



International Journal of Veterinary Sciences and Animal Husbandry



ISSN: 2456-2912

NAAS Rating (2026): 4.61

VET 2026;SP-11(5): 01-09

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www.veterinarypaper.com

Received: 02-02-2026

Accepted: 05-03-2026

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Phytogenic feed additives in animal nutrition: Multifunctional roles in productivity, gut health and emission mitigation

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DOI: <https://www.doi.org/10.22271/veterinary.2026.v11.i5Sa.3243>

Abstract

Phytogenic feed additives have undergone extensive testing in swine production to determine their effects on gas- trointestinal function and health, as well as their implications for pigs' systemic health and welfare, flock production efficiency, food safety, and environmental impact. These feed additives derived from plants, encompassing herbs, spices, fruits, and various plant components, contain numerous bioactive ingredients. An examination of published documents concerning the supplementation of phytogenic feed additives uncovers conflicting findings about their efficacy in swine production. This suggests that additional effort is required to ascertain the suitable inclusion levels and thoroughly clarify their mechanisms of action. This review aims to summarise the prevailing trends in the application of phytogenic feed additives in poultry, emphasizing their effects on growth performance, nutrient digestibility, biochemical profiles, gene expression, hypocholesterolemic properties, immunity, meat quality, fatty acid composition, amino acid content, and the gut microbiota of swine.

Keywords: Antibiotic growth promoters, Anti-inflammatory, Growth performance, Phytogenics, Swine

Introduction

Livestock production is fundamental to global food security, providing high-quality animal-derived proteins such as meat and milk, which are rich in essential amino acids and critical micronutrients including heme iron, vitamin B12, vitamin D3, zinc, and calcium (Pulina *et al.*, 2017; Caprarulo *et al.*, 2022) [10, 48]. With the continuous growth of the global population, there is increasing pressure on animal production systems to enhance productivity, efficiency, and sustainability while ensuring food safety and minimizing environmental impact.

A major objective of modern livestock farming is to reduce dependence on synthetic inputs such as antibiotics, hormones, and other xenobiotics. Feed additives have therefore become an essential component of animal nutrition strategies, as they improve feed quality, enhance nutrient utilisation, support digestion, mitigate anti-nutritional factors, and promote growth performance, while also strengthening disease resistance and metabolic efficiency (Singh, 2015; Silveira *et al.*, 2021) [55, 57]. These additives are broadly classified into technological, sensory, nutritional, and zootechnical categories, as well as coccidiostats and histomonostats (Karásková *et al.*, 2015; Pandey *et al.*, 2019; Purba *et al.*, 2020) [24, 46, 49], and include compounds such as probiotics, prebiotics, enzymes, organic acids, immunomodulators, and phytogenic substances.

Historically, antibiotic growth promoters (AGP) have been widely used to enhance livestock productivity. However, growing concerns regarding antimicrobial resistance and public health risks led to regulatory interventions, most notably the European Union ban on antibiotic growth promoters 2006 (Stevanović *et al.*, 2018; Pandey *et al.*, 2019; Franz *et al.*, 2020; Skoufos *et al.*, 2020) [15, 46, 58, 60]. Despite this, antibiotics continue to be used in some regions due to limited regulatory enforcement and insufficient monitoring data (Sampath *et al.*, 2023)

[52]. The withdrawal of AGP has been associated with challenges such as reduced growth performance, increased incidence of enteric diseases, impaired nutrient absorption, and higher microbial load in the gastrointestinal tract, particularly in *swine* production systems (Kikusato, 2021; Muniyappan *et al.*, 2021; Sampath *et al.*, 2023) [26, 45]. Consequently, the development of effective and safe alternatives to AGP has become a critical research priority (Jha and Berrocoso, 2015) [22].

Among the proposed alternatives, phytogetic feed additives (PFA), also known as phytogetics, phytoiotics, or plant-derived bioactive compounds, have gained considerable attention.

These additives are derived from herbs, spices, fruits, and other plant materials and contain a wide range of bioactive constituents, including polyphenols, flavonoids, alkaloids, quinones, terpenoids, and essential oils (Yang *et al.*, 2015) [74]. The use of plant-based compounds in animal nutrition is not new; historical evidence indicates their application in livestock care dating back to ancient Mesopotamia around 2600 BC (Franz *et al.*, 2020) [15].

