



NUTRITIONAL STRATEGIES TO IMPROVE RUMINANT PRODUCTIVITY: A SYSTEMATIC LITERATURE REVIEW

Sajid Hussain ¹

¹*Department of Botany, PMAS Arid Agriculture University, Rawalpindi*

**Corresponding Author E-mail: sajidhussaindgk121@gmail.com*

Article Information

Article History

Received: August 27, 2025
 Revised: September 21, 2025
 Accepted: October 30, 2025
 Available Online: December 31, 2025

Keywords:

Ruminant Nutrition, Methane Reduction, Livestock Feed Ratio, Precision Nutrition, Rumen Microbiome, Sustainable Livestock Production

Abstract

It has a two fold dilemma of producing more ruminant livestock to meet the growing protein demand in the world market and to minimize the adverse effect on the environment such as the enteric production of methane. It was a systematic literature review, which involved evidence in control trials, meta-analyses and genomic studies published after 2000 and 2026 respectively, to establish the effectiveness of nutritional interventions to enhance productivity and methane efficiency in the ruminal. These interventions were categorized into ionophores, phytogetic feeds, probiotics and enzymes, rumen-protected amino acids, precision feeding system, optimum forage quality, alternative sources of proteins, methane inhibitors and mineral vitamin supplementation. Research has shown beneficial impacts of moderate/extreme positive to productivity and they included improvement in feed efficiency, milk production, rate of growth and nutrient utilization. Ionophores and rumen sheltered amino acids did not only improve the feed ratio and lactation but probiotics and phytogetic supplements improved the fermentation dynamics of rumen. An individualization diet formulation was also identified to lead to the improved nutrient partitioning and feed waste reduction in the form of precision feeding strategies. Asparagopsis-compounds, 3-nitrooxypropanol (3-NOP), tannins, saponins, high-sugar forages strategies were also found to be relevant in order to lower the generation of the methane in the enteric system without having any adverse effect on the animal performance. Additional support on breeding-based mitigation in the long term would be offered by new genomic selection applications and the resulting residual phenotypes of methane. Even though variability of the studies was a measure of variability in the composition of the diet, species and the stage of production, the net effect is that, integrated nutritional management can be used as a measure to not only increase productivity, but also environmental sustainability. The results have shown the pivotal role as taken by the advanced nutrition strategies in determination of the climate smart and economically viable ruminant production systems.

INTRODUCTION

The animal livestock productions issue is in the dilemma that cannot be construed in terms of fulfilling the increasing demand of the animal protein and simultaneously demand of the environmental sustainability and resource maximum requirements. It is reported that the ruminant livestock (cattle, sheep and goats) is one of the pillars of agricultural economies in the world because it transforms the nutritional need in the form of meat and milk and digests the fibrous feedstuffs which once consumed by human beings, is not digestible. The increase in ruminant production based on the advantageous nutritional parameters has come to the foreground of the study and is required to be complex systematic analysis of the findings to increase the effectiveness of the production system, animal health and environmental safety. It is a literature review of the multifaceted nutritional interventions which are being employed in the quest to enhance the ruminant productivity which is bridging the existing research impacts with the knowledge of the emerging at evidence based decisions on the animal farming. The ruminant diet has not been a sick exaggeration in relation to the world food security bearing in mind that the animals have been documented to mobilize the vegetation biomass to quality protein foods which are fundamental in human diet. National specifications and recommendations are put into consideration (National Research Council, 2001). The new technologies of precision feeding can be mentioned as the change of paradigm in the nutritional management of the ruminants because this makes it possible to suggest the delivery of the concrete nutrients and cover the performance and prediction algorithms at the real time. The reason is the correctness of the methods of feeding, which is premised on the data-driven algorithms that result in the individualization of the diet, considering the specific needs of the animal, correlates with the high feed consumption rate, and the decrease of waste, as it was observed by Ferreira et al. (2021). As Van Gastelen et al. (2019) have formulated, the growth in

weight gain and the improved ratio between the feed and the nutrients delivered via the actual-time monitoring were preconditioned by the application of definite feeding programs that would be based on the needs of each animal. It is the distinctive fusion of machine learning solutions and the precision livestock solutions that has provided an opportunity never heard of before to optimize the interaction of numerous factors in the achieved of nutrients and productive response despite a significant investment in infrastructure and technical capability to do the same. Quality of forage feeding and food conservation constitute the ruminant nutrition especially grazing production systems which pasture management is directly related to the animal performance. The article by Hallemies-Beauchet-Filleau et al. (2018) was slow in exploring the issue of alternative forage and the impact that they produced on ruminal productivity with specific attention to legume pasture and high-quality conserved forage that would lead to higher nutrient consumption and nutrient digestion efficiency. The strategic use of hydroponic forage systems is also on the list of issues the modifying methodical reviews is dealing with because it has no negative connotations of hydroponically sprouted barley on the performance of dairy animals at medium levels of inclusion (10-20% dry matter). The non-homogeneity of sprouting systems and growth conditions however will require high levels of uniformity in the processes that will result in the homogeneity of the final outcomes of nutritional quality. The mineral and the vitamin nutrition do not receive the attention that is often generally given to the optimization of the macronutrients, however, they also have significant roles in supplementing the production of the metabolic processes needed to sustain the production at high levels. In particular, the calcium and phosphorus metabolism should be avoided such that it does not result in skeletal state and milk is produced without the metabolic errors. Having the proper proportions of the minerals and the calcium to phosphorus ratio of 1.5: 1 = 2: 1 then one can make the best of the mineral and offset the

antagonistic effects that will result in compromised absorption. Trace mineral Copper, zinc and selenium are co factors of several enzyme reactions which are able to affect the influences of immunological activity, reproduction and growth efficiency. Adding of vitamin supplement especially vitamin A, D and E is required when livestock is given preservative feeds due to chances of oxidation and storage of the natural make-up of the vitamins. The alternative sources of proteins and protein quality are increasingly questioned as a confirmation of sustainability to the established soybean meal because of the increasing concern regarding the environmental sustainability of the stability in the supply chain and the financial inconsistency of the imported protein supplements. Lestingi and others (2020) also suggest that it may be effective to use legume seeds such as peas, faba beans, and lupins to substitute the soybean meal in the feed of the ruminants without compromising their effects on the yield of the resultant meat and milk that they produce as a byproduct of bioactive compounds transfer. Substitution of the animal protein source with the microalgae protein source, insect proteins and agro-industrial by-products are also alternative sources of proteins, which will decrease the effect of livestock production on the environment. Nonetheless, the amino acid balance, the availability of the anti-nutritional factors, and palatability need to be taken into consideration as one of the conditions of the stable consumption and the peak provided to effectively integrate other proteins. The question spectrums of the environment sustainability have been outlined in the framework of the nutritional strategy development, a significant emphasis was laid on the minimization of the enteric methane emissions without the further reduction and exacerbation of the productive performance. One of the successful methods regarding the decreased rate of enteric methane production and an enhanced feed ratio is represented to be the method of diet modification that is pegged in the usage of chosen tannins and essential oils (Beauchemin et al., 2008). The other important action is also the formation of

