Article Type	Review article
Article Title	A thorough review of phytogenic feed additives in non-ruminant nutrition: production, gut health, and environmental concerns
Running Title (within 10 words)	Phytogenic additives in non-ruminant production and gut health
Author	Sarbani Biswas[1, 2], In Ho Kim[1, 2, *]
Affiliation	Department of Animal Biotechnology, Dankook University, Cheonan, 31116, Republic of Korea
ORCID	Sarbani Biswas (https://orcid.org/0000-0002-6732-286X) In Ho Kim (http://orcid.org/0000-0001-6652-2504)
Competing interests	No potential conflict of interest relevant to this article was reported.
Funding sources	Not applicable.
Acknowledgements	Not applicable.
Availability of data and material	Not applicable.
Authors' contributions	Conceptualization: Sarbani Biswas, In Ho Kim Writing - original draft: Sarbani Biswas Writing - review & editing: Sarbani Biswas, In Ho Kim
Ethics approval and consent to participate	Not applicable

1

First name, middle initial, last name	In Ho Kim
Email address	inhokim@dankook.ac.kr
Address	Department of Animal Biotechnology, Dankook University, No.29 Anseodong, Cheonan, Choongnam, 330-714, South Korea Smart Animal Bio Institute, Department of Animal Biotechnology, Dankook University, Cheonan, Choongnam, South Korea
Office phone number and Fax	+82-41-550-3652 and +82-41-565-2949

2

3

A thorough review of phytogenic feed additives in non-ruminant nutrition: production, gut health, and environmental concerns

Sarbani Biswas[1, 2], In Ho Kim[1, 2, *]

[1] Department of Animal Biotechnology, Dankook University, No. 29 Anseodong, Cheonan, Choongnam 330-714, South Korea.

[2] Smart Animal Bio Institute Dankook University, Cheonan, Korea.

Running Title: Phytogenic additives in non-ruminant production and gut health

* Corresponding author: In Ho Kim

Email: inhokim@dankook.ac.kr

Phone: 82-41-550-3652 / 82-10-8803-9598

Fax: +82-41-559-7881

Abstract

The increasing demand for sustainable livestock production has intensified interest in phytogenic feed additives as viable alternatives to conventional growth promoters and antibiotics. Derived from plant-based sources such as herbs, spices, and essential oils, phytogenic feed additives have demonstrated significant potential to enhance production performance, improve gut health, and mitigate environmental impact in non-ruminant systems. Bioactive compounds such as thymol, carvacrol, menthol, and anethole play a crucial role in modulating gut microbiota, strengthening immune responses, and reducing gastrointestinal disorders. Their antimicrobial and antioxidant properties further support animal health while reducing antibiotic dependence, addressing growing concerns over antimicrobial resistance. Additionally, they contribute to improved nutrient digestibility and feed efficiency, leading to enhanced growth performance. From an environmental perspective, their use is associated with lower greenhouse gas emissions and reduced waste contamination, aligning with sustainability goals in modern livestock systems. Phytogenic feed additives improve feed efficiency, leading to reduced feed waste and lower resource input, which in turn decreases the environmental burden of livestock production. Additionally, their antimicrobial properties may reduce the need for synthetic chemicals in animal health management, further minimizing the release of harmful substances into the environment. Despite these promising benefits, inconsistencies in research findings highlight the need for further studies to determine optimal inclusion levels and clarify their mechanisms of action. Future research should focus on developing standardized formulations, improving bioavailability, and assessing long-term effects on animal health and performance. Additionally, advancements in delivery technologies and synergistic combinations with other feed additives could enhance their efficacy. By synthesizing the latest developments, this review underscores the potential of phytogenic feed additives as a strategic tool for optimizing non-ruminant productivity, ensuring animal welfare, and promoting environmentally sustainable livestock production.

Keywords: environmental impact, gut health, immunity, non-ruminant animal, phytogenic feed additive

INTRODUCTION

Concerns over microbial resistance in human pathogens from the continuous use of antibiotics as performance enhancers in animals led to the ban on antibiotic growth promoters (AGPs) in livestock feed in developed countries in the early 2000s [1]. The removal of antibiotic supplementation has led to substantial growth in research focusing on developing effective alternative control (CON) methods, improved management practices, and dietary adjustments to boost animal health, welfare, and productivity [2].

Phytogenic feed additives (PFAs), also known as herbs or phytobiotics used in traditional treatments, utilized as alternatives to antibiotics, and incorporated into non-ruminant feed to enhance productivity [1]. Phytogenic compounds can be categorized based on their source and processing, encompassing herbs (flowering, non-woody, and non-perennial plants), spices (highly aromatic or flavorful herbs commonly used in human food), essential oils (EOs, volatile lipophilic compounds), and oleoresins (extracts obtained through non-aqueous solvents) [3]. They are valued for their ability to improve animal health and performance, reduce antibiotic usage in non-ruminant nutrition, and meet consumer preferences, thereby contributing positively to modern animal farming practices [4]. Additionally, PFAs provide various benefits for animals, including enhanced palatability, a stimulating effect on gastrointestinal activity, overall improvement in intestinal morphology, and higher meat quality [5]. Moreover, phytogenic compounds improve the physiology of the intestines [6] and have the potential to promote the synthesis of digestive enzymes like lipase, amylase, or carbohydrases, leading to a positive impact on nutrient utilization [7]. The study examining the impact of oregano EO in broiler diets on performance, carcass yield, and serum IgG levels suggested that this additive could serve as a potential substitute for traditional anticoccidial additives in broiler feeds [8]. Plant polyphenol-derived antibacterial compounds alter the intestinal microbiota in animals, providing a protective shield against competition for vital nutrients and leading to a reduction in detrimental substances that impede rapid growth and nutrient utilization [9]. Adding milk thistle to poultry diets boosts growth, productivity, immune function, and overall health, making it a beneficial natural supplement for enhanced performance and sustainable production [10]. Incorporating a probiotic-phytogenic mixed supplement into broiler diets resulted in consistent improvements in growth performance, bolstered immunological health, and fostered favorable microbiological conditions [11]. Likewise, growing pigs showed enhanced growth and nutrient absorption when fed a diet enriched with garlic extract without any adverse effects on fecal scores [12]. Scientists discovered that providing weaning piglets with additional plant extracts (*Houttuynia cordata* and *Taraxacum officinale*) improved their growth, nutrient utilization, and the integrity of the gut barrier [13]. Additionally, increasing the flavonoid dose to 0.06% in broilers improved feed intake, nutrient

digestibility, tibia ash, organ weights, and meat quality, suggesting it as a beneficial additive for productivity [14]. Ginseng combined with artichoke extract supplementation is an effective feed additive, enhancing growth performance, feed efficiency, meat quality parameters, defense mechanisms against oxidative stress, and reducing excreta gas emission in Hanhyup-3-ho chickens [15]. Moreover, supplementing the standard crude protein diet with 0.025% *Achyranthes japonica extract* (AJE) enhanced broiler growth performance, nutrient digestibility, while also reducing fecal ammonia (NH_3) emissions [16].

Despite promising in vitro and in vivo results, the bioavailability of phytogenic compounds remains a controversial issue. Moreover, evaluating each compound's unique effects and modes of action is challenging since phytogenic metabolism produces various chemicals with different chemical structures [17]. While natural feed additives are increasingly favored by veterinarians and producers, there remains a requirement for more scientifically rigorous data to substantiate their efficacy, demonstrate their effectiveness, and achieve widespread acceptance.

We hypothesized that the incorporation of PFAs in non-ruminant diets significantly enhances growth performance, improves health indicators, and boosts overall production efficiency while reducing the reliance on AGPs, thereby addressing concerns related to antibiotic resistance and promoting environmental sustainability. The study aims to provide comprehensive, scientifically rigorous data on the efficacy of PFAs, thereby contributing to the broader adoption of natural feed additives in non-ruminant production and supporting efforts to mitigate antibiotic resistance and enhance environmental sustainability.

MECHANISM OF ACTION OF PFAs

Understanding the intricate mechanisms of action of phytogenic compounds has been a significant focus of recent research and development aimed at enhancing animal performance and health [18]. The primary bioactive components of PFAs are polyphenols, whose composition and concentration differ based on several factors, including the type of plant, the specific plant parts used, the geographical origin, the season of harvest, environmental conditions, storage methods, and processing techniques [3, 19]. In piglets, these compounds exert antimicrobial effects throughout the gastrointestinal tract (GIT) similar to AGPs [20]. Windisch et al. [3] reviewed the potential mechanisms of phytogenic blends or substances, highlighting their promise in enhancing productivity through antioxidant and antimicrobial properties, improved diet palatability, gut function, pathogen suppression, and tissue recovery. Different chemical families of phytobiotics have unique modes of action; for example, phenolic compounds and flavonoids are notable for their potential antibacterial and antioxidant properties [21].

Platel and Srinivasan [22] suggested that phytobiotics stimulate digestive secretions such as saliva and bile, with their main nutritional action being the improvement of enzyme activity. While the exact mechanism of action is not fully understood, PFAs beneficially modify gut microflora by reducing pathogenic organisms, likely through altering membrane permeability to hydrogen ions, and also exhibit antibacterial, antiviral, antiparasitic, and antifungal properties [23]. While higher levels of certain compounds, especially polyphenols, can negatively affect digestive efficiency by binding to digestive enzymes, they also enhance nutrient absorption by increasing intestinal villi length and crypt depth (CD) [24]. Additionally, PFAs can modify lipid metabolism by inhibiting hepatic HMG-CoA reductase, reducing cholesterol synthesis in the liver, which can be used to produce low-cholesterol meat and eggs [25]. Condensed tannins exhibit potent anti-coccidial effects against chicken coccidia, and phytochemicals with both hydrophilic and lipophilic antioxidant properties are useful during stress periods (heat stress) [26]. Plant-derived compounds with distinct flavors enhance consumer appeal and intake in human and pig feeds, are used in ice cream and other products, and can improve digestion, though their effectiveness as flavoring agents in poultry production remains uncertain [27]. The beneficial impacts of the tested doses of the PFAs might have been more noticeable in less hygienic environments, with higher product dosages, or when using less digestible diets [28]. Therefore, the inconsistent findings about various modes of action in recent studies highlight the necessity for additional research to accurately utilize these types of feed additives in the nutrition of monogastric animals.

THE IMPLICATIONS OF PFA ON THE GIT

Effects of PFAs on intestinal morphology

Analyzing the impact of PFAs on intestinal morphology can provide insights into their role in enhancing gut health and structural integrity. Phytogenic compound positively influence nutrient digestibility by minimizing competition for nutrients between the bird and its gut microflora, and by potentially stimulating intestinal enzyme activity and inducing alterations in gut morphology [19]. PFAs contribute positively to intestinal morphology primarily by diminishing inflammation, fostering cellular growth, and potentially influencing mortality control [29]. Wang et al. [30] conducted research indicating a linear rise in duodenal mucus layer thickness in broilers with escalating concentrations of dietary PFAs. Grape-derived dietary polyphenols alter the gut morphology and intestinal microflora while enhancing the biodiversity of intestinal bacteria in broiler chicks [31]. The morphometric parameters of jejunum CD and villi height (VH) were evident only in 21-day-old chickens, with a significant interaction observed only in chickens fed a maize diet supplemented with plant origin active substances

[32]. Additionally, the inclusion of PFAs led to an elevation in VH throughout the small intestine in poultry [33] and pigs [34]. Flavonoids from plants, specifically genistein (5 mg/kg) and hesperidin (20 mg/kg) were administered to broilers challenged with lipopolysaccharide (LPS), demonstrating their efficacy in immune stimulation and enhancing gut morphology [35]. In their study, Reisinger et al. [36] noted that supplementing the diet with a PFA based on EOs resulted in heightened villus length (VL) and increased goblet cell density in the mid-ileum section of the small intestine in broilers subjected to a mild coccidial vaccine challenge. Birds supplemented with dietary genistein and hesperidin exhibited a significant increase in gut VL and villus width on days 21 and 42, and a decrease in CD in the duodenum on day 42 and in the ileum on day 21, irrespective of the LPS challenge [35]. Increased VH could also enhance the activity of enzymes released from the villus tips, potentially leading to improved digestibility [37].

