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Phytogenic Feed Additives in Ruminant Nutrition: Rumen Modulation, Performance, and Sustainability – A Review

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ABSTRACT

In order to satisfy consumer demands for natural and sustainable products, the livestock industry must adapt to stricter laws governing the use of antibiotic growth promoters (AGP). Phytogenic feed additives (PFAs) have drawn a lot of interest in this context as a substitute to enhance ruminant performance. Essential oils, polyphenols, saponins, tannins, and other plant-derived substances are all included in the large class of compounds known as PFAs. These substances include a wide variety of bioactive compounds that have intricate and multifaceted effects on the performance and health of ruminants. An overview of the state of knowledge regarding the application of PFAs in ruminant production is given in this review. It encapsulates their primary modes of action, which include host metabolism, digestive enzyme activity, and rumen microbiota modulation. The review specifically addresses PFAs' ability to alter rumen fermentation in a way that enhances volatile fatty acid (VFA) production, lowers ammonia concentration, and—above all—decreases enteric methane production. Examined are the ensuing impacts on productive performance. Because of their immunomodulatory, anti-inflammatory, and antioxidant qualities, which can lessen stress and increase resistance to disease, PFAs may also contribute to the advancement of animal welfare. The study also discusses some of the drawbacks of using PFAs, including response variability based on the plant source, extraction technique, dosage, and diet. This emphasizes how production and use of PFAs require standardization and quality control. This review paper concludes by summarizing the body of research on PFAs' use in ruminant production, including information on their mode of action, performance effects, possible health advantages, and environmental effects. Designing more sustainable and effective ruminant production systems that satisfy consumer demands and legal requirements is possible with the knowledge provided in this paper.

Introduction

Animals play a significant role in ensuring the world's food security. They supply billions of people worldwide with dietary protein in the form of meat and milk, and this number is predicted to rise as the world's population rises. For many years, the livestock industry has used feed additives to boost productivity, encourage growth, improve feed efficiency, and prevent disease. Before worries about antimicrobial resistance to antibiotic growth promoters (AGPs) became a growing public health concern, AGPs were used for many years. As a result, many nations or regions, including the European Union, have limited or outright prohibited their use [2]. In order to satisfy consumer demands for natural and ecologically friendly livestock production, there is a growing need for sustainable and feasible alternatives that can meet animal productivity requirements.

The most studied class of natural growth promoters is phytogenic feed additives (PFAs), sometimes referred to as phytobiotics or botanicals [3]. PFAs are made from a wide range of plants, such as herbs, spices, or their extracts. They are made up of intricate blends that include a wide variety of bioactive substances, including alkaloids, tannins, saponins, flavonoids, and essential oils [4]. Because they are produced by plants to defend themselves against animal predators, pathogens, or abiotic factors, these substances—also referred to as phytochemicals—are categorized as secondary metabolites. It has been demonstrated that including these compounds in ruminant diets can have beneficial physiological effects—discussed in the next sections—without running the risk of causing antibiotic resistance [5].

The primary site of action for PFAs in ruminants is the rumen. In order to release and synthesize nutrients that the animal can digest and absorb, the rumen—a fermentation vat full of bacteria, protozoa, fungi, and archaea—breaks down the cell walls of plants. By altering the fermentation pathways and enhancing digestive efficiency, the bioactive compounds found in PFAs have been demonstrated to change the activity and composition of this complex microbial community [4]. While some essential oils have been shown to have anti-methanogenic effects by targeting methanogenic archaea, which would reduce the production of enteric methane, a powerful greenhouse gas, others have been shown to have an antagonistic effect on bacteria that produce hyper-ammonia to improve nitrogen retention [6]. Given that rumen function plays a major role in determining the availability of nutrients like microbial protein and volatile fatty acids (VFAs), which are the byproducts of ruminal fermentation and provide the host with its primary source of amino acids and energy, respectively, PFAs may also affect nutrient metabolism in other areas of the gastrointestinal tract and, consequently, productive performance.