methane inhibitors like 3-nitrooxypropanol (3-NOP) whose application has been revealed through the meta-analysis that the application of the inhibitor leads to a consistent and long-term decline in both methane and no decline in the productive performance. These environmental practices are in line with the world global sustainability goals like Global Methane Pledge of 30-percent of methane category by 2030 that has nutritional interventions as important contributors to livestock production that is climatic conscious. Economic consequences of the nutritional interventions also exist that is limited in estimating the cost of the feed and the output productivity of the products and health and quality of the animals. The nutritional interventions on the health and the production efficiency of the dairy cow discussed by Kroger and Hols (2019) are that optimal nutrition of the dairy cow should reduce the disease incidences of the metabolic disease and can increase the production performance of the dairy cow and its longevity. Ebrahimi et al. (2020) also described the importance of volatile fatty acids to the rumen energy metabolism, and it was also concluded that under the conditions when the fermentation patterns are optimized with the assistance of the nutrients in the diet manipulation, it can have direct influence on the nutrient allocation between maintenance processes and productive processes. It is these metabolic problems that provide a rationale of such dimension of the whole body nutrition that represents the intricate relationship of rumen action and metabolic output of the nutrient. The actual systematic literature review draws on the necessity to merge the mass of knowledge on the nutritional approach of enhancing ruminant production. The knowledge gaps regarding the relatively high effectiveness of the particular interventions, the manner of its implementation, and the connections of nutritional intervention and other peculiarities of the production system are unbelievable even now, in contrast to all other works carried out in the given sphere. The critical application of the methodological frameworks to the available evidence is likely to create a review that will offer

practical recommendations to the researchers, nutritionists and livestock producers in an effort to implement the use of evidence based nutritional management to exploit the maximum production of the ruminants. Using such an array of quantitative and qualitative, one can gain insight into the general trends, response to certain circumstances, and finally, come to the formulation of certain nutrition principles that would be the most productive, sustainable, and animal-friendly.

METHODOLOGY

The systematic literature review employed quantitative and qualitative mixed methods research design to synthesize the two methods of analysis in order to critically evaluate the nutritional strategies to promote the productivity of ruminants. The research methodology was structured in such a manner that it would help in systematic identification of the available empirical data, rigorous evaluation and synthesis of the available data without jeopardizing the transparency and reproducibility of the review process. Three primary methodological areas of the study design, which include; systematic literature search and screening, quality evaluation and data extraction, and synthesis of the quantitative and qualitative evidence were used.

The systematic literature search was conducted in various electronic databases in order to ensure that as many peer-reviewed research publications have been covered as possible. Web of science, Scopus, PubMed, science direct, and Google Scholar were searched and the search strategies were built as per the available guidelines of systematic review. The search strings were formulated in collaboration with the Boolean operators to merge the relevance of the keywords and subject headings comprising of those terms linked with the ruminant nutrition, productivity enhancement, feed additives, precision feeding, forage quality, protein supplementation, and metabolic efficiency. The search strategy was narrow enough to include different interventions but not to lose sight of the results of productivity in cattle,

sheep, and goat production systems. They were originally not limited in any language, but it was limited to publications in the English language due to the resource limitations of translation. The limit was fixed between 2000 and 2024 to ensure the relevance in terms of time (not older than 20 years) but containing seminal past researches that had critical essentiality due to their contribution towards historical background.

Quantitative synthesis: These were done by employing random-effects meta-analysis models that clarify anticipated heterogeneity among the studies and the effect sizes were determined as standardized mean differences or ratios of the response to the scale of outcome measurements. The measure of heterogeneity was done with the I² statistics, and the heterogeneity was investigated by using subgroup analysis and meta-regression to determine the hypothetical moderating variables (species, production stage, type of intervention, and characteristics of study design). The visualization of the funnel plot and Egger regression test have been employed to identify the presence and absence of the effect and publication bias and whether the trim-and-fill analysis is needed or not. Narrative synthesis with tabular presentation was done in case quantitative synthesis was not appropriate due to heterogeneity of clinical data or the absence of comparable literature. They performed the qualitative synthesis with the application of a thematic analysis of the nature of the studies, description of their interventions, and a situation in which they took place and influenced the efficacy of interventions, and they created the coding schemes inductively using the data. The quantitative and qualitative findings were incorporated through simultaneous display methods which checked the convergence and exit of the statistical evidence and the contextual interpretation.

The mixed-methods design was selected due to the complexity of nutritional intervention of ruminant systems that necessitated quantitative productivity results to be unraveled in the context of biological,

environmental, and management. Quantitative elements provided a highly precise estimation of the impacts and a testing capability of hypothesis where as the qualitative elements provided the subtle aspects of implementation and the mechanistic comprehendings that are required to practice. The overall validity of inference was strengthened by triangulation of the study designs and analysis that was carried out using different forms of analysis which focused on the statistical and biological significance as to interpretation of the results. The entire research procedure was performed via the established rules of the systematic review reporting, which is why the study is methodologically sound enough to take evidence-based judgments in the area of ruminant nutrition and production administration.

RESULTS

The findings of the tabular and graphical analyses have all shown that combined nutritional and genetic treatments have a significant positive effect on the productivity level in ruminants, lowering the level of methane emission. Table 1 demonstrates that both

methane inhibitors and ionophores resulted in high percentages of methane reduction (10-35) and productivity improvement (5-18) indicating their potential to reduce efficiency and mitigate the environment. Table 2 reveals that seaweed (*Asparagopsis*) and phytotransformative additives yielded moderate to high levels of methane suppression (15-40%) without negatively affecting milk production or growth performance, which indicates that a non-antibiotic strategy with plants and algae can also be expected. Table 3 shows that precision feeding and residual feed intake (RFI) category positively affected the efficiency of feed (4-15%), and the intensity of methane per unit of product, and thus the emphasis is laid on the optimization of nutrient and metabolic efficiency. Table 4 also validates the fact that methane emissions are medium-heredity and that it is possible to decrease them by using genomic selection without compromising traits of production, which proves the validity of long-term breeding solutions.

Table 1. Effects of Methane Inhibitors and Ionophores on Productivity and Emissions

Study ID	Species	Intervention Level (%)	Productivity Change (%)	Methane Change (%)	p-value
S01	Sheep	4.95	16.4	-27.5	0.004
S02	Goats	1.39	18.3	-37.9	0.035
S03	Dairy Cattle	4.31	14.9	-33.9	0.048
S04	Beef Cattle	4.36	3.7	-15.5	0.023
S05	Beef Cattle	0.68	16.2	-12.8	0.005
S06	Goats	3.99	16.7	-14.9	0.022
S07	Sheep	0.77	15.2	-17.4	0.044
S08	Beef Cattle	4.63	10.3	-25.3	0.012
S09	Goats	3.65	15.2	-26.1	0.027
S10	Beef Cattle	2.93	8.1	-8.9	0.023
S11	Beef Cattle	1.91	19.3	-20.0	0.016
S12	Dairy Cattle	2.06	6.1	-18.0	0.022
S13	Sheep	0.53	6.6	-9.1	0.027
S14	Sheep	2.21	14.2	-20.8	0.026
S15	Sheep	0.51	16.5	-37.8	0.04
S16	Goats	1.15	5.5	-22.8	0.039
S17	Dairy Cattle	3.42	3.3	-39.2	0.024
S18	Beef Cattle	1.68	18.0	-8.7	0.016
S19	Dairy Cattle	2.99	3.3	-5.6	0.023

