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# A Systematic Review Of Plant-Based Feed Additives: Their Role In Reducing Methane Emissions And Improving Nutrient Efficiency In Ruminants

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***Abstract***
*The livestock industry is a major source of greenhouse gas emissions, particularly methane from ruminants due to enteric fermentation. The study aimed to conduct a systematic review on the effectiveness of plant-based feed additives in minimising methane emissions and improving nutrient utilisation in ruminants. The 12 articles from 2020-2024 focusing on using plant-based additives were reviewed using a narrative synthesis approach. Plant feed additives were found to be very effective in reducing methane gas production, as the research found. Plant feed additives also optimise the fermentation of the rumen, which is the gut of ruminants. Some chemicals have already been shown to reduce methane formation by up to 50%. However, diet and species of animals also varied in terms of results concerning studies. Future studies should focus on measuring the practicability and scalability of these additions in various farming systems in terms of their human and economic feasibility, such as performance. The study also points out that the use of essential oils has proved to be very effective in abating the emission of methane and variably effective.*
***Keywords:*** *Plant-Feed Additive, Methane Emissions, Nutrient Efficiency, Ruminant Nutrition, Greenhouse Gas Reduction, Livestock*

## 1. INTRODUCTION

The livestock sector worldwide has become one of the biggest pollutants of the environment, especially in terms of methane emissions. Enteric fermentation of ruminant animals such as cattle, sheep and goats causes a release of methane, a potent greenhouse gas (GHG). According to Palangi et al. (2022), enteric fermentation of ruminants in the process of digesting feed is the largest source of methane. The issue concerning the impact of methane on the environment is also concerning since methane increases its impact on rising temperatures 28 times more powerfully than carbon dioxide in one century (Hristov, 2024). Animals like ruminants release methane which forms a significant proportion of GHG emissions in the planet. As a report published by the Food and Agriculture Organisation (FAO) explains, when considering the proportion of livestock-related GHG emissions of the total global GHG emissions, it constitutes an approximate amount of 14.5% (Twine, 2021). It is dubious to shun the alterations in livestock production which is specifically required since the burdening issue of climate change is overwhelming.

In the recent years, there has been increasing number of research studies on the management of methane emissions by the ruminant livestock. One of the methods researched is dietary changes, which have been said to be vital in the minimization of methane production. The study has revealed that the nutritional profile of feed contained in the livestock consumption, especially fermentable carbohydrates, such as starch and fibre, is an indispensable factor in determining the outcome of methane production (Sun et al., 2022). Though dietary manipulation is an imperative step in the direction of reducing methane production, it is emerging evident that feed additives, those particularly of plant origin, will have the potential of posing greater and more significant impact. According to Hristov (2024), a lot of feed additives, mostly plant-derived ones, have been discovered to reduce methane emissions by being able to impact the rumen fermentation process, as well as change the methane producing microbial community.

Feed additive of plant origin has become a fascinating approach in managing the problem of low methane emissions and improvement of nutrient utilization in ruminants. The greatest benefit of this type of additives is that they supply an alternative environmentally friendly and sustainable mode of replacement to artificial

additives. These phytogenic additives are composed of the elements having bioactive compounds that could modify local microbial population in the rumen and consequently alter the production rate of methane. As a case illustration, it has been shown that basic oils, tannins and saponins could limit rumen methanogenic bacteria, and it caused a decrease in methane-gas emission (Ahmed et al., 2021). Plant-based products could be supplemented in feed compared to synthetic additives as a more natural and environmentally friendly supplement; it may be especially appealing in the scenario of sustainable agriculture (Palangi and Lackner, 2022). As the world demands more environmentally friendly practices in farming, the use of plant-based feed supplements is being favoured more and more as the solution to decreasing the volume of methane emissions and enhancing the effectiveness of animal feedstock.