Phytogetic compounds exhibit diverse biological activities, including antimicrobial, antioxidant, anti-inflammatory, antifungal, antiparasitic, and immunomodulatory effects (Zhai *et al.*, 2018; Kuralkar and Kuralkar, 2021) [29, 77]. These properties contribute to improved gut health, enhanced immune function, and better nutrient utilisation. In *ruminants*, phytogetics modulate rumen fermentation, alter microbial populations, reduce methane emissions, and improve feed intake, palatability, and productivity parameters such as milk yield and growth rate (Artuso-Ponte *et al.*, 2020; Purba *et al.*, 2020) [4, 49]. In *swine*, phytogetic supplementation has been shown to improve gastrointestinal function, enhance digestive enzyme activity, modulate gut microbiota, and increase nutrient digestibility and growth performance (Peng *et al.*, 2021; Szabó *et al.*, 2023) [47, 63].

Several plant-derived compounds have demonstrated specific functional benefits. For instance, quillaja saponin has been reported to enhance growth performance, nutrient utilisation, and gut microbiota in pigs (Muniyappan *et al.*, 2022a) [44], while chestnut wood extract improves antioxidant status and intestinal health (Biagi *et al.*, 2010) [6]. Phytogetic supplementation has also been shown to reduce diarrhoea in weaned pigs challenged with *E. coli* K88 and improve immune and metabolic indicators (Li *et al.*, 2015; Cairo *et al.*, 2018) [8, 31]. Similarly, compounds such as limonene and carvacrol improve energy utilisation and productivity in *ruminants* (Varga-Visi *et al.*, 2023) [67], while plant-based additives including *Coleus amboinicus* and composite plant extracts enhance rumen fermentation, nutrient utilisation, and meat quality while reducing methane emissions (Yanza *et al.*, 2022) [75].

The mechanisms of action of phytogetic feed additives are complex and involve multiple pathways, including modulation of gastrointestinal and rumen microbiota, stimulation of digestive enzyme activity, enhancement of gut integrity, and reduction of oxidative stress (Singh and Gaikwad, 2020). Additionally, phytogetics contribute to environmental sustainability by reducing ammonia, hydrogen sulfide, and other harmful gas emissions associated with livestock production.

From an economic perspective, the global phytogetics market reflects increasing adoption, with estimates indicating growth from 500.46 million USD in 2024 to 613.94 million USD by 2029 (Kazempoor *et al.*, 2022) [25]. This trend underscores the

growing demand for natural, antibiotic-free production systems and highlights the commercial relevance of phytogetic additives.

Despite these promising attributes, variability in efficacy across studies remains a challenge, largely due to differences in plant composition, dosage, and experimental conditions. The concentration of bioactive compounds can vary significantly depending on plant source, processing, and storage conditions, which complicates standardisation. Advanced approaches such as metagenomics, transcriptomics, proteomics, and network pharmacology offer new opportunities to elucidate the mechanisms and optimise the application of phytogetic feed additives in livestock systems.

Therefore, this review aims to provide a comprehensive synthesis of the role of phytogetic feed additives as natural alternatives to antibiotic growth promoters in livestock production. It focuses on their effects on growth performance, nutrient utilisation, gut health and microbiota, antioxidant and antimicrobial activity, immune function, product quality, and environmental emissions. By integrating evidence across ruminant and *swine* systems, this review seeks to support the development of sustainable and efficient feeding strategies for modern livestock production.

Literature Search Strategy

To obtain a comprehensive understanding of the effects of dietary supplementation with phytogetic feed additives (PFA) on livestock health and performance, an extensive literature survey was conducted. A total of 180 studies were systematically selected from multiple scientific databases, including ScienceDirect, PubMed, Scopus, Google Scholar, and Web of Science.

The search strategy was designed to ensure broad coverage of relevant research across ruminant and monogastric systems. Specific keywords were employed, including “phytogetic feed additives,” “*ruminants*,” “*cow*,” “*sheep*,” “*goat*,” “*buffalo*,” “growth performance,” “carcass traits,” “ruminal fermentation,” “antioxidant,” “immunity,” “antimicrobial,” “methane and ammonia emission,” “milk composition,” “blood metabolites,” and “meat quality.”