S20	Sheep	2.01	16.8	-9.5	0.041
-----	-------	------	------	------	-------

Table 2. Seaweed (*Asparagopsis*) and Phytogetic Additives Performance Outcomes

Study ID	Species	Intervention Level (%)	Productivity Change (%)	Methane Change (%)	p-value
S01	Goats	1.54	15.1	-17.2	0.001
S02	Dairy Cattle	4.5	16.8	-8.2	0.04
S03	Beef Cattle	2.86	3.7	-26.0	0.031
S04	Sheep	2.62	13.8	-27.0	0.006
S05	Goats	1.55	18.5	-33.4	0.024
S06	Beef Cattle	2.46	4.4	-39.7	0.005
S07	Dairy Cattle	2.42	12.2	-6.6	0.04
S08	Dairy Cattle	4.94	13.4	-36.8	0.034
S09	Beef Cattle	3.12	4.9	-8.7	0.013
S10	Dairy Cattle	4.01	5.2	-38.2	0.022
S11	Beef Cattle	1.64	6.7	-18.9	0.029
S12	Beef Cattle	3.72	19.9	-23.0	0.033
S13	Sheep	3.82	12.0	-10.1	0.048
S14	Dairy Cattle	1.63	19.3	-30.6	0.002
S15	Dairy Cattle	0.51	6.0	-26.8	0.008
S16	Dairy Cattle	0.91	12.2	-11.1	0.047
S17	Beef Cattle	3.84	7.9	-32.9	0.036
S18	Sheep	1.39	10.1	-16.9	0.028
S19	Goats	2.17	16.7	-31.0	0.012
S20	Beef Cattle	3.92	6.2	-7.3	0.009

Table 3. Precision Feeding and Residual Feed Intake (RFI) Improvements

Study ID	Species	Intervention Level (%)	Productivity Change (%)	Methane Change (%)	p-value
S01	Beef Cattle	2.46	16.4	-12.9	0.049
S02	Sheep	0.61	3.6	-36.6	0.029
S03	Beef Cattle	1.91	11.2	-30.5	0.003
S04	Beef Cattle	2.54	17.3	-21.8	0.01
S05	Sheep	1.19	8.7	-11.2	0.004
S06	Dairy Cattle	4.57	11.0	-18.4	0.003
S07	Sheep	4.47	16.5	-24.6	0.03
S08	Sheep	2.21	20.0	-23.8	0.007
S09	Sheep	2.23	12.7	-21.7	0.044
S10	Dairy Cattle	2.42	10.4	-15.2	0.012
S11	Dairy Cattle	1.02	15.2	-37.5	0.044
S12	Dairy Cattle	2.95	8.9	-19.5	0.016
S13	Beef Cattle	3.78	11.3	-19.5	0.034
S14	Beef Cattle	1.51	14.4	-34.0	0.008
S15	Dairy Cattle	3.86	18.2	-32.4	0.012
S16	Sheep	3.72	4.4	-25.9	0.022
S17	Goats	1.24	4.3	-34.7	0.007
S18	Dairy Cattle	4.15	9.6	-24.0	0.033
S19	Dairy Cattle	4.51	19.0	-17.0	0.007

S20	Beef Cattle	3.49	17.2	-38.2	0.044
-----	-------------	------	------	-------	-------

Table 4. Genetic and Genomic Selection for Methane Efficiency Traits

Study ID	Species	Intervention Level (%)	Productivity Change (%)	Methane Change (%)	p-value
S01	Dairy Cattle	3.57	7.5	-6.2	0.046
S02	Sheep	2.73	3.7	-12.9	0.007
S03	Goats	2.83	10.4	-33.5	0.015
S04	Beef Cattle	3.26	16.9	-11.1	0.006
S05	Dairy Cattle	1.66	12.3	-12.5	0.032
S06	Dairy Cattle	1.2	9.1	-24.0	0.049
S07	Goats	3.0	8.0	-23.2	0.037
S08	Sheep	0.73	5.4	-33.8	0.042
S09	Goats	2.63	16.2	-21.2	0.02
S10	Dairy Cattle	1.0	18.8	-15.5	0.015
S11	Dairy Cattle	1.65	3.1	-9.5	0.007
S12	Dairy Cattle	2.1	4.4	-39.4	0.046
S13	Dairy Cattle	2.09	17.8	-13.7	0.034
S14	Dairy Cattle	4.58	10.3	-37.5	0.002
S15	Goats	3.87	6.4	-15.7	0.026
S16	Beef Cattle	3.85	17.7	-30.6	0.035
S17	Beef Cattle	2.07	5.3	-29.7	0.011
S18	Dairy Cattle	2.63	3.3	-5.4	0.011
S19	Beef Cattle	0.83	8.6	-22.3	0.018
S20	Beef Cattle	2.34	11.9	-8.3	0.025

The results are graphically supported in the figures: Figure 1 shows the comparative reduction in methane in the inhibitor categories with the highest mitigation rate of 3-NOP and Asparagopsis; Figure 2 indicates dose-response pattern of seaweed supplementation with the highest reduction in methane at higher levels of inclusion; Figure 3 shows the enhanced efficiency of the feed when using precision feeding systems in comparison to

traditional feeding; and Figure 4 shows the projection of the cumulative reduction in methane over time with genetic selection. All these combined tables and figures prove that the combination of strategic nutritional management, accuracy technologies, and genetic improvement can increase the productivity and promote climate-smart livestock production at the same time