Effects of PFAs on the gut barrier integrity

The effects of PFAs on gut barrier integrity are crucial for their potential to improve intestinal health and strengthen the body's defense against pathogens. You et al. [38] observed improved performance in newborn pigs with the dietary addition of flavonoids, noting benefits such as the adjustment of beneficial gut bacteria, enhanced gut epithelial structure, better barrier functionality, and increased immune performance. Dietary polyphenols, by promoting immunoglobulins and reducing the release of pro-inflammatory cytokines may further improve gut health and integrity in monogastric animals [39]. Moreover, Yuan et al. [40] found that incorporating flavones extracted from *Eucommia ulmoides* leaves into the diet improved the intestinal morphology and integrity of challenged pigs by enhancing intestinal barrier function. Additionally, eckol has been identified as a potential feed supplement for influencing intestinal barrier functions, wound healing, and oxidative stress, leading to enhanced growth during the transition from suckling to weaning [41]. Enhanced pre-cecal digestive capacity decreases the influx of fermentable substances into the hindgut, thus restraining postileal microbial growth and the expulsion of bacteria in feces [3]. According to Kroismayr et al. [20], a reduction in immune defense activity in the GIT aligns with concurrent enhancements in zoo-technical performance, gut microbial composition, fermentation products, and apparent nutrient digestion facilitated by EOs.

Effects of PFAs on the intestinal microbiota

Exploring the impact of PFAs on the intestinal microbiota is essential for understanding their role in influencing gut microbial communities and enhancing digestive health. PFAs were documented to enhance the production of mucus in the intestines of broilers, with the assumption that this action could hinder the attachment of pathogens,

consequently aiding in the stabilization of microbial balance in the gut [32]. The antimicrobial properties of bioactive substances in herb extracts arise from the hydroxyl group, which can bind to bacterial protein molecules, leading to the release of vital cell components [42]. For example, the dietary supplementation with carvacrol, cinnamaldehyde, and capsaicin enhances mucus secretion, forming a protective barrier in the gut, which may reduce epithelial adhesion and intestinal populations of *Escherichia coli*, *Clostridium perfringens*, and fungi in chickens [32]. Carvacrol and thymol induce the collapse of the outer membrane in Gram-negative bacteria by releasing LPS, increasing the permeability of the cytoplasmic membrane to ATP, and depolarizing the cytoplasmic membrane [43, 44]. These compounds, found in thyme and oregano, exhibit antimicrobial properties by penetrating cell membranes and mitochondria, leading to cell lysis [43]. Mountzouris et al. [45] found that including PFAs (125 and 250 mg/kg) diet led to beneficial modulation of caecal microbiota in 42-day-old broilers, with a linear increase in *Lactobacillus*, *Bifidobacterium*, and Gram-positive cocci concentrations, while caecal coliforms at 14 days of age were significantly lower compared to the antibiotic Avilamycin. Mitsch et al. [46] also suggested that PFAs play a role in stabilizing the gut microbiota, consequently decreasing the colonization of clostridia within the GIT. Thus, PFAs significantly modulate the intestinal microbiota by enhancing beneficial bacteria and reducing pathogenic bacteria, thereby stabilizing gut microbial communities and promoting digestive health in non-ruminant livestock.

Effects of dietary PFA on immune function

Phytochemicals exert health-promoting effects by enhancing the host's defense mechanisms against microbial infections. The fundamental action of phenolic compounds on immune function includes stimulating the production of immunoglobulins and cytokines, enhancing phagocytosis, and promoting the release of interferon-γ [47]. In vitro studies have demonstrated that phytochemicals from sources such as dandelion, mustard, safflower, thistle, turmeric, reishi mushroom, and shiitake mushroom inhibit tumor cell growth and stimulate innate immunity. These effects are confirmed by *in vivo* trials showing that PFAs can modulate immune responses through multiple mechanisms [48]. For instance, supplementation with PFAs containing carvacrol primarily affects the cecal microbiota by increasing beneficial bacteria like *Bacteroides* spp. and *Clostridium* clusters IV and XIVa, which contribute to gut function and butyrate production [49]. Additionally, incorporating phenolic-rich soy isoflavones into the diet resulted in enhanced immune function, reduced incidence of diarrhea, and decreased plasma endotoxin levels in piglets challenged with LPS [50]. Likewise, tea polyphenols demonstrated the ability to modulate T lymphocyte activities, improve the CD4+/CD8+ ratio, facilitate immune recovery from

oxidative stress-induced damage, enhance cell-mediated immune response, and reduce the secretion of pro-inflammatory cytokines like IFN-γ, emphasizing their immunomodulatory potential [51]. Hence, PFAs enhance host defense mechanisms and immune responses through various pathways, including the modulation of intestinal microbiota, stimulation of immunoglobulin and cytokine production, and reduction of pro-inflammatory cytokine secretion, thereby improving overall health and resilience against infections in livestock animals. Table 1 illustrates the effect of PFA on the immunity of non-ruminants.

Effects of PFAs on anti-inflammatory and anti-oxidative function

Inflammation is a natural protective reaction triggered by tissue injury or infection to combat microorganisms and eliminate dead or damaged host cells [52]. PFAs are known to possess anti-inflammatory properties that can help modulate immune responses and reduce oxidative stress in non-ruminant animals. EOs like chamomile have anti-inflammatory effects and have been traditionally used for centuries to treat symptoms of eczema, dermatitis, and other notable irritations [53]. These EOs exert their anti-inflammatory benefits by interacting with signaling pathways involving various cytokines and regulatory transcription factors, and by regulating the expression of genes related to inflammation [54]. For example, resveratrol, when administered at 500 mg/kg as a phenolic compound, effectively modulated immune function and inflammatory response in yellow feather broilers experiencing heat stress, achieved through the inhibition of various signaling pathways including nuclear factor-kappa B (NF-κB), MAPK mitogen-activated protein kinase, and phosphoinositide 3-kinase/protein kinase B [55]. Alkaloids enriched with phenolic compounds can influence gut health by modulating the inflammation cascade through the inhibition of NF-κB activation [56]. Dietary carvacrol EOs, administered at 200 μL/L, reduced the expression of inflammatory cytokines in broiler chickens challenged with LPS, underscoring the anti-inflammatory role of carvacrol [57]. Lavender EO supplementation increased the activity of superoxide dismutase (SOD) and glutathione peroxidase (GSH-Px) enzymes, which are crucial for defending against oxidative stress [58, 59]. Phenolic compounds from the Labiatae plant family have been shown to enhance the oxidative stability of both pork [60] and poultry meat [61]. Feeding broiler chickens with *Artemisia annua*, a type of PFA, resulted in a significant reduction in thiobarbituric acid reactive substances values in both breast and thigh meat, suggesting the potential antioxidative properties of polyphenolic compounds or vitamin E in *Artemisia annua* [62]. Additionally, thymol supplementation reduced malondialdehyde levels in the duodenal mucosa, suggesting decreased fatty acid oxidation [63]. Mueller et al. [64] demonstrated that phytogenic substances such as broccoli, turmeric, oregano, thyme, and rosemary up-regulated antioxidant response element genes in the small intestine of

broilers, indicating reduced oxidative stress. Agricultural residues serve as a valuable reservoir of polyphenols and antioxidant compounds, which can be beneficial as bioactive elements for animal feed [65]. Therefore, PFAs enriched with phenolic compounds and EOs offer significant anti-inflammatory and antioxidant benefits, effectively modulating immune responses, reducing oxidative stress, and improving the health and quality of livestock products.

IMPLICATIONS OF PFAS ON PRODUCTIVITY

Effects of PFAs on growth rate and nutrient digestibility

PFAs influence several aspects of livestock performance, including the release of digestive juices and enzymes, immune system modulation, changes in intestinal morphology, and improvements in nutrient utilization, leading to enhanced overall performance [66]. Mahfuz et al. [67] noted that incorporating phenolic supplements into feed can positively affect antioxidant capacity, immune response, antibacterial properties, and overall production efficiency in pigs and poultry. For instance, adding 0.5 g/kg of anise seed, with anethole as the active component, to the diet notably enhanced body weight gain (BWG) and performance index in broilers; however, there were no significant effects on feed intake (FI) or feed conversion ratio (FCR) [68]. Furthermore, Choi et al. [69] documented a gradual increase in both the overall average daily gain (ADG) and feed efficiency in weaning pigs. It was reported that incorporating quercetin in the diet at concentrations of 0, 0.2, 0.4, and 0.6% resulted in enhanced BWG and increased FI during the period of 0 to 35 days [70]. Administering 50 or 100 mg of garlic and onion to the diet of broiler chickens resulted in a notable increase in body weight [71]. Similarly, fenugreek seed supplementation at 1%, 2%, and 3% levels significantly improved FCR in broilers [72]. Another study indicated that adding 1 or 2 g of anise seed to a broiler's diet resulted in enhancements in BWG and FCR, with no impact on FI [73]. Supplementing a low-protein diet with AJE showed promise in maintaining comparable growth performance by enhancing nitrogen digestibility and influencing the intestinal bacterial population in broilers [74]. Biswas et al. [75] observed a dose-dependent improvement in growth performance and nutrient utilization with increasing concentrations of gallic acid. Additionally, incorporating AJE into a low-protein diet maintained comparable growth performance and improved meat quality [76]. PFAs also positively impact nutrient digestibility, leading to increased total apparent dry matter and crude protein digestibility [77]. These improvements in feed conversion and growth efficiency are attributed to changes in gastrointestinal surface and enhanced digestive enzyme functionality [45]. The beneficial effects of phenolic content on growth may also stem from improved FI and enhanced nutrient absorption, which positively influence the intestinal epithelium [78].

Effects of PFAs on palatability and flavoring component

Flavor, perceived through taste and smell, can be enhanced or altered in feed using plant ingredients like herbs, spices, and their extracts, thereby improving palatability and influencing the sensory properties of the diets [66]. Phytobiotics are primarily asserted to positively impact the flavor and palatability of feed, thereby boosting production performance [3]. EOs, which are volatile compounds responsible for the distinctive fragrance of their sources, are named after their origins [79]. Evidence suggests that incorporating PFAs into swine diets can enhance FI [20]. However, the effects of EOs on palatability can vary. For instance, feeding pigs EOs from fennel and caraway, or thyme and oregano, caused a dose-dependent decrease in palatability [80]. In a choice feed experiment, supplementing with fennel (100 mg/kg) or caraway oil (100 mg/kg) significantly reduced FI, indicating that these flavors may decrease palatability. This decrease in palatability may be attributed to the strong, distinctive aromas and flavors of these EOs, which can lead to feed aversion in pigs. High doses of certain EOs may also activate bitter taste receptors, further reducing FI. Conversely, aromatic EOs that enhance feed flavor and palatability can lead to increased voluntary FI and subsequent weight gain. Thus, the impact on flavor and palatability varies based on the type and dosage of PFAs used.