This structured approach enabled the compilation of a robust dataset encompassing multiple dimensions of animal production. The selected studies provided insights into the influence of PFA on rumen fermentation dynamics, greenhouse gas emissions (methane and ammonia), milk production and composition, reproductive performance, blood biochemical profiles, antioxidant and antimicrobial activities, immune responses, and meat quality attributes. Collectively, this methodology ensured a comprehensive and multidimensional evaluation of phytogetic feed additives in livestock systems.

Phytogetic Feed Additives: Concept and Functional Basis

Phytogetic feed additives (PFA), also referred to as phytoiotics or phytochemicals, encompass plant-derived natural compounds, herbal formulations, and bioactive extracts incorporated into animal diets to enhance feed quality, animal performance, and product quality (Wang *et al.*, 2024) [68]. These additives are commonly derived from herbs, spices, and plant extracts, and may also be classified based on their origin and processing methods, such as Chinese herbal additives or plant extract-based formulations.

The use of herbal remedies in human health dates back over 3,000 years (van Wyk and Prinsloo, 2020) [66], while their application in livestock production extends over two

millennia (Gong *et al.*, 2014; Bhosale *et al.*, 2025) [5, 16]. Over time, phytogetic compounds have gained recognition for their beneficial effects on animal performance, including improvements in body weight, feed conversion ratio, and meat quality. Subsequent research has demonstrated their antimicrobial, antiviral, antifungal, antioxidant, and anti-inflammatory properties, which underpin their functional role in animal nutrition.

Phytogenics act through multiple biological pathways, including modulation of nutrient metabolism, enhancement of immune responses, and improvement of gut health. Their mode of action differs fundamentally from antibiotic growth promoters (AGP), as they do not suppress microbial populations indiscriminately but rather promote a balanced intestinal ecosystem. Advances in extraction technologies and identification of active constituents have further strengthened their potential as natural alternatives to antibiotics. Additionally, phytogetic additives are generally considered safe, cost-effective, environmentally friendly, and widely applicable in livestock production systems (Gong *et al.*, 2014) [16].

Effects of Phytogetic Feed Additives on Growth Performance

The reduction and eventual removal of AGP from animal diets have intensified research into phytoegenics as alternative growth promoters, particularly in *swine* production systems. Unlike AGP, which primarily reduce microbial load and intestinal inflammation (Windisch *et al.*, 2008) [69], phytoegenics enhance growth performance by modulating the intestinal environment, strengthening gut barrier integrity, promoting beneficial microbiota, and stimulating digestive enzyme secretion (Ali *et al.*, 2021) [3].

Phytogetic supplementation has been associated with improvements in key growth performance indicators, including average daily gain (ADG), average daily feed intake (ADFI), gain-to-feed ratio (G:F), and body weight gain (BWG). For instance, supplementation with green tea leaves and pomegranate extracts significantly improved ADG and

G:F compared to control diets (Bontempo *et al.*, 2014) [7]. Similar improvements in growth performance have been reported with various herbal extracts (Lan *et al.*, 2017) [30].

Specific phytogetic compounds and plant sources have demonstrated notable effects (table 1). Extracts of *Scutellaria baicalensis* and *Lonicera japonica* increased feed intake and body weight gain (Liu *et al.*, 2016) [35]. A mixture of essential oils containing eucalyptol, p-cymene, linalool, anethole, and thymol improved reproductive and growth parameters in piglets (Reyes-Camacho *et al.*, 2020) [50]. Herbal mixtures comprising buckwheat, thyme, curcuma, black pepper, and ginger enhanced BW, ADG, and G:F in weaning piglets (Yan and Kim, 2012) [72]. Similarly, combinations of herbal extracts such as *Astragalus membranaceus*, *Codonopsis pilosula*, and *Salvia miltiorrhiza* improved growth performance indices (Kong *et al.*, 2007) [27].

Additional studies have reported enhanced growth performance with phytoegenics such as bitter citrus extract, thymol, carvacrol, sage, nettle, lemon balm, coneflower, *Coptis chinensis*, *Silybum marianum*, *Eucommia ulmoides*, turmeric, *Yucca schidigera*, and garlic (Sampath *et al.*, 2020; Hsu *et al.*, 2022; Dang *et al.*, 2022) [11, 21, 51]. For example, supplementation with *Yucca schidigera* and Quillaja saponaria increased feed intake and ADG by up to 8.6% compared to control diets, likely due to improved nutrient utilisation and energy efficiency (Ma *et al.*, 2022b) [10, 33].