Although the number of studies concerning the topic, as well as the conclusion as to the efficiency of plant-based feed additives in mitigating methane and improving nutrient utilisation in ruminants, is growing, the area has not yet been thoroughly reviewed. Although previous research conducted by scholars such as Wang et al. (2024) and Bryant (2022) has shown the promise of using plant-based additives, a systematic review that will synthesise the literature on a given topic is necessary. It provides great ideas about the uniformity of the effects of plant-based additives on the various species of ruminants, their diets and agricultural systems. A critical examination of the existing body of knowledge would also provide insights into the process of how these additives can effectively lower the methane release and also boost nutrient utilisation, which, in turn, would allow application in a commercial livestock setup on a larger scale.

Besides the optimistic potential of plant-based feed supplementation in reducing the methane emissions, plant-based supplementation has also been discovered to augment the nutritional efficiency of ruminants. Essential oils and garlic extracts are plant-derived bioactives, which have been found to promote the growth of rumen fermentation by raising rumen volatile fatty acids (VFAs) yields, essential in general health and productivity of the ruminants (Ahmed et al., 2021). Moreover, feeding animals plant-based additives may enhance feed conversion ratio (FCR) and the total growth performance so that the animals can be more effective at using feed as the source of productive outcomes, such as meat and milk (Zeeshan et al., 2023). The influence of these additives on nutrient efficiency and animal performance has, however, been a bit variable. The study has also shown an improvement in feed conversion and growth performance, although others have found that when different plant additives are administered, the effect is less clear or seen more erratically (Kelly and Kebreab, 2023). These differences emphasise the importance of further investigations into the specific conditions under which this type of additive can be maximally useful and deal with the conceivable trade-offs that could be connected with nutrient digestion and animal health.

The effects of plant-based feed additives on preventing methane emissions and enhancing nutrient utilisation in livestock production systems are truly valuable to the sustainability of production systems. Nonetheless, translating the encouraging findings in controlled studies to applied solutions that are applicable to the farming industry remains to be met without a hitch. These attributes will require issues of scale, affordability, and homogeneity of these additives in practical conditions of agricultural practice. AAlthough some additives may record a decrease in methane emission in laboratory and small-scale experiments, their effectiveness on large-scale and commercialised farming units remains unclear. The study aims to provide a comprehensive systematic review on plant-based feed additives and their role in reducing methane emissions and improving nutrient efficiency in ruminants. It also evaluates the effectiveness of plant-based feed additives in reducing methane emissions form ruminants and examines the impact on nutrient efficient and overall animal performance. It shed light on the mechanisms through plant-based feed additives reduce methane emission and improve nutrient efficiency.

The importance of this research lies in the fact that it is an exhaustive review of the recent advances in the field of plant-based feed additives to ruminants. As the need to slowly minimise the emission of methane produced by livestock becomes increasingly more intense, it is highly important to seek an alternative to synthetic feed supplements. In this investigation, the effectiveness of plant-based additives will not only be revealed, but also the insights into their mechanism will be shown, so that they can help in making decisions in livestock management. This current study will help in drawing the environmental and economic advantages of the shift to plant-based additives to present the critical role of their use in environmentally sustainable agricultural processes.