Effects of PFAs on meat trait

Research on dietary EOs has shown various impacts on meat quality and lipid oxidation. For instance, Javan et al. [81] assessed the effects of EOs (*Zataria multiflora*) on microbiological growth and lipid peroxidation in refrigerated broiler breast fillets. In the study by Hong et al. [33], birds in the EO group exhibited increased tenderness in breast meat and greater juiciness in thigh meat compared to the CON and AGP groups, likely due to the ability of PFAs to enhance protein metabolism and water-holding capacity. As reported by Ranucci et al. [82], adding a plant extract mix (a combination of oregano EO and sweet chestnut wood extract, 0.2%) to the diet decreased meat lipid oxidation in pigs, which can be attributed to the antioxidant properties of polyphenols that scavenge free radicals and inhibit oxidative damage. Similarly, Ghazaghi et al. [83] observed that incorporating *Mentha spicata* (1-4%) into the diet enhanced the meat quality of Japanese quail by improving muscle fiber integrity and reducing oxidative stress. The inclusion of EOs also led to an enlarged longissimus muscle area and reduced yellowness in meat [84], potentially due to their role in modulating muscle protein synthesis and reducing lipid oxidation. PFAs reduced saturated fatty acid (SFA) levels while increasing monounsaturated and polyunsaturated fatty acids, particularly lowering hypercholesterolemic SFAs like lauric, stearic, myristic, and palmitic acids [85, 86], likely through their influence on lipid metabolism and enzyme

activity involved in fatty acid synthesis. Increased quercetin levels in the diet positively affected breast muscle development, improved meat quality parameters such as cooking loss and drip loss, and enhanced blood profiles [87], possibly due to its ability to regulate muscle cell differentiation and maintain cellular integrity. Moreover, EOs have been shown to improve the oxidative stability of meat from broilers [88] by enhancing endogenous antioxidant enzyme activity and reducing lipid peroxidation. The enhancement of meat quality traits through dietary supplementation with PFAs is largely attributed to the antioxidant properties of phytogenic compounds. In contrast, Simitzis et al. [89] found that adding dietary oregano EO at doses of 0.25, 0.5, and 1 ml/kg of feed did not lead to improvements in the lipid oxidation status of pork. This variability in results could be attributed to species-specific differences in fatty acid composition and antioxidant enzyme activity between poultry and swine, as well as variations in the bioavailability and metabolism of phytochemicals.

Effects of PFAs on egg quality

PFAs, particularly EOs and herbal extracts, have shown potential in enhancing egg production and quality in laying hens through various mechanisms. For example, addition of 200 mg/kg of EOs from thyme, sage, or rosemary was found to increase the proportion of eggshell [90]. Incorporating peppermint (*Mentha piperita*) leaves into the diet of 64-week-old Hy-Line brown laying hens resulted in a notable increase in egg weight, egg production, and overall egg mass [91]. Additionally, a mixture of herbal EOs improved eggshell thickness [92], and herb blends increased the hens' egg-laying capacity by 1.79% compared to the CON group [93]. These positive effects of PFAs may be attributed to their ability to enhance uterine health, increase calcium storage, and boost pancreatic secretions, thereby improving nutrient digestion and subsequently eggshell and egg quality [94]. However, there were no observed benefits in terms of relative shell weight when black cumin EO was added to the diet at three varying levels (1, 2, or 3 ml/kg) [90]. Similarly, adding oregano EO (50 or 100 mg/kg) to the diet at 32 weeks of age had no impact on egg quality attributes, such a yolk color score, Haugh unit, or shell thickness [61]. Similarly, the laying rate and the weight of settable eggs were not affected by an EO mixture at levels of 24, 36, or 48 mg/kg [95]. This discrepancy may be due to various factors such as the inherent variability of botanical composition, animal scenarios, environmental and management conditions, potential pathogen challenges, and the treatment technique used, which can alter the active substances and related compounds in the final product [3].

Effects of PFAs on blood parameters

The impact of PFA administration on the biochemical markers in serum helps illustrate the body's physiological status and nutrient metabolism. For instance, increased monocyte counts were observed in hens supplemented with fennel EO at 300 mg/kg [96], while higher lymphocyte numbers were associated with the inclusion of thyme powder at 0.2% [97], both of which serve as positive health indicators in laying hens. Supplementation of lavender EO reduced serum lipid parameters such as cholesterol and low-density lipoprotein cholesterol in broiler chickens [59]. Similarly, *Pulicaria gnaphalodes* powder decreased cholesterol and triglycerides [98], and a blend of oregano, anise, and citrus EOs lowered cholesterol levels [99]. In addition, supplementation of peppermint oil reduced serum cholesterol levels in laying hens [94]. Moreover, including a mixture of yeast and garlic extract supplements in broiler diets led to a progressive enhancement in immune function, characterized by a linear increase in blood immunoglobulin G levels [11]. Anise supplementation in poultry feed was also found to enhance lymphocyte counts [68]. Furthermore, the blood profile revealed a significant linear decrease in cholesterol levels and a tendency for triglyceride levels to decrease with micelle silymarin (MS) supplementation [100]. Adding 0.06% MS to a corn-soybean meal-based diet for 12 weeks significantly enhanced production performance and egg quality, positively affecting aspartate aminotransferase, alanine aminotransferase, and alkaline phosphatase levels, and indicating improvements in albumin, triglyceride, and cholesterol levels [101]. Research indicates that PFA may inhibit the enzyme HMG-CoA reductase, essential for liver cholesterol synthesis, thereby potentially reducing cholesterol levels in the bloodstream [102]. Table 2 and Figure 1 illustrates the response of non-ruminant animals to the phytogenic additive.

NOXIOUS GAS EMISSIONS IMPACTING THE ENVIRONMENT

Ammonia emissions from animal production pose significant health and welfare concerns for livestock and people living close to farms due to their negative impact on both animal well-being and air quality. It is hypothesized that improvements in protein digestibility can lead to better utilization of dietary amino acids, subsequently reducing the excretion of nitrogenous compounds in animal waste. Therefore, PFAs hold promise in mitigating emissions originating from animal production facilities. For instance, Zentner et al. [103] documented a 24% decrease in airborne NH_3 levels in growing-finishing pigs when fed PFAs comprised of oregano, thyme, anise, and citrus. El-Deek et al. [104] examined the impact of dietary crude protein levels (21% vs. 23%) with or without green tea supplementation or oxytetracycline on broiler growth. They found that a 21% protein diet supplemented with 1.5 g/kg of green tea improved growth rate and FCR without adverse effects. Notably, the lower protein diet with green tea supplementation may help mitigate environmental nitrogen emissions by reducing nitrogen excretion.

This reduction in nitrogen excretion is particularly important for minimizing NH_3 emissions, which can contribute to environmental pollution and negatively impact air quality in poultry facilities. Including *Quillaja saponin* (QS) in the diet not only improves performance but also reduces emissions of harmful gases like NH_3, hydrogen sulfide (H_2S), and CH_4, thereby enhancing barn environmental conditions and potentially mitigating environmental pollution associated with the swine industry [105]. Additionally, QS supplementation at 200 mg/kg in the diets of growing pigs effectively reduced NH_3 emissions from fecal gases, improving barn environments [106]. Bartoš et al. [107] also demonstrated that PFAs containing QS effectively lowered NH_3 emissions, offering a promising strategy for reducing NH_3 levels in pig production. Our previous research revealed that supplementing the diet of Hanhyup-3-ho chickens with an herbal mixture significantly reduced NH_3 and H_2S emissions from their excreta [15]. Similarly, Khan et al. [16] found that varying levels of crude protein and AJE supplementation decreased NH_3 emissions to the environment. Conversely, QS revealed a positive impact on the performance of weaning pigs without any adverse effects on gas emissions or fecal score, making it a suitable feed supplement for this group [108]. PFAs promote beneficial gut bacteria while suppressing harmful ones, leading to changes in fermentation processes and reduced NH_3 and CO_2 emissions, indicating more efficient nutrient utilization by pigs [11]. Overall, PFAs show significant potential in reducing NH_3 and other harmful gas emissions from livestock production facilities, thereby improving environmental conditions and addressing concerns related to air quality and animal welfare.

LIMITATIONS

The variability in PFA composition across different products poses a challenge in predicting their consistent effects. The long-term impacts and potential side effects of PFAs, especially at higher dosages, are not yet fully understood and require further investigation. Dietary PFAs interact with the GIT, impacting its structural integrity and function. For instance, curcumin, despite its poor bioavailability, has been shown to mitigate the adverse effects of Ochratoxin A exposure [109]. Although many studies demonstrate the effectiveness of supplementation with phytogenic preparations, some studies, such as Akbarian et al. [110] found no effect of lemon peel or orange peel extract on ileal histomorphology in birds exposed to heat stress. Similarly, Gaucher et al. [111] conducted an experimental program without antibiotics and discovered that commercial EO-based products were less economical, and slower at controlling clinical necrotic enteritis outbreaks under field conditions compared to antibiotics. A major challenge lies in the fact that most commercial products consist of multiple ingredients, complicating the evaluation of the effects of individual components. This complexity also hampers the evaluation

of published results. Moreover, comparing studies is problematic when botanical species are not clearly identified, especially when only a common name or a commercial product name is provided without details on its composition. The varying chemical composition of PFAs, shaped by their ingredients and environmental factors, highlights the need for standardizing active components to ensure consistent quality in commercial products [19]. The variability in formulation and administration methods of PFAs in poultry feed and water complicates the determination of optimal dosages. This balance is crucial for achieving the desired effects, as low doses may be ineffective, while high doses could lead to potential toxicity and impair barrier function [29]. Factors such as variations in bird genetics and overall diet composition significantly influence the effectiveness of PFAs. Moreover, careful consideration should be given to potential interactions between phytogenic additives and other feed supplements to optimize their benefits. Therefore, while PFAs show promise in influencing gastrointestinal integrity and health in non-ruminant animals, their variable compositions, potential interactions with other supplements, and the need for standardized formulations underscore the necessity for further research and careful consideration in their application.

FUTURE DIRECTIONS AND SUMMARY

Over the past decade, advancements in standardizing PFAs have led to their increased use in non-ruminant nutrition . These additives have been shown to enhance nutrient digestibility, improve gut morphology, modulate inflammatory responses, and promote beneficial intestinal microbiota, ultimately leading to better feed efficiency and growth performance. Additionally, PFAs contribute to improved immune function and reduced pathogen prevalence, making them a viable alternative to AGPs in non-ruminant production. From a user perspective, PFAs offer a sustainable approach to improving animal health, welfare, and productivity while reducing reliance on antibiotics. Additionally, their potential to lower gas emissions supports environmentally friendly livestock production. Given the global shift away from AGPs, PFAs represent a promising strategy for enhancing performance and sustainability in non-ruminant animal production systems. Despite the abundance of research on the impact of PFAs on animal health and performance, the precise mechanisms by which these feed additives work are not yet fully understood. Further investigation is needed to explore potential adverse effects and the consequences of over dosage, requiring both in vitro and in vivo trials to ensure their safe and effective use. Future research should prioritize conducting standardized trials with clear indications of PFAs composition to facilitate easier comparison of results. Additionally, exploring the potential synergistic effects of phytogenic compounds under standardized conditions could provide deeper insights.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no competing interests.

