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The role of phyto-genic feed additives in growth and immune response in livestock production: a global systematic review

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Phyto-genic feed additives in livestock production, particularly in addressing their impact on growth and the immune response within the sector, are very important in modern agriculture. Therefore, the objective of this systematic review is to critically assess the current evidence on the impact of phyto-genic feed additives on growth performance and immune response in livestock species. A systematic literature search was conducted according to the PRISMA guidelines. The searches were performed in multiple academic databases, Scopus, ScienceDirect, Web of Science and EBSCOhost (Academic Search Ultimate, AGRICOLA, and MEDLINE with full text), covering the period from January 1, 2010 to December 31, 2024. Among the 104 research papers downloaded, 20 were included and analysed directly in this study. The phyto-genic feed additives identified in this study include essential oils, mango leaves, rosemary oils, turmeric, black cumin, propolis, thyme, *Achyranthes*, *Lycium*, *Ajwain*, *Chenopodium*, the phytoncide *Dialium guineense*, and *Salix alba* extracts. The results show that in poultry, typical improvements in body weight gain or average daily weight gain range from 5 to 13%, while lambs show some of the strongest responses, with growth increases of up to 30%. In pigs, benefits are more evident under disease or stress conditions, highlighting the health-supporting role of phyto-genic feed additives. Rabbits respond moderately, particularly at optimal doses of bioactive-rich supplements such as propolis. In cattle, growth improvements are consistent but modest, suggesting that phyto-genic feed additives function more as complements than primary growth promoters. A key theme across all species is the importance of dose–response optimization. Many phyto-genic feed additives demonstrate nonlinear effects, where low-to-moderate inclusion levels increase growth, but excessively high levels either provide no additional benefit or impair feed efficiency. Additionally, the immunomodulatory potential of phyto-genic feed additives appears to be strongest in monogastric species (poultry, pigs, and rabbits), where rapid immune responses are critical to productivity. Evidence from numerous livestock studies suggests that phyto-genic feed additives are effective alternatives to traditional antibiotic growth promoters.

KEYWORDS

plant-based feed additive, growth performance, immune response, livestock production, global overview

1 Introduction

The livestock industry plays an important role in meeting the nutritional needs of a rapidly growing human population, providing high-quality animal protein that is essential for food security (Wu et al., 2014). As the world population is projected to reach more than 9.7 billion by 2050, the demand for meat, milk, and eggs is expected to increase substantially, placing unprecedented pressure on animal production systems to improve efficiency, sustainability, and product safety (Mills and Driscoll, 2022). To meet these challenges, livestock producers have historically relied on conventional feed additives, particularly antibiotic growth promoters (AGPs), to increase growth performance, optimize feed efficiency, and reduce the incidence of disease (Wythe et al., 2023). However, widespread and indiscriminate use of AGPs has raised serious concerns about antimicrobial resistance (AMR), public health risks, and the presence of drug residues in animal-derived foods (Salim et al., 2018). These challenges have stimulated regulatory restrictions and the consumer’s demand for safe, natural, and environmentally sustainable alternatives in animal nutrition (Manchee, 2018).

In this context, phytogetic feed additives (PFAs), also referred to as phytobiotics or botanicals, have emerged as promising candidates. PFAs encompass a diverse group of natural substances derived from plants, including herbs, spices, essential oils, and plant extracts, which are rich in bioactive secondary metabolites such as flavonoids, alkaloids, tannins, saponins, and terpenoids (Adetunji et al., 2025; Attia et al., 2025). These compounds exert multiple biological activities that can support animal health and performance, including antioxidant, antimicrobial, anti-inflammatory, and immunomodulatory effects (Ostojić Andrić et al., 2023). For example, essential oils such as thymol and carvacrol have demonstrated strong antimicrobial activity against pathogenic bacteria, while polyphenolic compounds such as curcumin and catechins exhibit potent antioxidant and anti-inflammatory functions (Memar et al., 2017; Yahfoufi et al., 2018; Puvača et al., 2021). Through these mechanisms, PFAs can contribute to improved utilization of nutrients, improved immune competence, and reduced susceptibility to diseases, thus promoting sustainable animal production.

Despite their potential, the effects of PFAs on growth performance and immune response remain inconsistent in all studies. Variations in plant species, extraction methods, active compound concentrations, dosage levels, and interactions with other dietary components often produce heterogeneous results. For example, while several studies reported significant improvements in average daily gain (ADG), feed conversion ratio (FCR), and immune parameters such as lymphocyte proliferation and antibody titers, others reported negligible or conflicting results (Attia et al., 2017; Adeyemi et al., 2021; Liu et al., 2023). Furthermore, species-specific responses add another layer of complexity; monogastric animals such as poultry and pigs may respond differently to PFAs than ruminants because of differences in digestive physiology and microbial ecosystems. Given the growing body of research and the variability of findings, there is a pressing need for a systematic evaluation of the evidence. Although narrative reviews have discussed the potential benefits of phytoGENICS, few have comprehensively synthesised quantitative and qualitative data across multiple species of livestock, with a focus on growth and immune

outcomes. A systematic review, applying rigorous inclusion criteria and a structured assessment of methodological quality, can clarify the extent to which PFAs are effective and under what conditions they are most beneficial.

