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Optimizing Economic Value Through Enhanced Nutrient Digestibility in Ruminants: Recent Advances and Implications

Hamdi Mayulu[1*], Taufan Purwakusumaning Daru[2], Fandini Meilia Andani[3], Ardiansyah[4], Irsan Tricahyadinata[5], Julinda Romauli Manullang[6]

[1,2,3,4,5,6] Mulawarman University, Samarinda, Indonesia

Corresponding Author's E-mail: hamdi.mayulu@unmul.ac.id

Abstract

Efficient nutrient digestibility is essential to optimize feed efficiency, performance, and productivity in ruminants production. Therefore, this review aims to explore economic implications of technology to increase nutrient digestibility in ruminants production systems. The review procedures were carried out using an exploratory approach through literature studies sourced from Web of Science, Scopus, and PubMed, which were scientific databases capable of storing high-quality articles. The results showed that innovation and technology in feed processing (such as Handheld Near-Infrared (NIR) spectroscopy devices, heating methods, precision grinding techniques, integrating ultrasonic treatment with enzyme supplementation and microwave-assisted alkali treatments), enzyme supplementation, specifically cellulase and xylanase combined with encapsulation techniques, probiotic, prebiotic and synbiotic supplementation can increase nutrient digestibility, fermentation rate, nutrient availability, and absorption. Increasing nutrient digestibility in ruminants offered significant economic benefits, such as reducing input costs and increasing livestock productivity. Integration of various strategies is key to increasing productivity and sustainability in ruminants production systems. Increasing nutrient digestibility not only achieved higher productivity but also contributed to a sustainable and efficient food production system and ensured the long-term continuity of ruminants production.

Keywords: digestibility, nutrient, ruminants, optimization, efficiency, economy

Introduction

Ruminants such as cattle, buffalo, sheep, and goats play an important role in the global agricultural system due to their ability to convert fibrous plant materials into high-value products (meat and milk) (Liu et al., 2021; Mayulu et al., 2022; Sanjorjo et al., 2023; Wang et al., 2023). The ability of ruminants to convert fibrous plant materials is due to their complex digestive systems, mechanisms (mechanical, fermentative, enzymatic, and chemical digestion) (Mayulu et al., 2023), and the symbiotic relationship with microbes (including bacteria, protozoa, fungi, archaea, and viruses) in the rumen (Choi et al., 2023; Huang et al., 2023; Silva et al., 2024) Several studies have shown that microorganisms are responsible for fermenting these materials and producing volatile fatty acids (VFA), which function as the main energy source for supporting metabolic functions. Despite the complex digestive system possessed by these animals, the efficiency of nutrient digestion is not always optimal. Most of nutrient in fibrous feeds, such as cellulose and hemicellulose (70%), remain undigested (Almassri et al., 2024) and tend to be excreted in feces, causing increased feed costs and low productivity. Inefficiency directly impacts economic viability of ruminants production, where feed costs are the largest expenditure (reaching 65-75% of total production costs) (Mayulu, 2021).

Efforts to increase the value and digestibility of nutrient in ruminants can be made by using feed processing technology in line with advances in science and technology. Technological processes play an important role in the production of high-quality feed by increasing digestibility, nutrient absorption, and overall efficiency (Tepe & Altaş, 2024). New processing technologies, such as extrusion and microwave treatment, have shown promise in increasing nutrient availability. Extrusion, which comprises forcing ingredients through a mold under high pressure and temperature, disrupts the complex structure of plant cell walls, making nutrient more accessible for microbial fermentation in the rumen. Previous studies have shown that microwave treatment of feed can increase fiber digestibility by breaking down lignocellulosic bonds, thereby increasing microbial access to cellulose and hemicellulose (Shishir et al., 2022; Tepe & Altaş, 2024). Extrusion and microwave technology interventions help to improve efficiency by ensuring more nutrient are absorbed by the host, leading to increased growth rates and productivity.