REFERENCES

1. Mohammadi Gheisar M, Kim IH. Phytobiotics in poultry and swine nutrition – a review. Ital J Anim Sci. 2018;17:92–9. https://doi.org/10.1080/1828051X.2017.1350120

2. Abdelli N, Solà-Oriol D, Pérez JF. Phytogenic feed additives in poultry: Achievements, prospective and challenges. Animals. 2021;11:3471. https://doi.org/10.3390/ani11123471

3. Windisch W, Schedle K, Plitzner C, Kroismayr A. Use of phytogenic products as feed additives for swine and poultry. J Anim Sci. 2008;86:140–148. https://doi.org/10.2527/jas.2007-0459

4. Biswas S, Ahn JM, Kim IH. Assessing the potential of phytogenic feed additives: A comprehensive review on their effectiveness as a potent dietary enhancement for nonruminant in swine and poultry. J Anim Physiol Anim Nutr (Berl). 2024a;108:711–723. https://doi.org/10.1111/jpn.13922

5. Latek U, Chłopecka M, Karlik W, Mendel M. Phytogenic compounds for enhancing intestinal barrier function in poultry–A review. Planta Med. 2022;88:218–236. https://doi.org/10.1055/a-1524-0358

6. Upadhaya SD, Kim SJ, Kim IH. Effects of gel-based phytogenic feed supplement on growth performance, nutrient digestibility, blood characteristics and intestinal morphology in weanling pigs. J Appl Anim Res. 2016;44:384–389. https://doi.org/10.1080/09712119.2015.1091334

7. Williams P, Losa R. The use of essential oils and their compounds in poultry nutrition. World Poult. 2001;17:14–15.

8. Alp M, Midilli M, Kocabağlı N, Yılmaz H, Turan N, Gargılı A, et al. The effects of dietary oregano essential oil on live performance, carcass yield, serum immunoglobulin G level, and oocyst count in broilers. J Appl Poult Res. 2012;21:630–636. https://doi.org/10.3382/japr.2012-00551

9. Klose V, Neureiter M, Mohnl M, Danner H, Donat C. Microbial antagonists in animal health promotion and plant protection. Microbes at Work. Berlin, Heidelberg: Springer Berlin Heidelberg; 2010;193–211. https://doi.org/10.1007/978-3-642-04043-6_10

10. Elnesr SS, Elwan HAM, El Sabry MI, Shehata AM. The nutritional importance of milk thistle (*Silybum marianum*) and its beneficial influence on poultry. Worlds Poult Sci J. 2023;79:751–768. https://doi.org/10.1080/00439339.2023.2234339

11. Biswas S, Kim IH. Efficacy of yeast and garlic extract mixture on growth performance, tract digestibility, excreta microbiota, gas emission, blood profile, and meat quality in broiler. Can J Anim Sci. 2023a;103:143–151. https://doi.org/10.1139/cjas-2022-0069

12. Biswas S, Kim IH. Determination of garlic extract efficacy on growth, nutrient digestibility, and fecal score of growing pigs via diet supplementation. Korean J Agric Sci. 2023b;50:391–398. https://doi.org/10.7744/kjoas.500304

13. Yan L, Zhang ZF, Park JC, Kim IH. Evaluation of *Houttuynia cordata* and *Taraxacum officinale* on growth performance, nutrient digestibility, blood characteristics, and fecal microbial shedding in diet for weaning

pigs. Asian-Australas J Anim Sci. 2012;25:1439–1444. https://doi.org/10.5713/ajas.2012.12215

14. Biswas S, Cho S, Ahn JM, Kim IH. Influences of flavonoid (quercetin) inclusion to corn-soybean-gluten meal-based diet on broiler performance. J Anim Physiol Anim Nutr (Berl). 2024b;108:64–71. https://doi.org/10.1111/jpn.13868

15. Hossain MM, Cho SB, Kang DK, Nguyen QT, Kim IH. Comparative effects of dietary herbal mixture or guanidinoacetic acid supplementation on growth performance, cecal microbiota, blood profile, excreta gas emission, and meat quality in Hanhyup-3-ho chicken. Poult Sci. 2024a;103:103553. https://doi.org/10.1016/j.psj.2024.103553

16. Khan SU, Jeon YH, Kim IH. Dietary inclusion of micelle silymarin enhances egg production, quality, and lowers blood cholesterol in Hy-line brown laying hens. J Anim Physiol Anim Nutr (Berl). 2024a;108:1038–1045. https://doi.org/10.1111/jpn.13948

17. Gil-Cardoso K, Ginés I, Pinent M, Ardévol A, Blay M, Terra X. Effects of flavonoids on intestinal inflammation, barrier integrity and changes in gut microbiota during diet-induced obesity. Nutr Res Rev. 2016;29:234–248. https://doi.org/10.1017/S0954422416000159

18. Hippenstiel F, Abdel-Wareth AAA, Kehraus S, Südekum KH. Effects of selected herbs and essential oils, and their active components on feed intake and performance of broilers – a review. Arch Geflu¨gelkd. 2011;75:226–234.

19. Applegate TJ, Klose V, Steiner T, Ganner A, Schatzmayr G. Probiotics and phytogenics for poultry: Myth or reality? J Appl Poult Res. 2010;19:194–210. https://doi.org/10.3382/japr.2010-00168

20. Kroismayr A, Schedle K, Sehm J, Pfaffl M, Plitzner C, Foissy H, Ettle T, Mayer H, Schreiner M, Windisch W. Effects of antimicrobial feed additives on gut microbiology and blood parameters of weaned piglets. Bodenkultur. 2008;59:111–120.

21. Rafeeq M, Bilal RM, Batool F, Yameen K, Farag MR, Madkour M, et al. Application of herbs and their derivatives in broiler chickens: a review. Worlds Poult Sci J. 2023;79:95–117. https://doi.org/10.1080/00439339.2022.2151395

22. Platel K, Srinivasan K. Stimulatory influence of select spices on bile secretion in rats. Nutr Res. 2000;20:1493–1503. https://doi.org/10.1016/S0271-5317(00)80030-5

23. Ponzilacqua B, Corassin CH, Oliveira CAF. Antifungal activity and detoxification of aflatoxins by plant extracts: potential for food applications. Open Food Sci J. 2018;10:24–32. https://doi.org/10.2174/1874256401810010024

24. Lee KW, Everts H, Beynen AC. Essential oils in broiler nutrition. Int J Poult Sci. 2004;3:738–752. https://doi.org/10.3923/ijps.2004.738.752

25. Mohamed AB, Al-Rubaee MA, Jalil AG. Effect of ginger (*Zingiber officinale*) and blood serum parameters of broilers. Int J Poult Sci. 2012;11:143–146. https://doi.org/10.3923/ijps.2012.143.146

458 26. Wei A, Shibamoto T. Antioxidant activities and volatile constituents of various essential Oils. J Agric Food
459 Chem. 2007;55:1737–1742. https://doi.org/10.1021/jf062959x

460 27. Yadav AS, Kolluri G, Gopi M, Karthik K, Malik YS, Dhama K. Exploring alternatives to antibiotics as health
461 promoting agents in poultry-a review. J Exp Biol Agric Sci. 2016;4:368–383.
462 http://dx.doi.org/10.18006/2016.4(3S).368.383

463 28. Humer E, Rohrer E, Windisch W, Wetscherek W, Schwarz C, Jungbauer L, et al. Gender-specific effects of
464 a phytogenic feed additive on performance, intestinal physiology and morphology in broiler chickens. J Anim
465 Physiol Anim Nutr (Berl). 2015;99:788–800. https://doi.org/10.1111/jpn.12238

466 29. Patra AK, Amasheh S, Aschenbach JR. Modulation of gastrointestinal barrier and nutrient transport function
467 in farm animals by natural plant bioactive compounds–A comprehensive review. Crit Rev Food Sci Nutr.
468 2019;59:3237–3266. https://doi.org/10.1080/10408398.2018.1486284

469 30. Wang H, Kim KP, Kim IH. Evaluation of the combined effects of different dose levels of Zinc oxide with
470 probiotics complex supplementation on the growth performance, nutrient digestibility, faecal microbiota,
471 noxious gas emissions and faecal score of weaning pigs. J Anim Physiol Anim Nutr (Berl). 2021;105:286–
472 293. https://doi.org/10.1111/jpn.13493

473 31. Viveros A, Chamorro S, Pizarro M, Arija I, Centeno C, Brenes A. Effects of dietary polyphenol-rich grape
474 products on intestinal microflora and gut morphology in broiler chicks. Poult Sci. 2011;90:566–578.
475 https://doi.org/10.3382/ps.2010-00889

476 32. Jamroz D, Wertelecki T, Houszka M, Kamel C. Influence of diet type on the inclusion of plant origin active
477 substances on morphological and histochemical characteristics of the stomach and jejunum walls in chicken.
478 J Anim Physiol Anim Nutr (Berl). 2006;90:255–268. https://doi.org/10.1111/j.1439-0396.2005.00603.x

479 33. Hong JC, Steiner T, Aufy A, Lien TF. Effects of supplemental essential oil on growth performance, lipid
480 metabolites and immunity, intestinal characteristics, microbiota and carcass traits in broilers. Livest Sci.
481 2012;144:253–262. https://doi.org/10.1016/j.livsci.2011.12.008

482 34. Namkung H, Li J. Gong M, Yu H, Cottrill M, de Lange CFM. Impact of feeding blends of organic acids and
483 herbal extracts on growth performance, gut microbiota and digestive function in newly weaned pigs. Can J
484 Anim Sci. 2004;84:697–704. https://doi.org/10.4141/A04-005

485 35. Kamboh AA, Zhu WY. Individual and combined effects of genistein and hesperidin on immunity and
486 intestinal morphometry in lipopolysacharide-challenged broiler chickens. Poult Sci. 2014;93:2175–2183.
487 https://doi.org/10.3382/ps.2014-03971

488 36. Reisinger N, Steiner T, Nitsch S, Schatzmayr G, Applegate TJ. Effects of a blend of essential oils on broiler
489 performance and intestinal morphology during coccidial vaccine exposure. J Appl Poult Res. 2011;20:272–
490 283. https://doi.org/10.3382/japr.2010-00226

491 37. Baurhoo B, Phillip L, Ruiz-Feria CA. Effects of purified lignin and mannan oligosaccharides on intestinal
492 integrity and microbial populations in the ceca and litter of broiler chickens. Poult Sci. 2007;86:1070–1078.
493 https://doi.org/10.1093/ps/86.6.1070

494 38. You T, Tang J, Yin S, Jia G, Liu G, Tian G, et al. Effect of dietary licorice flavonoids powder on performance,
495 intestinal immunity and health of weaned piglets. J Anim Physiol Anim Nutr (Berl). 2023;107:147–156.
496 https://doi.org/10.1111/jpn.13694

497 39. Lipiński K, Mazur M, Antoszkiewicz Z, Purwin C. Polyphenols in monogastric nutrition – A review. Ann
498 Anim Sci. 2017;17:41–58. https://doi.org/10.1515/aoas-2016-0042

499 40. Yuan D, Hussain T, Tan B, Liu Y, Ji P, Yin Y. The evaluation of antioxidant and anti-inflammatory effects
500 of *Eucommia ulmoides* flavones using Diquat-challenged piglet models. Oxid Med Cell Longev.
501 2017;1:8140962. https://doi.org/10.1155/2017/8140962

502 41. Lee SI, Kim IH. Eckol alleviates intestinal dysfunction during suckling-to-weaning transition via modulation
503 of PDX1 and HBEGF. Int J Mol Sci. 2020;21:4755. https://doi.org/10.3390/ijms21134755

504 42. Bessam FH, Mehdadi Z. Evaluation of the antibacterial and antifongigal activity of different extract of
505 flavonoiques *Silybum marianum* L. Adv Environ Biol. 2014;8:1–9.