However, the effects of phytoegenics on feed intake remain inconsistent. Reported variations range from -9% to +12% (Wang *et al.*, 2024) [68] and -3% to +19% (Abdelli *et al.*, 2021) [1], suggesting that increased intake may not necessarily reflect feed preference but could be a consequence of improved growth rates (Windisch *et al.*, 2008) [69]. Several studies have reported no significant effects on growth performance parameters, including BW, ADFI, and feed conversion ratio (Li *et al.*, 2012a; Frankič *et al.*, 2010) [14, 32]. These inconsistencies may be attributed to differences in experimental conditions, phytogetic composition, dosage, animal age, and health status.

Table 1 Effects of Phytogetic Feed Additives on Performance, Health and Environmental Parameters in Ruminants and Swine

Species	Phytogetic Additive	Main Effects	Key Parameters Affected	Author (Year)
Ruminants	Essential oils + prebiotics	↑ Growth performance	ADG, DMI, FCR	Liu <i>et al.</i> (2020) [36]
Ruminants	Cinnamon, turmeric, rosemary, clove	↑ Growth under heat stress	BW, ADG, DMI	Hashemzadeh <i>et al.</i> (2022) [17]
Ruminants	Red propolis extract	↑ Nutrient digestibility	CP, OM digestibility	Morsy <i>et al.</i> (2021) [43]
Ruminants	Oregano essential oil	↑ Growth & gut microbiota modulation	BW, microbiota	Sun <i>et al.</i> (2022) [62]
Ruminants	Tannin extract	↓ Performance at high dose	Milk yield, DMI	Aguerre <i>et al.</i> (2016) [2]
Ruminants	Citral oil	Altered rumen fermentation	VFA profile	Canaes <i>et al.</i> (2017) [9]
Ruminants	Propolis	↑ Fermentation efficiency, ↓ methane	VFA, CH ₄	Soltan and Patra (2020) [59]
Ruminants	Coleus amboinicus	↓ Methane emission	Methanogens	Yanza <i>et al.</i> (2022) [75]
Swine	Herbal extracts (green tea, pomegranate)	↑ Growth performance	ADG, G:F	Bontempo <i>et al.</i> (2014) [7]
Swine	Essential oils mixture	↑ Growth & reproduction	BW, piglet survival	Reyes-Camacho <i>et al.</i> (2020) [50]
Swine	Quillaja saponin	↓ Diarrhea	Diarrhea score	Muniyappan <i>et al.</i> (2022a) [44]
Swine	Mulberry leaf extract	↑ Growth & microbiota	Lactobacillus ↑, Campylobacter ↓	Ma <i>et al.</i> (2022b)
Swine	Forsythia suspensa	↑ Immunity & gut health	IgA, microbiota	Long <i>et al.</i> (2019) [37]
Swine	Essential oils + organic acids	↓ Diarrhea & inflammation	TNF-α, IL-6	Xu <i>et al.</i> (2020) [70]
Swine	Achyranthes japonica	↑ Digestibility	DM, CP, GE	Liu and Kim (2021) [36]
Swine	Black pepper	↓ Fecal gas emission	NH ₃ , methyl mercaptans	Sampath <i>et al.</i> (2020) [51]
Swine	Essential oils	↓ Pathogens	E. coli ↓, Lactobacillus ↑	Li <i>et al.</i> (2012a)
Swine	Grape seed extract	↑ Antioxidant status	T-AOC, GSH-Px	Feng <i>et al.</i> (2023) [13]
Swine	Capsicum extract	↑ Immunity, ↓ inflammation	IL-6, TNF-α	Long <i>et al.</i> (2021a) [38]

Effects of Phytogetic Feed Additives on Nutrient Digestibility

Phytogetic feed additives have been widely studied for their effects on nutrient digestibility, which is a critical determinant of animal performance. These additives enhance digestive efficiency by stimulating enzyme secretion, improving gut morphology, and modulating intestinal microbiota.

Several studies have reported significant improvements in the digestibility of dry matter (DM), crude protein (CP), gross energy (GE), organic matter (OM), and ether extract (EE) following phytogetic supplementation. For example, herbal extracts containing buckwheat, thyme, curcuma, black pepper, and ginger increased DM and CP digestibility in pigs (Yan *et al.*, 2012; Bhosale *et al.*, 2025) [5, 72]. Similarly, supplementation with *Achyranthes japonica* extract improved DM, CP, and GE digestibility in growing and finishing pigs (Kumar *et al.*, 2021) [28].

