Indian J Anim Health (2024), 63(2)- Special Issue: 43-52
DOI: https://doi.org/10.36062/ijah.2024.spl.01124

Invited Review Article

Rumen bypass protein: An effective technology for enhancing performance of ruminants

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Abstract

Protection of feed protein from rumen degradation is important in productive ruminants which need diet with high concentrations of crude protein. The protein supplied through rumen microbial fermentation may fall short of the nutrient demands placed on the animals during the early growth period, lactation, or stress conditions. Protected protein bypasses the rumen and provides additional essential amino acids for absorption in the small intestine. Therefore, inefficient use of the feed nitrogen may be avoided using rumen protein protection technology. Although naturally protected protein sources such as cottonseed cake, maize gluten meal, coconut cake, etc. can be used, protection of feed protein can be achieved through various techniques such as tannin supplementation, formaldehyde treatment, heat treatment alone or in combination with organic acids, or directly protecting amino acids from rumen degradation through various physical and chemical methods such as encapsulation, use of alcohols, tannins, bentonite, aldehydes etc. Supplementation of rumen protected or bypass protein in ruminants increases nutrient utilization, nitrogen retention, and overall amino acid availability without negatively affecting rumen fermentation. Calves supplemented with rumen protected protein demonstrated better growth parameters such as improved average daily gain and feed utilization efficiency. In productive animals, supplementation of bypass protein demonstrated higher milk yields and better overall reproductive performance in terms of early postpartum oestrus, reduced prepubertal period, and improved pregnancy maintenance. Therefore, large-scale application of rumen protected protein technology is an important strategy to achieve quality livestock production and to improve nutrient utilization with minimal wastage of limited feed resources.

Keywords: Bypass protein technology, Dairy animals, Livestock productivity, Protein utilization, Rumen protected protein

Highlights

- Rumen bypass protein feeding prevents protein wastage and improves nutrient utilization.
- Techniques include physical (heat, encapsulation) and chemical (formaldehyde, acids) methods.
- Increased amino acid availability at lower digestive tract without affecting rumen fermentation
- Protected protein supplementation improves growth, milk production, and reproductive performance.
- Widespread adoption of bypass protein technology is essential to maximize the efficient use of limited protein resources.

INTRODUCTION

Nutrient requirements of growing and high-yielding animals during lactation, pregnancy, transition period, and stress are considerably higher as compared to the maintenance requirements. In these situations, the amount of protein supplied through synthesis by microbial biomass and rumen fermentation might fall short of the nutritional demands, which often coincides with the reduction in feed intake, especially in early lactation and stress conditions. Lactating dairy cows in commercial dairy farms convert about 20-35% of the total dietary crude protein to milk, while the rest is excreted, resulting in environmental pollution and wastage of resources from a managemental point of view (Chase *et al.*, 2012). Ruminants have a lower efficiency of N use compared to non-ruminants and about 70-75% of the nitrogen (N) ingested is excreted in manure (Huhtanen and Hristov, 2009). This inefficiency is attributable primarily to the inefficient use of N in the rumen. Protected protein technology involves feed management through passive rumen manipulation. Dietary proteins are protected from hydrolysis, allowing these nutrients to bypass rumen and get digested and absorbed from the lower digestive tract. Rumen protected protein supplementation is important in productive ruminants which need diet with high quality and quantity of crude protein (CP) supplied mainly by protein concentrates.

Benefits of rumen protein protection technology

Feeding of rapid degradable proteinous oil cakes result in excessive ammonia production in rumen.

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Excess ammonia is absorbed through the rumen wall and increases the formation of urea in the liver, which ultimately increases urinary nitrogen excretion with a loss of energy (Bach *et al.*, 2005). Reduction in the ruminal protein degradation of high-quality proteins can increase protein utilisation and reduce nitrogen environmental emissions. Protected protein bypasses the rumen and provides additional essential amino acids for absorption in the small intestine (Walli, 2005). Rumen protected protein supplementation is important in productive ruminants which need diets with high concentrations of CP supplied mainly by protein concentrates. Inefficiency rises when highly degradable concentrates like groundnut cake, mustard cake etc. are used (Dey *et al.*, 2006) as feed amino acids are converted to compounds such as nucleic bases or amino sugars, which are not utilized for protein synthesis. Various strategies have been employed to protect proteins from rumen degradation, among which heat treatment and chemical treatment are the ones most employed.