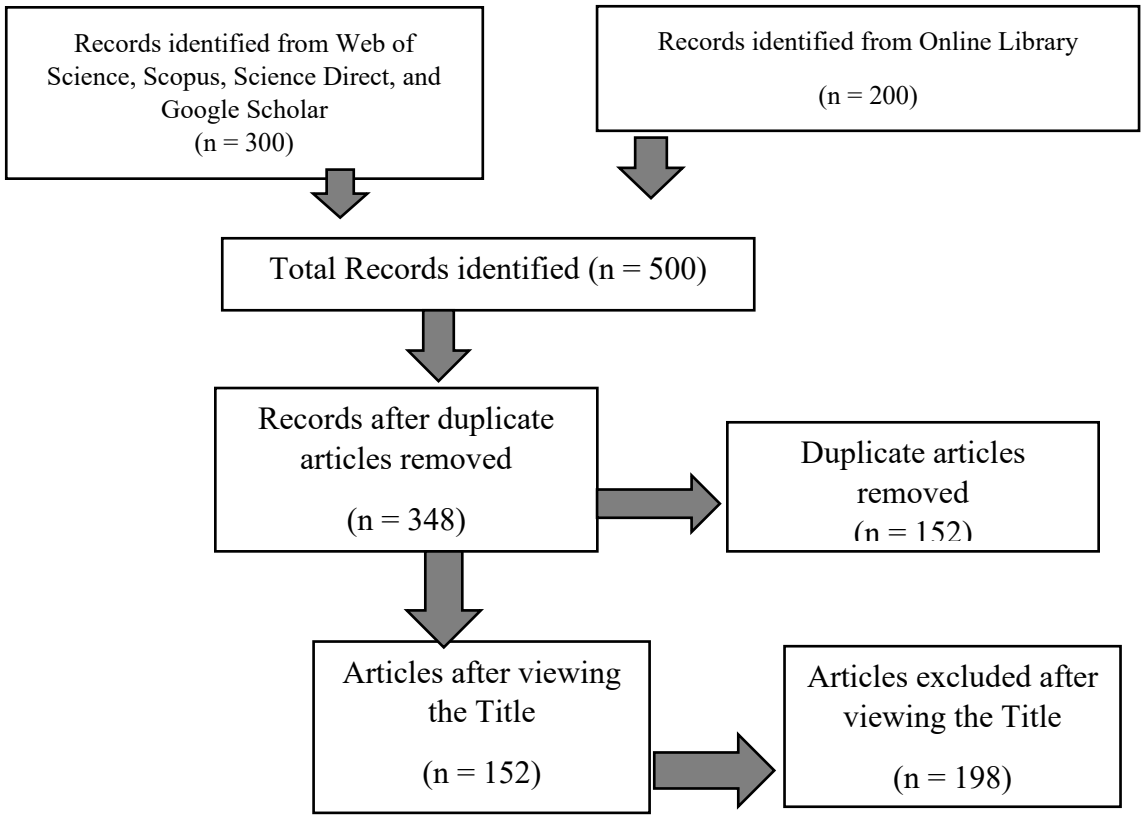
The novelty of the study is that the researchers systematically synthesised existing evidence and provided more coherent and clearer knowledge about plant-based additives to livestock production. It will detect the missing works of the existing literature and offer recommendations on further investigation in order to present more efficient solutions. These results are vital, especially to policymakers and other stakeholders in need of agricultural-based information and recommendations on the benefits of adopting sustainable feeding strategies in the livestock sector.

## 2. Methods

### Research Strategy

A systematic review is applied as the basis of the study to define the effectiveness of the plant-based feed additives on the emission of methane and nutrient efficiency in ruminants. The role of the methodology of conducting the given review is to start with the vast searching of various scholarly databases, namely Web of Science, Scopus, Science Direct, as well as Google Scholar, which offer an enormous range of peer-reviewed articles. The key words used in the study include: plant based feed additives, methane emissions, nutrient efficiency, ruminants, and enteric methane using Boolean operator of AND and OR to filter the search. The objective of the research was to garner the studies that may have been published since 2020 to 2024 so that recent studies that may portray the current trends in research and development in the field must be included. Articles that have been more specifically written on the influence of plant-derived additives such as essential oils, herbs, tannins and saponins on methane production by ruminants or nutrient utilisation were given precedence. It was searched in such a manner that it covers a wide area of researches conducted on different species of ruminants such as cattle, sheep and goats. Studies that were considered reports of replications were not included and the remaining articles were screened in terms of their relevance to the research topic, methane emission, and feed efficiency in livestock.

