agriculture. *Environmental Research Letters, 2013.* 8, 015009. https://doi.org/10.1088/1748-9326/8/1/015009

[58] Ugbogu, E. A., Elghandour M. M. M. Y., Ikpeazu, V. O., Buendía, G. R., Molina, O. M, & Arunsi, U. O. (2019). The potential impacts of dietary plant natural products on the sustainable mitigation of methane emission from livestock farming. *Journal of Cleaner Production*. 2019, 213, 915–25. https://doi.org/10.1016/j.jclepro.2018.12.233

[59] Van Dorland HA, Wettstein HR, Leuenberger H, Kreuzer M. Effect of supplementation of fresh and ensiled clovers to ryegrass on nitrogen loss and methane emission of dairy cows. *Livestock Science*. 2007, 111(1-2), 57-69. https://doi.org/10.1016/j.livsci.2006.11.015

[60] Van Gastelen, S., Dijkstra, J., & Bannink, A. Are dietary strategies to mitigate enteric methane emission equally effective across dairy cattle, beef cattle, and sheep? *Journal of Dairy Scienc*e. 2019, 102(7), 6109-6130. https://doi.org/10.3168/jds.2018-15785

[61] Van Soest PJ. Nutritional ecology of the ruminant. O & B Books. Inc., Corvallis, OR. 1982. 374. 33.

[62] Waghorn GC, Clark DA. Feeding value of pastures for ruminants. *New Zealand Veterinary Journal*. 2004, 52(6): 320-31. https://doi.org/10.1080/00480169.2004.36448