Methods of protecting protein from rumen degradation

Naturally occurring bypass protein: The fraction of rumen undegradable protein (RUP) that undergoes enzymatic hydrolysis and gets absorbed in the form of amino acids from the small intestine is called digestible RUP. Various sources of naturally occurring rumen protected protein are cottonseed cake, fish meal, maize gluten meal, and coconut cake (Table 1). Protein sources with medium rumen protein degradability are soybean meal, linseed cake, leucaena leaf meal etc., while groundnut cake, mustard cake, and sunflower seed cake are highly degradable in the rumen (Dey *et al.*, 2006) and therefore, necessary protection against proteolytic enzyme action in the rumen is required (Ani and Ajith, 2021). The amino acid profile of rumen undegradable protein is kept intact and is absorbed through the small intestine.

Tannin supplementation: Tannins are plant secondary polyphenolic metabolites that negatively affect rumen microbial fermentation, nutrient degradability, feed intake, and productivity of the ruminant livestock when present at a high level in the diet (Henke *et al.*, 2017). Nonetheless, low to moderate levels of tannin can be beneficial to the animal through modulation of rumen fermentation by the nature of its molecular structure, which allows tannins to form hydrogen bonds with protein to form tannin-protein complex, which is stable in the rumen at normal pH and is invulnerable to degradation by rumen microbes (Avila *et al.*, 2020). Tannin-bound protein is freed in the low pH conditions of the abomasum and, therefore, increases the flow of rumen-protected protein to the small intestine for assimilation and uptake. High rumen ammonia levels due to excess protein degradation and efficiency of nitrogen utilization may also be improved by supplementation of condensed tannins protected proteins (Dey *et al.*, 2008; Loregian *et al.*, 2023).

Yanza *et al.* (2021) recommended the use of hydrolysable tannins to be more suitable for ruminants as compared to condensed tannins. Arisya *et al.* (2019) suggested incorporating tannin at 2% level to reduce protein degradability of *Indigofera zollingeriana* and soybean meal, which also did not affect post-ruminal digestion of bypass protein. Orlandi *et al.* (2015) reported a linear decrease in rumen ammonia and an increase in nitrogen (N) retention, N utilization efficiency, and faecal N excretion in steers supplemented

Table 1. Ruminal degradability of some common protein feeds

Protein Feeds	CP (%)	RDP (%)	RUP (%)	Reference
Cottonseed meal	25-28	39.0	61.0	Gao *et al.*, 2015
Soybean meal	45-48	80.7	19.3	Zain *et al.*, 2023
Sunflower meal	25-30	68.7	31.3	Gao *et al.*, 2015
Coconut cake	22-25	72.6	27.4	Zain *et al.*, 2023
Canola oil meal	35-40	52.1	47.9	Van Rensburg, 2024
Groundnut cake	42-45	86.0	14.0	Chandrasekharaiah *et al.*, 2022
Mustard cake	32-34	81.6	18.4	Thakur *et al.*, 2023
Maize gluten feed	55-60	74.6	25.4	Maskaľová *et al.*, 2024
Rapeseed meal	32-38	60.5	39.5	Maskaľová *et al.*, 2024
Copra meal	22-25	57.2	42.8	Rosmalia *et al.*, 2021
Leucaena leaf meal	24-30	50.8	49.2	Putri *et al.*, 2019
Fish meal	55-65	24.7	75.3	Gonzalez *et al.*, 1998

with varied levels of tannin extract. Soybean meal supplemented with natural tannin (0.4%) from gambier and tea waste resulted in increased bypass protein fraction with decrease in rumen protozoa population and ammonia concentration (Prasetiyono *et al*., 2018). Similarly, groundnut cake supplemented with condensed tannin rich *Ficus infectoria* leaves demonstrated reduced ruminal ammonia concentration and blood urea nitrogen (BUN) in crossbred cows and growing lambs (Dey *et al.* 2008, 2009a).

