Effects of Feed Additives on Performance, Nutrient Digestibility, Feed Intake, and Health of Weaned Calves: A Review

Virna Ananda Zulkarnaen[1], Yulianri Rizki Yanza[2], Sauland Sinaga[3], *Ainissya Fitri[4]

[1]Faculty of Animal Husbandry, Universitas Padjadjaran, Sumedang 45363, West Java, Indonesia

[2]Department of Animal Nutrition and Feed Technology, Faculty of Animal Husbandry, Universitas Padjadjaran, Sumedang 45363, West Java, Indonesia

[3]Department of Animal Production, Faculty of Animal Husbandry, Universitas Padjadjaran, Sumedang 45363, West Java, Indonesia

[4]Research Center for Applied Zoology, National Research and Innovation Agency (BRIN), Bogor 16911, West Java, Indonesia

***Corresponding Author**

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ABSTRACT

The weaning transition period, spanning 3-6 months of age, is a critical physiological phase marked by rumen development, immune system maturation, and heightened susceptibility to nutritional stress in beef and dairy calves. In recent years, phytogenic and bioactive feed additives, including tannins, saponins, essential oils (EOs), amino acids (AAs), and phenolic compounds, have emerged as promising alternatives to antibiotic growth promoters (AGPs). This review systematically examined the effects of these additives on average daily gain (ADG), feed intake, nutrient digestibility, and health parameters in weaned calves aged 3–6 months. Low to moderate doses of hydrolysable tannins (0.1-3% dry matter intake) enhance nitrogen retention and either maintain or slightly increase average daily gain without compromising nutrient digestibility. EO blends at optimal doses (150–600 mg/kg DM) improved feed intake, dry matter digestibility, and immune markers, including immunoglobulins and antioxidant enzyme activity. Rumen-protected lysine and methionine supplementation are critical for maximizing growth and nitrogen retention. The combined use of these additives shows synergistic potential, although controlled trials in the 3–6-month age group remain limited. Optimizing the dose, form, and combination strategy is essential for practical application in calf nutrition.

Keywords: Tannins, essential oils, phenolic compounds, amino acids, weaned calves, feed additives

INTRODUCTION

The weaning period is one of the most physiologically stressful phases in the life of beef and dairy calves. Calves weaned between 3 and 6 months of age undergo simultaneous challenges, including dietary transitions from liquid to solid feed, rumen microbiome establishment, social separation stress, and rapid immunological maturation. These compounding stressors often result in reduced feed intake, impaired growth performance, and elevated susceptibility to respiratory and enteric diseases, collectively known as weaning stress syndrome (Kholif, 2023; Campolina et al., 2023; Özdemir, 2025).

Conventionally, antibiotic growth promoters (AGPs) are used to control pathogenic bacteria and improve feed conversion efficiency in poultry. However, increasing global concerns regarding antimicrobial resistance, stricter regulatory frameworks, and consumer demand for antibiotic-free animal products have accelerated the search for natural, sustainable alternatives. Phytogenic feed additives (PFAs), bioactive compounds derived from plants, represent promising alternatives owing to their multifunctional properties, including antimicrobial,

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antioxidant, anti-inflammatory, and rumen-modulating activities (Campolina et al., 2023; Biyik et al., 2023; Luo et al. 2024; Kholif, 2023).

The most studied PFAs in ruminant nutrition are tannins, saponins, essential oils (EOs), and phenolic compounds (PCs). Tannins are polyphenolic secondary metabolites, classified as either condensed (proanthocyanidins) or hydrolyzable, and are known for their ability to bind to dietary proteins and influence rumen fermentation. Saponins, glycoside compounds found in legumes and medicinal plants, act as natural rumen modifiers by suppressing ciliate protozoa, improving nitrogen use efficiency, and modulating volatile fatty acid (VFA) profiles (Al Rharad et al 2025; Yanza et al. 2021; Yanza et al. 2024). Essential oils, volatile aromatic compounds extracted from plants, possess broad-spectrum antimicrobial and antioxidant properties, modulate rumen microbial communities, and promote gut health in young ruminants (Özdemir, 2025; Campolina et al., 2023; Biyik et al., 2023; Luo et al., 2024). Additionally, amino acid supplementation, particularly rumen-protected lysine and methionine, addresses key nutritional bottlenecks in young calves by improving protein synthesis, immune development, and hepatic metabolism (Zou et al., 2023).