Therefore, this systematic review aims to critically assess the current evidence on the impact of phytogetic feed additives on growth performance and immune response of livestock species. Specifically, it seeks to evaluate the effectiveness of PFAs in improving key production metrics such as ADG, body weight gain, and FCR; examine their influence on immune parameters, including antibody response, cytokine levels, and leukocyte activity; and identify species-specific trends and methodological limitations that may explain variability in results. By synthesising findings from various experimental studies, this review aims to provide an evidence-based perspective on the role of PFAs as sustainable alternatives to AGPs, thus educating researchers, nutritionists and policymakers in the advancement of animal production systems that align with global goals of food safety, environmental sustainability and public health protection.

2 Methods and materials

The systematic literature search was conducted according to the PRISMA guidelines (Preferred Reporting Items for Systematic Reviews) (Rethlefsen et al., 2021). The searches were performed in multiple academic databases, including Scopus, ScienceDirect, Web of Science, and EBSCOhost (Academic Search Ultimate, AGRICOLA and MEDLINE with full text), covering the period from January 1, 2010 to December 31, 2024, as summarised in Table 1. To accommodate platform-specific constraints, the search string used for ScienceDirect was adapted to meet the character limit of the database (≤ 8 search fields) while maintaining alignment with the objectives of the review. Only peer-reviewed articles published in English were considered. Nonprimary literature,

TABLE 1 Search strategies used across databases.

Databases	Search terms (strings)	Applied filters
Scopus	("phytogetic feed additive" OR "plant-based feed additive" OR "herbal feed additive") AND ("growth performance") AND ("immune response") AND ("livestock "OR "cattle""OR"sheep"OR "goat" OR "pig""OR"swine"OR "poultry" OR "broiler" OR ""rabbit ")	Document Type: Article; Language: English. Publication date: 2010-2024
Web of Science		
Academic Search Ultimate (EBSCOhost)		
AGRICOLA (EBSCOhost)		
MEDLINE with full text (EBSCOhost)		
ScienceDirect	("phytogetic feed additive" OR "plant-based feed additive" OR "herbal feed additive") AND ("growth performance") AND ("immune response") AND ("livestock")	

including review articles, book chapters, short communications, conference proceedings, letters, and editorials, was excluded to ensure methodological rigour and focus on original research. The restriction on English-language studies was due to their dominance in scientific publishing, indexing consistency, and practical constraints such as translation resources. All references were first exported to EndNote for deduplication and consolidation and then imported into Covidence software for title and abstract screening, followed by full-text evaluation.

2.1 Inclusion and exclusion criteria

Inclusion criteria:

- Phytogetic (plant-derived) feed additives, including essential oils, herbs, spices, plant extracts, or their combinations, are administered via diet or drinking water.
- Livestock species (cattle, sheep, goats, pigs, poultry, and rabbits).
- Studies reporting effects on at least one growth performance indicator (average daily gain, feed conversion ratio and body weight gain) or the immune response parameter (leukocyte counts, antibody titers and cytokine levels).
- Originally published research articles.
- Studies published in English.
- Studies published between 2010 and 2024.
- The studies were conducted globally with no regional limitations.

Exclusion criteria:

- Review articles, meta-analyses, editorials, commentaries, conference abstracts without full-text availability, and grey literature.
- Studies on nonlivestock species (laboratory rodents, fish, or companion animals).
- Studies using nonphytogetic feed additives (antibiotics, minerals, enzymes, probiotics) without a phytogetic component.
- Studies focusing solely on nutritional composition or feed formulation, without reporting animal performance outcomes.
- Studies that did not report growth or immune response metrics.
- Articles published in languages other than English.
- Studies without a control or comparison group.
- Studies with no accessible full text or incomplete data.
- Studies published before 2010 and after 2024.

2.2 Bias risk assessment

The methodological quality and risk of bias of all included studies were independently assessed by two reviewers via the

Systematic Review Centre for Laboratory Animal Experimentation (SYRCLE) risk of bias tool. The evaluation covered key methodological domains, namely, selection bias (random sequence generation, baseline comparability, and allocation concealment), performance bias (random housing and blinding of caregivers), detection bias (random outcome assessment and blinding of evaluators), attrition bias (management of incomplete outcome data), and reporting bias (selective outcome reporting), in addition to consideration of other potential sources of bias.

3 Results

3.1 Characteristics of the included studies

The results of the systematic search process are illustrated in [Figure 1](#). The initial search yielded a total of 104 records from the following databases: Scopus (n=20), Web of Science (n=19), EBSCOhost (including Academic Search Ultimate (n=10), AGRICOLA (n=4), MEDLINE with full text (n=6)), and ScienceDirect (n=45). Following the retrieval, a total of 31 duplicate records were removed; 30 of these were identified by Covidence, and one was manually removed. The remaining 73 records were subjected to title and abstract screening, which resulted in the exclusion of 30 studies. Full-text screening was subsequently performed on the remaining 43 articles. During this stage, 23 articles were excluded according to the established eligibility criteria. Consequently, 20 studies were selected for inclusion in the final review.