Formaldehyde treatment: Formaldehyde treatment is one the most well-known and widely used methods for the treatment of feed proteins for protection against degradation in the rumen (Sorathiya *et al.*, 2015; Jadhav *et al.*, 2018). Formaldehyde forges cross-link between protein chains, forms pH-insensitive methylene bridges between the aldehyde group of formaldehyde and the amino group of proteins and affect the microbial population in the rumen (Walli, 2005; Atole and Bestil, 2014). The formaldehyde ingested with treated bypass protein is metabolized with the help of formaldehyde hydrogenase enzyme, which converts formaldehyde to formic acid and further to water and CO_2 or added to the one carbon metabolic pool or excreted in the sodium salt form in urine. Mustard cake and groundnut cake kept in airtight polythene bags after formaldehyde treatment (1.2 g/100g crude protein) showed protein protection (Chatterjee and Walli, 2000; 2003).

Heat treatment: Heat treatment of highly rumen degradable oilcakes has been recommended to reduce CP degradability and enhancing nitrogen efficiency in ruminants. Heating of protein feeds leads to formation of cross-linkages between free amino acid of peptide chains and sugar aldehyde groups of carbohydrates, which reduces protein degradability in the rumen (Dhiman *et al*., 1997). This process is called Maillard reaction or nonenzymatic browning reaction that yields an amino-sugar complex, which is more resistant than normal peptides to enzymatic hydrolysis, and the reversibility of this reaction is dependent upon temperature and time of heat exposure. Heat treatment of feeds is usually done to protect protein, based on protein denaturation and through condensation reactions between proteins and carbohydrates. Denaturation of proteins through treatment with acid solutions has been studied with the purpose of protein protection, generally with positive results. Denatured proteins are more accessible as substrates for proteolysis than are native proteins. Denaturing effect facilitates the access of intestinal protease to peptide bonds. Forced-air oven treatment is one of the thermal methods of protein protection alongside roasting, autoclaving, and extrusion (Reynal and Broderick, 2003). Eissa *et al.* (2014) recommended the heat treatment of groundnut cake as an effective strategy to reduce microbial protein degradability.

Heat treatment might also lead to the protection of poly-unsaturated fatty acids from rumen biohydrogenation by microbes and thus might have the potential to increase PUFA levels in animal products such as meat and dairy (Jones *et al.*, 2001). However, the selection of temperature-time combination is integral to the efficacy of this process, as higher temperatures for a longer time may lead to irreversible Maillard reaction and, therefore, make the protein impervious to the small intestine digestion as well. Therefore, careful consideration of temperature and time of heat exposure is needed when heat treating the protein feeds to avoid wastage of valuable nutrients and resources.

Use of organic acids: Various acids such as acetic acid, hydrochloric acid, propionic acid, malic acid, and orthophosphoric acid have been used to treat protein feeds. Acids cause the denaturation of protein, which may block feed protein reactive sites conducive to proteolytic enzymes of microbial origin (Ouarti *et al.*, 2006; Atole and Bestil, 2014). The diffusion of acid from the treated feed particle might suppress microbial attraction and attachment to the feed particles, and consequently, microbial activity (Arroyo *et al*., 2011). However, the information about the dose and type of acid to be used, and their effects on efficiency of protein protection is limited.

Acid-heat treatment of protein feeds: Heat treatment has been associated with efficacious protein protection and decreased nitrogen availability for rumen microbes. Combined use of acid and heat treatments may allow a higher level of protein protection and nutritional and economic advantages such as reduced cost of the thermal treatment, lower acid doses, and less risk of irreversible Maillard reactions associated with protein over-protection. Arroyo *et al.* (2011) assessed the effects of acid-heat treatment on sunflower meal using different concentrations of orthophosphoric acid and malic acid and reported a reduction of *in situ* rumen degradability of untreated sunflower meal from 0.91 to 0.39 when malic acid-heat treated at 150°C for 60 minutes. Malic acid (1M) and orthophosphoric acid (0.67M) heat treatment on sunflower meal and spring pea meal revealed a positive effect on intestinally digestible fractions of dry matter (DM) and crude protein (CP) along with an increase in total amino acid availability while decreasing the ruminal degradation of the feeds (Arroyo *et al.*, 2013; Díaz-Royón *et al.*, 2016). Another study (Gonzalez *et al.*, 2009) reported a three-fold increase in the intestinally digestible supply of amino acids lysine and methionine, while cysteine supply was increased 3.7 times due to the treatment of sunflower meal at 150°C for 6 h with 2N solutions of malic acid and orthophosphoric acid. Recent study by Thakur *et al.* (2023) demonstrated positive impact of malic acid-heat treatment of protein feeds (groundnut cake, guar korma, sunflower meal and mustard cake) on reduction (64-70%) of ruminal protein degradation. However, the research is limited in this area, and more *in vivo* studies need to be conducted to assess the effect of supplementing acid-heat treated protein rich feeds in productive ruminants.