Although phytogenic additives have been widely studied in adult ruminants, calves aged 3–6 months remain underexplored. This age range is significant because it marks the critical period when the rumen actively develops and transitions into function. This is the period when dietary interventions are most likely to produce lasting "metabolic programming" effects, influencing rumen architecture, immune competence, and nitrogen use efficiency in adult life. Studies have shown that calves at this stage may particularly benefit from targeted dietary supplements (Özdemir, 2025; Campolina et al., 2023).

This review aimed to synthesize existing research on the effects of added tannins, saponins, essential oils, phenolics, and amino acids on weaned calves aged (3-6) months in terms of growth performance, nutrient intake and digestibility, and health indicators.

Effects of Feed Additives on Performance, Nutrient Digestibility, and Feed Intake

Tannins

Tannins are classified into two major categories: condensed tannins (CT) and hydrolyzable tannins (HT). Their biological effects in ruminants depend substantially on the type, source, dose, and physiological condition of the animal. In weaned and growing calves, tannin supplementation exhibited dose-dependent effects on growth performance and nutrient utilization.

Hydrolysable tannins (0.1–3% DMI) at low-to-moderate doses consistently enhance nitrogen retention by decreasing urinary nitrogen excretion and increasing fecal nitrogen, a shift resulting from the formation of tannin–protein complexes that reduce ruminal protein degradation and improve post-ruminal amino acid flow (Table 1). Zhang et al. (2024) reported that tannin extract supplementation improved ADG by modulating nitrogen metabolism and enhancing serum antioxidant enzyme activities in Simmental fattening cattle. Similarly, a meta-analysis by Yanza et al. (2021) demonstrated that tannin extracts at recommended doses maintain or slightly improve ADG across ruminant species, whereas high doses of condensed tannins (>50 g/kg DM) are associated with decreased dry matter (DM), organic matter (OM), and neutral detergent fiber (NDF) digestibility.

Table 1. Summary of Effects of Tannin Supplementation on Performance and Nutrient Digestibility in Calves and Heifers

Additive Type	**Dose**	**ADG Effect**	**DMI Effect**	**Digestibility**	**N Retention**	**Reference**
HT (extract)	0.1–3% DMI	↑ or ↔	↔	↔ (low dose)	↑	Al Rharad et al. (2025); Yanza et al. (2021)

CT (condensed)	>50 g/kg DM	↓	↓	↓ DM, NDF, CP	↓	Al Rharad et al. (2025); Yanza et al. (2021)
Encapsulated tannin	Moderate	↔	↔	↔	↑	Oliveira et al. (2025)
HT + milk (calves)	Low-moderate	↑	↔	↔	↑	Serri et al. (2022)
Mixed HT+CT	0.1–3% DMI	↔	↔	↔	↑	Al Rharad et al. (2025); Yanza et al. (2021)

Note: ↑ = increase; ↓ = decrease; ↔ = no significant effect; HT = hydrolysable tannin; CT = condensed tannin; DMI = dry matter intake; DM = dry matter; NDF = neutral detergent fiber; CP = crude protein; N = nitrogen

Liu et al. (2025) found that in calves, supplementing tannin during the preweaning period altered rumen fermentation parameters and microflora composition, affecting protozoa and bacteria populations in a way that suggested more efficient fermentation. Serri et al. (2022) showed that adding hydrolyzable tannin extracts to calf milk enhanced calf performance, blood metabolites, and decreased pathogen shedding, thereby validating the use of tannins during the crucial transition period. Yuste et al. (2019) examined the transition from milk/pasture to high-concentrate diets in beef calves and found that tannins modulated bacterial dynamics in a manner supportive of rumen health.

Regarding feed intake, most studies indicate that tannins at optimal doses (0.1–3% DMI) do not significantly reduce dry matter intake (DMI), as confirmed by meta-analysis data. However, high doses of condensed tannins negatively affect palatability and reduce voluntary intake through astringency. Tannin encapsulation has been proposed as a strategy to mitigate these negative palatability effects while preserving their beneficial properties.