Another major area of innovation is the use of enzymes supplements to increase the breakdown of fiber in ruminants diets. Enzymes, such as cellulase and xylanase, are added to feed to help break down complex carbohydrates, including cellulose and hemicellulose (xylan), which are difficult to digest (Mu et al., 2023). This supplementation method has been shown to increase fiber digestibility, nutrient absorption, and improve feed conversion ratios, leading to better ruminants performance (Almassri et al., 2024). The use of enzymes is beneficial in high-forage rations, where the fiber content is relatively high (30-70% NDF on a dry matter basis), and microbial fermentation is not sufficient to break down all the fibrous materials (Almassri et al., 2024). The method not only improves nutrient digestibility but also reduces feed waste, which contributes to lower feed costs for ruminants producers (Velázquez-De Lucio et al., 2021).

Microbial management through the use of probiotics and prebiotics is emerging as a promising strategy to optimize rumen fermentation and improve nutrient absorption. Probiotics are live microorganisms that provide health benefits to the host and act to defeat and replace pathogenic bacteria in the digestive tract when given in sufficient quantities (Sanjorjo et al., 2023). In addition, probiotics are often used to increase rumen microbial populations and promote efficient fiber digestion. Microbes compete with pathogenic bacteria, stabilize rumen pH, and increase VFA production, which is important for energy metabolism in ruminants (Galli et al., 2024). Prebiotics are non-digestible feed additives that promote the growth and activity of beneficial gut bacteria. The combination of probiotics and prebiotics has been shown to increase nutrient utilization, reduce methane emissions, and improve overall ruminants health. The integration of microbial interventions in rations is a sustainable approach because it reduces dependence on synthetic feed additives and antibiotics as well as reduces environmental waste (Sanjorjo et al., 2023).

Although feed processing technology has progressed, it has several challenges, namely optimizing the use of feed processing technology to achieve maximum nutrient utilization without incurring excessive costs. For example, the associated economic consideration for the implementation of enzyme supplementation and microbial management needs to be considered despite the ability to increase nutrient digestibility. The costs of producing or purchasing supplements are potentially high, and their effectiveness varies depending on the type of feed and the physiological condition of ruminants. Knowledge about technology affecting long-term production results such as milk, meat production, growth rates, and overall profitability is still limited. Therefore, a review is needed to explore economic implications of technology to increase nutrient digestibility in ruminants production systems.

Methodology

This review used an exploratory approach through literature studies sourced from Web of Science, Scopus, and PubMed which were scientific databases capable of storing high-quality articles. This study used several keywords, such as "Nutrient digestibility in ruminants", "Feed processing techniques", "Enzyme supplementation in ruminants", "Probiotics and prebiotics in ruminants feed", "Rumen fermentation and efficiency", "Economic impact of feed digestibility". The inclusion criteria were studies published in the last five years (2020 to 2024) to ensure that the review was up-to-date, and the full text was written in English.

Literature Review

Recent Advances in Ruminants Digestive Efficiency

The nutritional value of feed and its use by ruminants were 2 important factors that influenced the profitability and sustainability of ruminants production systems (Shishir et al., 2022). Feed was a crucial factor that influenced production efficiency and ruminants health (Xiao & Meng, 2024). The increase in feed costs over the last decade due to increasing demand, shortages of raw materials, and the global crisis had created significant challenges for the livestock industry, specifically ruminants (Xiao & Meng, 2024). In addition, the spike in feed costs had an impact on the large feed costs that ruminants producers had to incur, hence optimizing feed utilization to make it more efficient and improving feed processing technology was important to increase productivity, product quality, and sustainability of production practices (M. G. Martin et al., 2024; Xiao & Meng, 2024). The following were strategies for achieving ruminants digestive efficiency.