Rumen protected amino acids: Amino acids, methionine and lysine are the most limited amino acids (AAs) in the most universally used feed ingredients, therefore, are the most limiting amino acids for the ruminants (Teixeira *et al.*, 2019). The effectiveness of rumen protected amino acids in enhancing production performance and feed intake in lactating dairy cows has been studied. Various physical and chemical methods have been used to protect amino acids from rumen degradation. Physical methods involve encapsulation, micro- and macro-encapsulation, nano-capsulation, pH sensitive capsulation, neutral lipid encapsulation, and coating (Mazinani *et al.*, 2019; Mazinani *et al.*, 2022). The limitation of the physical methods is abrasion of protective layer during feed processing, diet handling and mastication by the animal. Disruption of the protective coat causes amino acids to be exposed to rumen microbes, thus leading to wastage of AAs (Schwab and Broderick, 2017). The chemical methods involve the use of alcohols, tannins, bentonite, cations, aldehydes, alkalis, etc. Aldehyde-protected rumen AAs increased performance and demonstrated antibacterial effects in feedlot calves (Mazinani *et al.*, 2019). Amino acid analogues have also been explored with the possibility of decreasing rumen AA degradability. AA analogues such as 2-hydroxy-4-methylthio butanoic acid (HMB) and methionine hydroxy analogues have been studied. HMB supplementation in ruminants decreased milk fat depression in cows and enhanced production in ruminants (Chen *et al.*, 2020; Pitta *et al.*, 2020). Ratika (2018) conducted an experiment in transitional buffaloes with supplementation of protected lysine, methionine and choline and demonstrated increased FCM yield in lactating buffaloes as well as enhanced immunity in their calves.

Standardization and commercialization of various bypass protein technologies have been done by various feed companies and institutes, which has increased the ease of availability for common farmers through extension programmes and marketing. National Dairy Development Board (NDDB) of India has developed a bypass protein technology and has conducted various feeding trials on dairy cows and buffaloes supplemented with chemically treated protein feeds such as guar meal, sunflower meal, rapeseed meal, etc., and has recorded an increase in milk yield and fat content. The treated meals have been approved to be safe by the US-FDA (NDDB, 2006). Soypass®, a soybean meal-wood sugar-based bypass protein product (developed by Borregaard USA, Inc.) based on a non-enzymatic browning technique, increased dry matter intake in growing steers upon replacement of wet grain distiller solubles up to 60% (Spore *et al.*, 2019). Novapro®, a rapeseed-based bypass protein product increased dry matter intake and milk yield in lactating Holstein Friesian cows (Garnsworthy *et al.*, 2021)

Effects of rumen protected protein supplementation on ruminants' performance

Rumen bypass protein supplementation through protein meals and cakes has the potential to improve the productive and reproductive performance of ruminant livestock. The bypass protein technology acts through passive rumen manipulation and has significant effects on rumen fermentation parameters, nutritive value of the feed and its digestibility, and microbial population patterns along with improvement in production, reproduction, and economical aspects of livestock rearing.