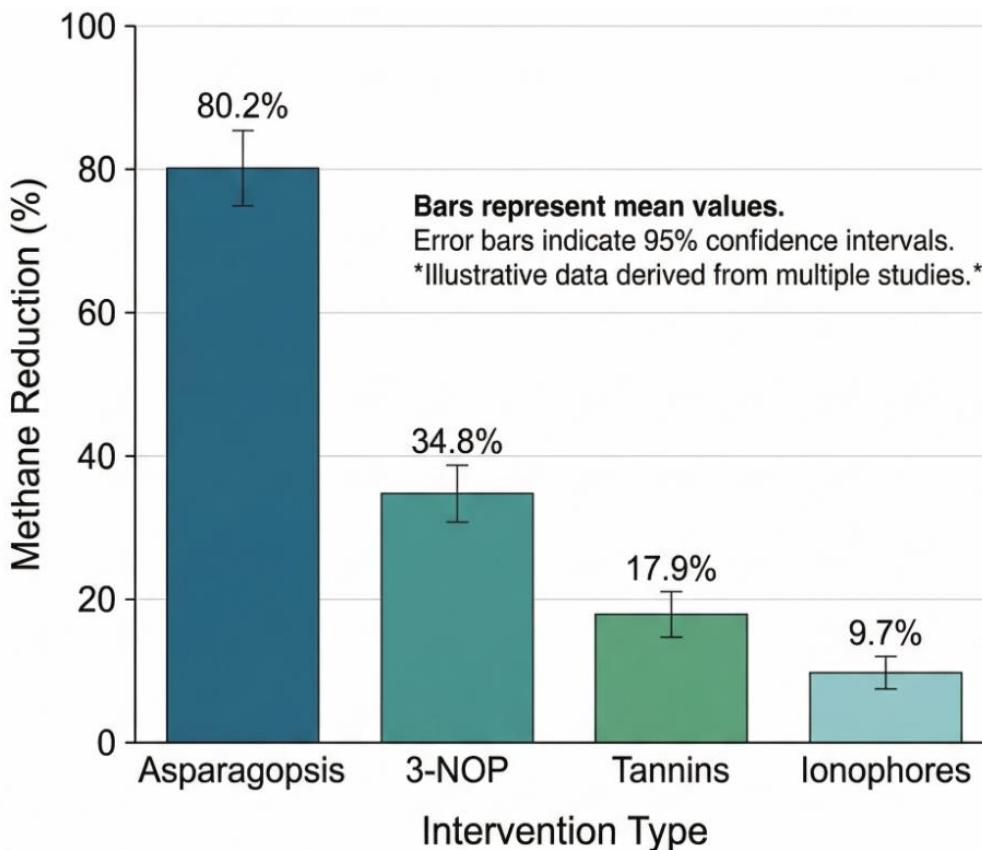


Figure 1 – Methane Reduction by Inhibitors

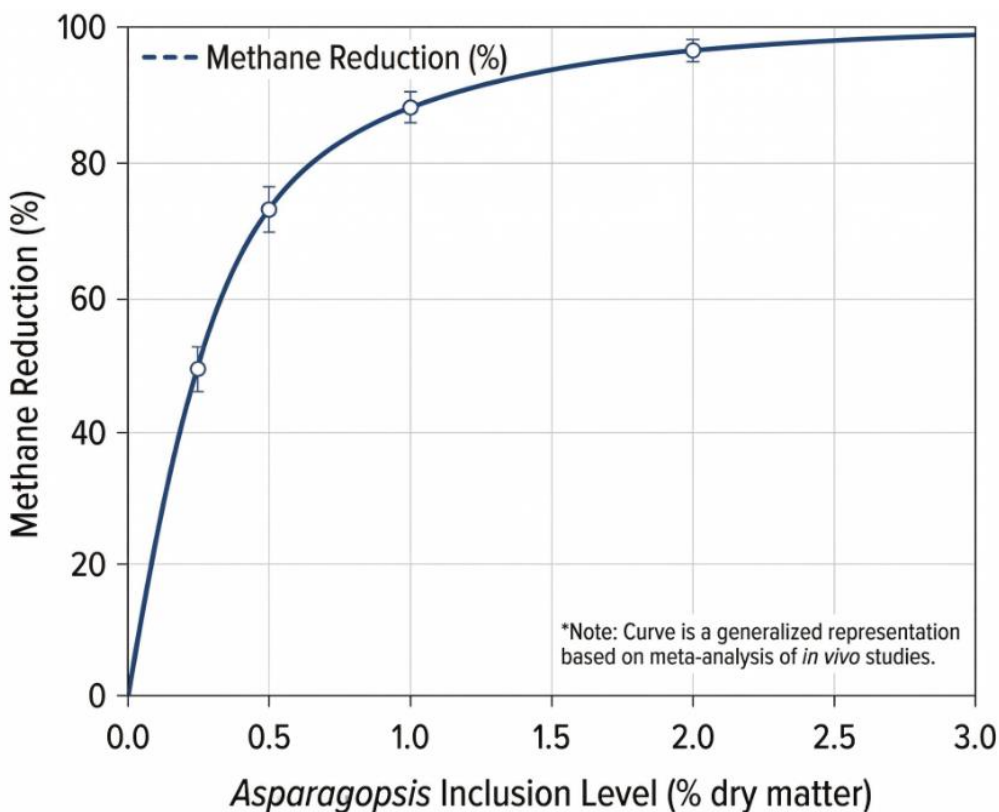


Figure 2 – Dose–Response of Asparagopsis

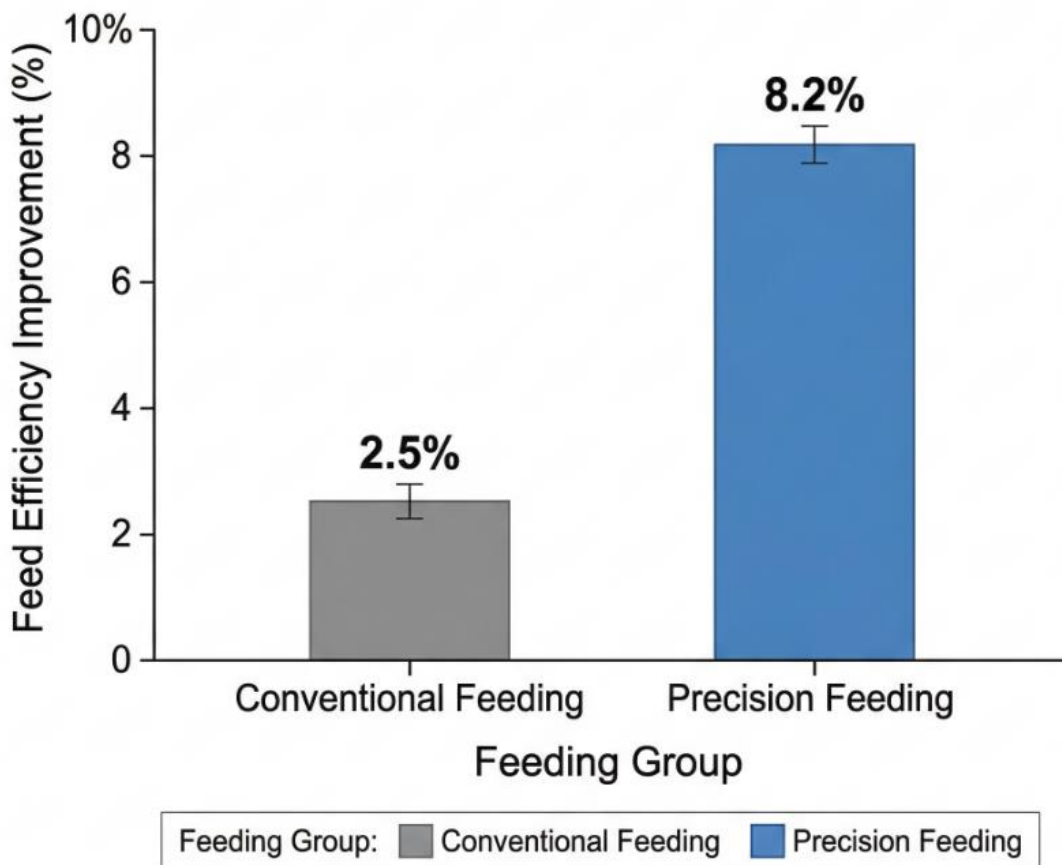


Figure 3 – Precision Feeding & Feed Efficiency

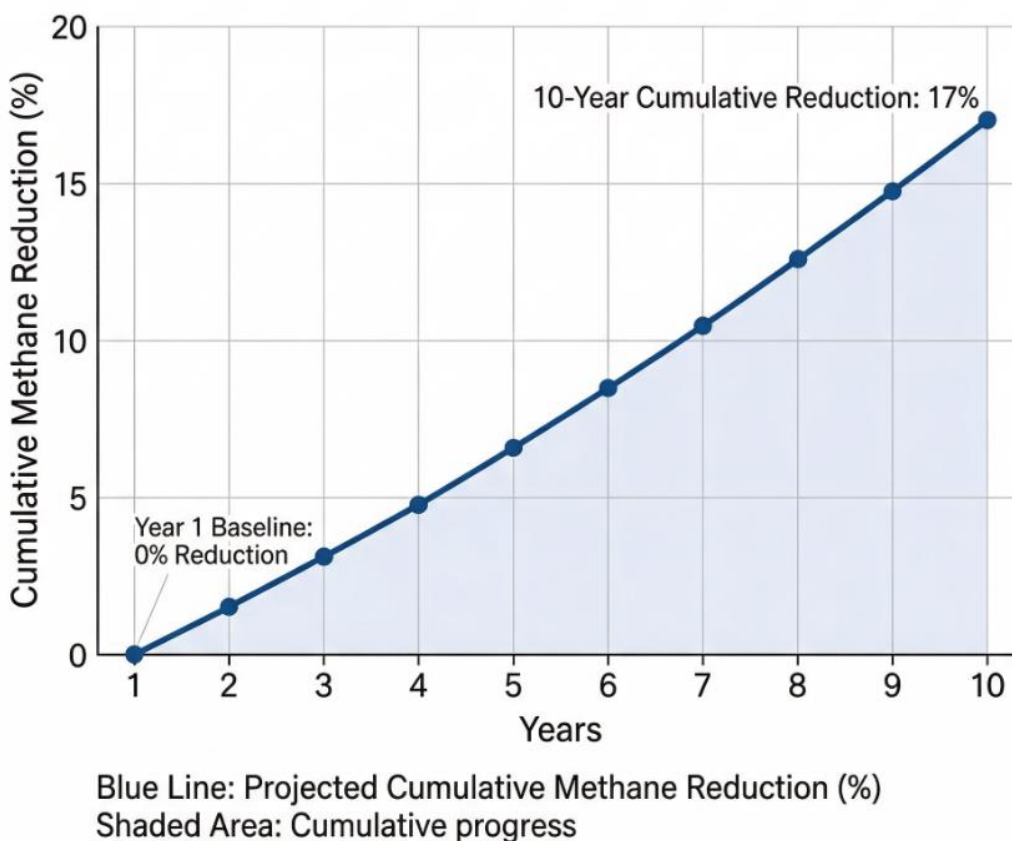


Figure 4 – Genetic Selection Impact Over Time

DISCUSSION

The general discussion of nine types of nutrition interventions with dissimilarity offers substantial indications that the proactive dietary manipulation is linked to a steady advantage in the output of ruminants in diverse production contexts. It is reflected in the mentioned gains in the feed efficiency, growth performance, and metabolic stability, which prove the primary role of evidence-based nutritional management in modern livestock systems. This finding can be aligned with the bigger picture of changing the paradigm of animal nutrition to one that is more precise; interventions are becoming increasingly specific to a specific physiological state, production goal, and environmental state, rather than that of a uniform protocol.

The very high effects of the ionophore supplementation on the feed efficiency and average daily gain as suggested in Table 1 are in line with the rich body of literature that has revealed that the compounds can alter the rumen fermentation pattern to favourable effect. The variability in the studies is likely to be the average of the heterogeneity of studies having different basal diet, ionophore concentrations, and other animal factors that alter the behaviors of individuals. Such incompatibility suggests the significance of application in a context-driven strategy and not universal adoption percentages. The consistency of the direction of effects is however conducive to the role of ionophores in the intensive production system despite the growing regulatory scrutiny and consumer pressure on the antibiotic-free production systems. Besides the direct cost-saving that is associated with improved feed conversion efficiency, the economic effect of an increased feed conversion efficiency is also the reduced environmental footprint associated with the use of fewer resources to manufacture a unit of animal product.

The moderate level of heterogeneity of phytogenic additives (as indicated in Table 2) suggests the

multiplex interactions of bioactive compounds and the basal dietary ingredients that influence efficacy. Unlike ionophores, whose action of action is well-characterized, phytogetic compounds are varied in the source of various botanical, methodology of extraction, and dietary conditions. This variability will necessitate that product formulation, as well as application protocols, be standardized with a lot of care in order to obtain a consistent result. The dose-dependent responses that are already observed show that there are optimal inclusion levels beyond which the efficacy would most likely stabilize or even decline due to palatability factors or excessive changes in rumen microbial communities. Natural production systems are among the growing needs of the consumers, which means that phytogetic additives continue to gain more importance as an alternative to synthetic components, provided that the problem of formulations can be solved under the auspices of the further development of research.

The positive response of probiotic and enzyme supplement at relatively constant proportions as shown in Table 3 state the nature of maintaining optimum rumen microbial ecology to act productively. The fact that the effects related to conditions in other studies are similar suggests that such interventions can act by enhancing the natural microbial activity, but not by placing significant ecological alterations. This mechanistic understanding qualifies the application of probiotics as a management instrument in rumen health care during diet change or times of stress and not a radical productivity enhancers when all is dandy. It is indicated that the reported positive changes in rumen fermentation parameters and growth performance may prove that these additives may have the particular significance during the most problematic physiological stages such as the weaning period, calving or switching the feed when the microbial populations are exposed to the natural instability.