Beyond their activity in the gut, many PFAs may also have systemic effects because they are partially absorbed and biotransformed by the animal. The anti-inflammatory and antioxidant properties of many plant compounds are widely recognized. These characteristics may help them mitigate the adverse effects of environmental and metabolic stress, including heat stress and the metabolic stress experienced by dairy cows during their transition period [7]. These feed additives can therefore significantly impact the health, welfare, and resilience of the animal by modifying its immune response and antioxidant capacity [6]. Although the exact mechanisms underlying these advantages are unknown, they frequently have an impact on productive performance as well. According to reports, PFAs can enhance the growth performance of small ruminants and beef cattle, as well as the quantity and quality of milk produced by dairy cows and goats [1]. Additionally, they have been suggested as possible anti-parasitic or anti-mycotoxin additives, which could be employed as supplementary instruments for managing the health and nutrition of animals [8].

Despite the well-established advantages of PFAs, there are a number of obstacles to their practical implementation. First off, because these substances are extracted from natural sources, their chemical makeup can differ based on the plant's origin, location, harvesting time, and extraction technique. This could help to explain why responses to various PFAs can differ from one another. Numerous ongoing studies are focused on determining the ideal dosage as well as any possible interactions with other dietary ingredients or feed additives [9]. Furthermore, because PFAs are complex mixtures of several bioactive compounds, it can be difficult to understand how they work. To better understand their modes of action and the connections between the feed additive, the rumen microbiota, and the host's metabolism, "omics" technologies are needed.

We offer a current and thorough examination of the application of phytogenic feed additives in ruminant nutrition in this review. First, we go over the main types of PFAs, their bioactive ingredients, and how they work. We then assess how they affect animal health, productivity, and rumen fermentation and metabolism. We also discuss their potential to mitigate methane emissions and other pertinent environmental consequences. Lastly, we go over the main obstacles to their application and potential avenues for further study to help realize these natural compounds' potential in the creation of more effective and sustainable ruminant production systems [10].

Types and Bioactive Components of Phytogenic Feed Additives

A broad class of feed additives called phytogenic feed additives (PFAs), sometimes referred to as phyto-additives or phytobiotics, are used to increase the health and productivity of poultry and cattle [5]. Known for their abundant bioactive components, also referred to as phytochemicals, they are made up of a variety of plant-based ingredients, such as fruits, spices, herbs, and other botanicals [4]. When added to ruminant feed, these naturally occurring substances—secondary metabolites that plants produce to protect against predators, diseases, and environmental stressors—can have a number of beneficial biological effects. A PFA's chemical makeup, amount of active ingredients, and physical form all directly affect its activity; these factors can change depending on the plant's origin, growing environment, time of harvest, and processing technique [10]. The various PFA types, their main bioactive components, and their extraction and preparation techniques will all be covered in this section.

Taxonomy of Phytogenic Additives

Phytogenic feed additives are usually classified in a number of ways according to their physical form, botanical origin, plant part, and the main class of bioactive compounds they contain.

Taxonomy by Botanical Origin: A vast botanical library is the source of phytogenics. They are frequently divided into several general categories, such as:

• Herbs: The fresh or dried leafy green or flowering portion of a plant. Oregano (Origanum vulgare), peppermint (Mentha piperita), thyme (Thymus vulgaris), and rosemary (Rosmarinus officinalis) are common examples used for ruminant nutrition and are frequently high in phenolic compounds and essential oils.

• Spices: Any other plant part used for its strong or fragrant qualities, including the seed, fruit, root, or bark. Common spices like garlic (Allium sativum), ginger (Zingiber officinale), cinnamon (Cinnamomum verum), and clove (Syzygium aromaticum) contain a variety of active compounds, including gingerol (ginger) and allicin (garlic) [11].

• Fruits and Other Botanicals: Teas or extracts made from various plant materials, including fruits, herbs, and spices. Green tea extracts, grape pomace, and citrus peels are examples of this. Polyphenols like flavonoids and tannins are particularly abundant in this category.