Essential Oils

Essential oils (EOs) are complex mixtures of volatile compounds, including terpenoids, phenylpropanoids, and other secondary metabolites derived from aromatic plants such as oregano (*Origanum vulgare*), thyme (*Thymus vulgaris*), cinnamon (*Cinnamomum zeylanicum*), lemon grass (*Cymbopogon citratus*), and rosemary (*Rosmarinus officinalis*) (de Sousa et al., 2023; Özdemir, 2025; Campolina et al., 2023). Their primary bioactive components, including thymol, carvacrol, eugenol, citronella, and cinnamaldehyde, exhibit antimicrobial, antioxidant, and anti-inflammatory properties.

EOs used at appropriate doses in milk, milk replacer (MR), or starter feed increased feed intake, average daily gain (ADG), and feed efficiency (FE) in pre-weaned calves (Table 2). A meta-analysis by Ferreira et al. (2024) demonstrated that EO supplementation in beef cattle improved intake, performance, and ruminal fermentation profiles, with increased propionate and decreased acetate-to-propionate ratios. In dairy heifers, Campolina et al. (2021) reported that a commercial blend of EOs (anise, cinnamon, garlic, rosemary, and thyme) administered in milk replacer at 1 g/day improved intestinal development, with heavier pancreas and small intestines, larger ileum villi, and higher cecal butyrate concentrations, while maintaining nutrient digestibility comparable to that of the control.

In Simmental calves receiving an EO blend in both milk and starter feed, body weight at weaning was 6.58% higher than that of the controls, with concurrent improvements in IGF-1 and lower fecal scores, suggesting better digestive health and growth (Özdemir, 2025). A study on Holstein steers demonstrated that oregano essential oil improved rumen development, rumen functionality, and microorganism composition, further supporting the rumen-priming role of EOs during early life (Luo et al., 2024).

Importantly, a dose-response relationship has been established: optimal doses (150–600 mg/kg DM) consistently enhance digestibility and ADG, whereas excessive doses reduce digestibility and impair rumen fermentation (Ferreira et al., 2024). Microencapsulation has been shown to provide more stable and sustained delivery of EO active compounds, improving their efficacy and reducing potential palatability issues (Campolina et al., 2021; Campolina et al., 2023).

Table 2. Effects of Essential Oil Blends on Performance and Digestibility in Weaned/Pre-Weaned Calves

EO Blend / Type	Dose	ADG	DMI	Digestibility	Health Effect	Reference
Anise, cinnamon, garlic, rosemary, thyme	1 g/day (MR)	↔ descriptive	↔	↔	↑ intestinal villi, ↑ cecal butyrate	Campolina et al. (2023)
Rosemary EO	0.5 g/day	↑	↑	↑	↑ blood antioxidant, ↓ fecal score	Biyik et al. (2023)
Oregano EO	4 g/day	↑ ADG	↑	↑ DM, fiber	↑ IgG, microbiome modulation	Luo et al. (2024); Özdemir (2025)
Commercial EO blend	150–600 mg/kg DM	↑	↑	↑	↑ IgA, IgM, ↓ TNF-α, IL-6	Wang et al. (2025)
Orange EO	500 mg/kg DM	↑	↔	↑ NDF, ADF	↑ antioxidant	Wang et al. (2025)

Note: ↑ = increase; ↓ = decrease; ↔ = no significant effect; MR = milk replacer; DM = dry matter; IgG/A/M = immunoglobulins

Amino Acid Supplementation (Lysine and Methionine)

Lysine and methionine are the most limiting amino acids for growth and nitrogen retention in young ruminants. During the weaning transition in calves aged 3–6 months, the rumen microbiome has not yet developed the protein synthesis capacity needed to meet the demands of an animal that is rapidly growing on solid feed. Without dietary supplementation, deficits in these two amino acids indirectly lead to reduced growth and impaired metabolic function (Seleem et al., 2025).