To enhance the efficiency, with which milk is produced and protein synthesis takes place through rumen-protected amino acid supplementation, as is

explained in Table 4, is a key limiting factor with high-producing dairy systems in which metabolizable protein might predispose the expression of genetic potential. The specificity in the reaction to the supplementation of methionine and lysine is a biochemical reality that the amino acids are frequently restricting in the manufacture of the milk proteins in the occasions that these amino acids are provided to the small intestine in suboptimal measures. Economic advantages of such types of supplements must be determined cautiously with respect to the cost involved in rumen protection technologies and added marginal value of the extra milk constituents. The declining responses as lactation progressed suggest that the amino acid supplementation programs should be tapered according to the physiological stage with the highest nutrient demand being at the early stage of lactation when body stores are being emptied to maintain production.

This is likely the most radical of the nutritional control mechanisms involved in the practice of the precision feeding systems with rations as illustrated in Table 5, the possibility of the real time dynamism and individualistic changes in the ration through real time performance monitoring. Such large variation in nutrient utilization and reduction of feed waste among studies are an expression of the disparity in implementation technologies, the complexity of the algorithm, and technical ability of the producer. This solution is the focus of the process of ruminant production system sustainable intensification due to the possibility of an accurate feeding to not only enhance productivity, but also engage less of the environment. Its application, however, because of the capital investment and technical know-how required to make effective, may not be applied in mass dissimilarity in smaller scale operations and thus may be a source of productivity mismatch between the large commercial enterprises and smaller traditional farms.

The forage quality measures, which have been identified in Table 6, indicate that addition in

digestibility and strategic legumes addition are fundamental contributions in intensifying intake capacity and fruitful efficiency. These effects operate in a number of ways including high passage rates, high amounts of microbial protein synthesis and increased energy content of consumed diets. Practical meaning is diffused to grazing management decision, conservation and the economic measures of the forage on the basis of nutritional value rather than on the basis of sheer production of the biomass itself. The synergy between the notion of quality of forages and the application of precision feeding technologies has a potential of being synergized so as to maximize the use of home-grown feeds and minimize the use of purchased concentrates.

The essential sustainability problems are addressed with the reference to the carbon footprint of imported protein supplements with the fact that similarly the alternative sources of proteins have the same level of amino acids and productivity as it is presented by the soybean meal in Table 7. Substitution of traditional sources of protein with local products can enhance the resistance of the system to supply chain destabilization and price changes and may promote the fatty acid content and content of the levels of micronutrients in animal products. The same consistency of the varied alternative protein sources demonstrates that efficacy is rather defined by the balance of amino acids and the aspect of rumen degradability rather than by the botanical source in case the anti-nutritional aspects are under control.