Feed Processing and Treatment

Nutrient value of ruminants feed ingredients varied significantly, depending on the source, variety, and processing method. Feed processing technology played a significant role in maintaining or even improving nutritional quality (Xiao & Meng, 2024), such as grinding, mixing, pelleting, coating, extrusion, encapsulation (Tepe & Altaş, 2024), ensiling, and steam flaking could help preserve nutrient, increase digestibility and nutrient absorption as well as increase overall feed efficiency (Xiao & Meng, 2024). Recent advances in feed processing techniques allowed the use of several renewable techniques and methods including Handheld Near-Infrared (NIR) spectroscopy devices, heating methods, precision grinding techniques, integrating ultrasonic treatment with enzyme supplementation, and microwave-assisted alkali treatments. Infrared was a part of the electromagnetic spectrum that lied between the visible region and microwaves with wavelengths ranging from 0.5 to 100 μm. In addition, its rays were divided into 3 types, namely: 1) Near-IR (NIR) with a wavelength between 0.75 to 1.4 μm at temperatures below 400ºC; 2) Mid-IR (MIR) with a wavelength between 1.4 to 3 μm at temperatures between 400ºC to 1000ºC; and 3) Far-IR (FIR) with wavelengths between 3 and 1000 μm at temperatures above 1000ºC (Aboud et al., 2019). The type of NIR that was mostly used in animal husbandry was Handheld NIR spectroscopy which consisted of NeoSpectra (1350-2550 nm, Si-ware Systems Inc., Cairo, Egypt), TrinamiX (1450-2450 nm, TrinamiX Inc., Ludwigshafen, Germany), and Agrocares Scanners F-Series (1300-2550 nm, AgroCares, Wageningen, The Netherlands) (Yamada et al., 2024).

NIR reflectance spectroscopy device detected variations in the chemical composition of feed, including dry matter, crude protein, fiber content (actual neutral detergent fiber/aNDF, acid detergent fiber/ADF, acid detergent lignin/ADL) (Yamada et al., 2024), concentrations of compounds such as starch and non-starch polysaccharides, as well as predict feed properties (such as digestibility or rumen degradation) (Cherney et al., 2021; Mendes de Oliveira et al., 2024; Sun et al., 2022). NIR devices increased the possibility of analyzing nutrient features in rations and facilitated daily ration adjustments based on accurate and real-time analysis of the nutritional content of feed ingredients. This could thereby facilitate the provision of balanced rations, increase feed utilization efficiency, reduce environmental impacts, and increase the profitability as well as sustainability of ruminants production (Abeni, 2022; Yamada et al., 2024). Infrared penetration resulted in vibrations of water molecules at a frequency of 60,000 to 150,000 MHz and caused heating. Electromagnetic radiation caused thermal movement of molecules. In addition, energy transmitted by radiation at wavelengths shorter than infrared caused chemical changes in electrons in radiation-absorbing molecules such as chemical bonds, including chemical bonds in feed ingredients (Aboud et al., 2019).

Heating methods in feed processing involved dry heating, moist heating, and microwave irradiation. Dry heating referred to a conventional method where heat penetrated from the surface to the inside of the feed. Moist heating consisted of adding water or steam to increase the heating temperature, while microwave irradiation produced heat through molecular friction between water and other primary components in the feed to ensure that the feed processing process was shorter. Different heating techniques had distinctive effects on feed nutrition, depending on the type or ingredients of the feed, and its physical and chemical characteristics (Prates et al., 2023). According to previous studies, thermal processes could influence the structural, molecular, and functional characteristics of feed ingredients (Kokić et al., 2022) including increasing fiber and lipid content and reducing ash content (Carboni et al., 2024). Hydrothermal processing modified the crystal structure of starch granules, increased starch gelatinization, facilitated access of rumen microbes and enzymes to starch granules, increased digestibility while maintaining nutritional integrity and energy use for ruminants (Han et al., 2022).