Rumen-protected forms of lysine and methionine can solve this problem by bypassing ruminal degradation and improving duodenal amino acid flow, protein synthesis, and overall nitrogen retention. A study on Holstein steer calves confirmed that supplementation with rumen-protected methionine and lysine improved feedlot performance and digestion characteristics without impairing nutrient digestibility (Zou et al., 2023). The optimal lysine-to-methionine ratio (Lys:Met ratio of approximately 100:32) has been established to maximize growth and nitrogen retention in heifers aged 7–9 months (Kong et al., 2021).

Kong et al. (2021) demonstrated that amino acid deficiency, particularly lysine deficiency, significantly reduced ADG, feed efficiency, and nitrogen retention in heifers. This study highlighted that lysine is the first limiting amino acid for growth, whereas methionine plays a complementary role. Zou et al. (2023) found that supplementing rumen-protected lysine and methionine reduced overall protein requirements in Holstein bulls. This supplementation altered nitrogen metabolism in the liver, demonstrating a clear protein-sparing effect.

Additionally, amino acid supplementation improves intestinal morphology, gut barrier integrity, and immune gene expression in growing calves. Gebeyew et al. (2021) found that low-protein diets supplemented with methionine and lysine altered gut microbial composition and improved immune status in growing lambs, an effect that may similarly apply to weaned calves (Gebeyew et al., 2021). The critical molecular pathways include hepatic lipid metabolism modulation, epigenetic regulation and protein biosynthesis (Kong et al., 2021).

Effects of Feed Additives on Calf Health

Immune System Modulation by Tannins

Tannins exert immunomodulatory effects through multiple pathways in weaned calves. At the molecular level, tannins enhance the antioxidant defense system by increasing serum superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GSH-Px) activities while reducing malondialdehyde (MDA) concentrations. Zhang et al. (2024) reported significant improvements in serum antioxidant indices in Simmental fattening cattle receiving tannin extract supplementation, along with lower levels of oxidative stress biomarkers (Zhang et al., 2024).

In pre-weaning calves, tannin supplementation through milk has been shown to modulate blood metabolite profiles and pathogen shedding, suggesting direct gastrointestinal health benefits. Serri et al. (2022) demonstrated that hydrolyzable tannins in calf milk reduced the shedding of enteric pathogens and improved blood metabolite profiles, likely through direct antimicrobial effects on pathogenic bacteria in the gastrointestinal tract (Serri et al., 2022). The antimicrobial activity of tannins against *Escherichia coli*, *Salmonella* spp., and *Clostridium perfringens* has been well studied and is attributed to their ability to bind microbial proteins and disrupt cell membrane function (Yanza et al., 2021).

Tannins modulate the systemic immune response by influencing leukocyte populations and immunoglobulin production. Snider et al. (2025) reported that dietary inclusion of tannin-based supplements improved health outcomes in yearling beef heifers grazing endophyte-infected tall fescue, demonstrating health-protective effects. At the rumen level, tannins reduce urinary nitrogen excretion, thereby lowering environmental ammonia exposure, which is associated with respiratory health benefits in housed calf-rearing systems (Yanza et al., 2021).

In terms of blood biochemical parameters, tannin supplementation has been associated with improved serum albumin and total protein levels, lower blood urea nitrogen (BUN), and normalization of hepatic enzyme activities, collectively indicating improved liver function and metabolic health (Ren et al., 2023). However, high doses of condensed tannins can induce oxidative stress and impair liver function, emphasizing the importance of dose management (Al Rharad et al., 2025).

Health-Promoting Effects of Essential Oils

Essential oils have emerged as one of the most comprehensively studied natural feed additives for calf health, demonstrating immunomodulatory, antioxidant, and antimicrobial properties (Ferreira et al., 2024).

A meta-analysis specifically focused on serum immune and biochemical indicators in suckling calves demonstrated that EO supplementation significantly increased serum immunoglobulin (IgA, IgG, and IgM) levels, enhanced lymphocyte proliferation, and reduced pro-inflammatory cytokine (TNF-α and IL-6) levels (Wang et al., 2025; Nora et al., 2024). These effects are directly manifested as reduced morbidity and mortality during the high-risk weaning period. Luo et al. (2024) showed that oregano essential oil supplementation in calves regulated rumen microbiota composition and increased serum antibody levels, providing both direct immune stimulation and indirect benefits through microbiome modulation (Luo et al., 2024).