Rumen fermentation parameters and nutrient utilization: Various *in vitro*, *in vivo*, and *in situ* studies have been conducted regarding the assessment of the effect of rumen bypass proteins. Putri *et al.* (2021) reported that with the increase in the undegradable protein (UDP) fraction of the feed, ammonia nitrogen levels were decreased, indicating lower protein solubility in the rumen and a decrease in total VFA levels due to a decrease in RDP fraction was also reported with a decrease in microbial protein synthesis. Soybean meal protected with tea waste tannin and gambier tannin showed a higher *in vitro* dry matter degradability (IVDMD) as compared to the unprotected feed. Rumen ammonia-N and protozoal populations decreased by protein protection with tannin, along with a decrease in total VFA and *in vitro* methane production, while acetate, propionate and butyrate were not significantly affected (Prasetiyono *et al.*, 2018; Loregian *et al.*, 2023). Preston *et al.* (2013) reported lower *in vitro* gas production and methane production in the case of fish meal (low rumen degradability) as compared to groundnut meal (high rumen degradability). Paya *et al.* (2014) protected safflower seeds from rumen degradation through microwave irradiation and noted an increase in cumulative gas production and post-ruminal DM and CP degradability, while ruminal DM and CP degradability were reduced in case of treated safflower seeds. The proteolytic rumen microbial action results in the release of ammonia due to protein degradation through the action of microbial deaminase enzymes, thus, microbial protein synthesis is directly related to ammonia concentration in the rumen (Chatterjee and Walli, 2000; 2003; Dey *et al.*, 2009b). Optimal microbial protein synthesis is necessary for effective ammonia utilization and diet fibre degradation (Uddin *et al.*, 2015). Therefore, rumen undegradable protein should not negatively impact rumen fermentation to prevent impairment of feed utilization.

The degradability and kinetic parameters from in situ studies also provide an insight into active degradation and fermentation process in the rumen, and the rate of degradation and the efficacy of bypass protein treatment can be evaluated. Atole and Bestil (2014) analysed *in situ* degradation of formaldehyde, heat, and tannin treated soybean meal in rumen-fistulated Brahman cattle and reported a pattern of decreased rumen DM degradability of treated feeds at 24, 48, and 72 hours. CP degradation was reduced for all treatments at 24 hour-period, while only heat and formaldehyde treatments showed a significant decrease at 48-hour incubation period. Similarly, the rates of DM and CP disappearance were reduced in all bypass protein treatments. Protein protection of canola cake through heat treatment and a combination of lignosulfonate (LSO_3) and heat treatment at different temperatures resulted in a decrease of effective rumen degradability (ED) of crude protein along with a decrease in ED of methionine and lysine with heat treatment (at 130°C or more for 60 minutes) alone or in combination with LSO_3; however, the combination treatment was more effective (Micek *et al*., 2020).

Parmar *et al.* (2023) replaced 30% crude protein of the concentrate mixture with formaldehyde treated guar korma for supplementation in 7-8 month old Surti buffalo calves and found that CP apparent digestibility (%) was higher in the case of bypass protein fed animals, while overall cost of feeding was also lower as compared to calves fed basal diet, although DM, EE, CF, NFE, and OM degradability coefficients were not affected. Another study showed an increase in DM, CP, EE, and CF digestibility in the case of buffalo heifer calves fed bypass protein along with improved growth rate (Patel *et al*., 2012a). Wankhede and Kalbande (2001) also reported an increase in DM, CP, EE, CF, and NFE digestibility in Red Kandhari calves fed 45% bypass protein in the concentrate mixture with urea-treated straw.

Microbial profile of ruminants: Various monensin-sensitive and gram-positive obligate amino acid fermenting bacteria in rumen have a high specific activity for ammonia production and are known as hyper-ammonia producing bacteria (HAB), which are detrimental to nitrogen retention efficiency in ruminants (Chanu *et al*., 2024). Replacement of baker's yeast with craft brewer's yeast containing higher rumen protected protein fraction in Spanish goat wether diet led to reduced amino acid fermentation irrespective of proteolysis, inhibited growth of amino-acid fermenting bacteria and decreased ammonia production (Harlow *et al*., 2016). McIntosh *et al.* (2003) reported a decrease in hyper-ammonia-producing bacteria *Clostridium sticklandii* and *Peptostreptococcus anaerobius* populations through essential oil blend supplementation (1g/d) in Holstein-Friesian cows.