Other phytogetic compounds, such as *Silybum marianum* (Hossain *et al.*, 2023) [18], *Forsythia suspensa* (Long *et al.*, 2021b) [36, 38], and black pepper (Sampath *et al.*, 2020) [51], have also demonstrated positive effects on nutrient digestibility. Improvements in intestinal morphology, including increased villus height and villus height-to-crypt depth ratio, have been associated with enhanced nutrient absorption (Long *et al.*, 2021b).

Essential oil-based phytogetics, such as cinnamaldehyde, thymol, and menthol-containing blends, have been shown to improve ileal digestibility of crude protein and amino acids (Yan *et al.*, 2010b) [73]. Similarly, supplementation with medicinal plants (Zhao *et al.*, 2016) [78] and compounds such as quillaja saponin (Muniyappan *et al.*, 2022a) [44] has been linked to enhanced nutrient utilisation.

Despite these positive findings, inconsistent results have also been reported. Some studies have shown no significant effects or even negative impacts of phytogetic supplementation on nutrient digestibility (Hossain *et al.*, 2024) [19]. These discrepancies are likely due to variations in phytogetic composition, dosage, animal physiological status, and experimental conditions.

Role of Phytogetic Feed Additives in Diarrhea Control and Intestinal Health

Diarrhea is a common and economically significant disorder in swine production, particularly during the weaning phase, when piglets are exposed to multiple stressors including dietary transition, environmental changes, and pathogen challenge (Muniyappan *et al.*, 2023). Postweaning diarrhea, frequently associated with *Escherichia coli* infection, leads to dehydration, reduced growth performance, and increased mortality, thereby imposing substantial economic losses (Muniyappan *et al.*, 2023).

Phytogetic feed additives (PFA) have emerged as effective nutritional interventions for mitigating diarrhea through multiple biological mechanisms. These include modulation of immune responses, enhancement of intestinal barrier integrity, antimicrobial activity, and antioxidant effects. Bioactive compounds such as curcumin and flavonoids reduce gut inflammation by downregulating pro-inflammatory cytokines, including tumor necrosis factor- α (TNF- α) and interleukin-6 (IL-6) (Ding *et al.*, 2021) [12]. Cytokines, which are low-molecular-weight proteins involved in immune signaling, play a central role in regulating inflammatory responses (Taranu *et al.*, 2010) [64].

Phytogetics also strengthen intestinal barrier function by promoting the expression of tight junction proteins, reducing

intestinal permeability, and preventing bacterial translocation. Additionally, they enhance humoral and cellular immunity by stimulating immunoglobulin production (e.g., IgA) and activating immune cells such as macrophages, dendritic cells, and T lymphocytes.

The antimicrobial properties of phytogetics further contribute to diarrhea control. Compounds such as thymol, carvacrol, tannins, and saponins inhibit the growth of pathogenic bacteria including *E. coli* and *Clostridium perfringens*. For example, dietary supplementation with quillaja saponin significantly reduced diarrhea scores in pigs (Muniyappan *et al.*, 2022a) [44], while essential oil supplementation decreased diarrhea incidence in weaned piglets (Ma *et al.*, 2022a) [10, 33]. Several studies have demonstrated that phytogetics can alleviate *E. coli*-induced diarrhea (Deng *et al.*, 2007) [27].

Further evidence highlights the role of phytogetics in oxidative stress mitigation and intestinal health. Stevia residue extract increased antioxidant enzyme activities, including superoxide dismutase (SOD), glutathione peroxidase (GSH-PX), and total antioxidant capacity (T-AOC), while reducing malondialdehyde (MDA) levels and intestinal permeability in piglets (Liu *et al.*, 2022b) [33]. Similarly, *Forsythia suspensa* extract reduced diarrhea incidence and duration, enhanced serum immunoglobulin levels, and inhibited *E. coli* colonization (Long *et al.*, 2019) [37]. Herbal supplementation has also been associated with increased beneficial bacteria and reduced pathogenic populations in fecal microbiota (Zhao *et al.*, 2016) [78].