Particle size in ruminants feed processing was an important parameter that influenced the performance of the digestive system (Lyu et al., 2020). Precision grinding techniques were mechanical methods applied in processing feed ingredients to break down and reduce the size of grain particles into smaller fragments. Particle size reduction through precision grinding techniques was a common practice to enhance palatability, digestibility, feed efficiency, and growth performance (Acosta et al., 2020). The reduction in particle size in turn resulted in an increase in surface area that facilitated contact by digestive enzymes to other important feed components such as starch, proteins, and lipids (Acosta et al., 2020). The fiber component in feed ingredients had the potential to be fermented more easily when the surface area of the feed ingredient components increased. Precision grinding techniques applied to grain feed not only increased starch digestibility but also contributed to better levels of rumen microbial fermentation. Finer and more uniform particle sizes allowed for more consistent release of nutrient in the rumen, leading to improved feed efficiency and higher production (Acosta et al., 2020; Ortolani et al., 2020).

Ultrasound was a technique for destroying plant cell walls and releasing polysaccharides and other substances that were difficult to extract at lower temperatures in a short time. Ultrasound was considered a clean technique in feed ingredient processing, extraction, homogenization, and modification of physicochemical properties (Grassino et al., 2020; Guo et al., 2019; Pollini et al., 2019; Wu et al., 2022). The ultrasonic treatment could decompose polysaccharides (such as lignin, cellulose, and hemicellulose) into monomeric sugars which were then used for bioenergy and reduce cellulose crystallinity (Wu et al., 2022). In addition, the ability to remove lignin content in ultrasound treatment was attributed to the oxidation of bonds during ultrasound while the removal of hemicellulose was attributed to its amorphous nature. The degradation of polysaccharides that occurred made it easier for subsequent biomass processing. Ultrasonic waves could break down plant cell wall, making it more accessible to digestive enzymes. Previous studies showed that ultrasonography was a mature technology that could be used independently or integrated with other technologies such as enzymes to make it more effective. The integration of ultrasonic waves and enzyme supplementation improved fiber digestibility, thereby significantly increasing feed conversion rates and reducing feed waste. In addition, the combination promoted better nutrient absorption without increasing feed intake, thereby offering a cost-effective solution for ruminants producers (Wu et al., 2022).

Feed ingredient processing techniques using microwave-assisted treatments had been explored to develop a more efficient and sustainable approach to increasing digestibility of ruminants feed ingredients. Microwaves produced high-frequency waves that caused disruption of cell walls and the release of biomass biochemicals such as lipids, proteins, and carbohydrates (Pérez et al., 2024; Vinhas et al., 2023). These technologies were a form of electromagnetic radiation with a wavelength shorter than radio waves, but longer than infrared waves, usually ranging from 1 mm to 1 m, with frequencies of 300 MHz and 300 GHz. Microwaves when interacted with a material, could induce rotation and collision of molecules, which caused energy loss and heating. The heating effect facilitated the conversion of lignocellulosic biomass products that could be used by ruminants (Pérez et al., 2024). Microwave methods in feed production increased feed utilization by changing some physicochemical properties that improved enzymatic hydrolysis. In this study, microwave treatment could cause significant changes to the protein composition of feed ingredients due to the breaking of C-N bonds in the polypeptide chains backbones which resulted in increased crude protein levels. Microwave exposure to some or all starch groups affected changes in ether extract and the NDF component significantly reduced the amount of hemicellulose (Poolthajit et al., 2024). This induced changes in the ultrastructure of lignocellulose complexes, molecular changes, polymer degradation, and disintegration of the crystalline arrangement of cellulose molecules. Fragmentation of the lignocellulose structure reduced the particle size and increased the outer surface area of cellulose by 56% (Dębowski et al., 2024) making it more accessible to digestive enzymes and ultimately increasing its digestibility. Microwave treatment was particularly useful in areas where low-quality forage dominated the feed supply because it offerred an effective way to improve feed quality and increase ruminants productivity.