Major Bioactive Compounds (Polyphenols, Essential Oils, Saponins)

Because PFAs contain a wide variety of bioactive compounds, they exhibit a wide range of biological activities. Although there may be hundreds of phytochemicals in a single plant, these are frequently divided into a few main chemical classes according to their characteristics and structure. Polyphenols, essential oils, and saponins are the most prevalent bioactive substances found in PFAs; each has a distinct mode of action [9].

• Flavonoids: Quercetin, green tea catechins, and anthocyanins, the largest class of plant phenols, are potent antioxidants that can scavenge free radicals and chelate metal ions, shielding cells from oxidative damage.

• Tannins: These high-molecular-weight polyphenols are well-known for their capacity to precipitate and bind proteins [12, 13]. Because of this trait, they can control rumen fermentation by preventing proteolytic bacteria, which can lessen the breakdown of proteins and the generation of ammonia [12][14]. On the other hand, palatability and nutrient digestibility may be adversely affected by elevated tannin levels [12]. Condensed tannins and hydrolyzable tannins are the two primary categories of tannins, and each has unique biological properties [12].

• Phenolic Acids: These substances, which include caffeic acid and gallic acid, have potent anti-inflammatory and antioxidant qualities [15].

Modes of Action

Phytogenic feed additives (PFAs) can work in a number of ways. Increased intestinal motility and the regulation of gut microbiota fermentation have been connected to PFAs' positive effects in ruminants [16]. They also improve the availability of nutrients at the level of the gastrointestinal tract [17]. PFAs have been demonstrated to modify systemic physiological pathways, particularly immune and antioxidant responses, in addition to these local effects [18]. A single PFA may benefit the host in a number of ways, either concurrently or sequentially.

Direct Antimicrobial and Anti-protozoal Effects in the Rumen

Targeting the Microbial Ecosystem's Composition: Phytogenic feed additives (PFAs) change the rumen's fermentation environment to improve fiber digestibility and possibly increase the host's nutritional value [19]. In order to effectively break down fibrous plant cell walls, the rumen is home to more than a thousand different species of bacteria, archaea, protozoa, and fungi [20]. PFAs can modify nutrient flow through the host to target more productive pathways by adjusting the populations of different microbial community members in the rumen [21]. PFAs have shown antimicrobial qualities against methanogens, protozoa, and ruminal bacteria, making them viable substitutes for antibiotic feed additives [20]. These supplements can boost immunity, milk production, and rumen fermentation [19].

Antimicrobial Activity

It has been demonstrated that bioactive substances, particularly essential oils and certain polyphenols, possess antimicrobial properties against rumen bacteria and other parasites and microbes that could infect ruminant gastrointestinal tracts. Since it is believed to be the main way that certain essential oils influence microbial fermentation in the rumen, their antimicrobial action is particularly significant. By dissolving in the lipid bilayer of microbial cell membranes, the lipophilic bioactive compounds increase the fluidity and disorder of the lipids and make the membrane more permeable. The dissipation of the proton motive force, the efflux of vital ions and metabolites, and ultimately cell death result from the disruption of membrane structure and permeability. Bioactive substances that have been demonstrated to have antimicrobial effects on the membranes of both Gram-positive and Gram-negative bacteria include terpenes like thymol and carvacrol.

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Specific Inhibition of Bacteria

Certain bacteria in the rumen are not affected by PFAs, so their antimicrobial effects are not universal. PFAs have the ability to selectively inhibit certain microorganisms, such as hyper-ammonia-producing (HAP) bacteria [24]. HAP bacteria ferment amino acids at a very high rate, resulting in the rapid release of ammonia. By using PFAs to inhibit the growth and activity of these bacteria, it is possible to lower the concentration of ammonia in the rumen [24], decrease the total amount of ammonia in the rumen, increase the flow of ammonia to more advantageous fermentation pathways, such as the production of microbial protein, which in turn improves the efficiency of nitrogen utilization [25], and decrease nitrogen excretion into the environment. Because HAP bacteria are a diverse group of bacteria, using PFA can also spare or stimulate fibrolytic bacteria, which are microbes that ferment cellulose and hemicellulose, which include Ruminococcus and Fibrobacter [4].