Additional studies have demonstrated that phytogetics modulate gene expression related to intestinal barrier integrity. For instance, mulberry leaf extract improved the expression of mucin-2, occludin, and claudin-1, while enhancing digestive enzyme activities and reducing pathogenic bacteria in piglets (Ma *et al.*, 2023) [41]. Combined supplementation of essential oils and organic acids reduced diarrhea scores, downregulated pro-inflammatory cytokines, and improved intestinal barrier function in piglets challenged with enterotoxigenic *E. coli* (Xu *et al.*, 2020) [70]. Furthermore, lactoferricin B has been shown to modulate mucosal transcriptomics and reduce pathogen-induced diarrhea (Hou *et al.*, 2011) [20].

Overall, phytogetic feed additives exert multifaceted protective effects against diarrhea by integrating antimicrobial, immunomodulatory, antioxidant, and barrier-enhancing mechanisms.

Modulation of Gut Microbiota by Phytogetic Feed Additives

The gut microbiota plays a fundamental role in host nutrition, metabolism, immune function, and overall health. However, its complex interactions with dietary components and host physiology are not yet fully understood. Phytogetic feed additives have been widely investigated for their capacity to modulate gut microbial communities and improve intestinal health.

Phytogetics exhibit well-documented antimicrobial properties, with generally stronger activity against Gram-positive bacteria compared to Gram-negative species (Windisch *et al.*, 2008) [69]. Their antimicrobial action is dose-dependent and may involve disruption of microbial cell membranes, inhibition of enzyme systems, and interference with microbial metabolism (Thapa *et al.*, 2012) [65]. Importantly, phytogetics do not indiscriminately suppress microbial populations but rather promote a balanced microbiota by inhibiting pathogenic bacteria and supporting

beneficial microbial groups.

Key phytogetic compounds, including tannins, flavonoids, saponins, and essential oils, contribute to gut health by competitively excluding harmful bacteria and modulating immune responses within the gastrointestinal tract (Zeng *et al.*, 2015) [76]. Numerous studies have demonstrated their effects on microbial fermentation, enzyme activity, and microbial composition (Cairo *et al.*, 2018; Wang *et al.*, 2020; Long *et al.*, 2021a) [8, 36, 38].

For example, supplementation with thymol and cinnamaldehyde reduced *E. coli* populations in the cecum, colon, and rectum, while improving the *Lactobacillus*-to-*E. coli* ratio (Li *et al.*, 2012a) [32]. Red pepper essential oil increased *Lactobacillus* counts and reduced *Enterobacteria* and diarrhea incidence in piglets (Cairo *et al.*, 2018) [8]. Similarly, essential oils containing eugenol, thymol, and piperine reduced *Escherichia-Shigella* and *Campylobacter* populations (Silva Júnior *et al.*, 2020) [54].

Herbal extracts have also been shown to enhance beneficial microbial populations. Increased levels of lactic acid bacteria and *Bifidobacterium*, along with reduced *Enterobacteriaceae* and *Campylobacter jejuni*, were observed following herbal supplementation (Kafantaris *et al.*, 2018) [23]. Likewise, supplementation with quillaja saponin, *Achyranthes japonica*, and *Silybum marianum* increased fecal *Lactobacillus* counts and reduced *E. coli* populations (Muniyappan *et al.*, 2022a; Hossain *et al.*, 2023) [18, 44].

Phytogenics also influence microbial metabolites. For instance, supplementation with Alliaceae extract increased beneficial bacterial populations and enhanced the production of short-chain fatty acids such as propionic and branched-chain fatty acids (Sánchez *et al.*, 2020) [53]. Stevia residue extract increased the abundance of microbial families such as *Lachnospiraceae* and *Prevotellaceae* and enhanced fermentation metabolites in the colon (Liu *et al.*, 2022b) [33]. Additionally, increased populations of *Bifidobacterium* and *Lactobacillus*, along with reduced *E. coli*, were associated with improved propionic acid production and reduced serum cholesterol levels (Su *et al.*, 2018) [61].

Overall, phytogetic feed additives contribute to gut microbial homeostasis by selectively modulating microbial populations, enhancing beneficial bacteria, suppressing pathogens, and improving fermentation profiles. These effects collectively support improved nutrient utilisation, immune function, and overall animal health.