3.2 Synthesis of findings

The purpose of this systematic review was to assess the impact of phytogetic feed additives on the growth performance and immune response of livestock. [Table 2](#) shows that the majority of the studies included in this review have focused primarily on broiler chickens ([Hong et al., 2012](#); [Ghasemi et al., 2014](#); [Li et al., 2015](#); [Attia et al., 2017](#); [Ahsan et al., 2018](#); [Oso et al., 2019](#); [Long et al., 2020](#); [Shafiee et al., 2020](#); [Adeyemi et al., 2021](#); [Kalia et al., 2021](#); [Saei et al., 2021](#); [Xie et al., 2021](#); [Liu et al., 2023](#); [Ogbuwu and Mbajorgu, 2023](#); [Adil et al., 2024](#); [Hossain et al., 2024](#)), whereas only one has focused on pigs ([Chang et al., 2022](#)), rabbits ([Hashem et al., 2017](#)), lambs ([Shaaban et al., 2021](#)), and cattle ([Yang et al., 2023](#)).

3.2.1 Effect of some phytogetic feed additives on broiler growth and immunomodulation

[Adeyemi et al. \(Adeyemi et al., 2021\)](#) assessed the influence of dietary supplementation with mango leaf (ML), an antibiotic blend (70% oxytetracycline + 30% neomycin), and tert-butylhydroxyanisole (BHA) on the growth performance and immune indices of broilers. Compared with the control diet, mango leaf supplementation at 2.5–5 g/kg and antibiotic

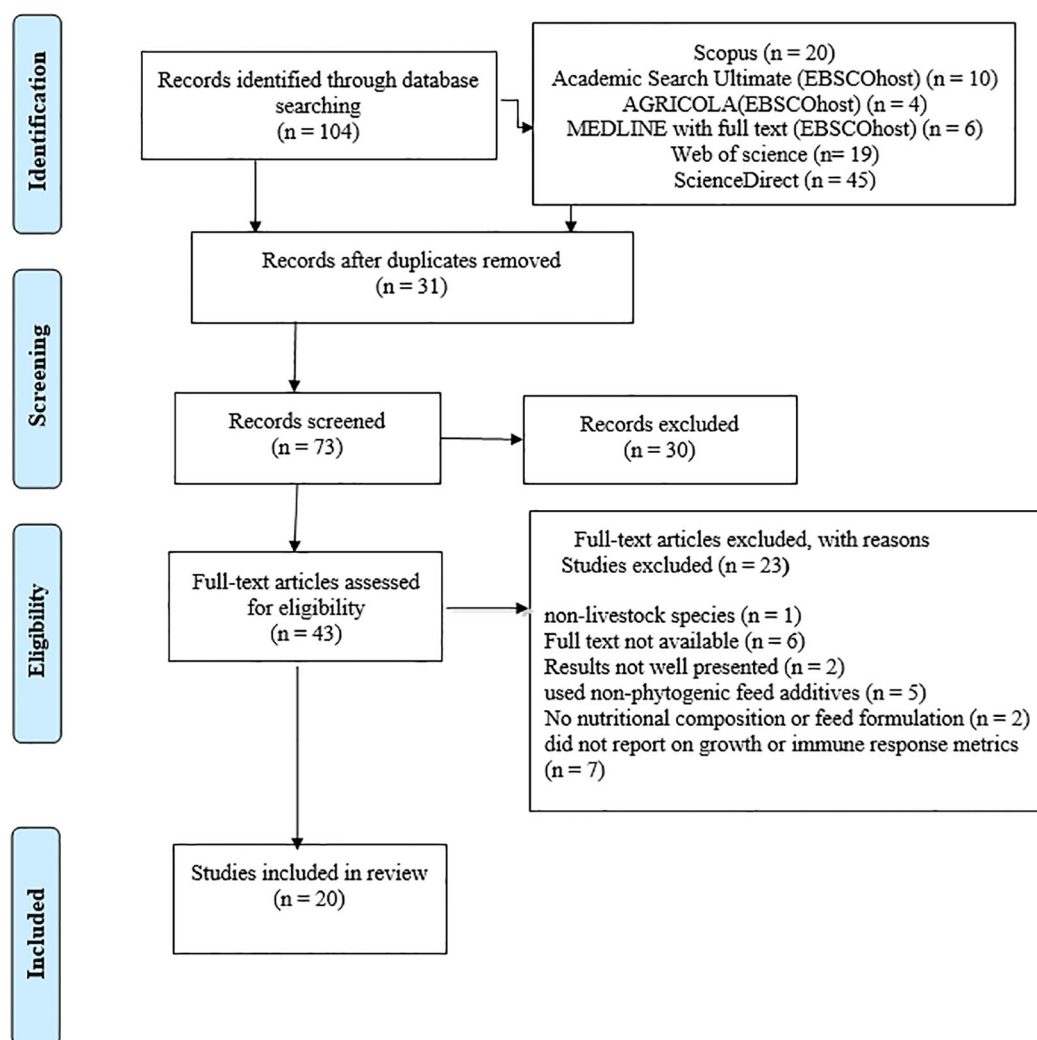


FIGURE 1

The PRISMA flow diagram presents the systematic procedure for the identification, screening, assessment of eligibility, and inclusion of studies for the current review.