Campolina et al. (2023) demonstrated that a blend of EOs in milk replacer led to significantly improved intestinal morphology in dairy calves, including heavier small intestines and larger ileum villi. These structural improvements enhance the absorptive surface of the gut, supporting better nutrient utilization and stronger intestinal barrier function against pathogen invasion (Campolina et al. 2023). The blend of EOs in calves also showed lower eosinophil counts and respiratory tract weights, suggesting reduced inflammatory responses and better respiratory health (Campolina et al., 2021).

Biyik et al. (2023) found that rosemary essential oil supplementation in pre-weaning Holstein calves improved blood antioxidant parameters, reduced fecal scores (indicating lower incidence of diarrhea), and improved rumen fermentation, supporting its practical utility as a health additive (Biyik et al., 2023). EO supplementation has been shown to reduce the incidence of diarrhea and respiratory disease in calves, the two most common causes of pre- and post-weaning mortality in cattle production systems worldwide (Özdemir, 2025).

Plant extracts supplied to pre-weaned dairy calves improved redox status, as evidenced by lower levels of oxidative stress markers (Liu et al., 2025). The antioxidant effects of EOs are attributed to their phenolic terpene components (thymol, carvacrol, and eugenol), which directly scavenge reactive oxygen species and upregulate endogenous antioxidant enzyme expression (de Sousa et al., 2023).

Table 3. Health Effects of Feed Additives in Calves: Summary of Key Immunological and Biochemical Outcomes

Feed Additive	Health Outcome	Mechanism	Evidence Level	Reference
Tannins (HT)	↑ SOD, CAT, GSH-Px; ↓ MDA	Antioxidant activity	In vivo (cattle)	Zhang et al. (2024)
Tannins (HT)	↓ Pathogen shedding	Antimicrobial (membrane disruption)	In vivo (calves)	Serri et al. (2022)
Saponins (QS)	↑ Immune adjuvant activity	Antigen-presenting cell stimulation	Review	Kholif (2023)
Saponins	↑ Microbial protein synthesis	Defaunation (↓ protozoa)	Meta-analysis	Yanza et al. (2024)
Essential oils	↑ IgA, IgG, IgM; ↓ TNF-α, IL-6	Immunomodulatory	Meta-analysis (calves)	Wang et al. (2025)
Essential oils	↑ Intestinal villi height	Gut development	In vivo (dairy calves)	Campolina et al. (2023)
Essential oils	↓ Fecal score, ↓ diarrhea	Antimicrobial, microbiome	In vivo (calves)	Biyik et al. (2023); Luo et al. (2024)
Amino acids (Lys, Met)	↑ Gut barrier integrity; ↑ villus height	Protein synthesis, immune gene expression	In vivo (lambs/heifers)	Gebeyew et al. (2021); Kong et al. (2021)

Note: ↑ = increase/improvement; ↓ = decrease/reduction; HT = hydrolysable tannin; QS = Quillaja saponaria; Lys = lysine; Met = methionine; SOD = superoxide dismutase; CAT = catalase; GSH-Px = glutathione peroxidase; MDA = malondialdehyde; IgA/G/M = immunoglobulins; TNF-α = tumor necrosis factor-alpha; IL-6 = interleukin-6

Amino Acids and Calf Immune Health

The immunological significance of amino acid adequacy in weaned calves is substantial and often underappreciated in practical nutritional programs. Lysine deficiency during the weaning period has been shown to impair gut barrier integrity, reduce villous architecture quality, and suppress immune gene expression, collectively increasing the risk of disease in calves transitioning to solid diets (Kong et al., 2021).

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Gebeyew et al. (2021) demonstrated that lambs on low-protein diets supplemented with methionine and lysine showed altered gut microbial composition, with an increase in beneficial commensal bacteria (Lactobacillus spp. and Bifidobacterium spp.) and a reduction in potentially pathogenic species (Gebeyew et al., 2021). This microbiome shift has downstream effects on immune priming, competitive exclusion of pathogens, and mucosal immunity. The same study reported an improved immune status, as evidenced by higher serum IgG and IgA concentrations in the amino acid-supplemented group (Gebeyew et al., 2021).