Anti-Protozoal Activity

One important element of the rumen microbiota is protozoa. Although they play a part in the breakdown of fiber, they are also significant rumen bacterial predators, which helps the rumen produce ammonia and turnover microbial proteins at extremely high rates. They also have methanogenic archaea inside their cells and on their surface as endosymbionts. Thus, there are two obvious benefits to ruminant productivity from defaunation (a decrease in the protozoal population) of the rumen microbiota. As a result, the host animal will emit less methane and the rumen will use nitrogen more efficiently [25].

Saponins are the most active anti-protozoal agents among the PFA group. These substances have the ability to attach to cholesterol on the protozoan cell membrane's surface, causing the cell to develop pores and ultimately lyse and die [26]. As a result, there would be less bacterial predation and a net outflow of microbial protein (high-quality protein) from the rumen to the small intestine. Additionally, it would prevent interspecies hydrogen transfer from protozoa to methanogens, which would reduce the production of methane [27]. It has also been demonstrated that essential oils have anti-protozoal properties [28].

Enzyme Modulation

PFAs' mode of action is significantly influenced by the inhibition and stimulation of enzymes. When plant extracts, essential oils, or isolated bioactive compounds are added to the diet, it is not unusual to observe evidence of multiple enzymes being modulated. Another potential mechanism for PFAs' effects on rumen nitrogen metabolism is the modulation of microbial urease, which was discussed in the previous section. Likewise, it has been demonstrated that certain PFA compounds alter deaminase activity in vitro. Deamination, the enzymatic removal of an amino group from a molecule, such as an amino acid, that produces ammonia, is carried out by deaminase enzymes [5]. Consequently, their inhibition also results in the diet's protein being preserved. Amylase, a starch-degrading enzyme that is also widely distributed in the saliva and small intestine of herbivores and monogastric animals, respectively, is another example of a microbial enzyme that has been shown to be impacted by PFAs. Since many PFAs have been demonstrated to increase fat digestibility in animals with monogastric digestion, a similar argument could be made for lipase, an enzyme that catalyzes the hydrolysis of dietary fats.

Antioxidant Activity

Once in circulation, absorbed bioactive compounds found in plant feed additives (PFAs) or their metabolites can affect systemic physiological pathways and metabolic processes outside of the digestive tract [29][30]. These substances have the ability to profoundly affect important metabolic pathways and host functions within the systemic circulation, which may change an animal's resilience, growth, and health [16]. Modification of the host's antioxidant defense system, specifically the activity of important antioxidant enzymes, is a well-documented effect. Plant-derived antioxidant compounds have the ability to upregulate these enzymes, which are essential for preserving redox homeostasis [30].

Animals with high metabolic demands, like dairy cows or broilers that grow quickly, produce more reactive oxygen species, which, if not sufficiently countered by antioxidant defense mechanisms, can cause cellular oxidative stress. In these situations, the activity of host enzymes such as glutathione peroxidase (GPx), catalase (CAT), and superoxide dismutase (SOD) can be changed by dietary supplementation with PFAs or bioactive compounds [29]. Animals are protected by antioxidant compounds in multiple ways:

1.Free radical scavenging: By contributing hydrogen atoms or electrons, a variety of substances neutralize free radicals [30].

2.Metal chelation: Certain compounds form complexes with transition metals, such as copper and iron ions, to stop them from taking part in reactions that produce free radicals [31].

3.Upregulation of endogenous antioxidant enzymes: By upregulating gene expression, a variety of antioxidant compounds provide long-term protection against oxidative stress by increasing the activity of endogenous antioxidant enzymes, including SOD, CAT, and GPx [32].