inclusion improved growth performance and modulated immune responses in broilers. At the starter phase (1–21 days), body weight gain increased by approximately 6–7% in the supplemented groups (793–797 g) compared with the control group (746 g), with the antibiotic group achieving the greatest gain (901 g). Over the entire 42-day period, the carcass weights were 7.3–7.5% greater in the antibiotic and 2.5 g/kg mango leaf groups than in the control group, whereas the feed conversion ratio remained similar across the treatments (~1.83–1.88). Immune modulation was evident, with anti-inflammatory interleukin-10 increasing from 4.24 pg/mL in the control to 12.18–17.85 pg/mL in the supplemented groups, and proinflammatory interleukin-1 β decreased by up to 68% (270 pg/mL in the control vs. 87 pg/mL in high mango leaves). The tumor necrosis factor- α levels decreased by 32–61% relative to those in the control. Conversely, the levels of humoral immune markers were reduced, with immunoglobulin M and A concentrations decreasing by 46–70% and 65–85%, respectively, in the supplemented groups.

Adil et al (Adil et al., 2024). evaluated the effects of free rosemary essential oil (F-REO) and nanoprotected rosemary essential oil (N-REO) on the immune-antioxidant status of broiler chickens as alternatives to antibiotics. In a 42-day trial, 420 Cobb broilers (1-week-old) were assigned to seven dietary treatments, including a control, enramycin (100 mg/kg), chitosan nanoparticles (150 mg/kg), F-REO (100 or 200 mg/kg), and N-REO (100 or 200 mg/kg). Compared with the control, supplementation with N-REO, particularly at 200 mg/kg, significantly ($P < 0.05$) increased the serum immunoglobulin concentration, with the IgG and IgM concentrations reaching 368.09 mg/mL and 652.79 mg/mL, respectively. Anti-sheep red blood cell (SRBC) antibody titers improved from 5.52 log₂ in the control group to 6.49 log₂ in the high-N-REO group, while cell-mediated immunity (cutaneous basophil hypersensitivity response) increased from 1.34 to 1.76 mm. The relative weights of the immune organs were slightly greater in the supplemented birds, with the bursa

TABLE 2 Overview of phytogetic feed additives used in the included studies.

Author, year	Country	Animal type	Sample size	Intervention (type & dose)	Comparator	Duration	Purpose	Key outcomes	Main findings
(Adeyemi et al., 2021)	Nigeria	Broilers	240	Mango leaf 2.5–5 g/kg	Antibiotic & control	42 d	Growth & immune	BWG ↑ 6–7%, IL-10 ↑, IgM ↓	Mango leaf improved growth and anti-inflammatory cytokines
(Adil et al., 2024)	India	Broilers	420	Rosemary oil (100–200 mg/kg, free & nano)	Enramycin, control	42 d	Immune	IgG/IgM ↑, SRBC titers ↑, CBH ↑	Nano-REO (200 mg/kg) boosted both humoral & cell-mediated immunity
(Ahsan et al., 2018)	Pakistan	Broilers	480	Commercial PFA (100–150 mg/kg)	Control	42 d	Growth	No sig. effect on BWG, FCR	No measurable benefit at tested doses
(Attia et al., 2017)	Egypt	Broilers	252	Turmeric (0.5–2 g/kg), MOS, OTC	Control	35 d	Growth	FCR improved at 1 g/kg	1 g/kg turmeric comparable to MOS, OTC
(Chang et al., 2022)	China	Pigs	180	PFA blends (citrus, thymol, carvacrol, grape seed, fenugreek)	E. coli challenge control	21 d	Growth & immune	ADG ↑, IgG ↑, TNF-α ↓	PFA3 most effective vs. E. coli
(Ghasemi et al., 2014)	Iran	Broilers	350	Black cumin (5–20 g/kg), probiotic, prebiotic, synbiotic	Control	42 d	Growth & immune	BWG ↑ (10 g/kg), FCR ↓, CBH ↑	10 g/kg black cumin & synbiotic best
(Hashem et al., 2017)	Egypt	Rabbits	150	Propolis (150–300 mg/kg), Moringa roots (150–300 mg/kg)	Vitamin E, control	5 weeks	Growth & immune	BW ↑, FCR improved	Propolis at 150 mg/kg best for growth
(Hong et al., 2012)	Korea	Broilers	240	Essential oils (oregano, anise, citrus; 125 ppm)	Antibiotic, control	42 d	Growth & immune	BWG ↑ 12.9%, FCR ↓	EO outperformed antibiotic
(Hossain et al., 2024)	Korea	Broilers	360	Achyranthes japonica extract (0.02–0.06%)	Control	35 d	Growth	BWG ↑ 5.7% at 0.06%	Linear growth improvement
(Kalia et al., 2021)	India	Broilers	105	Salix alba extract (100–800 mg/kg BW)	Control	42 d	Growth & immune	BW ↑, FCR ↓, IL-2 ↑	Best at 300 mg/kg
(Li et al., 2015)	Korea	Broilers	64	Phytoncide (0.5–1 g/kg)	Tylosin, control	35 d	Growth	BWG ↑, FCR ↓	Dose-dependent linear gains
(Liu et al., 2023)	China	Broilers	270	Polyherbal mix (1000 mg/kg)	Antibiotic, control	42 d	Growth & immune	BW ↑, IgG ↑, IL-4 ↑	PHM boosted ADG and immunity
(Long et al., 2020)	China	Broilers	256	Lycium barbarum polysaccharide (1–4 g/kg)	Control	42 d	Growth & immune	ADG ↑ (55.9 vs. 52 g/d), IgG ↑	2 g/kg best
(Ogbuewu and Mbajiorgu, 2023)	Nigeria	Broilers	200	Dialium guineense stem bark (0.5–2 g/kg)	Control	42 d	Growth & immune	BW ↑ (3002 g at 0.5 g/kg), FCR ↓	Low dose optimal
(Oso et al., 2019)	Nigeria	Broilers	192	Herbal blend (Aerva lanata, Piper betle, Cynodon dactylon, and Piper nigrum) 1–2%	Antibiotic, control	42 d	Growth	BWG ↑, FCR ↓ (1.47)	1% blend matched antibiotic