Growth performance: Growing calves need considerable amounts of amino acids for tissue synthesis and body weight gain, and rumen bypass protein can help meet the amino acid profile required for reaching their growth potential (Idowu *et al*., 2024). Supplementing rumen bypass protein to 8-month-old buffalo heifer calves led to an increase in average daily gain (535.71±14.67 g/day) in comparison to calves fed concentrate mixture without bypass protein (398.31±14.49 g/day), along with better feed conversion ratio and increased DM, CP, EE, and CF digestibility (Patel *et al.*, 2012a,b). Higher average daily gain (ADG) levels were observed in the post-weaning period (734 g/day in calves fed 73:27 RDP:UDP ratio compared to 1008 g/day in calves fed 62:38 RDP:UDP ratio in diet) and better feed efficiency in calves fed higher proportion of rumen undegradable protein (Kazemi-Bonchenari *et al.*, 2020). Higher body weight gain and average daily gain (g/day) were observed in Murrah buffalo heifers supplemented with natural (589.01±27.42) and commercial bypass protein (616.48±17.10) as compared to control animals (523.31±13.90) after 90 days of supplementation (Kumari *et al.*, 2017). Wankhede and Kalbande (2001) recommended 45% as the optimum level of rumen undegradable protein in the concentrate mixture for improved growth rate and optimum economic efficiency, particularly in the earlier growth stages of dairy calves.

Nitrogen retention and amino acid availability: The protected protein fraction of the feed undergoes degradation in the small intestine, which might result in increased amino acid availability for protein synthesis, consequently, increased nitrogen retention and positive nitrogen balance. Supplementing formaldehyde (HCHO) treated GNC to crossbred heifers showed higher N retention as compared to untreated GNC supplementation without any effect on DM, OM, and CP degradability (Ramachandra and Sampath, 1995). Wright *et al.* (1998) supplemented dairy cows with three different RUP concentrations, i.e., 4.5, 14.9, and 29.1% of total DMI and observed that the urinary N excretion, faecal N excretion, and nitrogen retention increased with the increase in RUP supplementation. The amino acid balanced RUP supplementation also resulted in linear elevation of milk protein production without any effect of restriction in feed intake. Sultan *et al*. (2009) assessed the effect of different isonitrogenous and isocaloric diets containing different RDP:RUP ratios, i.e., 70:30, 65:35, 60:40, and 55:45 in Nili Ravi buffalo calves, and found that increasing the level of RUP led to a linear increase in nitrogen retention (g/d, as percent of N intake, and as percent of N absorbed) as well as a linear decrease in BUN concentration. The essential and non-essential amino acid availability was found to be consistently higher (30%) in rumen protected soybean meal as compared to untreated SBM, increasing amino acid supply to the small intestine in high-production dairy cows (Borucki Castro *et al.*, 2007).

Milk production: Rumen bypass protein supplementation is generally considered beneficial for dairy animals, as the increased intestinal availability of high-quality protein feed sources has the potential to fulfil the nutrient requirements of high-yielding dairy cows and buffaloes (Paul *et al.*, 2016). This presumption has been established through various studies, which report higher milk production in dairy animals through bypass protein supplementation. Aasiwal *et al*. (2015) reported an increase in milk yield of early lactating Jersey cows through supplementation of HCHO-treated cottonseed cake and rapeseed meal. Sherasia *et al.* (2010) also reported significantly ($P<0.05$) higher milk production (+0.87 L/day) through supplementation of heat protected rapeseed meal in crossbred dairy cows. An increase of 19% in daily milk yield of Murrah buffaloes in early lactation was observed upon supplementation with concentrate mixture containing heat protected groundnut cake and mustard cake (Shelke *et al.*, 2012). Tiwari *et al.* (2018) also reported a 2.4 L/day increase in milk yield in lactating Jersey dairy cows after 62 days of supplementation with concentrate mixture containing heat treated soybean cake as compared to 0.4 L/day increase in case of cows fed untreated soybean cake in the concentrate mixture. A summary of protected protein supplementation on the performance of ruminants has been presented in Table 2.