Rumen-protected lysine and methionine have been shown to improve hepatic function in growing calves by modulating lipid metabolism, reducing the risk of fatty liver, and supporting the synthesis of acute-phase proteins (Kong et al., 2021). The importance of methionine in supporting immune function is further highlighted by its role as a methyl group donor in epigenetic regulation, influencing gene expression patterns that govern immune competence and stress responses (Seleem et al., 2025).

The practical recommendation for weaned calves is to supplement diets with rumen-protected Lys and Met at a Lys:Met ratio of approximately 100:32, which has been validated for maximizing both growth performance and immune development (Zou et al., 2023). Supplementation is particularly critical when calves are fed corn-soybean meal-based diets, which are typically deficient in metabolizable lysine (Kong et al., 2021).

Table 4. Recommendation of an optimal dose Ranges for Feed Additives in Weaned Calves (3–6 Months)

Feed Additive	Optimal Dose Range	Form	Target Effect	Key Caution
Hydrolysable tannins	0.1–3% DMI	Powder / encapsulated	↑ N retention, ↑ ADG, ↓ methane	Avoid >3% DMI (↓ digestibility)
Condensed tannins	<1% DMI	Powder	Antimicrobial, antioxidant	Avoid >50 g/kg DM
Essential oils (blends)	150–600 mg/kg DM	Microencapsulated	↑ performance, ↑ immunity	Dose-response: avoid excess
Rumen-protected Lys	Per Lys:Met ≈ 100:32	Encapsulated	↑ growth, ↑ N retention	Cost consideration
Rumen-protected Met	Per Lys:Met ≈ 100:32	Encapsulated	↑ immune function, hepatic	Combined with Lys

Note: ↑ = increase; ↓ = decrease; ↔ = no significant effect

Combined Supplementation and Synergistic Potential

Individual additive studies provide a compelling case for combined supplementation strategies in weaned calves aged 3–6 mo. The co-administration of tannins, saponins, essential oils, rumen-protected amino acids, and phenolic compounds appears to target different but complementary biological pathways, suggesting the possibility of additive or synergistic interactions. Repetto et al. (2025) found that finishing steers fed a total mixed ration supplemented with a blend of essential oils, tannins, and bioflavonoids showed improvements in average daily gain and rumen fermentation parameters similar to those achieved with monensin, a commonly used conventional ionophore (Repetto et al., 2025). This finding has substantial practical relevance given the increasing regulatory restrictions on the use of ionophores and antibiotic growth promoters in major livestock-producing regions. Furthermore, Zhang et al. (2021) found that blending origanum oil, hydrolyzable tannins, and tea saponin significantly reduced enteric methane output in both in vitro fermentation systems and in vivo ruminant models, highlighting the environmental benefits of phytogenic combinations (Zhang et al., 2021).

Collectively, these observations suggest that multicomponent phytogenic formulations may offer a biologically and economically viable alternative to conventional chemotherapeutic additives in calf-rearing programs.

The combination of tannins with rumen-protected amino acids represents one of the most mechanistically coherent and practically promising co-supplementation strategies identified in recent studies. Oliveira et al. (2025) showed that combining microencapsulated escape lysine with hydrolyzable tannins as a protective adjuvant in sheep feed led to improved post-ruminal nitrogen flow, nitrogen retention, and growth compared to unsupplemented controls (Oliveira et al., 2025). The dual protein-sparing mechanism, which involves dietary tannins reducing ruminal protein degradation and rumen-protected amino acids providing a consistent supply of duodenal metabolizable lysine and methionine, is theoretically sound and consistent with the established principles of bypass protein nutrition (Zou et al., 2023; Kong et al., 2021). Microencapsulation technologies present a particularly attractive delivery platform for combined phytogenic additives from a formulation standpoint, providing targeted gastrointestinal release profiles, improved thermal and oxidative stability during feed processing, and mitigation of palatability-reducing volatile losses (Campolina et al., 2023). The practical implication of this approach is the potential to reformulate calf starter diets with reduced crude protein inclusion levels without compromising the supply of metabolizable amino acids, which is a strategy that simultaneously lowers feed costs, reduces urinary nitrogen excretion, and diminishes the environmental burden of intensive calf-rearing systems.