(Continued)

TABLE 2 Continued

Author, year	Country	Animal type	Sample size	Intervention (type & dose)	Comparator	Duration	Purpose	Key outcomes	Main findings
(Saei et al., 2021)	Iran	Broilers	200	Ajwain extract (150–450 ppm)	Virginiamycin, control	42 d	Growth	BW ↑ (2763 g at 300 ppm), FCR ↓	300 ppm optimal
(Shaaban et al., 2021)	Egypt	Lambs	40	Thyme, celery, or mixture	Control, salinomycin	90 d	Growth	ADG ↑ (111 g/d celery)	Celery best; improved FCR
(Shafiee et al., 2020)	Iran	Broilers	240	Cumin (0.75%)	Control	42 d	Growth & immune	BWG ↑, FCR ↓ (1.75), Ig ↑	0.75% cumin enhanced both
(Xie et al., 2021)	China	Broilers	240	Fermented <i>Chenopodium album</i> (2–8 g/kg)	Control	42 d	Growth & immune	ADG ↑, FCR ↓, Ig ↑	4–8 g/kg most effective
(Yang et al., 2023)	Canada	Cattle	120	PFA commercial blend	Monensin,	110 + 120 d	Growth	ADG ↑	Slightly less efficient than monensin

The ↓ symbol means there was a decrease, and the ↑ symbol means there was an increase.

increasing from 0.19% in the control to 0.24% in high N-REO birds. These findings indicate that N-REO at 200 mg/kg can enhance both humoral and cell-mediated immune responses in broilers beyond the levels achieved by conventional antibiotic supplementation.

Ahsan et al (Ahsan et al., 2018). evaluated the effects of different levels of inclusion of a commercial phytogetic feed additive (PFA) on the growth performance of broiler chickens, as shown in Table 3. In a 42-day trial, 480 Ross 308 male chicks (initial weight 43 ± 3 g) were randomly assigned to four dietary treatments: a corn–soybean basal diet (control) or a basal diet supplemented with 100 mg/kg (PFA100), 125 mg/kg (PFA125), or 150 mg/kg (PFA150) PFA. Across all the feeding phases (days 1–21, 22–42, and 1–42), no significant differences ($P > 0.05$) were detected in body weight gain, feed intake, or the feed conversion ratio among the treatments. For the entire trial period, body weight gain ranged from 2808 g (PFA125) to 2893 g (control), while feed conversion ratios varied slightly from 1.77 (control) to 1.83 (PFA100).

Attia et al (Attia et al., 2017). evaluated the growth-promoting potential of turmeric (*Curcuma longa* Linn.) as an alternative to the antibiotic oxytetracycline (OTC) and as a comparator to mannan oligosaccharide (MOS) in broiler diets. In a 35-day trial, 252 Hubbard broiler chicks (1 day old) were randomly allocated to six dietary treatments: an unsupplemented control; turmeric at 0.5, 1.0, or 2.0 g/kg diet; MOS at 1 g/kg diet; or OTC at 50 mg/kg diet, each with seven replicates of six chicks. Turmeric supplementation at 1 g/kg significantly improved the feed conversion ratio (FCR) over the 1–35-day period (1.68) compared with the control (1.82) and the highest turmeric concentration (2.0 g/kg; 1.83) ($P < 0.05$). While body weight gain over the full trial was not significantly affected ($P = 0.095$), chicks fed 1 g/kg turmeric, MOS, or OTC presented numerically greater total gains (1833 g, 1838 g, and 1792 g, respectively) than did the control (1718 g). The feed intake patterns varied between growth phases, with turmeric at 1 g/kg producing the highest overall intake (3352 g). Survival rates were 100% in all the groups, and the European Production Efficiency Index (EPEI) was significantly greater ($P < 0.05$) for MOS (303) and turmeric at 1 g/kg (279) than for the control (262).