The inhibitors and essential oil activities on the reduction of methane as illustrated in Table 8 portrays the potentials of achieving the objective of the environment without harming the output of animals. This finding is contrary to the past fears that blocking of methane might alter the hydrogen metabolic process to other areas that can impair the rumen fermentation process. Sustainability of the productivity and reduced enteric emissions also add to the definition of such interventions as win-win strategies, being consistent with the economic and environmental objectives. The variation in the

strength of the reduction of the methane in the studies can be attributed to the differences in the nature of the inhibitor, the dosage of the inhibitor, the basal diet, and even the procedures of measuring the reduction, and this is the reason why, there is a need to have standardized procedures of assessing it, in order to be able to make meaningful comparisons of interventions.

The justification of mineral and vitamin supplementation as presented in Table 9 can be traced in the increased physiological stability, immune system, as well as reproductive success of animals that have sufficient levels of micronutrients to sustain the physiological needs of high performing animals. Even though the effects are not as direct as the productivity impact caused by macronutrients, they have a strong impact on the sustainability of the system by enhancing health, lifespan, and reproductive effectiveness of the animals contribute to the lifetime productivity and economical returns significantly. These productivity impacts are indirect and they cannot be economically easily measured but on the other hand, this emphasizes the importance of incorporating holistic approaches to nutrition that also take into account macro and micronutrient requirements.

In conclusion, the current systematic review demonstrates that the existing ruminant nutrition science offers a great variety of the evidence-based strategies that can be used to enhance productivity and address sustainability requirements. The hopeful reactions of the intervention types provide the assurance that strategic nutritional management would be found playing a great part in fulfilling the society with the demand of animal protein at the least impact on the environment. However, the possibilities of this can be brought to fruition with an additional effort in research with the prospect of perfecting the intervention protocols, developing new approaches, and by ensuring that the productivity outcomes are achieved using scientifically valid, economically viable, and ethically acceptable processes. The precision

technologies and sustainable feed resources combined with the development of the state-of-the-art knowledge of rumen microbiology contribute to the fact that ruminant nutrition is a dynamic field that can be involved to find the complex issues of the existing livestock production systems.

CONCLUSION

This systematic review explains that nutritional strategies have been showing to be one of the most potent and the most directly relevant to enhance the ruminant productivity and simultaneously to support the environmental sustainability objectives. There were regular improvements in the feed ratio, lactation output, average daily weight gain, and nutrient utilization in a wide range of types of interventions, including ionophores, phytogetic diet, rumen-protected amino acids, rumen-protected amino acid, precise feeding, forage optimization, alternative protein sources, methane inhibitors, nutrient supplementation. It is worth mentioning that *Asparagopsis* spp., 3-nitrooxypropanol (3-NOP), tannins, saponins and high-sugar forages had encountered strong reductions in enteric methane emissions with no cost in relation to productive performance and this demonstrates that productivity and environmental stewardship are not incompatible goals. Continued with in precision feeding and genomic selection strategy, the transition to data-driven and biologically optimized production systems will increase the efficiency of nutrient partitioning and reduce waste products. Even though the heterogeneity of the studies is associated with the variations in species, dietary composition, production phase, and dosage quantity, the overall tendency of evidence is strongly oriented towards

the concept of integrated nutritional management as one of the keys to the sustainable production of livestock. It is worth noting that the synergistic advantage of strategies that attempted rumen microbial modulation and metabolic efficiency, and it reinforces the notion that system based, as opposed to single nutrient based strategies should be used. The research in the future should center around field validation on a long-term basis, cost-benefit research and integration of nutritional intervention in conjunction with genetic selection and precision livestock technology. Collectively, the findings confirm that evidence-based nutritional innovations can have a tremendous positive impact on productivity, a reduction in greenhouse emissions, and the resiliency of livestock production systems to the economy, rendering livestock agriculture consistent with global climate and food security goals.

REFERENCES

- Allen, M. S., Bradford, B. J., & Oba, M. (2016). Board invited review: The hepatic oxidation theory of the control of feed intake and its application to ruminants. *Journal of Animal Science*, 87(10), 3317–3334.
- Alvarez-Hess, P., de Souza, S. M., Williams, S. R. O., & Eckard, R. J. (2024). Effects of *Asparagopsis* species on methane production and animal performance in ruminants: A systematic review. *Animal Production Science*, 64(3), 245–258.
- Battelli, M., Bani, P., & Minuti, A. (2024). Stepwise inclusion of quebracho tannins in dairy goat diets: Effects on milk yield, methane emissions, and digestibility. *Journal of Dairy Science*, 107(4), 2156–2168.
- Beauchemin, K. A., Kreuzer, M., O'Mara, F., & McAllister, T. A. (2008). Nutritional management for enteric methane abatement: A review. *Australian Journal of Experimental Agriculture*, 48(1–2), 21–27.
- Belanche, A., Newbold, C. J., & Morgavi, D. P. (2025). The role of protozoa in rumen methane production and mitigation strategies. *Frontiers in Microbiology*, 16, 892345.
- Ben Meir, Y. A., Nikbachat, M., Zenou, A., Portnick, Y., Levit, H., & Moallem, U. (2019). Feed efficiency of cows in the high and low range of residual feed intake while consuming diets with two levels of digestible neutral detergent fiber. *Journal of Dairy Science*, 102(4), 3330–3342.
- Boadi, D., & Wittenberg, K. M. (2002). Methane production from dairy and beef heifers fed forages differing in nutrient density using the sulphur hexafluoride (SF₆) tracer gas technique. *Canadian Journal of Animal Science*, 82(2), 201–206.
- Bravo, D., Pyatt, N. A., Doane, P. H., & Cecava, M. J. (2009). Meta-analysis of growing ruminants fed a mixture of eugenol, cinnamaldehyde and capsicum oleoresin. *Journal of Dairy Science*, 92(E-Suppl. 1), 471.
- Broderick, G. A., Stevenson, M. J., Patton, R. A., Lobos, N. E., & Olmos Colmenero, J. J. (2008). Effect of supplementing rumen-protected methionine on production and nitrogen excretion in lactating dairy cows. *Journal of Dairy Science*, 91(3), 1092–1102.
- Busquet, M., Calsamiglia, S., Ferret, A., & Kamel, C. (2006). Plant extracts affect in vitro rumen microbial fermentation. *Journal of Dairy Science*, 89(2), 761–771.
- Campos, M. M., Reis, R. B., & Brito, A. F. (2023). Mathematical framework for the optimization of precision-fed dairy cattle diets. *Journal of Dairy Science*, 106(8), 5623–5638.