Despite these promising developments, a critical limitation hinders the direct translation of current evidence into age-specific nutritional guidelines for 3–6-month-old calves. Most available data come from studies on adult beef or dairy cattle, finishing steers, or small ruminants, with relatively few controlled trials specifically targeting the post-weaning transitional period in calves (Al Rharad et al., 2025; Yanza et al., 2021). This distinction is not trivial. Calves aged 3–6 months occupy a unique physiological niche characterized by rapid and dynamic rumen epithelial development, ongoing microbial community succession, progressive attenuation of passive immunity, and a critical metabolic shift from milk-based energy substrates to volatile fatty acid-based fermentative metabolism (Yanza et al., 2024; Luo et al., 2024). These developmental characteristics create a biological context in which additive interactions, dose-response relationships, and adverse effect thresholds may differ substantially from those established in mature animals. High doses of condensed tannins, for example, have been shown to impair nutrient digestibility and suppress rumen fermentation in adult cattle (Al Rharad et al., 2025; Yanza et al., 2021); however, the tolerance thresholds in structurally and functionally immature rumen epithelia of weaned calves remain poorly characterized. Similarly, the optimal EO dose range of 150–600 mg/kg DM reported in meta-analyses of adult cattle (Ferreira et al., 2024) may not directly translate to calves, whose rumen volume, microbial diversity, and epithelial absorptive capacity are still undergoing maturation.

There is a pressing need for rigorously designed, age-stratified randomized controlled trials that investigate the individual and combined effects of tannins, saponins, essential oils, rumen-protected amino acids, and phenolic compounds in calves over the 3–6-month transition period. Future studies should incorporate comprehensive outcome measures encompassing rumen fermentation indices, gut morphology, systemic immune biomarkers (IgG, IgA, IgM, and cytokine profiles), oxidative stress markers, and growth performance parameters, along with multi-omics characterization of the rumen and intestinal microbiomes. Integrating metagenomics, metabolomics, and transcriptomics into this research area would significantly enhance the understanding of the mechanisms underlying phytogenic synergy and enable the detection of early response biomarkers for real-time nutritional tracking. Furthermore, the development of precision nutrition frameworks that account for individual variation in rumen microbiome maturation status, breed, and pre-weaning management history would enhance the clinical utility and commercial scalability of combined phytogenic supplementation strategies in intensive and semi-intensive calf production systems.

CONCLUSION

The weaning transition period between 3 and 6 months of age represents a critical physiological and metabolic window for beef and dairy calves. This review highlights that phytogenic and bioactive feed additives, specifically tannins, essentials oils, and rumen-protected amino acids serve as potent, sustainable alternatives to conventional antibiotic growth promoters (AGPs) by targeting distinct yet complementary physiological pathways. Hydrolyzable tannins (0.1-3% DMI) succesfully optimize nitrogen efficiency and enhance post-ruminal amino acid flow without compromising nutrient digestibility, while also reducing enteric pathogen shedding. Meanwhile, essential oil blends (150-600 mg/kg DM) consistenly improve dry matter intake, average daily gain (ADG), and gut morpholigal development (such as villus height), while bolstering systemic immunity throught elevated immunoglobulin levels (IgA, IgG, IgM) and reduced diarrhea incidence. Additionally, rumen-protected Amino Acids (Lys:Met ≈ 100:32) mitigate the biological bottlenecks of an immature rumen by directly improving protein biosynthesis, nitrogen retention, and hepatic metabolic health. Furthermore, multi-component formulations such as combining microencapsuled essentials oils, tannins, and amino-acids demonstrate significant synergistic potential. This co-supplementation strategy offers a dual benefit: it mimics the performance-enhancing effects of conventional ionophores while providing a clear protein-sparing effect that reduces both feed costs and environmental nitrogen/methane emissions.

Author Contributions

All authors contributed equally to this work.

Conflict Of Interest

Authors declare that they have no conflict of interests.

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