Ghasemi et al (Ghasemi et al., 2014). evaluated the comparative effects of black cumin seeds (*Nigella sativa* L.) at three inclusion levels (5 g/kg, 10 g/kg, and 20 g/kg), a probiotic (1 g/kg), a prebiotic (1 g/kg), and a synbiotic (1 g/kg) on growth performance and the immune response in male broiler chickens. A total of 350-day-old Ross 308 chicks were randomly assigned to seven dietary treatments, each with five replicates of ten birds, and fed from day 0 to day 42. Over the entire experimental period, birds receiving 10 g/kg of black seed (BS2), probiotic, or synbiotic diets presented significantly greater ($P < 0.05$) body weight gains (BWGs; 2167 g, 2165 g, and 2204 g, respectively) than did the control group (2057 g). The feed conversion ratio (FCR) over 0–42 days was also greater ($P < 0.05$) in the BS2, probiotic, prebiotic, and synbiotic groups (1.79, 1.79, 1.84, and 1.77 g/g, respectively) than in the control group (1.91 g/g). The immune parameters were positively influenced by supplementation: the cutaneous basophil hypersensitivity (CBH) response to phytohemagglutinin-P was significantly greater ($P < 0.05$) in the BS3 (0.77 mm) and synbiotic (0.75 mm) groups than in the control (0.59 mm) group. Similarly, primary antibody titers against sheep red blood cells (SRBCs) were highest in the probiotic (6.65 $\log_2$) and synbiotic (6.83 $\log_2$) groups, with comparable improvements observed in secondary antibody titers.

Hong et al (Hong et al., 2012). examined the use of a supplemental essential oil blend (125 ppm; oregano, anise, and citrus peel) as a growth promoter and potential alternative to antibiotics in 240 Arbor Acres broilers over a 42-day feeding trial. Compared with the negative control, both the essential oil and antibiotic (100 ppm oxytetracycline) groups presented significant ($P < 0.05$) improvements in the feed conversion ratio (FCR) throughout the period (1.60 in the essential oil group vs. 1.71 in the control group), with the essential oil group outperforming the antibiotic group from days 21–42. The total weight gain from 0–42 days increased by 12.9% with essential oil supplementation (2291.2 g) compared with that of the control (2030.1 g). The survival rate improved by ~10% in both the essential oil and antibiotic groups. The immune response data revealed that

TABLE 3 Effects of phytogetic feed additives on growth performance.

Study (author, year)	Species	Phytogetic additive	Key growth metrics (ADG/BWG)	Feed efficiency (FCR/G: F)
(Adeyemi et al., 2021)	Broiler	Mango leaf (2.5–5 g/kg)	BWG ↑ 6–7%	~1.83–1.88 (ns)
(Ahsan et al., 2018)	Broiler	PFA (100–150 mg/kg)	No effect	No change
(Attia et al., 2017)	Broiler	Turmeric (1 g/kg)	BWG ↑ (1833 g vs 1718 g)	FCR ↓ (1.68 vs 1.82)
(Chang et al., 2022)	Pig	Citrus-thymol-carvacrol blends	ADG ↑	G: F ↑
(Ghasemi et al., 2014)	Broiler	Black cumin (10 g/kg)	BWG ↑ (2167 g vs 2057 g)	FCR ↓ (1.79 vs 1.91)
(Hashem et al., 2017)	Rabbit	Propolis (150 mg/kg)	BW ↑	FCR improved
(Hong et al., 2012)	Broiler	Essential oils blend (125 ppm)	BW ↑ 12.9%	FCR ↓ (1.60 vs 1.71)
(Hossain et al., 2024)	Broiler	Achyranthes extract (0.06%)	BWG ↑ 5.7%	FCR slight ↓
(Kalia et al., 2021)	Broiler	Salix alba (300 mg/kg)	BW ↑	FCR ↓ (3.48 vs 4.73)
(Li et al., 2015)	Broiler	Phytoncide (1 g/kg)	BWG ↑	FCR ↓ (1.60 → 1.60)
(Liu et al., 2023)	Broiler	Polyherbal mix (1000 mg/kg)	ADG ↑ (43.9 vs 42.1 g/d)	G: F improved
(Long et al., 2020)	Broiler	LBP (2 g/kg)	ADG ↑ (55.9 vs 52 g/d)	FCR ↓ (1.57 vs 1.68)
(Ogbuewu and Mbajorgu, 2023)	Broiler	DGSB (0.5 g/kg)	BW ↑ (3002 g)	FCR ↓ (1.90)
(Oso et al., 2019))	Broiler	Herbal blend (1–2%)	BW ↑ 2168 g	FCR ↓ (1.47)
(Saei et al., 2021)	Broiler	Ajwain (300 ppm)	BW ↑ (2763 g)	FCR ↓ (1.47)
(Shaaban et al., 2021)	Lamb	Celery	ADG ↑ (111 g/d)	FCR improved (12.6 vs 15.3)
(Shafiee et al., 2020)	Broiler	Cumin (0.75%)	BWG ↑ (2155 g vs 1914 g)	FCR ↓ (1.75 vs 2.02)
(Xie et al., 2021)	Broiler	FCAL (4–8 g/kg)	ADG ↑ (57.9 vs 53.9 g/d)	FCR ↓ (1.52 vs 1.74)
(Yang et al., 2023)	Cattle	PFA	ADG ↑ (1.31 vs 1.20)	G: F ~0.161 vs 0.156

↑, increase; ↓, decrease.

essential oil supplementation resulted in sheep red blood cell (SRBC) antibody titers but significantly ($P < 0.05$) increased Newcastle disease virus (NDV) antibody titers ($10.44 \log_2$) compared with those in the antibiotic group ($9.06 \log_2$). Additionally, compared with the control (1.03 mm), essential oil enhanced cell-mediated immunity, with a greater delayed-type hypersensitivity (DTH) response (1.57 mm). These findings indicate that essential oils can match or exceed antibiotic growth-promoting effects while also enhancing certain immune parameters.