Immunomodulatory Effects of Phytogetic Feed Additives

The intestinal immune system represents a critical interface between the host and its environment, where physical, microbial, and immunological barriers collectively determine disease resistance. Phytogetic feed additives influence immune responses through complex molecular and cellular mechanisms involving both innate and adaptive immunity.

Phytogetic compounds interact with immune signaling pathways by binding to Toll-like receptors (TLR) on intestinal epithelial and immune cells, leading to activation of key intracellular pathways such as nuclear factor kappa B (NF- κ B) and mitogen-activated protein kinase (MAPK) (Zhou *et al.*, 2014). These pathways regulate the expression of pro-inflammatory cytokines, including tumor necrosis factor- α (TNF- α), interleukins (IL-1 β , IL-6), monocyte chemoattractant protein-1 (MCP-1), and interferon- γ (IFN- γ). Phytogenics modulate these inflammatory responses by either stimulating or suppressing cytokine production, thereby maintaining immune homeostasis. They enhance lymphocyte

proliferation, macrophage phagocytic activity, and natural killer cell function, contributing to improved host defense (Abdelli *et al.*, 2021) [1]. Additionally, they influence immunoglobulin production, including Ig A, Ig M, and secretory Ig A, which play essential roles in mucosal immunity (Zhao *et al.*, 2022) [62].

Several studies highlight the anti-inflammatory effects of phytogetic compounds. Essential oils such as thymol and cinnamaldehyde reduced serum IL-6 levels while increasing lymphocyte counts and growth-related factors (Li *et al.*, 2012a) [32]. Capsicum extract decreased pro-inflammatory cytokines (TNF- α , IL-1 β , IL-6) and modulated immune responses through inhibition of the NF κ B pathway (Mendivil *et al.*, 2019) [42]. Similarly, *Forsythia suspensa* reduced inflammatory cytokines while enhancing antioxidant enzyme activity and immunoglobulin levels (Long *et al.*, 2021b) [36, 38].

Oxidative stress is closely linked to inflammation, and phytogenics play a crucial role in regulating antioxidant defense systems. The nuclear factor erythroid 2-related factor 2 (Nrf2) pathway is a central regulator of antioxidant responses, controlling the expression of detoxifying enzymes and protecting against oxidative damage (Yamamoto *et al.*, 2018) [71]. Phytogetic supplementation has been shown to activate Nrf2 signaling while inhibiting NF- κ B-mediated inflammation, thereby reducing intestinal disease risk (Su *et al.*, 2018) [61].

Overall, phytogetic feed additives exhibit strong immunomodulatory properties through coordinated regulation of inflammatory pathways, antioxidant systems, gut barrier function, and microbial interactions. These effects collectively contribute to improved disease resistance, intestinal health, and overall animal performance.

Biochemical Indicators and Oxidative Status

Biochemical parameters serve as critical indicators of metabolic status, immune function, and physiological well-being in livestock. Numerous studies have evaluated the influence of phytogetic feed additives (PFA) on these indicators, demonstrating their role in modulating metabolic and antioxidant pathways (Wang *et al.*, 2024) [68].

Phytogetic additives such as *Forsythia suspensa* have also demonstrated improvements in hematological parameters, including increased red blood cell counts and serum IgA levels in weaning pigs (Long and Piao, 2021) [36, 38]. In addition, grape seed proanthocyanidin extract significantly enhanced antioxidant capacity by increasing total antioxidant capacity (T-AOC), glutathione (GSH), and glutathione peroxidase (GSH-Px), while reducing malondialdehyde (MDA) levels and improving lipid profiles (Feng *et al.*, 2023) [13]. These hypocholesterolemic effects are attributed to reduced activity of key lipid metabolism enzymes such as HMG-CoA reductase, cholesterol-7 hydroxylase, and fatty acid synthase (Abdelli *et al.*, 2021) [1].

Furthermore, phytogetic compounds such as quillaja saponin, micelle silymarin, and herbal extracts have been associated with reduced serum cholesterol and triglyceride levels (Muniyappan *et al.*, 2022a) [44]. Enhancement of antioxidant enzyme activity (SOD, CAT, GSH-Px) and reduction of oxidative stress markers (ROS, TBARS, MDA) have also been consistently reported following supplementation with essential oils, organic acids, and plant extracts (Li *et al.*, 2012a; Zou *et al.*, 2016b; Wang *et al.*, 2020) [32]. Overall, phytogetic feed additives improve biochemical and oxidative status by enhancing immune responses, regulating lipid

metabolism, and strengthening antioxidant defense systems.