Enzyme Supplementation

The digestive system of ruminants was specifically designed to use high fiber feed, including forage (with a lignin content of 15 to 20%, hemicellulose 25 to 30%, and cellulose 40 to 50%) and between 40 and 100% of ruminants feed consisted of forage. However, almost 70% of the forage was not digested properly, hence multienzyme supplementation was needed (Almassri et al., 2024). Hemicellulose consisted of xylan, a heteropolysaccharide substituted with monosaccharides such as L-arabinose, D-galactose, D-mannoses, and organic acids such as acetic acid, ferulic acid, glucuronic acid which were linked together with the help of glycosidic and ester bonds (Bhardwaj et al., 2019) components were difficult to degrade by ruminants digestion, hence polymerization was needed through the use of enzymes. The use of exogenous enzymes remained the main strategy to improve feed digestibility (Sureshkumar et al., 2023). Enzyme supplementation in particular with xylanase and cellulase significantly increased the breakdown of fibrous components and increased the feed conversion ratio (Martínez et al., 2020; Mu et al., 2023). In addition, xylanase was an enzyme that played a major role in breaking down xylan (which was a complex hydropolysaccharide consisting of various monosaccharides such as L-arabinose, D-galactose, as well as D-mannoses and organic acids such as acetic acid, ferulic acid, glucuronic acid which were linked together with the help of glycosidic and ester bonds) which was categorized as a carbohydrase and belonged to the glycosyl hydrolase enzyme family (Bhardwaj et al., 2019). Xylan was an important carbohydrate component found in the cell walls of various feed ingredients (Sureshkumar et al., 2023). According to several studies, xylanase through potential mechanisms could degrade cell walls, reduce viscosity and provide easily fermentable xylo-oligosaccharides, thereby modifying nutrient availability and increasing growth performance and nutrient digestibility (Sureshkumar et al., 2023).

The enzyme that was capable of degrading cellulose in lignocellulosic biomass (residues/waste of plant materials such as rice straw, corn cobs, and wheat straw) including forage was cellulase. In this study, cellulase enzymes played a fundamental role in hydrolyzing β-glycosidic bonds in carbohydrate molecules (Ilić et al., 2023). These enzymes helped break down complex carbohydrates, such as cellulose and hemicellulose, which were abundant in fibrous plant materials and difficult for ruminants to digest efficiently (Almassri et al., 2024). Enzyme supplementation increased digestibility of fibrous feed components and resulted in a better feed conversion ratio which had an impact on ruminants productivity (Almassri et al., 2024). Different combinations of enzymes catalyzed a greater proportion of nutrient present in the feed, ultimately contributing to increased feed efficiency (Sureshkumar et al., 2023). Supplementation of xylanase and cellulase enzymes facilitated better breakdown of fiber resulting in increased digestibility, which contributed to a more balanced nutrient supply in the rumen. This approach was particularly useful for diets based on agricultural by-products, where the fiber content was higher, and digestibility was often a limiting factor in ruminants productivity.