506 43. Helander IM, Alakomi HL, Latva-Kala K, Mattila-Sandholm T, Pol I, Smid EJ, et al. Characterization of the
507 action of selected essential oil components on gram-negative bacteria. J Agric Food Chem. 1998;46:3590–
508 3595. https://doi.org/10.1021/jf980154m

509 44. Xu J, Zhou F, Ji BP, Pei RS, Xu N. Carvacrol and thymol had desired antimicrobial effect on *E. coli*. The
510 antibacterial effects were attributed to their ability to permeabilize and depolarize the cytoplasmic membrane.
511 Lett Appl Microbiol. 2008;47:174–179. https://doi.org/10.1111/j.1472-765X.2008.02407.x

512 45. Mountzouris KC, Paraskevas V, Tsirtsikos P, Palamidi I, Steiner T, Schatzmayr G, et al. Assessment of a
513 phytogenic feed additive effect on broiler growth performance, nutrient digestibility and caecal microflora
514 composition. Anim Feed Sci Technol. 2011;168:223–231. https://doi.org/10.1016/j.anifeedsci.2011.03.020

515 46. Mitsch P, Zitterl-Eglseer K, Köhler B, Gabler C, Losa R, Zimpernik I. The effect of two different blends of
516 essential oil components on the proliferation of *Clostridium perfringens* in the intestines of broiler chickens.
517 Poult Sci. 2004;83:669–675. https://doi.org/10.1093/ps/83.4.669

518 47. Christaki E, Giannenas I, Bonos E, Florou-Paneri P. Innovative uses of aromatic plants as natural
519 supplements in nutrition. Feed Additives. 2020;19-34. https://doi.org/10.1016/B978-0-12-814700-9.00002-
520 9

521 48. Lee SH, Lillehoj HS, Hong YH, Jang SI, Lillehoj EP, Ionescu C, et al. *In vitro* effects of plant and mushroom
522 extracts on immunological function of chicken lymphocytes and macrophages. Br Poult Sci. 2010;51:213–
523 221. https://doi.org/10.1080/00071661003745844

524 49. Paraskeuas VV, Mountzouris KC. Modulation of broiler gut microbiota and gene expression of Toll-like
525 receptors and tight junction proteins by diet type and inclusion of phytogenics. Poult Sci. 2019;98:2220–
526 2230. https://doi.org/10.3382/ps/pey588

527 50. Zhu C, Wu Y, Jiang Z, Zheng C, Wang L, Yang X, et al. Dietary soy isoflavone attenuated growth
528 performance and intestinal barrier functions in weaned piglets challenged with lipopolysaccharide. Int

Immunopharmacol. 2015;28:288–294. https://doi.org/10.1016/j.intimp.2015.04.054

51. Deng Q, Xu J, Yu B, He J, Zhang K, Ding X, et al. Effect of dietary tea polyphenols on growth performance and cell-mediated immune response of post-weaning piglets under oxidative stress. Arch Anim Nutr. 2010;64:12–21. https://doi.org/10.1080/17450390903169138

52. Stevenson DE, Hurst RD. Polyphenolic phytochemicals – just antioxidants or much more? Cell Mol Life Sci. 2007;64:2900–2916. https://doi.org/10.1007/s00018-007-7237-1

53. Kamatou GPP, Viljoen AM. A Review of the application and pharmacological properties of α-Bisabolol and α-Bisabolol-rich oils. J Am Oil Chem Soc. 2010;87:1–7. https://doi.org/10.1007/s11746-009-1483-3

54. Miguel MG. Antioxidant and anti-inflammatory activities of essential oils: A short review. Molecules. 2010;15:9252–9287. https://doi.org/10.3390/molecules15129252

55. He S, Yu Q, He Y, Hu R, Xia S, He J. Dietary resveratrol supplementation inhibits heat stress-induced high-activated innate immunity and inflammatory response in spleen of yellow-feather broilers. Poult Sci. 2019;98:6378–6387. https://doi.org/10.3382/ps/pez471

56. Artuso-Ponte V, Pastor A, Andratsch M. The effects of plant extracts on the immune system of livestock. Feed Additives. 2020;295–310. https://doi.org/10.1016/B978-0-12-814700-9.00017-0

57. Liu SD, Song MH, Yun W, Lee JH, Lee CH, Kwak WG, et al. Effects of oral administration of various essential oils on blood metabolites, intestine development, microbial enumeration and meat quality in broilers. Indian J Anim Res. 2019;53:762–767. https://doi.org/10.18805/ijar.B-836

58. Su G, Zhou X, Wang Y, Chen D, Chen G, Li Y, Jun H. Effects of plant essential oil supplementation on growth performance, immune function and antioxidant activities in weaned pigs. Lipids Health Dis. 2018;17:139. https://doi.org/10.1186/s12944-018-0788-3

59. Barbarestani SY, Jazi V, Mohebodini H, Ashayerizadeh A, Shabani A, Toghyani M. Effects of dietary lavender essential oil on growth performance, intestinal function, and antioxidant status of broiler chickens. Livest Sci. 2020;233:103958. https://doi.org/10.1016/j.livsci.2020.103958

60. Janz JAM, Morel PCH, Wilkinson BHP, Purchas RW. Preliminary investigation of the effects of low-level dietary inclusion of fragrant essential oils and oleoresins on pig performance and pork quality. Meat Sci. 2007;75:350–355. https://doi.org/10.1016/j.meatsci.2006.06.027

61. Florou-Paneri P, Giannenas I, Christaki E, Govaris A, Botsoglou N. Performance of chickens and oxidative stability of the produced meat as affected by feed supplementation with oregano, vitamin C, vitamin E and their combinations. Archiv Fur Geflugelkunde. 2006;70:232–240.

62. Cherian G, Orr A, Burke IC, Pan W. Feeding *Artemisia annua* alters digesta pH and muscle lipid oxidation products in broiler chickens. Poult Sci. 2013;92:1085–1090. https://doi.org/10.3382/ps.2012-02752

63. Placha I, Takacova J, Ryzner M, Cobanova K, Laukova A, Strompfova V, Venglovska K, Faix S. Effect of

thyme essential oil and selenium on intestine integrity and antioxidant status of broilers. Br Poult Sci. 2014;55:105–114. https://doi.org/10.1080/00071668.2013.873772

64. Mueller K, Blum NM, Kluge H, Mueller AS. Influence of broccoli extract and various essential oils on performance and expression of xenobiotic- and antioxidant enzymes in broiler chickens. British J Nutr. 2012;108:588–602. https://doi.org/10.1017/S0007114511005873

65. Castrica M, Rebucci R, Giromini C, Tretola M, Cattaneo D, Baldi A. Total phenolic content and antioxidant capacity of agri-food waste and by-products. Ital J Anim Sci. 2019;18:336–341. https://doi.org/10.1080/1828051X.2018.1529544

66. Steiner T, Syed B. Phytogenic feed additives in animal nutrition. Medicinal and aromatic plants of the world: Scientific, production, commercial and utilization aspects. 2015;1:403-423. https://doi.org/10.1007/978-94-017-9810-5_20

67. Mahfuz S, Shang Q, Piao X. Phenolic compounds as natural feed additives in poultry and swine diets: a review. J Anim Sci Biotechnol. 2021;12:48. https://doi.org/10.1186/s40104-021-00565-3

68. Soltan MA, Shewita RS, El-Katcha MI. Effects of dietary anise seeds supplementation on growth performance, immune response, carcass traits and some blood parameters of broiler chickens. Int J Poult Sci. 2008;7:1078–1088. https://doi.org/10.3923/ijps.2008.1078.1088

69. Choi Y, Hosseindoust A, Goel A, Lee S, Jha PK, Kwon IK,Chae BJ. Effects of Ecklonia cava as fucoidan-rich algae on growth performance, nutrient digestibility, intestinal morphology and caecal microflora in weanling pigs. Asian-Australas J Anim Sci. 2016;30:64–70. https://doi.org/10.5713/ajas.16.0102

70. Dang DX, Cho S, Wang H, Seok WJ, Ha JH, Kim IH. Quercetin extracted from Sophora japonica flower improves growth performance, nutrient digestibility, cecal microbiota, organ indexes, and breast quality in broiler chicks. Anim Biosci. 2022;35:577–586. https://doi.org/10.5713/ab.21.0331

71. Aji SB, Ignatius K, Asha'Adatu Y, Nuhu JB, Abdulkarim A, Aliyu U, et al. Effect of feeding onion (*Allium cepa*) and garlic (*Allium sativum*) on some performance characteristics of broiler chickens. Res J Poultry Sci. 2011;4:22–27.

72. Mamoun T, Mukhtar MA, Tabidi MH. Effect of fenugreek seed powder on the performance, carcass characteristics and some blood serum attributes. Adv Res Agri Vet Sci. 2014;1:6–11.

73. Alhajj MS, Alhobaishi M, El Nabi AG, Al-Mufarrej SI. Immune responsiveness and performance of broiler chickens fed a diet supplemented with high levels of Chinese star anise fruit (*Illicium verum* Hook. F). J Anim Vet Adv. 2015;14:36–42.

74. Hoque MR, Kim IH. Effect of *Achyranthes japonica* Nakai extract on growth performance, apparent nutrient digestibility, excreta microbial count and gas emission in broilers fed different protein diets. J Anim Feed Sci. 2022;32:34–42. https://doi.org/10.22358/jafs/155126/2022

75. Biswas S, Cho SB, Kim IH. An evaluation of gallic acid supplementation to corn-soybean-gluten meal-based diet in broilers. Poult Sci. 2023a;102:102738. https://doi.org/10.1016/j.psj.2023.102738

76. Hossain MM, Cho SB, Kim IH. Effects of adding graded levels of Achyranthes japonica root extract to low, fecal microbiota, and meat quality parameters in broilers. Can J Anim Sci. 2023a;103:26–32. https://doi.org/10.1139/cjas-2022-0092

77. Hernández F, Madrid J, García V, Orengo J, Megías MD. Influence of two plant extracts on broilers performance, digestibility, and digestive organ size. Poult Sci. 2004;83:169–174. https://doi.org/10.1093/ps/83.2.169

78. Valenzuela-Grijalva NV, Pinelli-Saavedra A, Muhlia-Almazan A, Domínguez-Díaz D, González-Ríos H. Dietary inclusion effects of phytochemicals as growth promoters in animal production. J Anim Sci Technol. 2017;59:8. https://doi.org/10.1186/s40781-017-0133-9

79. Barrow S, Oyen LPA, Dung NX. Plant resources of South-East Asia no. 19. Essential-oil plants. Kew Bull. 1999;54:502.

80. Schöne F, Vetter A, Hartung H, Bergmann H, Biertümpfel A, Richter G, Müller S, Breitschuh G. Effects of essential oils from fennel (*Foeniculi aetheroleum*) and caraway (*Carvi aetheroleum*) in pigs. J Anim Physiol Anim Nutr (Berl). 2006;90:500–510. https://doi.org/10.1111/j.1439-0396.2006.00632.x

81. Javan AJ, Ghazvinian K, Mahdavi A, Vayeghan AJ, Staji H, Sahar GK. The effect of dietary *Zataria multiflora* Boiss. essential oil supplementation on microbial growth and lipid peroxidation of broiler breast fillets during refrigerated storage. J Food Process Preserv. 2013;37:881–888. https://doi.org/10.1111/j.1745-4549.2012.00714.x

82. Ranucci D, Beghelli D, Trabalza-Marinucci M, Branciari R, Forte C, Olivieri O, Badillo Pazmay GV, Cavallucci C, Acuti G. Dietary effects of a mix derived from oregano (*Origanum vulgare* L.) essential oil and sweet chestnut (*Castanea sativa* Mill.) wood extract on pig performance, oxidative status and pork quality traits. Meat Sci. 2015;100:319–326. https://doi.org/10.1016/j.meatsci.2014.09.149

83. Ghazaghi M, Mehri M, Bagherzadeh-Kasmani F. Effects of dietary *Mentha spicata* on performance, blood metabolites, meat quality and microbial ecosystem of small intestine in growing Japanese quail. Anim Feed Sci Technol. 2014;194:89–98. https://doi.org/10.1016/j.anifeedsci.2014.04.014

84. Yan L, Wang JP, Kim HJ, Meng QW, Ao X, Hong SM, Kim IH. Influence of essential oil supplementation and diets with different nutrient densities on growth performance, nutrient digestibility, blood characteristics, meat quality and fecal noxious gas content in grower–finisher pigs. Livest Sci. 2010;128:115–122. https://doi.org/10.1016/j.livsci.2009.11.008