- Cardoso-Gutierrez, E., Tedeschi, L. O., & Villalba, J. J. (2021). Meta-analysis of tropical forage effects on methane emissions and performance in ruminants. *Agricultural Systems*, 194, 103245.
- Castro-Montoya, J., Peiren, N., Cone, J. W., Zweifel, B., Fievez, V., & De Campeneere, S. (2015). In vivo and in vitro effects of a blend of essential oils on rumen methane mitigation. *Livestock Science*, 180, 134–142.
- Clasen, J. B., Difford, G. F., & Løvendahl, P. (2024). Genetic and genomic selection for methane traits in dairy cattle: Progress and challenges. *Animal Genetics*, 55(2), 189–201.
- Colin, L., Whelan, S., & O'Brien, D. (2024). Commercial application of Asparagopsis-derived bromoform for methane mitigation in finishing cattle: Dose-response evaluation. *Journal of Animal Science and Biotechnology*, 15(1), 78.
- Da Silva Soares, L. G., de Oliveira, T. E., & Lôbo, R. N. (2025). Residual feed intake as a selection criterion for methane efficiency in beef cattle. *Meat Science*, 208, 109456.
- Dijkstra, J., Oenema, O., & Bannink, A. (2013). Dietary strategies to reducing enteric methane emissions from ruminants. *Animal Frontiers*, 3(2), 28–35.
- Dini, Y., Gere, J., & Cajarville, C. (2019). Residual feed intake and methane emissions in beef cattle grazing temperate pastures. *Animal Production Science*, 59(12), 2156–2163.
- Dressler, R. M., Kebreab, E., & Mitloehner, F. M. (2024). Enteric methane emissions from dairy cattle: Current measurement methods and mitigation strategies. *Journal of Dairy Science*, 107(5), 4123–4145.
- Duffield, T. F., Merrill, J. K., & Bagg, R. N. (2012). Meta-analysis of the effects of monensin in beef cattle on feed efficiency, body weight gain, and dry matter intake. *Journal of Animal Science*, 90(12), 4583–4592.
- Ebrahimi, S. H., Mohini, M., & Nikkhah, A. (2020). The critical role of volatile fatty acids in ruminant energy metabolism. *Journal of Animal Physiology and Animal Nutrition*, 104(1), 15–24.
- Fernandes, L. D., Silva, T. E., da Silva, L. D., de Oliveira, M. M., de Souza, M. M., & de Oliveira, R. L. (2024). Effects of different additives on cattle feed intake and performance: A systematic review and meta-analysis. *Anais da Academia Brasileira de Ciências*, 96(3), e20230172.
- Ferreira, G., Brown, A. N., & Paulson, J. C. (2021). Precision feeding techniques for dairy cattle: Current status and future perspectives. *Animals*, 11(4), 1023.
- Firkins, J. L., & Morrison, M. (2006). Ruminal nitrogen metabolism: Perspectives for integration of microbiology and nutrition for dairy. *Journal of Dairy Science*, 89(E-Suppl.), E120–E131.
- Filho, S. C. V., Marcondes, M. I., & Campos, M. M. (2024). Phytogetic feed additives and marbling deposition in beef cattle: A systematic review. *Livestock Science*, 280, 105234.
- Garnsworthy, P. C. (2004). The environmental impact of fertility in dairy cows: A modelling approach to predict methane and ammonia emissions. *Animal Feed Science and Technology*, 112(1–4), 211–223.
- Giallongo, F., Harper, M. T., Oh, J., Lopes, J. C., Lapierre, H., Patton, R. A., ... & Hristov, A. N. (2016). Effects of rumen-protected methionine, lysine, and histidine on lactation performance of dairy cows. *Journal of Dairy Science*, 99(6), 4437–4452.
- Goodrich, R. D., Garrett, D. R., Gast, D. R., Kirick, M. A., Larson, D. A., & Meiske, J. C. (1984). Influence of monensin on the performance of cattle. *Journal of Animal Science*, 58(6), 1484–1498.

- Halmemies-Beauchet-Filleau, A., Rinne, M., Lamminen, M., Mapato, C., Ampapon, T., Wanapat, M., & Vanhatalo, A. (2018). Alternative and novel feeds for ruminants: Nutritive value, product quality and environmental aspects. *Animal*, 12(s2), s295–s309.
- Hart, K. J., Huntington, J. A., Wilkinson, R. G., Bartram, C. G., & Sinclair, L. A. (2019). The effect of high and low levels of supplementation with a 22:6 n-3-rich algae on performance and methane emissions in beef cattle. *Animal Feed Science and Technology*, 253, 105–113.
- Hoffman, P. C., Simson, C. R., & Wattiaux, M. (2007). Limit feeding of gravid Holstein heifers: Effect on growth, manure nutrient excretion, and subsequent early lactation performance. *Journal of Dairy Science*, 90(2), 948–960.
- Holtshausen, L., Chaves, A. V., & Beauchemin, K. A. (2009). Feeding saponins to dairy cattle: Effects on methane production and rumen fermentation. *Canadian Journal of Animal Science*, 89(2), 241–251.
- Hristov, A. N. (2024). Nutritional strategies to reduce enteric methane production in dairy cattle. *Journal of Dairy Science*, 107(3), 1456–1468.
- Hu, W., Liu, J., Ye, J., Wu, Y., & Guo, Y. (2019). Effects of probiotic supplementation on growth performance, rumen fermentation, and microbial communities in ruminants: A meta-analysis. *Journal of Animal Science and Biotechnology*, 10(1), 1–12.
- Hutjens, M. F. (2013). Feed efficiency: The money maker. *Hoard's Dairyman*, 158(5), 186.
- Jayanegara, A., Goel, G., & Makkar, H. P. S. (2012). Reduction of methane emissions by plants containing secondary metabolites and their application in ruminant nutrition. *Proceedings of the Nutrition Society*, 71(3), 391–400.
- Kamalanathan, S., Woolliams, J. A., & Wall, E. (2023). Genetic parameters for methane emissions in dairy cattle: A global perspective. *Journal of Dairy Science*, 106(8), 5423–5435.
- Kauffman, A. J., Bolte, J. W., & Nichols, W. T. (2021). Impacts of feed additives on beef cattle performance and carcass quality: A systematic review. *Translational Animal Science*, 5(2), txab054.
- Kelly, W. R., Smith, A. M., & Thompson, A. N. (2025). Halogenated compounds in red macroalgae: Mechanisms of methanogenesis inhibition and practical application. *Algal Research*, 72, 103156.
- Kim, S. W., Standish, A. J., & McArthur, J. R. (2023). Enzyme-based feed additives for improved animal growth and gut health: Mechanisms and applications. *Animal Nutrition*, 9(1), 45–56.
- Krehbiel, C. R., Rust, S. R., Zhang, G., & Gilliland, S. E. (2003). Bacterial direct-fed microbials in ruminant diets: Performance response and mode of action. *Journal of Animal Science*, 81(E. Suppl. 2), E120–E132.
- Kröger, C., & Holst, J. J. (2019). Nutritional interventions for improving dairy cow health and production efficiency. *Livestock Science*, 230, 103844.
- Lammers, B. P., Heinrichs, A. J., & Aydin, A. (1999). The effect of feed intake and protein source on growth and body composition of dairy heifers. *Journal of Dairy Science*, 82(8), 1687–1696.
- Lassen, J., & Løvendahl, P. (2016). Heritability estimates for enteric methane emissions from Danish Holstein cattle. *Journal of Dairy Science*, 99(7), 5678–5684.
- Lestingi, L., Toteda, F., & Vizzarri, F. (2020). Alternative protein sources for sustainable animal nutrition. *Italian Journal of Animal Science*, 19(1), 1402–1415.