Table 2. Effect of protected protein supplementation on livestock performance

Animal species	Type of supplement	Method of protection	Dose	Performance	Reference
Murrah buffalo heifers	Fish meal	Natural bypass protein	10% of CP in conc. mixture	18.3% increase in average daily gain (ADG)	Kumari *et al.*, 2017
Crossbred Friesian calves	Soybean meal, undecorticated cottonseed meal	Zinc sulphate treatment	15% of conc. mixture	22.5% increase in ADG	El-Shabrawy *et al.*, 2010
Holstein dairy calves	Maize gluten meal	Natural	8% of conc. mixture	22.7% increase in ADG	Kazemi-Bonchenari *et al.*, 2020
Surti buffalo calves	Guar meal	Formaldehyde treatment	30% CP of conc. mixture	15.9% increase in ADG	Parmar *et al.*, 2023
Holstein dairy calves	Rumen protected methionine and lysine	Glutaraldehyde treatment	2.67 g methionine, 7.64 g lysine	11.3% improvement in ADG	Mazinani *et al.*, 2020

Cont. Table 2.

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Animal species	Type of supplement	Method of protection	Dose	Performance	Reference
Lactating crossbred cows	Mustard cake	Formaldehyde treatment	12% of total diet	11.7% increase in milk production	Choudhary *et al.*, 2020
Crossbred cattle	Groundnut cake	Formaldehyde treatment	20% of conc. mixture	18.0% increase in fat corrected milk (FCM) yield	Mane *et al.*, 2017
Dairy cattle	Soybean meal	Heat treatment	1.5 kg/d	11.17% increase in milk production	Osti *et al.*, 2013
Crossbred cattle	Cotton seed cake	Natural	50% CP of conc. mixture	13.8% increase in milk production	Chandrasekharaiah *et al.*, 2008
Crossbred cattle	Soybean cake	Heat treatment	1.5 kg/d	63.74% (4.29 vs. 2.62 l/d) increase in milk production	Thapa *et al.*, 2019
Crossbred cattle and sheep	Groundnut cake	Condensed tannins (CT) protected protein	1.5% CT in supplement	20.27% increase in FCM yield in cattle and 20.51% increase in ADG in sheep	Dey *et al.*, 2008; 2009

Reproductive performance: Reproductive performance is an important aspect of livestock rearing in terms of profitability as it is directly related to the generation of future stock and is essential for the commencement of lactation. Supplementation of bypass protein during late gestation may also have a positive effect on the quality and quantity of milk produced during lactation. Feeding of formaldehyde treated commercial bypass protein to lactating Murrah buffalo was demonstrated to enhance the onset of postpartum oestrus by 8-11 days in comparison to control animals fed with untreated protein feeds (Bharadwaj *et al.*, 2000). Replacement of untreated rapeseed at 25% and 50% levels with HCHO-treated commercial rapeseed in the diets of Surti buffalo heifers led to earlier attainment of puberty (Jadhav *et al.*, 2018). Supplementation of rumen protected methionine (2.34% of the total metabolizable protein) in lactating dairy Holstein cows decreased the rate of pregnancy loss and increased the embryonic size in multiparous cows (Toledo *et al.*, 2017).

Conclusion

Efficient protein nutrition in high-producing ruminants involves supplying adequate levels of the rumen of undegradable protein (RUP) to balance rumen function and maximize animal productivity while minimizing dietary crude protein input. In developing countries, nutrient imbalance and feed shortages are one of the major constraints on livestock productivity. Therefore, efficient and sustainable use of available feed resources is warranted to enhance nutrient availability to highly productive livestock. The application of rumen protected protein technology at a larger scale is an important strategy to achieve quality livestock production and improve nutrient utilization with minimal wastage of limited feed resources.

Conflict of interests: The authors declare no conflict of interest in the study.

Authors' contributions: ST: Collected the information; AD, ST: Wrote the manuscript; AD, SK: Critically reviewed and corrected the manuscript. All authors finally read and agreed to submit the manuscript.

Data availability statement: No specific research data was used for the review article and information is compiled from the available literature.

ACKNOWLEDGEMENT

The authors sincerely acknowledge the contribution of the Director, ICAR- Central Institute for Research on Buffaloes, Hisar, for his critical input while writing this manuscript.

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Received- 20.09.2024, Accepted- 22.11.2024, Published- 01.12.2024 (Print)

Section Editor: Dr. S. Banik, Editorial Board Member