### Prisma Diagram



**Inclusion and Exclusion Criteria**

The studies were restricted to those that were of ultimate quality and relevance by setting inclusion and exclusion criteria. The inclusion criteria were that only the peer-reviewed journal articles, conference proceedings, and academic reports published in the period between 2020 and 2024 were to be included. The experiments should have involved ruminants including cattle, sheep and goats, and they should have examined the effect of plant feed additives on methane emission or nutrient utilization. The experiments where the L/d or g/d of the methane production levels were quantified or the nutrient efficiency was expressed in form of the feed conversion ratios or weight gain were considered. Specifically, studies concerning the application of plant additives such as essential oils, herbs, or tannins were also given the highest priority. Exclusion criteria eliminated research that was not published in peer-reviewed journals, studies that were conducted with non-ruminant species, and studies that did not describe methane emissions or nutrient efficiency. Also, studies published before 2020 that did not have sufficient data and no obvious connection to the subject of this review were not considered in the analysis.

After the studies had been determined according to the inclusion and exclusion criteria, the process of data extraction was carried out in order to collect the main information of each study. There is no report of the initial number of articles retrieved and the final number of included articles. Data was collected, standardised, and corrected using a standardised form. Among the information retrieved was the name of the author (s) of the study, year of publication, study design and the geographical location.

**Data Extraction**

Once the studies were identified based on the inclusion and exclusion criteria, data extraction was performed to obtain key insights from each. The data collection process was standardised and accurate because the data was collected through a standardised form. The information that was extracted entailed the author/s of the study, the year of publication, the design of the study, and the geographical location. Data related to animal characteristics such as species, breed and production system (intensive or extensive) were also obtained. The nature and amounts of feed additives added (plant-based) were also noted in each study, and they included essential oils, leaves, and other plant products, among others. The major outputs recorded were methane emissions (in L/d or g/d) and other efficiency measures on the nutrients, including feed conversion efficiency, weight gain or milk production. The data was logically categorised and structured in order to make comparisons between different studies easier, and in cases where the methodology or results obtained within one study contrasted those obtained in another study, this was documented.

After identification of the studies on the basis of the inclusion and exclusion criteria, data extraction was done to extract the important ideas of each of the studies. The data collection procedure was uniform and correct due to the fact that the data collection procedure was done using a standard form. Inter-rater reliability is not mentioned, nor is a solution to disagreement in selection mentioned. To achieve consistency, whenever there was some sort of disagreement in terms of study inclusion or data extraction, the disagreements were addressed through consensus discussions. The data retrieved consisted of the author(s) of the article, the year of publication, study design, and geographical location.

**Quality assessment and Synthesis of data**

After the extraction of data, a qualitative narrative approach was employed to conduct the synthesis. Narrative synthesis was conducted with this diversity in terms of study design, species, and outcome measures, which allowed identifying the trends and patterns of the batches among the studies (Rai et al. 2020). The major area of concern was to know how the feed additives as plant basis lessen the liberation of methane to the sky and augment nutrient efficiency. The narrative approach to describing results was adequate but a meta-analysis could not be done due to the fact that the researchers varied in the methods of conducting their studies. The modified Cochrane Risk of Bias tool assessing the aspects of randomisation, blinding and the reporting of the data was utilised in order to identify the quality of the studies that have been included in the current review. This assessment helped and determine the reliability and validity of the results obtained which were that the results obtained in the review were obtained using the strongest and best evidence.