The stability and activity of enzymes were highly dependent on environmental factors such as pH, ionic strength, temperature, and the presence of proteases and other biochemicals that increased or inhibited their activity and/or caused denaturation. Encapsulation referred to a technology that allowed protection of feed enzymes from the environment in the rumen and abomasum. This protected bioactive compounds against biotic and abiotic stress in the environment by coating them in a carrier matrix. Encapsulation technology helped protect the encapsulated core ingredients (enzymes or other active ingredients) against rumen degradation by reducing their reactivity or transfer to the external environment and/or from unfavorable environmental conditions, resulting in increased bioavailability of the active ingredients in the gastrointestinal tract (Almassri et al., 2024). In addition, more nutrient could be absorbed in the abomasum and small intestine (Garba & Sema, 2023). Encapsulation could increase feed efficiency by ensuring that nutrient were delivered to the digestive organ where it was most effectively used (Garba & Sema, 2023). The application of this technology in ruminants feed was proven to be able to protect active compounds from rumen degradation, thereby enabling increased bioavailability of compounds in the lower digestive tract of ruminants (Almassri et al., 2024; Tolve et al., 2021). Subsequently, the use of specific enzymes combined with encapsulation technology increased the nutritional value of feed ingredients, increase the efficiency of nutrient digestion, and overall ruminants performance (Almassri et al., 2024). Encapsulated enzymes retained their activity for a longer period, leading to a sustained increase in feed digestibility. This technique was considered effective in processing feed, specifically those processed with high heat such as pelleting or extrusion, where unprotected enzymes usually lost their potency. Advances in enzyme technology described the important role of enzymes in optimizing nutrient digestibility for ruminants, by increasing fiber breakdown reducing feed waste, and increasing nutrient absorption, enzyme supplementation continued to be a key strategy for improving economic efficiency of livestock production.

Probiotics, Prebiotics, and Synbiotics

The growth and development as well as productivity of ruminants were determined by many factors including genetics, age, sex, and ratio. Ruminants not only needed sufficient and optimal amounts of feed for growth and development but also paid attention to the level of digestibility. The improved growth performance of ruminants could be attributed to better nutrient digestibility (Al-Shawi et al., 2020). In addition, the use of probiotics and prebiotics or a combination of the 2 (synbiotics) was performed to increase feed digestibility. Probiotics were sometimes used in livestock as extra supplements to help animals be less sick and die less, eat better, and make more meat or milk (Al-Shawi et al., 2020). These probiotics are basically live little organisms or parts of microbial cells, and they help hosts because they change the gut microbes and make hosts healthier (Michalak et al., 2021; Sanjorjo et al., 2023). In this study, the probiotics worked by helping with food digestion and producing organic acids plus other things that affected the microbes in the rumen, which made ruminants produce more. Some probiotics used were lactic acid bacteria like Lactobacillus, Streptococci, Bifidobacteria, and others, or yeast like Saccharomyces and even fungi like Aspergillus (Sanjorjo et al., 2023).

Probiotics mainly worked by making lots of antibacterial and bacteriostatic stuff, like organic acids, bacteriocins, diacetyl, antibiotics, and hydrogen peroxide (Lambo et al., 2021). These also helped produce amino acids, vitamins like vitamin B, and more digestive enzymes like α-galactosidase. All this helped with digestion and made it easier for the body to absorb nutrients (Michalak et al., 2021). Probiotics could enhance intestinal morphology as well as barrier function, and increased enzyme activity, the production of short-chain volatile fatty acids, and growth performance (Galli et al., 2024). In addition, it was shown to exhibit positive effects on microbial ecosystems, nutrient synthesis, growth performance, muscle production, and meat quality. Probiotic supplementation (*Lacticasebacillus rhamnosus* and *Saccharomyces cerevisiae*) for 2.5 months could maintain microbial balance in ruminants tract (Saha et al., 2023). Changes in the structure of commensal microbial communities in the rumen ecosystem significantly influenced fermentation, digestion, and absorption of nutrient from feed. Increasing the fermentation rate, especifically of fiber and the overall feed conversion ratio not only led to higher energy extraction from fibrous feed ingredients but also improved the overall health of the rumen microbial population (Nalla et al., 2022). Probiotic-mediated mechanisms for improving digestive efficiency also included control of ration-induced acidosis and detoxification of harmful metabolites. This study showed that probiotics increased the growth of rumen and intestinal epithelial cells which increased the capacity for nutrient absorption (Nalla et al., 2022).