85. Ahmed ST, Islam MM, Bostami ABMR, Mun HS, Kim YJ, Yang CJ. Meat composition, fatty acid profile and oxidative stability of meat from broilers supplemented with pomegranate (*Punica granatum* L.) by-products. Food Chem. 2015;188:481–488. https://doi.org/10.1016/j.foodchem.2015.04.140

86. Galli GM, Gerbet RR, Griss LG, Fortuoso BF, Petrolli TG, Boiago MM, et al. Combination of herbal components (curcumin, carvacrol, thymol, cinnamaldehyde) in broiler chicken feed: Impacts on response parameters, performance, fatty acid profiles, meat quality and control of coccidia and bacteria. Microb Pathog. 2020;139:103916. https://doi.org/10.1016/j.micpath.2019.103916

87. Ahammad GS, Kim IH. Effects of micellar quercetin supplementation on growth performance, nutrient

digestibility, fecal microbiota, meat quality, and physiological status in broiler chickens. Animals. 2024;14:1918. https://doi.org/10.3390/ani14131918

88. Giannenas I, Florou-Paneri P, Papazahariadou M, Christaki E, Botsoglou NA, Spais AB. Effect of dietary supplementation with oregano essential oil on performance of broilers after experimental infection with *eimeria tenella*. Arch Anim Nutr. 2003;57:99–106. https://doi.org/10.1080/0003942031000107299

89. Simitzis PE, Symeon GK, Charismiadou MA, Bizelis JA, Deligeorgis SG. The effects of dietary oregano oil supplementation on pig meat characteristics. Meat Sci. 2010;84:670–676. https://doi.org/10.1016/j.meatsci.2009.11.001

90. Bolukbasi SC. The effect of feeding thyme, sage and rosemary on laying hen performance, cholesterol and some proteins ratio of egg yolk and *Escherichia Coli* count in feces. Arch fur Geflugelkd. 2008;72:231–237.

91. Abdel-Wareth AAA, Lohakare JD. Effect of dietary supplementation of peppermint on performance, egg quality, and serum metabolic profile of Hy-Line Brown hens during the late laying period. Anim Feed Sci Technol. 2014;197:114–120. https://doi.org/10.1016/j.anifeedsci.2014.07.007

92. Mousavi A, Mahdavi AH, Riasi A, Soltani-Ghombavani M. Synergetic effects of essential oils mixture improved egg quality traits, oxidative stability and liver health indices in laying hens fed fish oil. Anim Feed Sci Technol. 2017;234:162–172. https://doi.org/10.1016/j.anifeedsci.2017.10.001

93. Gerzilov V, Nikolov A, Petrov P, Bozakova N, Penchev G, Bochukov A. Effect of a dietary herbal mixture supplement on the growth performance, egg production and health status in chickens. J Central Eur Agric. 2015;16:10–27. https://doi.org/10.5513/JCEA01/16.2.1580

94. Abdel-Wareth AAA, Lohakare JD. Productive performance, egg quality, nutrients digestibility, and physiological response of bovans brown hens fed various dietary inclusion levels of peppermint oil. Anim Feed Sci Technol. 2020;267:114554. https://doi.org/10.1016/j.anifeedsci.2020.114554

95. Bozkurt M, Alçiçek A, Çabuk M, Küçükyilmaz K, Çatli AU. Effect of an herbal essential oil mixture on growth, laying traits, and egg hatching characteristics of broiler breeders. Poult Sci. 2009;88:2368–2374. https://doi.org/10.3382/ps.2009-00048

96. Nasiroleslami M, Torki M. Including essential oils of fennel (*Foeniculum vulgare*) and ginger (*Zingiber officinale*) to diet and evaluating performance of laying hens, white blood cell count and egg quality characteristics. Adv Environ Biol. 2010;4:341–345.

97. Ghasemi R, Zarei M, Torki M. Adding medicinal herbs including garlic (*Allium sativum*) and thyme (*Thymus vulgaris*) to diet of laying hens and evaluating productive performance and egg quality characteristics. Am J Anim Vet Sci. 2010;5:151–154. https://doi.org/10.3844/ajavsp.2010.151.154

98. Shirani V, Jazi V, Toghyani M, Ashayerizadeh A, Sharifi F, Barekatain R. *Pulicaria gnaphalodes* powder in broiler diets: consequences for performance, gut health, antioxidant enzyme activity, and fatty acid profile. Poult Sci. 2019;98:2577–2587. https://doi.org/10.3382/ps/pez010

99. Paraskeuas V, Fegeros K, Palamidi I, Theodoropoulos G, Mountzouris KC. Phytogenic administration and

669 reduction of dietary energy and protein levels affects growth performance, nutrient digestibility and
670 antioxidant status of broilers. J Poult Sci. 2016;53:264–773. https://doi.org/10.2141/jpsa.0150113

671 100. Khan SU, Jeon YH, Kim IH. Dietary inclusion of micelle silymarin enhances egg production, quality, and
672 lowers blood cholesterol in Hy-line brown laying hens. J Anim Physiol Anim Nutr (Berl). 2024b;108:1038–
673 1045. https://doi.org/10.1111/jpn.13948

674 101. Ahammad GS, Jeon YH, Kim IH. Assessing the influence of micelle silymarin on laying hens' performance,
675 egg quality, water loss and blood profile. J Anim Physiol Anim Nutr (Berl). 2024b;108:1326–1335.
676 https://doi.org/10.1111/jpn.13979

677 102. Li Y, Wu Y, Li YJ, Meng L, Ding CY, Dong ZJ. 2019. Effects of Silymarin on the in vivo pharmacokinetics
678 of simvastatin and its active metabolite in rats. Molecules. 2019;24:1666.
679 https://doi.org/10.3390/molecules24091666

680 103. Zentner E, Steiner T, Padoan D. Impact of essential oils on ammonia and odor emissions of growing-
681 finishing pigs. 2012. In 4th European symposium of porcine health management, Brussels (pp. 25-27).

682 104. El-Deek AA, Al-Harthi MA, Osman M, Al-Jassas F, Nassar R. Effect of different levels of green tea
683 (*Camellia sinensis*) as a substitute for oxytetracycline as a growth promoter in broilers diets containing two
684 crude protein levels. Arch Geflu¨gelkd. 2012;76:81–87.

685 105. Biswas S, Kim IH. Assessment of Quillaja saponin as a feed supplement in maize-soybean-oilseed rape
686 meal-based diet for enhanced growing pig performance. J Anim Feed Sci. 2023c;33:193–199.
687 https://doi.org/10.22358/jafs/171702/2023

688 106. Dang DX, Kim IH. Effects of *Quillaja* saponin supplementation on growth performance, nutrient
689 digestibility, fecal microbiota, and fecal gas emission in growing pigs. Can J Anim Sci. 2021;101:667–673.
690 https://doi.org/10.1139/cjas-2020-0185

691 107. Bartoš P, Dolan A, Smutný L, Šístková M, Celjak I, Šoch M, Havelka Z. Effects of phytogenic feed additives
692 on growth performance and on ammonia and greenhouse gases emissions in growing-finishing pigs. Anim
693 Feed Sci Technol. 2016;212:143–148. https://doi.org/10.1016/j.anifeedsci.2015.11.003

694 108. Khan SU, Song J ho, Kim IH. Inclusion of dietary *Quillaja* saponin and seaweed on growth efficiency,
695 noxious gas emissions, and fecal score in weaning pigs. Can J Anim Sci. 2024c;104:102–108.
696 https://doi.org/10.1139/cjas-2023-0031

697 109. Ruan D, Wang WC, Lin CX, Fouad AM, Chen W, Xia WG, Wang S, Luo X, Zhang WH, Yan SJ, Zheng
698 CT, Yang L. Effects of curcumin on performance, antioxidation, intestinal barrier and mitochondrial function
699 in ducks fed corn contaminated with ochratoxin A. Animal 2019;13:42–52.
700 https://doi.org/10.1017/S1751731118000678

701 110. Akbarian A, Golian A, Kermanshahi H, Farhoosh R, Raji AR, De Smet S, Michiels J. Growth performance
702 and gut health parameters of finishing broilers supplemented with plant extracts and exposed to daily
703 increased temperature. Spanish J Agric Res. 2013;11:109–119. https://doi.org/10.5424/sjar/2013111-3392

111. Gaucher ML, Quessy S, Letellier A, Arsenault J, Boulianne M. Impact of a drug-free program on broiler chicken growth performances, gut health, *Clostridium perfringens* and *Campylobacter jejuni* occurrences at the farm level. Poult Sci. 2015;94:1791–1801. https://doi.org/10.3382/ps/pev142

112. Wang R, Yu H, Fang H, Jin Y, Zhao Y, Shen J, Zhou C, Li R, Wang J, Fu Y, Zhang J. Effects of dietary grape pomace on the intestinal microbiota and growth performance of weaned piglets. Arch Anim Nutr. 2020a;74:296–308. https://doi.org/10.1080/1745039X.2020.1743607

113. Hao R, Li Q, Zhao, J., Li, H., Wang, W., Gao, J. Effects of grape seed procyanidins on growth performance, immune function and antioxidant capacity in weaned piglets. Livest Sci. 2015;178:237–242. https://doi.org/10.1016/j.livsci.2015.06.004

114. Wang M, Huang H, Hu Y, Huang J, Yang H, Wang L, Chen S, Chen C, He S. Effects of dietary microencapsulated tannic acid supplementation on the growth performance, intestinal morphology, and intestinal microbiota in weaning piglets. J Anim Sci. 2020b;98. https://doi.org/10.1093/jas/skaa112

115. Zeng Z, Xu X, Zhang Q, Li P, Zhao P, Li Q, Liu J, Piao X. Effects of essential oil supplementation of a low-energy diet on performance, intestinal morphology and microflora, immune properties and antioxidant activities in weaned pigs. Anim Sci J. 2015;86:279–285. https://doi.org/10.1111/asj.12277

116. Bilić-Šobot D, Kubale V, Škrlep M, Čandek-Potokar M, Prevolnik Povše M, Fazarinc G, Škorjanc D. Effect of hydrolysable tannins on intestinal morphology, proliferation and apoptosis in entire male pigs. Arch Anim Nutr. 2016;70:378–388. https://doi.org/10.1080/1745039X.2016.1206735

117. Liu H, Hu J, Mahfuz S, Piao X. Effects of hydrolysable tannins as zinc oxide substitutes on antioxidant status, immune function, intestinal morphology, and digestive enzyme activities in weaned piglets. Animals. 2020;10:757. https://doi.org/10.3390/ani10050757

118. Hassan FAM, Awad A. Impact of thyme powder (*Thymus vulgaris* L.) supplementation on gene expression profiles of cytokines and economic efficiency of broiler diets. Environ Sci Pollut Res. 2017;24:15816–15826. https://doi.org/10.1007/s11356-017-9251-7

119. Mohiti-Asli M, Ghanaatparast-Rashti M. Comparison of the effect of two phytogenic compounds on growth performance and immune response of broilers. J Appl Anim Res. 2017;45:603–608. https://doi.org/10.1080/09712119.2016.1243119

120. Akhavan-Salamat H, Ghasemi HA. Alleviation of chronic heat stress in broilers by dietary supplementation of betaine and turmeric rhizome powder: dynamics of performance, leukocyte profile, humoral immunity, and antioxidant status. Trop Anim Health Prod. 2016;48:181–188. https://doi.org/10.1007/s11250-015-0941-1

121. Guo S, Cheng Q, Li Y, Duan R, Hou Y, Yi D, Ding B. Effects of dietary coated-oleum cinnamomi supplementation on the immunity and intestinal integrity of broiler chickens. Anim Sci J. 2018;89:1581–1590. https://doi.org/10.1111/asj.13094

122. Liu S, Song M, Yun W, Lee J, Lee C, Kwak W, Han N, Kim H, Cho J. Effects of oral administration of different dosages of carvacrol essential oils on intestinal barrier function in broilers. J Anim Physiol Anim Nutr (Berl). 2018;102:1257–1265.