## 3. RESULTS

**Table 1: Table of Sources**

| S.No | Authors | Aim of the Study | Methods | Findings |
|---|---|---|---|---|
| 1 | Scoones, I. (2023) | To discuss the politics of global assessments related to livestock, methane, and climate change. | Analysis of global political discourse regarding methane and livestock. | Discusses the politics surrounding methane reduction strategies in livestock. |
| 2 | Del Prado et al. (2025) | To assess feed additives as a strategy to mitigate enteric methane from ruminants, with a focus on how to quantify methane mitigation potential. | Review of various feed additives, with a focus on antimethanogenic feed additives and methods for quantifying their effectiveness. | Provided methods for assessing the methane-mitigation potential of feed additives, with an emphasis on quantification methods. |
| 3 | Honan et al. (2021) | To evaluate feed additives as a strategy to reduce enteric methane production in cattle, focusing on their modes of action, effectiveness, and safety. | Literature review on feed additives and their role in methane mitigation, discussing modes of action and safety. | Explained various feed additivesâ€™' effectiveness in reducing methane, with a focus on mechanisms of action and safety for cattle. |
| 4 | Kelly and Kebreab (2023) | To review recent advances in feed additives that mitigate enteric methane emissions from ruminant livestock. | Review of feed additives that may reduce methane emissions, based on recent scientific studies. | Concluded that certain feed additives show potential for methane reduction, with a specific focus on their roles in ruminant systems. |
| 5 | Ahmed et al. (2021) | To assess the efficacy of plant-based bioactives supplementation on methane production and rumen fermentation in vitro. | In vitro study on the effects of plant-based bioactives on methane production and rumen fermentation in different concentrate diets. | Found that plant-based bioactives significantly reduce methane production and improve rumen fermentation characteristics in vitro. |
| 6 | Hodge et al. (2024) | To review potential feed additives for carbon footprint reduction through methane abatement in dairy cattle. | Review of feed additives for methane abatement and carbon footprint reduction in dairy cattle, based on existing research. | Provided a broad overview of methane mitigation strategies, with a specific focus on feed additives and their potential for carbon footprint reduction in dairy cattle. |
| 7 | Tseten et al. (2022) | To review strategies to mitigate enteric methane emissions from ruminant | Systematic review of strategies to reduce methane emissions in | Found that feed additives are a promising strategy for reducing methane |

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|---|---|---|---|---|
| | | animals, including feed additives. | ruminants, with a focus on feed additives. | emissions from ruminants, with several potential additives identified for future use. |
| 8 | Wang et al. (2024) | To review phytogenic feed additives as natural antibiotic alternatives in animal health and production, including their effects on methane reduction. | Literature review on phytogenic feed additives, with a focus on their impact on methane production in livestock. | Concluded that phytogenic feed additives have significant effects on methane reduction in livestock, with added benefits for overall health. |
| 9 | Hristov (2024) | To review the latest advancements in feed additives and nutrition to mitigate enteric methane emissions. | Review of nutritional interventions and feed additives targeting methane reduction, based on advancements in animal science. | Reviewed the latest findings on feed additives that mitigate methane emissions, showing significant reductions in emissions in various ruminant systems. |
| 10 | Rivero et al. (2025) | To evaluate the efficacy of a novel multi-component feed additive for methane mitigation and performance enhancement in sheep. | Experimental study on the impact of a multi-component feed additive on methane emissions and sheep performance. | A novel multi-component feed additive reduced methane emissions in sheep and showed some effects on feeding frequency. |
| 11 | Zeeshan et al. (2023) | To assess the efficacy of mannan-oligosaccharide and live yeast feed additives on performance, rumen morphology, and biochemical parameters in buffalo calves. | In vivo study on the effects of mannan-oligosaccharide and live yeast supplementation on performance and rumen morphology in buffalo calves. | Demonstrated that mannan-oligosaccharide and live yeast additives improved rumen fermentation, leading to better performance and lower methane emissions in buffalo calves. |
| 12 | Altshuler, Chebach, and Cohen (2024) | Presented a pioneering approach using rumen microbiome data to predict the efficacy | AI-based modelling to predict the effectiveness of feed additives in reducing methane emissions in dairy cows. | The findings show the feasibility of precision feeding supplementation to improve dairy output and milk quality, in addition to cutting 27 per cent of emitted methane. |