Probiotics were increasingly being combined with prebiotics and synbiotics to increase their effects (Michalak et al., 2021; Sanjorjo et al., 2023). These were feed substances that cannot be digested (non-digestible) but could stimulate microbial growth and/or activity (Sanjorjo et al., 2023). Prebiotic compounds included proteins, peptides, lipids, oligosaccharides, and certain polysaccharides such as cello-oligosaccharides, inulin, and lactulose. The purpose of these substances was to act as a substrate for bacterial strains that were beneficial to health, which occurred in the gastrointestinal tract (Michalak et al., 2021). In addition, prebiotics exerted a beneficial influence on the host by selectively stimulating the growth and activity of 1 or several types of bacteria in the large intestine. This study showed that it essentially functioned as “food” for beneficial bacteria in the gut, helping to increase bacterial numbers and encouraging a healthier microbiota (Ji et al., 2023). Probiotics and prebiotics played an important role in increasing the microbial population, increasing the efficiency of the fermentation process, and being an important component in optimizing rumen function to increase digestibility of feed nutrient, productivity, and overall production efficiency.

Synbiotic referred to a combination of probiotics and prebiotics, which were defined as bioactive substances or physiologically active feed ingredients with synergistic effects. The combination was intended to provide nutrient and carriers for probiotic bacteria and strengthen the effects of probiotics and prebiotics on ruminants (Michalak et al., 2021). Synbiotic was not just a combination of probiotics and prebiotics, but the components in their composition were synergistic (Bren et al., 2023). The use of synbiotics offerred greater potential to optimize nutrient utilization and improve economic and environmental sustainability of ruminants production systems.

Economic Implications of Improving Digestibility

Feed digestibility was an important issue that needed to be considered when preparing rations because it was closely related to its physicochemical composition (D. S. Martin et al., 2023). This was also an important indicator in measuring the quality of feed nutrient (Mayulu, 2023). Increasing nutritional digestibility in ruminants offerred significant economic benefits by optimizing feed utilization, reducing input costs, and increasing ruminants productivity, considering that feed was the largest expense in ruminants production (reaching 65 to 75% of total production costs) (Boudalia et al., 2024; Mayulu, 2021). Optimizing feed utilization to increase digestibility could be achieved through the use of feed processing technology (including supplementation of enzymes, probiotics, prebiotics, and synbiotics) and exploration of alternative feed resources (such as agricultural by-products). Improved digestibility suggested that ruminants used more energy and nutrient from lower-quality feed or generally cheaper by-products.

This approach allowed for more flexible and cost-effective feeding strategies, thereby reducing dependence on conventional feed ingredients such as high-quality grains or forages. Feed processing and treatment technology was also able to increase the availability of nutrient and good feed digestibility, thereby potentially reducing the overall amount of feed needed. Reducing feed costs was highly expected by livestock producers, specifically when feed prices were high or in areas with limited feed resources. A significant reduction in daily feed costs could increase economic efficiency by up to 57% (Boudalia et al., 2024). In addition, good nutritional digestibility resulted in increased ruminants performance which directly produced economic benefits. Increased feed conversion efficiency showed that ruminants grew faster or produced more production per unit of feed, resulting in higher overall output.

Conclusion

In conclusion, recent advances in ruminants nutrition described the importance of improving nutrient digestibility for economic benefit. Innovation and technology in feed processing (such as Handheld NIR spectroscopy devices, heating methods, precision grinding techniques, integrating ultrasonic treatment with enzyme supplementation and microwave-assisted alkali treatments), enzyme supplementation, specifically cellulase and xylanase combined with encapsulation techniques, probiotic, prebiotic and synbiotic supplementation could increase nutrient digestibility, fermentation rate, nutrient availability and nutrient absorption. This could lead to more efficient nutrient utilization. Increasing nutrient digestibility in ruminants offerred significant economic benefits, namely reducing input costs and increasing livestock productivity. In addition, the integration of various strategies along with the development of the livestock industry could be the key to increasing productivity and sustainability in ruminants production systems. Increasing nutrient digestibility could not only achieve higher productivity but also contributed to a more sustainable and efficient food production system and ensured the long-term continuity of ruminants production.

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