Particularly during times of high metabolic demand, like peak lactation, environmental stress (like heat stress), or the transition period, PFAs can support cellular health and functions and prevent oxidative damage by lowering oxidative stress [18].

Impacts on the Microbial Population and Rumen Fermentation

A dense and varied microbial population, comprising bacteria, archaea, protozoa, and fungi, is found in the rumen, a complex anaerobic fermentation environment [33]. The process by which this microbial ecosystem converts plant structural carbohydrates into absorbable end products is essential for ruminant productivity and is mostly regulated by the diet of the host animal [34]. The microbiota and its metabolic pathways can be directly impacted by PFAs and their bioactive compounds. One of the main ways that PFA supplements may enhance animal performance is by changing the ruminal environment [35].

Alterations in Rumen Microbiome Composition

One well-researched aspect of PFAs' effects on the rumen ecosystem is their antimicrobial activity, particularly that of essential oils and their constituents like thymol, carvacrol, and cinnamonaldehyde. They are lipophilic molecules that can directly inhibit microbial cellular machinery or interact with the phospholipid bilayers of microbial cell membranes to cause ion leakage or membrane rupture. Some essential oils or their isolated constituents can show selectivity in their microbial targets, indicating that the activity of many PFA components is not completely non-specific [35]. Ciliate protozoa are the primary target of the majority of PFAs. Because they are eventually digested and their amino acids recovered by the host animal, protozoa's consumption of bacteria and other microorganisms for nourishment is a significant source of intraruminal nitrogen recycling and a decrease in the net microbial protein outflow to the small intestine. Thus, fewer protozoa in the rumen reduce bacterial predation and may improve the efficiency of microbial protein synthesis [36]. PFAs, such as oils or extracts high in saponins, have frequently been demonstrated to reduce protozoal populations [27].

It has also been demonstrated that PFAs lower the number of bacteria known as hyper-ammonia-producing (HAP) bacteria, which are named for their quick deamination of amino acids and consequent overproduction of ammonia. Certain PFA compounds prevent the growth of HAP bacteria, which conserves dietary protein and frees up more peptides and amino acids for other microbes or for digestion and absorption. The only rumen microbes that produce methane, methanogenic archaea, are also susceptible to the antimicrobial activity. One of the most straightforward methods for reducing methane emissions is the use of essential oils and tannins, which have been shown to directly inhibit methanogens, or the H2-producing bacteria and protozoa with which they coexist [17]. According to a study that used 16S rRNA amplicon sequencing to characterize the rumen microbial population and found a direct correlation with changes in fermentation patterns, the population of buffalo calf rumen microbes was found to change significantly with phyto-additive supplementation [18]. The primary cause of the rumen microbial landscape shifting in favor of a more efficient fermentation profile that reduces energy and protein loss is this selective antimicrobial activity, which is essential to PFA benefits.

Impact on Volatile Fatty Acid (VFA) Production

Up to 70% of the host animal's metabolizable energy intake is made up of the volatile fatty acids (acetate, propionate, and butyrate), which are the primary byproducts of rumen fermentation and its primary energy source [38]. Propionate is a direct gluconeogenic precursor and is utilized as an energy source more effectively than acetate, and the VFA ratio also has significant effects on metabolism [39]. Therefore, a decrease in the acetate-to-propionate (A: P) ratio is typically regarded as an improvement in overall fermentation and energy efficiency [40].

PFAs' capacity to modify the microbial community and its metabolic pathways is also connected to their impact on VFA production and relative ratios [41]. Certain additives encourage the production of VFAs with higher nutritional value for the host by altering microbial populations. For example, the inhibition of microbes that produce H2 will divert H2 from being available to methanogens to other metabolic pathways, such as the production of propionate from lactate or fumarate [40]. In addition to directly increasing energy yield, this effect has a significant indirect impact on reducing methane [42]. Numerous PFA compounds have been shown to raise total VFA concentrations; although this may just be the result of increased substrate fermentation, such outcomes are not unusual [43]. Effects, however, vary greatly and may even go against the grain in various contexts and studies [44]. Numerous factors, including PFA type and dosage, basal diet, and animal species, may contribute to this discrepancy [40][41]. The A: P ratio is typically lower in these situations, though some studies may not show a change in total VFA while others do [45].