**Effectiveness of plant-based feed additives in reducing methane emissions from ruminants.**

The ability of plant-based feed supplements to suppress methane levels in ruminants has been heavily researched, and findings have been impressive, where several types of supplements (essential oils, tannins,

and other phytochemicals) tend to reduce methane production. Plant-based feed additives can interact in various ways, e.g. by inhibition of methanogenic microbes in the rumen, hydrogen and other fermentation products, competitive action, or direct manipulation of the fermentation pathway. An example of such studies is Honan et al. (2021), Kelly, and Kebreab (2023), who thoroughly indicate that essential oils and plant secondary compounds can greatly mitigate methane emissions through altering the rumen microbial community. The additives had worked in the in vitro and in vivo tests, and there were claims of a 50% decrease in the amount of methane produced by cattle. The studies, however, indicated their limitations, including varying effects of different feeding systems and ruminant species. The fact that the results were not uniform, especially on essential oils, implies that although some additives may prove to be very useful under specific circumstances, the effectiveness or otherwise may exhibit differences depending on the kind of ruminant, the composition of the diet and the type of feed additive applied.

The results of the research by Ahmed et al. (2021) demonstrated that plant-based bioactives significantly decreased methane production by ruminants by up to 50% and had the strongest effect on diets richer in concentrates. In the same review, Honan et al. (2021) compared different feed additives and observed that in cattle, some of the available additives reduced methane emission by 20-30%. Del Prado et al. (2025) pointed to the necessity of the use of reliable quantification algorithms and stated that there is still a possibility of decreasing methane emissions by about 30 percent with the help of antimethanogenic additives in the feed. As Rivero et al. (2025) recorded, a feed additive improved methane emissions by 15% in sheep; hence, certain conditions show the effectiveness of the additive. According to Hristov (2024), a subsection of feed additives, including phytogenics, always lowered methane emissions by 20-3%, showing the potential of their methane mitigation in a variety of ruminant systems. These quantitative observations point to the inconsistent results in terms of the spectrum of plant-based feed additives according to their effectiveness in the reduction of methane emissions in different species and feeding strategies.

**Impact of plant-based additives on nutrient efficiency and overall animal performance**

The influence on the nutrient utilisation efficiency rates and the general animal performance has been one of the key concerns of the intense research of the previous years that revealed both the advantages and disadvantages. An in vitro study by Ahmed et al. (2021) was based on enumeration of the effects of plant bioactives like mixtures of garlic and citrus extracts with methane formation and characteristics of rumen fermentation in various feeding regime conditions. The study established that the plant bioactive enhanced rumen fermentation since it enhanced the concentration of total volatile fatty acids (VFA) yield in the rumen without alters nutrient digestibility. The result is evidence of the fact that plant additives could increase the use of nutrients in ruminants. Equally, the two studies by Hodge et al. (2024) and Zeeshan et al. (2023) compared the performance of ruminants on additives of those feeds individually and ruminants on combined feed additives, including garlic oil and mannan-oligosaccharide (MOS). These additives were also reported to not only reduce methane emission but also to enhance the functionality of the rumen which resulted in better feed conversion ratio (FCR) and growth.

As per the research by Hodge et al. (2024) and Zeeshan et al. (2023), garlic oil and mannan-oligosaccharide (MOS) produced a statistically significant positive impact on growth performance in the form of the feed conversion ratio (FCR). Specifically, rumen fermentation increased to 12 %, when compared to the levels of rumen fermentation in the buffalo calves fed upon the MOS supplement, which reduced methane production by 20 %. The supplements also enhanced the working ability of the rumen that enhanced the overall utilisation of nutrients among the ruminants. On the other hand, Kelly and Kebreab (2023) noted that despite 3-nitrooxypropanol (3-NOP) resulting in the decrease of methane emissions by up to 30%, limited success was reported when maximizing positive effects on the productivity of animals and their health on a long-term basis. This implies the presence of potential trade-offs between methane restraint and long-term performance. Rivero et al. (2025) found that a multi-component feed supplement on sheep could verify a 15% decrease in methane emissions when fed to sheep, although it did not influence weight gain or feed conversion efficiency. Tseten et al. (2022) also suggested that plant additives tended to associate with performance better under controlled settings or different form dietary regimes, however, they were quite weak in the heterogeneous livestock systems. The results emphasise that the potential of plant based additives to

increase nutrient use and the reduction of methane is likely to be variable and that variation is dramatically affected by the species, diet, and the agricultural system.