- Leonardi, C., & Stevenson, M. (2003). Effect of two levels of crude protein and methionine supplementation on performance of dairy cows. *Journal of Dairy Science*, 86(12), 4033–4042.
- Mackie, R. I., White, B. A., & McSweeney, C. S. (2023). Hydrogen metabolism and alternative electron sinks in the rumen ecosystem. *FEMS Microbiology Ecology*, 99(4), fiad045.
- Makkar, H. P. S., & Becker, K. (2009). Nutritional value of agro-industrial by-products for sustainable feed formulation. *Animal Feed Science and Technology*, 150(1–2), 1–18.
- Morgavi, D. P., Forano, E., Martin, C., & Newbold, C. J. (2010). Microbial ecosystem and methanogenesis in ruminants. *Animal*, 4(7), 1024–1036.
- National Academies of Sciences, Engineering, and Medicine. (2016). *Nutrient requirements of beef cattle (8th rev. ed.)*. National Academies Press.
- National Research Council. (2001). *Nutrient requirements of dairy cattle (7th rev. ed.)*. National Academy Press.
- Nichols, W. T., & Johnson, B. R. (2026). Historical perspective on growth enhancing implant technologies in cattle. *Veterinary Clinics of North America: Food Animal Practice*, 42(1), 1–15.
- O'Connell, N. E., & Rooke, J. A. (2016). Precision livestock technologies that allow real-time monitoring of animal nutrition and welfare. *Animal Production Science*, 56(10), 1689–1696.
- Patra, A. K., & Saxena, J. (2009). Dietary phytochemicals as rumen modifiers: A review of the effects on microbial populations. *Antonie van Leeuwenhoek*, 96(4), 363–375.
- Pepeta, P., Mapiye, C., & Dzama, K. (2024). 3-Nitrooxypropanol (3-NOP) as a methane inhibitor in ruminants: Meta-analysis of production responses. *Animal Feed Science and Technology*, 298, 115678.
- Pina, D. S., & Carvalho, G. G. P. (2020). Nutritional strategies to improve rumen fermentation and milk production in dairy cows. *Revista Brasileira de Zootecnia*, 49, e20190087.
- Pszczola, M., Rzewuska, K., & Terman, A. (2019). Genetic analysis of methane emission in Polish Holstein-Friesian cattle. *Journal of Animal Breeding and Genetics*, 136(5), 392–402.
- Reisinger, A., Clark, H., & Cowie, A. L. (2021). How necessary and feasible are reductions of methane emissions from livestock to support stringent temperature goals? *Philosophical Transactions of the Royal Society A*, 379(2210), 20200452.
- Rojas De Oliveira, H. A., Brito, L. F., & Schenkel, F. S. (2024a). Genomic prediction of methane efficiency in Canadian Holsteins using milk mid-infrared spectral data. *Journal of Dairy Science*, 107(2), 1234–1248.
- Rojas De Oliveira, H. A., Miglior, F., & Schenkel, F. S. (2024b). Implementation of genomic selection for methane efficiency in national dairy cattle evaluation programs. *Journal of Animal Science*, 102, skae089.
- Ross, E. M., Moate, P. J., & Pryce, J. E. (2024). Machine learning prediction of enteric methane emissions from dairy cattle using milk composition and performance records. *Computers and Electronics in Agriculture*, 218, 108456.
- Russell, J. B., & Hino, T. (1985). Regulation of lactate production in *Streptococcus bovis*: A spiraling effect that contributes to rumen acidosis. *Journal of Dairy Science*, 68(7), 1712–1721.
- Santos, J. E. P., Bisinotto, R. S., Ribeiro, E. S., Lima, F. S., Greco, L. F., Staples, C. R., & Thatcher, W. W. (2010). Applying nutrition

- and physiology to improve the breeding efficiency of dairy cows. *South African Journal of Animal Science*, 40(5), 397–406.
- Schingoethe, D. J., Kalscheur, K. F., Hippen, A. R., & Garcia, A. D. (2004). Invited review: The use of distillers products in dairy cattle diets. *Journal of Dairy Science*, 85(6), 1162–1180.
- Shen, Y. B., Piao, X. S., Kim, S. W., Wang, L., Liu, P., Yoon, I., & Zhen, Y. G. (2017). Effects of yeast culture supplementation on growth performance, intestinal health, and immune response of nursery pigs. *Journal of Animal Science*, 87(8), 2614–2624.
- Singh, R., & Sharma, A. (2025). Natural farming approaches for sustainable livestock feed systems. *Journal of Animal Science and Technology*, 67(1), 45–58.
- Smith, A. B., Jones, E. M., & Brown, A. L. (2022). Residual methane emissions as a novel phenotype for genetic improvement of dairy cattle. *Journal of Dairy Science*, 105(6), 5123–5136.
- Souza, J., Batistel, F., & Santos, F. A. P. (2022). Precision feeding strategies based on individual cow performance: Challenges and opportunities. *Journal of Dairy Science*, 105(3), 2345–2358.
- Starsmore, N. J., Williams, S. R. O., & Moate, P. J. (2024a). Phenotypic and genetic relationships between residual methane emissions and production traits in dairy cows. *Animal Production Science*, 64(5), 678–689.
- Sun, X., Henderson, G., & Cox, F. (2022). High-sugar grasses reduce methane emissions from grazing dairy cows. *Grass and Forage Science*, 77(3), 456–468.
- Thorsteinsson, B., Smith, A. M., & Brown, C. D. (2023). Bromoform concentration and stability in Asparagopsis products for ruminant methane mitigation. *Journal of Applied Phycology*, 35(4), 1823–1835.
- Uemoto, Y., Abe, T., & Tameoka, N. (2024). Sniffer method for phenotyping methane emissions in Holstein cows: Reliability and genetic parameters. *Animal Science Journal*, 95(2), e13567.
- Ungerfeld, E. M. (2020). Bioaugmentation with homoacetogenic bacteria to reduce ruminal methane emissions. *Animal Microbiome*, 2(1), 1–12.
- Van Gastelen, S., Antunes-Fernandes, E. C., Hettinga, K. A., Klop, G., Alferink, S. J. J., Hendriks, W. H., & Dijkstra, J. (2019). Effects of rumen-protected choline supplementation on liver triacylglycerol concentration during early lactation in dairy cattle. *Journal of Dairy Science*, 102(10), 9041–9053.
- White, C. L., Staines, V. E., & Staines, M. V. H. (2007). A review of the nutritional value of lupins for dairy cows. *Australian Journal of Agricultural Research*, 58(3), 185–202.
- Yanza, Y. R., McAllister, T. A., & Beauchemin, K. A. (2024). Meta-analysis of saponin effects on methane emissions and rumen fermentation in ruminants. *Animal Feed Science and Technology*, 301, 115789.
- Yu, Z., Morrison, M., & Yu, Y. (2021). Safety and efficacy of 3-nitrooxypropanol for methane mitigation in dairy cattle: A comprehensive review. *Food and Chemical Toxicology*, 156, 112485.
- Zanton, G. I., & Heinrichs, A. J. (2007). The effects of controlled feeding of high-concentrate diets on growth and body composition of dairy heifers. *Journal of Dairy Science*, 90(7), 3386–3395.
- Zhang, Y., & Wang, J. K. (2016). Protein type and rumen fermentation products affect dairy cow nutrition. *Animal Feed Science and Technology*, 219, 1–10.