Influence on pH and Ammonia Concentration

Acidosis can result from rapid pH drops brought on by high substrate intakes or rapid fermentation rates; rumen pH is a primary determinant of the health of the microbial ecosystem and an indirect indicator of the health status of the host animal [46]. The production of VFA and the buffering ability of saliva, which can be diluted by water and feed intake, determine the pH of the rumen [47]. By changing fermentation rates, PFAs may have an indirect impact on rumen pH [31]. Some PFAs can modulate the activity of starch-fermenting bacteria and prevent large pH fluctuations in high-concentrate diets, which can experience rapid pH drops when substrate fermentation exceeds the buffering capacity of feed and saliva [48]. Rumen ammonia nitrogen (NH3-N) is an intermediate in nitrogen metabolism that provides rumen microbes with their only source of nitrogen. However, the ammonia generated is taken up into the bloodstream, transformed into urea by the liver, and eliminated in significant amounts by the kidneys when the rate of protein degradation exceeds the rate at which rumen microbes can use the resulting peptides and amino acids. Many of the active ingredients in PFAs, such as tannins and essential oils, have demonstrated the capacity to lessen this loss of dietary nitrogen, which is a loss of dietary protein and an energy drain on the animal [5]. By binding dietary protein, tannins can prevent excessive rumen degradation and increase the amount of bypass protein that can pass through the rumen and be absorbed in the small intestine. Additionally, essential oils have the ability to directly suppress HAP bacterial activity, which lowers the rumen's rate of amino acid deamination [4]. It has also been demonstrated that other PFA ingredients, such as carvacrol, have this latter effect. Improved nutrient utilization results from a decrease in ruminal NH3-N because more nitrogen is effectively utilized for microbial protein synthesis and less energy is lost on urea synthesis. Calves' rumen fermentation characteristics were altered in comparison to controls when the effects of phyto-feed additives on fermentation patterns, including rumen ammonia concentration, were examined [18].

Impact of PFAs on Nutrient Digestibility and Metabolism

The final and rate-limiting stages in the production of animal products like meat, milk, and wool are the digestive process and the use of nutrients derived from feed. They are therefore of paramount importance to the animal producer, and post-absorptive metabolism is directly and significantly impacted by the modulatory effects of PFA supplementation on the rumen environment, rumen fermentation, and nutrient digestion. PFAs have the ability to improve the breakdown of complex feed ingredients and the host animal's utilization of the nutrients released by this process by changing fermentation patterns and boosting the efficiency of microbial ecosystems [20]. PFA use has been associated with improvements in growth rates, feed conversion, and animal performance [6], and this increase in digestive efficiency is one of the main mechanisms behind the beneficial effects of PFA supplementation.

Enhancement of Fiber and Protein Digestibility

The enzymes generated by fibrolytic rumen microbes are the only ones that can break down structural carbohydrates (fiber) like cellulose and hemicellulose [49]. Thus, the digestion of fiber is particularly crucial for the nutrition of ruminants that consume forages high in fiber. PFA can have both beneficial and detrimental effects on the digestion of fiber, particularly when taken in large quantities. Broad-spectrum antimicrobial substances, like essential oils, can suppress the digestion of fiber by indiscriminately reducing the activity of helpful cellulolytic bacteria at high dosages [50]. Nonetheless, the use of PFAs can be beneficial at more suitable dosages [51]. PFAs lower the rate of bacterial predation in the rumen and promote the growth of a more resilient fiber-digesting microbial community by suppressing protozoal populations [52]. By stabilizing rumen pH and avoiding sharp or abrupt drops, which can be harmful to pH-sensitive cellulolytic microbial species, these additives can also aid in the digestion of fiber [34].