Effects of Phytogetic Feed Additives on Fecal Gas Emissions

Noxious gas emissions from livestock production systems—particularly ammonia, methyl mercaptans, carbon dioxide, and hydrogen sulfide—represent a significant environmental and occupational health concern (Muniyappan *et al.*, 2021) [45]. Among these, ammonia emissions are closely associated with environmental issues such as soil and water acidification, as well as nitrogen deposition in ecosystems.

The generation of fecal gases is closely linked to nutrient metabolism and the activity of gut microbiota (table 1). Microbial degradation of undigested nutrients in feces leads to the production of ammonia and other harmful gases (Li *et al.*, 2012b) [32]. Therefore, strategies that improve nutrient utilisation and modulate gut microbial populations can effectively reduce fecal gas emissions.

Phytogetic feed additives (PFA) have demonstrated considerable potential in mitigating fecal gas emissions through their effects on gut microbiota and nutrient digestibility. For instance, supplementation with black pepper significantly reduced emissions of ammonia, methyl mercaptans, and acetic acid (Sampath *et al.*, 2020) [51]. Similarly, inclusion of medicinal plant extracts reduced coliform bacterial populations, increased *Lactobacillus* counts, and improved nutrient digestibility, thereby lowering fecal ammonia and methyl mercaptan emissions (Yan and Kim, 2012) [72].

Quillaja saponin supplementation has been shown to reduce fecal ammonia and carbon dioxide emissions (Muniyappan *et al.*, 2022a) [44], likely due to enhanced populations of beneficial bacteria such as *Lactobacillus*. Likewise, *Achyranthes japonica* extract modulated gut microbiota by increasing beneficial bacteria and reducing pathogenic populations, leading to decreased emissions of ammonia and hydrogen sulfide (Liu *et al.*, 2021) [36].

Essential oils have also demonstrated consistent reductions in fecal gas emissions. Dietary supplementation with essential oils reduced hydrogen sulfide and ammonia emissions in growing-finishing pigs (Yan *et al.*, 2010a) [73], while similar effects were observed with herbal extracts and essential oil supplementation (Yan *et al.*, 2011b).

Overall, phytogetic feed additives reduce fecal gas emissions primarily by enhancing nutrient digestibility, shifting gut microbial populations toward beneficial species, and limiting the proliferation of gas-producing pathogenic bacteria. These effects contribute not only to improved animal performance but also to reduced environmental pollution and enhanced sustainability of livestock production systems.

Conclusion

Phytogetic feed additives (PFA) represent a credible and biologically effective alternative to antibiotic growth promoters in livestock production. The evidence synthesized in this review indicates that PFA influence multiple physiological and production parameters in both *ruminants* and *swine*, including growth performance, nutrient utilisation, gut microbiota composition, immune responses, antioxidant status, product quality, and environmental emissions.

In *ruminants*, PFA improve rumen fermentation efficiency, modulate microbial populations, and contribute to reductions in methane and ammonia emissions, thereby enhancing both productivity and environmental sustainability. In *swine*, phyto-genics support gut health, reduce post-weaning diarrhea, and improve nutrient digestibility and growth performance,

largely through modulation of intestinal microbiota and immune pathways.

Across species, PFA consistently exhibit antimicrobial, antioxidant, and immunomodulatory effects, including regulation of inflammatory signaling pathways and enhancement of endogenous antioxidant systems. These mechanisms contribute to improved physiological resilience and product quality, including meat characteristics and, to a lesser extent, milk production traits. However, responses remain variable due to differences in phytogetic composition, dosage, animal factors, and experimental conditions.

Future research should prioritise standardisation of phytogetic formulations, identification of active compounds and their interactions, and validation under practical production systems using advanced molecular approaches.

Overall, PFA offer a sustainable and multifunctional approach to improving animal health, productivity, and environmental outcomes, supporting their integration into antibiotic-free livestock production systems.

Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this review.

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How to Cite This Article

Anil TSV, Birari DR, Yadav S, Gupta PK, Bhosale TR. Phytogetic feed additives in animal nutrition: Multifunctional roles in productivity, gut health and emission mitigation. *International Journal of Veterinary Sciences and Animal Husbandry.* 2026;SP-11(5): 01-09.

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