123. Paraskeuas VV, Mountzouris KC. Modulation of broiler gut microbiota and gene expression of Toll-like receptors and tight junction proteins by diet type and inclusion of phytogenics. Poult Sci. 2019a;98:2220–2230. https://doi.org/10.3382/ps/pey588

124. Yang JY, Zhang HJ, Wang J, Wu SG, Yue HY, Jiang XR, Qi GH. Effects of dietary grape proanthocyanidins on the growth performance, jejunum morphology and plasma biochemical indices of broiler chicks. Animal. 2017;11:762–770. https://doi.org/10.1017/S1751731116002056

125. Jahanian E, Jahanian R, Rahmani HR, Alikhani M. Dietary supplementation of *Echinacea purpurea* powder improved performance, serum lipid profile, and yolk oxidative stability in laying hens. J Appl Anim Res. 2017;45:45–51. https://doi.org/10.1080/09712119.2015.1091344

126. He X, Hao D, Liu C, Zhang X, Xu D, Xu X, Wang J, Wu R. Effect of supplemental oregano essential oils in diets on production performance and relatively intestinal parameters of laying hens. Am J Mol Biol. 2017;7:73–85. https://doi.org/10.4236/ajmb.2017.71006

127. Nazar FN, Videla EA, Marin RH. Thymol supplementation effects on adrenocortical, immune and biochemical variables recovery in Japanese quail after exposure to chronic heat stress. Animal. 2019;13:318–325. https://doi.org/10.1017/S175173111800157X

128. Koncicki A, Śmiałek M, Tykałowski B, Pestka D, Stenzel T. The influence of phytoncides on the immune system of broiler chickens and turkeys. Cent Eur J Immunol. 2015;3:287–291. https://doi.org/10.5114/ceji.2015.54588

129. Ding X, Wu X, Zhang K, Bai S, Wang J, Peng H, Xuan Y, Su Z, Zeng Q. Dietary supplement of essential oil from oregano affects growth performance, nutrient utilization, intestinal morphology and antioxidant ability in Pekin ducks. J Anim Physiol Anim Nutr (Berl). 2020;104:1067–1074. https://doi.org/10.1111/jpn.13311

130. Hossain MM, Bo Cho S, Kim IH. *Silybum marianum* seed extract as a potential phytogenic feed additive for improving growth performance and nutrient digestibility in growing pigs. Can J Anim Sci. 2023b;104:80–85. https://doi.org/10.1139/cjas-2023-0053

131. Hossain MM, Hwang HS, Pang M, Choi MK, Kim IH. Effect of dietary *Achyranthes japonica* extract on growth performance of growing pigs and absorption rate of quercetin in blood. J Anim Sci Technol. 2024c;66:103–114.

132. Park JH, Sureshkumar S, Kim IH. Influences of dietary flavonoid (quercetin) supplementation on growth performance and immune response of growing pigs challenged with *Escherichia coli* lipopolysaccharide. J Anim Sci Technol. 2020;62:605–613. https://doi.org/10.5187/jast.2020.62.5.605

133. Lee J, Kim HA, Kang YJ, Kim YK, Shin MC. Effect of *Sasa quelpaertensis* Nakai extract on gut microbiota and production performance in pigs. J Anim Sci Technol. 2024;66:740–748. https://doi.org/10.5187/jast.2023.e84

134. Elkomy AE, El-Saadany AS, Shreif EY, Bayoumi AA, Abd El-Maged MH, Alagawany M, Saleh AA, Cho S, Kim IH, Eltahan HM. Anise and grape seed oils as a feed additive to improve the performance, immune response, and antioxidant activity and reduce caecal pathogenic microbes of quail. Arch Anim Breed.

2023;66:379–390. https://doi.org/10.5194/aab-66-379-2023

135. Hossain MM, Cho S, Kim IH. *Achyranthes japonica* extract as phytogenic feed additive enhanced nutrient digestibility and growth performance in broiler. J Anim Sci Technol. 2024b;66:471–481. https://doi.org/10.5187/jast.2023.e56

136. Hoque MR, Kim IH. Effect of quercetin supplementation on growth performance, nutrient digestibility, excreta bacterial count, noxious gas emission, and meat quality of broilers when fed different protein diets. Can J Anim Sci. 2023;103:185–191. https://doi.org/10.1139/cjas-2021-0122

137. Saleh AA, El-Tahan HM, Shaban M, et al. Effect of dietary supplementation of betaine and organic minerals on growth performance, serum biochemical parameters, nutrients digestibility, and growth-related genes in broilers under heat stress. Poult Sci. 2023;102:103051. https://doi.org/10.1016/j.psj.2023.103051

138. Ahammad GS, Jang SY, Kim IH. Effects of micelle silymarin in corn-soybean meal-based diet on laying hens' performance, egg quality, and blood profile, with comparative assessment of blood absorption rates between powdered and micelle silymarin. Poult Sci. 2024c;103:104029. https://doi.org/10.1016/j.psj.2024.104029

Table 1. Impact of dietary PFA inclusion on non-ruminant immunity

Animal and species	Feed Additive, Major Components, and Dose	Immune Response	References
Weaned piglets (Songliao black pigs)	Grape pomace; polyphenols; 5%	▪ Increased the number of *Lactobacillus delbrueckii*, *Olsenella umbonata*, and *Selenomonas bovis* in caecum. ▪ Enhanced VH: CD ratio of jejunum. ▪ Lowered MRNA expression of pro-inflammatory cytokines (IL-1β, IL-8, IL-6, and TNF-α). ▪ Augmented IgG in serum.	[112]
Piglets (Duroc × Landrace × Yorkshire)	Grape seed extract; procyanidins; 50, 100, and 150 mg/kg	▪ Improved IgG, IgM, C-4, IL-2, T-AOC, SOD, GSH-Px in serum. ▪ Decreased MDA in serum.	[113]
Piglets (Duroc × Landrace × Yorkshire)	Chinese gallnut; tannic acid; 500, 1000, and 1500 mg/kg	▪ Heightened VH: CD ratio of duodenum. ▪ Enhanced gene expression of solute carrier family 6, member 19, solute carrier family 15, and member 1 in ileum. ▪ Decreased gene expression of solute carrier family 5 and member 1 in jejunum. ▪ Lowered maltase activities in ileum. ▪ Elevated colonic bacterial community.	[114]
Piglets ([Yorkshire × Landrace] × Duroc)	Brown algae; eckol; 0.05% and 0.1%	▪ Lowered the levels of stress hormones (cortisol, epinephrine, and norepinephrine). ▪ Reduced antioxidants (SOD and glutathione peroxide).	[41]
Male pigs (Duroc × Landrace × Large White)	Cinnamaldehyde; EOs; 50, 100, and 200 ppm	▪ Reduced TC and TG in serum. ▪ Increased goblet cell and lactase activities in jejunum and sucrose activities in duodenum. ▪ Augmented VH: CD ratio in ileum. ▪ Improved expression of occluding and glucose transporter-2 gene in duodenum and ileum.	[58]
Piglets (Duroc × Landrace × Large White)	Cinnamaldehyde and thymol; EOs; 0.025%	▪ Increased VH of jejunum. ▪ Lowered *E. coli* and total anaerobes in rectum. ▪ Enhanced albumin, IgA, IgG, and T-AOC in plasma.	[115]

Fattening boars (Landrace × Large White)	Tannins; tannic acid; 1%, 2%, and 3%	▪ Improved VH and mucosal thickness in duodenum. ▪ Lessened mitosis and apoptosis count in large intestine.	[116]
Piglets (Landrace × Yorkshine × Duroc)	Chestnut wood, tannic acid; 1000 mg/kg	▪ Heightened CAT, GSH-Px, IgM and lower MDA in serum. ▪ Improved trypsin, lipase and amylase activities. ▪ Enhanced VH: CD ratio of jejunum. ▪ Elevated propionic acid, butyric acid, and acetic acid concentrations in the colon.	[117]
Broiler (Cobb 500)	Thyme powder; EOs, carvacrol, phenolic acids, ellagic acid, and flavonoid; 2000, 5000, and 8000 mg/kg	▪ Enhanced lymphocytes, white blood cells, and IgG. ▪ Heightened TNF-α, IFN-γ, NF-κBP50 by all the doses. ▪ Reduced IL-6 by the dose of 8000.	[118]
Broiler (Ross 308)	Oregano; EOs; 5%	▪ Increased secondary antibody titer and IgG titer. ▪ Decreased H/L ratio.	[119]
Broiler (Ross male)	Turmeric rhizome; phenolic compounds; 16.2 mg/g	▪ Increased total secondary antibody titer. ▪ Decreased H/L ratio.	[120]
Broiler (Ross 308)	Thyme; thyme oil; 0.5 g/kg	▪ Decreased MDA in duodenal mucosa and kidney. ▪ Increased IgA in duodenal mucosa. ▪ Enhanced intestinal barrier integrity.	[63]
Broiler (mixed-sex, Cobb 500)	*Oleum cinnamomi*; cinnamaldehyde; 50, 100, 200, and 300 mg/kg	▪ Decreased serum Ig levels. ▪ Lowered ileal secretory IgA contents at day 21 and commonly down-regulated duodenal and ileal mRNA expression of IL-1β and IL-8 at day 42. ▪ Augmented VH: CD ratio of jejunum and upregulated intestinal claudin-1 expression. ▪ Up and down regulated jejunal (at day 21) and duodenal (at day 42) mucin-2 expression.	[121]
Broiler (mixed-sex, Ross 308)	Carvacrol EO; carvacrol, thymol, paracymene; 200, 300, or 400 µl	▪ Increased activity of the sucrase and lactase in intestinal mucosa. ▪ Improved intestinal barrier function. ▪ Significantly heightened OCLN, CLDN-1, CLDN-3, CLDN-5, ZO-1, and ZO-2 mRNA expression.	[122]

Broiler (male Cobb 500)	PFA; menthol and anethole; 100 and 150 mg/kg	▪ Significant effect on microbial fermentation at ileum and a retarding effect in ceca with additional variable VFA molar patterns. ▪ Increased the ileal mucosa expression of claudin 5 (CLDN5) and MUC2 genes. ▪ Decreased cecal TLR2 gene expression.	[123]
Broiler (Cobb 500)	Grape; Proanthocyanidins; polyphenols; 7.5, 15, and 30 mg/kg	▪ Augmented jejunum morphology. ▪ Increased T-SOD, ALT, ALP, and CRE concentration in serum. ▪ Diminished MDA value in serum.	[124]
Bovans Brown laying hens	Peppermint; EOs; 74, 148, 222, and 296 mg/kg	▪ Increased TP in serum. ▪ Lessened serum cholesterol.	[94]
Hy-line White (Leghorn)	*Echinacea purpurea*; polyphenols; 2.5, 5, 7.5 and 10 g/kg	▪ Lessened TC, TG, in serum. ▪ Reduced cholesterol in egg yolk. ▪ Increased HDL in serum.	[125]
Hy-line layer	Oregano; EOs; 50, 100, and 150 mg/kg	▪ Heightened VH: CD ratio of duodenum. ▪ Augmented gene expression on glucose transporter 2, peptide transporter 1, sodium-glucose cotransporter 1 in duodenum and jejunum.	[126]
Quail (female)	PFA; thymol; 2 g/kg (80 mg/bird per day)	▪ Enhanced albumen, glucose, globulins, and TP in plasma. ▪ Increased inflammatory responses. ▪ Improved H/L ratio in blood.	[127]
Turkey	PFA; mixed EOs; 1 mL/L	▪ Elevated the percentage of CD4+ T lymphocytes in the thymus and the spleen. ▪ Enhanced the percent of CD8+ T lymphocytes in the cecal tonsils and the blood. ▪ Improved the higher percent of CD4+ and CD8+ T lymphocytes in the thymus and ileal mucosa.	[128]
Duckling (Cherry valley)	Oregano; EOs; 100 mg/kg	▪ Increased VH: CD ratio in jejunum. ▪ Improved SOD in serum and T-AOC in jejunum mucosa. ▪ Reduced MDA in serum and liver tissue. ▪ Decreased mRNA expression of ZO-3 and sIgA.	[129]

Abbreviation: VH: CD, villus height to crypt depth; T-AOC, total antioxidant capacity; SOD, superoxide dismutase; GSH-Px: glutathione peroxidase; MDA, malondialdehyde; TP, total protein; HDL, high-density lipoprotein; TC, total cholesterol; TG, triglycerides; T-SOD, total superoxide dismutase; ALT, alanine aminotransferase; ALP, alkaline phosphatase; CRE: creatinine; TLR2, toll-like receptor 2; VFA, volatile fatty acids; ZO-3, zonula occludens-3; sIgA, secretory immunoglobulin A; CLDN, claudin; OCLN, occludin; TNF-α, tumor necrosis factor-alpha; IFN-γ, interferon-gamma; NF-κB, nuclear factor-kappa B; H/L, heterophil to lymphocyte.