Hossain et al (Hossain et al., 2024). evaluated the effects of *Achyranthes japonica* extract (AJE) supplementation on growth performance in 360 Ross 308 broilers over 35 days. The birds were allocated to four treatments: control (basal diet), 0.02% AJE, 0.04% AJE, and 0.06% AJE, with five replicates of 18 birds each. AJE supplementation led to a significant linear increase ($p < 0.05$) in body weight gain (BWG) during days 7–21 and 21–35 and across the entire experimental period, with the highest BWG observed in the 0.06% AJE group (1,825 g vs. 1,726 g in the control, +5.7%). The feed intake (FI) also increased linearly from days 21–35 and overall, increasing from 2,905 g in the control to 2,992 g with 0.06% AJE (+3.0%). The feed conversion ratio (FCR) increased with increasing AJE, from 1.683 in the control to 1.642 at 0.06% inclusion, although the differences were not statistically significant. These findings suggest that AJE can enhance growth performance in broilers,

with the greatest effect at 0.06% inclusion, which is likely supported by improvements in nutrient digestibility.

Kalia et al (Kalia et al., 2021). evaluated the effects of *Salix alba* leaf aqueous extract on the growth performance and immune response of broiler chickens reared under high-altitude cold desert conditions (3,500 m). A total of 105 one-day-old RIR crossbred broilers were randomly allocated into seven dietary treatment groups: a control group (basal diet) and six groups supplemented with *S. alba* extract at 100, 150, 200, 300, 400, or 800 mg kg⁻¹ body weight. Compared with the control group, the *Salix 300* group presented the greatest improvement in final body weight (476.10 g on day 42) and feed conversion ratio (3.48) (360.80 g; FCR = 4.73; $p < 0.05$). The immune response was also enhanced at this dosage, with significantly higher plasma IL-2 concentrations (9.22 pg mL⁻¹) and lower IL-1 (6.24 pg mL⁻¹) and IL-6 (7.89 pg mL⁻¹) concentrations than those in the control (IL-2 = 8.51 pg mL⁻¹; IL-1 = 6.46 pg mL⁻¹; IL-6 = 8.26 pg mL⁻¹; $p < 0.05$). These findings suggest that *S. alba* extract, particularly at 300 mg kg⁻¹ body weight, can enhance broiler growth performance and modulate immune function, making it a promising phytogetic feed additive for high-altitude poultry production.

Li et al (Li et al., 2015). evaluated the effects of dietary phytoncide, a phytogetic extract from Korean pine, as an alternative to tylosin on the growth performance of broiler

chickens over a 35-day feeding trial. Sixteen broilers per cage were allocated to one of four treatments: a positive control (basal diet + 0.2 g tylosin/kg) or a basal diet supplemented with 0, 0.5, or 1.0 g phytoncide/kg. Throughout the overall experimental period (days 0–35), body weight gain (BWG) increased linearly ($p = 0.01$) from 1,621 g in the control to 1,677 g at 1.0 g/kg phytoncide. The feed intake also increased significantly ($p = 0.03$) from 2,639 g to 2,683 g, whereas the feed conversion ratio (FCR) improved ($p = 0.03$) from 1.637 to 1.600 with increasing phytoncide inclusion. During the starter phase (days 0–14), BWG and FCR showed similar linear improvements ($p < 0.05$), indicating enhanced growth efficiency.

Long et al (Long et al., 2020). investigated the effects of dietary *Lycium barbarum* polysaccharide (LBP) supplementation on the growth performance and immune function of broiler chickens. A total of 256 one-day-old Arbor Acres male broiler chicks were randomly assigned to four dietary treatments: a basal diet without supplementation (control) or a basal diet supplemented with 1,000, 2,000, or 4,000 mg/kg LBP for six weeks, with eight replicates of eight birds per treatment. Compared to the control, supplementation with 2,000 mg/kg of LBP significantly increased body weight on day 42 (2,389.71 g vs. 2,228.41 g, $P = 0.002$) and average daily gain during both the growth phase (76.60 g/d vs. 71.90 g/d, $P = 0.039$) and the overall experimental period (55.87 g/d vs. 52.03 g/d, $P = 0.037$). The feed-to-gain ratio was lower during the starter phase with 1,000 mg/kg (1.60) and 2,000 mg/kg (1.57) LBP than in the control (1.68, $P = 0.014$). The immune response was enhanced, as birds receiving LBP presented higher serum IgA (0.481–0.489 mg/mL vs. 0.384 mg/mL, $P = 0.002$) and IgG concentrations (0.798–0.889 mg/mL vs. 0.749 mg/mL, $P = 0.004$) than those in the control group did.