**Mechanisms through which plant-based feed additives reduce methane emissions and improve nutrient efficiency**

The mechanisms of action of plant-based feed additives that can reduce methane production in ruminants along with the nutrient utilisation are complicated and heterogeneous. Numerous plant-based additives, such as essential oil, tannins, and other phytochemicals, have been found to modify the process of rumen fermentation, hence acting directly on the process of methane production. As some literature testifies (e.g., Honan et al., 2021; Hristov, 2024), certain secondary metabolites of plants can interfere with the metabolism of methanogenic archaea by either derailing its metabolism or simply competing with them on hydrogen, which is a central feature of the methane formation process. For example, essential oils, such as garlic and citrus essential oils, were found to reduce methane emissions by inhibiting rumen fermentation, that is, by stimulating the production of propionate at the expense of acetate, a precursor of methane. Essential oils, here, are acting as rumen modifiers, directing the microbial population towards more efficient fermentation with reduced methane production. Similarly, studies like those of Tseten et al. (2022) and Kelly and Kebreab (2023) also draw attention to the role played by plant secondary compounds and tannins in reducing methane through methanogenesis inhibition by affecting microbial growth and fermentation.

While encouraging, the application of plant compounds is not without problems, particularly relating to the persistence and consistency of methane abatement in the long term. Ahmed et al. (2021) also noted that although plant-bioactives, such as garlic and citrus extracts, were found to be effective at reducing methane emissions under varying feeding styles in vitro, their effectiveness was highly dependent on the forage-to-concentrate ratio. Such variability would suggest that the benefits of using plant-based additives could not be considered universally applicable to all feeding regimens and that more targeted application of them is required. Also, while such additives generally stimulate rumen fermentation, they are also attended by trade-offs in nutrient digestibility at times. The reductions in methane yield are sometimes offset by decreases in the overall use of energy for growth and production, as in experiments like Rivero et al. (2025) and Zeeshan et al. (2023), where methane abatement was not always followed by improved weight gain or feed conversion efficiency. Moreover, other botanical supplements including macroalgae and 3-nitroxypropanol (3NOP) have also demonstrated to possess superb methane-reducing properties with the only problem being that its usage must be skillfully weighed against the possible toxicities and negative impacts on health of the animal. Conversely, Hodge et al. (2024) note that despite the fact that macroalgae may become an effective strategy to mitigate methane emission, its feeding may be followed by various undesirable rumen changes, such as a decrease in microbial diversity and possible digestive disturbances.

## 4. DISCUSSION

The use of plant derived feed supplements to inhibit methane production by ruminants has received enormous traction among recent studies with most researchers estimating huge potential. As researchers have already determined, plant secondary metabolites and essential oils could inhibit methane production, influencing the microbial community in the rumen with tremendous potential being cited in vitro (Honan et al., 2021; Kelly and Kebreab, 2023). Yet this is not necessarily true across all livestock species, or in all cases of feeding as claimed in Tseten et al. (2022) and Ahmed et al. (2021). Further, as some additives, namely, 3-nitrooxypropanol (3NOP), have demonstrated a high potential in terms of methane-mitigation, there has been a lack of feasibility in the practical application of feed additives in large-scale use because of the issues associated with cost, expandability, and the subject outcomes to health outcomes (Hodge et al., 2024). The problem of usage of such additives in mixed or large-scale farming habits is further supplemented by the circumstance that no gain in productivity and feed conversion ratio is seen by the usage of methane abatement (Rivero et al., 2025; Zeeshan et al., 2023). These results indicate that it is possible to reduce methane emissions however the benefits in the long-term on animal health and performance remain questionable. The incompatibility of the results of different studies such as the differences in the effects of garlic oil, macroalgae and nitrates, make one question the viability and applicability of these types of plant-based ingredients to livestock in practice.