792

793

Table 2: The response of non-ruminant animals to the phytogenic additive

Animal and species	Feed additive and major components	Dose	Growth performance outcome	Other responses	References
Growing pigs ([Yorkshire × Landrace] × Duroc)	*Silybum marianum*; Flavonoid	0.05% and 0.1%	ADG and ADFI ↑; FCR ↕	Digestibility of DM, nitrogen, energy ↑; Blood profile of bile acid, AST, and ALT ↕	[130]
Growing pigs ([Yorkshire × Landrace] × Duroc)	*Quillaja saponin*; Saponin	200 mg/kg	ADG ↑; ADFI and FCR ↕	Fecal ammonia emission and fecal coliform bacteria ↓	[106]
Weaning pigs ([Yorkshire × Landrace] × Duroc)	*Houttuynia cordata* and *Taraxacum officinale;*	1 g/kg	ADG and G:F ↑;	Digestibility of nutrient ↕; lymphocyte concentration ↑; *E coli* populations in the feces ↓	[13]
Growing pigs ([Yorkshire × Landrace] × Duroc)	*Achyranthes japonica*; Flavonoids, polyphenol, and saponin	0.025% and 0.05%	ADG and ADFI ↑; Gain to feed ratio ↕	Nutrient digestibility, fecal microbial count, and gas emission ↕; Blood absorption rate ↑	[131]
Growing pigs ([Yorkshire × Landrace] × Duroc)	Quillaja saponin; Saponin	0.01%	BW and ADG ↑; FCR ↓	Digestibility of DM, nitrogen ↑; NH_3, H_2S, and CH_4 emissions ↓, Faecal score ↓	[105]
Growing pigs ([Landrace × Yorkshire] × Duroc)	Quercetin; Flavonoid	0.1%	ADG ↑	Digestibility of DM and nitrogen ↑; IL-6 ↓; IgG and WBC concentrations ↑; and lymphocytes percentage ↑	[132]
Weaned piglets (Duroc × Landrace × Yorkshire)	Glycyrrhiza; Licorice flavonoids	0, 50, 150 and 250 mg/kg	ADG ↑; FI/body gain ↓	Diarrhoea index and pH in caecum and colon ↓; Intestinal morphological structure ↑	[38]
Landrace finishing pigs	*Sasa quelpaertensis* Nakai	450 ml	ADG ↑	*Firmicutes* and *Actinobacteria* phyla ↑; *Bacteroidetes* and *Spirochaetes* phyla ↓;	[133]

				Bifidobacterium and *Lactobacillus* genera ↑, *Treponema*, *Prevotella*, and *Turicibacter* ↓; Backfat thickness ↓	
Broilers (Ross 308)	Quercetin; Saponin	0.2, 0.4, and 0.6 g/kg QS	BWG and FI ↑, FCR ↕	Digestibility of DM and energy, cecal lactic acid bacteria counts ↑; Breast muscle, pH, and water holding capacity of meat↑; Drip loss of meat ↓	[70]
Laying hens (Hy-Line brown)	Micelle silymarin; Silybin, silydianin, and silychristin	0, 0.03, and 0.06%	FCR ↓	Egg weight, egg yolk color, albumen height, eggshell strength, and egg shell thickness↑; Downgraded egg ↓; Blood profile of AST, ALT, and lactate dehydrogenase ↓	[101]
Quails (Old Japanese)	Anise (Ans) and grape seed (Grp)	Ans 0.5%, Grp 0.5%, and Ans 0.25% + Grp 0.25%	BW ↑; FCR ↓	Dressing percentage, carcass yield, immune organs' relative weight ↑; Abdominal fat ↓, Low density lipoprotein ↓, High density lipoprotein ↑; Total antioxidant capacity ↑; *Lactobacillus* count ↑; *E. coli* and *Salmonella* count ↓	[134]
Broilers (Ross 308)	*Achyranthes japonica*; Saponin, flavonoid, and polyphenol	0.02%; 0.04%, and 0.06%	BWG and FI ↑; FCR ↕	Digestibility of DM, nitrogen, energy ↑; Excreta microbial counts, noxious gas emissions, and meat quality ↕; Blood absorption rate ↑	[135]
Broilers (Ross 308)	Quercetin, Flavonoid	0.025% and 0.050%	BWG ↑; FI and FCR ↕	Digestibility of DM ↑; Meat quality of drip loss ↓; Excreta	[136]

				microbial counts and noxious gas emissions ↕	
Broilers (Ross 308)	Betaine	0 and 2,000 ppm	BW and FI ↑; FCR ↓	Mn, Zn, Cu, and Fe digestibility ↑; Serum total protein and globulin concentrations ↑; Gene expressions were reversed	[137]
Laying hens (Hy-Line brown)	Micelle silymarin; Silybin, silydianin, and silychristin	0%, 0.03% and 0.06%	BW and FCR ↕	Haugh units, egg weight, eggshell strength, and albumen height ↑, Egg yolk color, eggshell thickness, and egg water loss ↓; Blood profile of alkaline phosphatase, AST cholesterol ↓	[138]
Broilers (Ross 308)	Quercetin; Flavonoid	0%, 0.02%, 0.04% and 0.06%	BW and FI ↑; FCR ↕	Digestibility of DM and energy ↑; Tibia ash ↑; Organ weights of breast muscle, colour lightness and redness of meat ↑; drip loss of meat ↓	[14]
Laying hens (Hy-Line brown)	Micelle silymarin; Silybin, silydianin, and silychristin	0%, 0.02%, 0.04%, and 0.06%	FI ↑; FCR ↓	Egg production, egg shell thickness and eggshell strength, and yolk colour ↑; Blood profile of cholesterol and triglyceride ↓	[108]

Abbreviation: ADG, average daily gain; ADFI, average daily feed intake; FCR, feed conversion ratio; AST, aspartate aminotransferase; ALT, alanine aminotransferase; DM, dry matter; NH_3, ammonia; H_2S, hydrogen sulfide; CH_4, methane; FI, feed intake; BW, body weight; Mn, manganese; Zn, zinc; Cu, copper; Fe, iron; IL, interleukin; Ig, immunoglobulin. The symbol ↑ indicates an increase in response criteria, ↓ indicates a decrease in response criteria, and ↕ indicates no effect on response criteria.

794

795

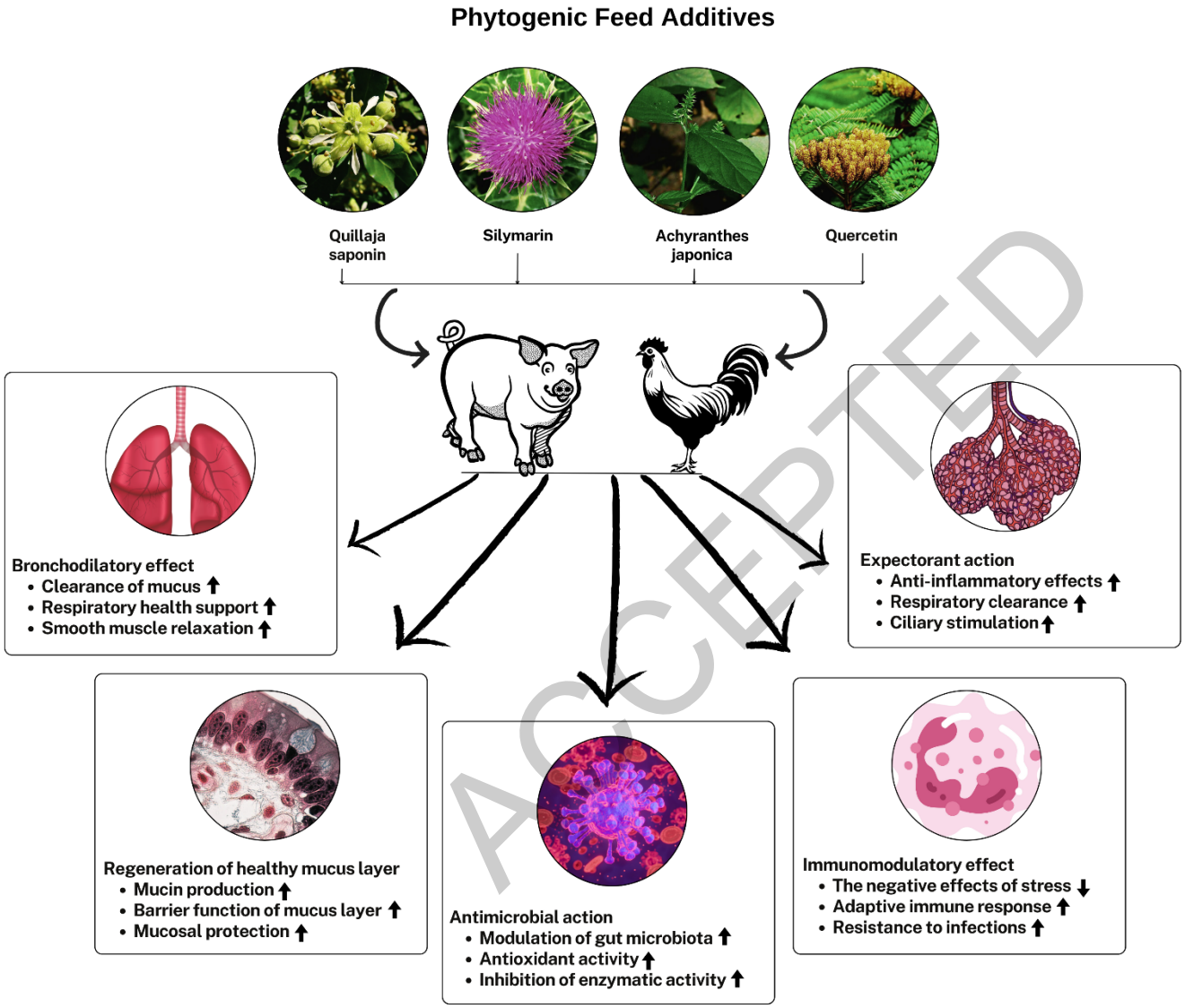

Fig. 1. Effects of PFAs on non-ruminant animal health

796