As was previously mentioned, PFAs influence protein digestibility by modifying the rumen's nitrogen metabolism. Therefore, substances like tannins and essential oils that lower the rate of amino acid deamination and ammonia production or shield dietary protein from excessive rumen degradation can also increase rumen escape protein levels. For high-producing animals whose amino acid needs might not be satisfied by microbial protein alone, protein conversion to RUP or bypass protein rather than RDP can be especially advantageous [53]. Therefore, the efficiency of protein utilization is directly increased when the small intestine receives more high-quality dietary protein. Furthermore, nitrogen is more effectively utilized for microbial protein synthesis, which is a high-quality protein source for the host animal, as a result of the decrease in ammonia production and the increase in microbial biomass outflow from the rumen [16]. There is a consistent trend that many phyto-additives can improve nutrient digestibility, even though the majority of studies examining the impact of PFAs on digestibility have been conducted in non-ruminant species [16]. It has been demonstrated that one of the primary mechanisms by which this effect is accomplished is the increased stimulation of the digestive process, including the secretion of enzymes [52].

Improvement in Feed Intake and Feed Conversion Ratio

The main factor influencing growth is feed intake, which phyto-additives may be able to influence [54]. PFAs may increase intake through their aroma and effects on gut health, but highly aromatic essential oils may decrease feed intake if used in high concentrations [54][55]. The feed conversion ratio (FCR), which calculates how much feed is needed to support one unit of animal

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weight gain, is where the effects are most frequently seen. When the animal's FCR increases, it gains weight more effectively and uses less feed to achieve the same weight [54]. PFA supplementation can alter this metric, mainly by altering the effectiveness of nutrient utilization. The animal can access more dietary energy and protein when nutrient digestibility is improved [54]. More energy is available for the animal's growth when rumen fermentation is made more efficient, for instance, by producing more propionate and lowering energy loss to methane [21]. The animal has more amino acids for muscle deposition because of advancements in microbial protein synthesis and the delivery of dietary protein to the small intestine [52][31]. Goats given various additives have shown improvements in FCR, which is one of the main causes of reported increases in nutrient digestibility [52][16]. Although no changes in feed intake were noted in that study, this effect was also reported in beef cattle given certain additives [56]. Because increased feed efficiency lowers the cost of feed for meat production as well as the environmental impact per unit of meat produced, it is a clear way that improvements in nutrient utilization also translate into financial and environmental savings [55].

The new goal was not to totally stop methane production [21]. For the animal's long-term health, it is neither practical nor always desirable to completely stop the rumen's production of methane. Anaerobic fermentation must produce methane as a byproduct. In order to preserve the rumen's redox balance and guarantee the fermentation process' sustainability, some flux is unavoidable and required. Therefore, the goal is to achieve equilibrium by lowering methane to a level that is sustainable for the environment without impairing animal productivity [21].

Conclusion and Future Perspectives

In the post-antibiotic growth promoter era, phytogenic feed additives (PFAs) have become reputable and versatile nutritional tools for ruminant production systems. PFAs can positively alter the microbial ecology and fermentation pathways of the rumen, improving nutrient uptake, increasing productivity, and significantly lowering enteric methane emissions, according to the data compiled in this review. Selective antimicrobial and anti-protozoal activities, changes in ruminal enzyme activity, changes in volatile fatty acid profiles toward more energetically efficient pathways, and systemic improvements in antioxidant and immune status are the main mechanisms underlying these effects.

PFAs have an impact on rumen function, but they also improve animal health and welfare by reducing metabolic and oxidative stress, especially in high-yielding animals and during physiologically taxing times like early lactation or environmental heat stress. Enhancements in microbial protein synthesis, feed efficiency, and nitrogen utilization further demonstrate their potential to improve ruminant production systems' environmental sustainability and financial profitability. Crucially, PFAs are positioned as promising elements of climate-smart livestock strategies due to their ability to lower methane emissions without sacrificing rumen function.