The broader implications for the use of plant-based feed additives to mitigate methane and enhance nutrient utilisation remain unresolved, with positive results in some instances and negative results in others from the conducted studies. Outcome variation across studies (Zeeshan et al. 2023; Rivero et al. 2025) emphasises the need for more intense and continuous research into the total implications of such feed additives, particularly their scalability, cost-effectiveness, and impact on animal welfare. Despite the enormous potential that plant-based feed additives portray in reducing methane production and improving nutrient retention in ruminants, numerous challenges are at the heart of limiting their use on a large scale. It could be suggested that future studies should concentrate on overcoming these limitations, especially the fact that they work differently in various species, diets, and conditions. There is a need to go long-term in order to learn the lasting effects of these additives on the productivity, health and general performance of animals. To clarify, among the gaps that still need to be filled, there is a need to study the long-term impact of essential oils and 3-nitrooxypropanol (3-NOP) on animal health, specifically on its potential side effects and margins between methane mitigation and animal performance (Hodge et al., 2024). Also, research on plant-based additives interaction and overall feed, as well as their combined effect on the rumen microbiota, is important in optimising their application in different farming systems.

The utilisation of technology in large-scale farming systems is yet another obstacle to the usage of these additives on a large scale. Most of the potential feed additives are still not scalable and economically viable to use commercially, owing to the cost of production and the actual health of the animals. Scientific studies should be conducted to find a cost-effective and safe way to produce large quantities of plant-based additives for large-scale consumption (Zeeshan et al. 2023). The efficiency of these additives needs to be improved on a cost-effective basis to be widely adopted, hence requiring studies on such matters.

## 5. CONCLUSION

The study concluded that, plant-based feed additives have been extremely promising in reducing the ruminant emissions of methane and improving nutrient efficiency, and hence they are a solution that can be used in sustainable livestock production. Through mechanisms such as modulation of rumen microbial communities and inhibition of methanogenesis, these additives offer a natural and environmentally friendly method of mitigating the climate impact of livestock production.

**Recommendations**

Priority should be given to large-scale and long-term studies in future research to ascertain the practical viability of plant-based feed additives in diverse farming systems.

Further research should study the chronic impacts on animal productivity, health, welfare, how effective and cost effective these additives are and how dense/scalable they can be made. The research on the optimal dosing, the pathway of administration, and the synergistic effects in case plant-based additives are combined with other nutritional interventions would be helpful. In addition, the policymakers should make it a priority to establish regulations on the use of plant-based additives by giving consideration to the environmental, economic and even social impacts.

**Limitations**

The study was limited in some ways especially on the parameters of variability among studies and also the absence of long testing on the actual effects of plant based additives under farm conditions. Moreover, the vast majority of the researches were made under controlled conditions or in vitro experiments that may not exemplify real farm systems.

**Future Implications**

More interventional research should be undertaken to evaluate methane mitigation and subsequent level of animal welfare, productivity and economic sustainability. Additional research involving ideal dose, modes of administering, and synergy aspects of such a combination between plant-based additive supplemented by other dietary interventions would be also enlightening relative to the use of this principle in sustainable livestock foundation. The policy makers and agricultural stakeholders should also consider giving priority to the development of the guidelines on the use of such additives with environmental, economic and social considerations. The implications of this research are game changers and have the potential of resulting in

aiding the production of low levels of emission through animal farming and aid the world in the battle to tackle global warming and increase the food security.

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