Notwithstanding these benefits, reactions to PFAs are still unpredictable and situation-specific, depending on a variety of elements, including the plant's source, chemical makeup, dosage, diet, animal species, and stage of production. The need for careful selection, standardization, and quality control of phytogenic products is highlighted by the potential negative effects that inappropriate formulations or excessive inclusion levels may have on digestibility or product quality. Furthermore, the precise identification of causal mechanisms is made more difficult by the complex and synergistic nature of phytochemical mixtures.

To clarify the relationships between PFAs, rumen microbiota, and host metabolism, future research should concentrate on dose-response relationships, long-term in vivo studies, and the use of cutting-edge "omics" technologies. Formulation techniques that optimize efficacy while guaranteeing consistency and safety in commercial production settings should also receive more attention.

Phytogenic feed additives, in summary, are an environmentally sound and scientifically validated strategy for enhancing ruminant sustainability, health, and productivity. PFAs can be crucial in creating resilient, effective, and low-emission ruminant production systems that meet contemporary consumer demands and legal requirements if they are developed and implemented strategically.

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الإضافات الغذائية النباتية في تغذية المجترات: تنظيم بيئة الكرش والأداء والاستدامة – مراجعة

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الملخص

لإرضاء احتياجات المستهلكين من المنتجات الطبيعية والمستدامة، يجب على صناعة الماشية التكيف مع القوانين الأكثر صرامة التي تحكم استخدام المحفزات الحيوية للنمو .(AGP) لقد جذبت المضافات الغذائية النباتية (PFAs) الكثير من الاهتمام في هذا السياق كبديل لتعزيز أداء المجترات. تشمل هذه الفئة الكبيرة من المركبات المعروفة باسم PFAs الزيوت الأساسية، والبوليفينولات، والصابونين، والتانينات، وغيرها من المواد المستمدة من النباتات. تحتوي هذه المواد على مجموعة واسعة من المركبات الحيوية النشطة التي لها تأثيرات معقدة ومتعددة الأوجه على أداء وصحة المجترات. يقدم هذا الاستعراض نظرة عامة على حالة المعرفة فيما يتعلق بتطبيق PFAs في إنتاج المجترات. يوضح طرق عملها الأساسية، والتي تشمل تمثيل المضيف، ونشاط إنزيمات الهضم، وتعديل ميكروبيوم الكرش. يتناول الاستعراض بشكل خاص قدرة PFAsعلى تغيير عملية التخمير في الكرش بطريقة تعزز إنتاج الأحماض الدهنية الطيارة (VFA) وتخفض تركيز الأمونيا وتقلل، قبل كل شيء، من إنتاج الميثان الانتقائي. يتم فحص التأثيرات الناتجة على الأداء الإنتاجي. قد تساهم PFAs أيضًا في تحسين رفاهية الحيوان بفضل خصائصها المنشطة للمناعة، والمضادة للالتهابات، ومضادات الأكسدة، التي يمكن أن تخفف من الضغط وتزيد من مقاومة الأمراض. تناقش الدراسة أيضًا بعض العيوب المتعلقة باستخدامPFAs ، بما في ذلك تباين الاستجابة بناءً على مصدر النبات، ووسيلة الاستخراج، والجرعة، والنظام الغذائي. وهذا يبرز كيف أن إنتاج واستخدام PFAs يتطلبان التوحيد القياسي ومراقبة الجودة. تختتم هذه الورقة المراجعة بتلخيص الأبحاث حول استخدام PFAsفي إنتاج المجترات، بما في ذلك المعلومات حول طريقة عملها، وتأثيرات الأداء، والفوائد الصحية المحتملة، والتأثيرات البيئية. من الممكن تصميم أنظمة إنتاج مجترات أكثر استدامة وفعالية تلبي احتياجات المستهلكين والمتطلبات القانونية بفضل المعرفة المقدمة في هذه الورقة.

الكلمات المفتاحية: الاضافات الغذائية النباتية – ميكروبيوم الكرش ، تخمير الكرش ، الميثان