Similarly, Ogbuewu and Mbajorgu (2023) investigated whether the inclusion of Dialium guineense stem bark (DGSB) in broiler diets influenced growth performance in Ross 308 broilers. Birds receiving 0.5 g/kg DGSB presented the highest final live weight (3,002 g) and ADG (78.23 g/day) and the lowest FCR (1.90; $P < 0.05$). Higher inclusion rates (≥ 1.0 g/kg) increased the ADFI but were associated with poorer FCR values. DGSB supplementation also affected immune-related haematological parameters, including white blood cell and lymphocyte counts, indicating potential immunomodulatory effects. Both studies suggest that targeted phytochemical feed additive inclusion can simultaneously improve growth metrics and modulate immune responses in broiler production.

Oso et al (Oso et al., 2019). evaluated the effects of a phytochemical blend (PB) comprising *Aerva lanata*, *Piper betle*, *Cynodon dactylon*, and *Piper nigrum* on the growth performance of broiler chickens in a 42-day feeding trial. A total of 192 birds were allocated to four dietary treatments: a basal diet, a basal diet supplemented with chlortetracycline (antibiotic control), and basal diets with either 1% or 2% PB. Body weight gain (BWG) during the starter phase (1–14 days) increased linearly with PB inclusion ($P = 0.023$), with the 1% PB group showing comparable performance to the antibiotic group during the grower phase (15–21 days). Over the entire rearing period (1–42 days), 1% PB supplementation resulted in the highest BWG (2,167.8 g/bird) and the most efficient feed conversion ratio

(FCR = 1.47), both of which were significantly better ($P < 0.0001$) than those of the basal diet and similar to or greater than those of the antibiotic group.

Saei et al (Saei et al., 2021). investigated the effects of dietary supplementation with alcoholic extract of *Trachyspermum copticum* L. on the growth performance of Ross 308 broiler chickens over 42 days. A total of 200 birds were assigned to treatments that received 0, 150, 300, or 450 ppm aqueous extract in drinking water, with a Virginiamycin-supplemented group serving as an antibiotic control. The final body weight (FBW) was significantly influenced by ajwain supplementation ($P = 0.049$), with the 300-ppm group achieving the highest FBW of 2,763 g, which was comparable to that of the Virginiamycin group (2,645 g) and significantly greater than that of the 450-ppm group (2,258 g). The feed intake varied significantly between treatments ($P = 0.011$), with the 150-ppm group consuming the most feed (4,037 g) and the 450-ppm group having the lowest intake (3,682 g). The feed conversion ratio (FCR) was also affected ($P = 0.045$), with the 450-ppm group achieving the most efficient FCR of 1.47 compared to the other groups.

Shafiee et al (Shafiee et al., 2020). reported that the dietary inclusion of cumin (*Cuminum cyminum*) significantly improved growth performance and immune responses in broiler chickens over a 42-day rearing period. Broilers fed 0.75% cumin achieved the greatest body weight gain (BWG) of 2,155 g and an improved feed conversion ratio (FCR) of 1.75 g feed/g gain over the entire period, whereas control birds fed 0.75% cumin presented 1,914 g BWG and 2.02 FCR. Similarly, 0.75% cumin enhanced humoral immunity, with sheep red blood cell (SRBC) titers reaching 6.25 log₂ RDF at 14 days post-immunization compared with 4.25 log₂ RDF in control birds. Cell-mediated immunity, assessed by cutaneous basophil hypersensitivity (CBH), was also elevated, with swelling of 987 μ m in the 0.75% cumin group versus 519 μ m in the control 12 h after injection. These results demonstrate that 0.75% cumin in the diet promotes both growth and immunocompetence in broilers, suggesting its potential as a natural alternative to in-feed antibiotics.

Xie et al (Xie et al., 2021). reported that dietary supplementation with fermented *Chenopodium album* L. (FCAL) positively influenced growth performance and immune responses in broiler chickens over 42 days. During the starter period (days 1–21), Table 4 shows that broilers fed 4 and 8 g/kg FCAL achieved average daily gains (ADGs) of 32.67 g/d and 34.89 g/d, respectively, which were greater than the 30.80 g/d reported for the control group, whereas 8 g/kg FCAL also improved the feed conversion ratio (FCR) to 1.58 versus 1.75 for the control group. During the finisher period (days 22–42), 2 g/kg FCAL increased the ADG to 88.68 g/d and reduced the FCR to 1.52 compared with 79.72 g/d and 1.74 in the controls. Across the whole period (days 1–42), 4 and 8 g/kg FCAL elevated the ADG to 57.38–57.93 g/d, whereas it was 53.87 g/d in the controls. Regarding the immune response, serum insulin-like growth factor-1 (IGF-1) increased significantly with 8 g/kg FCAL on day 21 (184.50 ng/mL vs. 172.26 ng/mL in controls), and immunoglobulin A (IgA) and IgM were elevated at both 21 and 42 days, while the proinflammatory cytokines IL-1 β and IL-8 were reduced on day

TABLE 4 Reported effects and recommended inclusion levels.

Phytogenic feed additive	Livestock	Recommended dosage	Effects	References
Mango leaf	Broilers	2.5–5 g/kg	Growth ↑, IL-10 ↑, TNF-α ↓	(Adeyemi et al., 2021)
Rosemary oil	Broilers	200 mg/kg	Ig ↑, SRBC ↑, CBH ↑	(Adil et al., 2024)
Turmeric	Broilers	1 g/kg	FCR ↓, BWG ↑	(Attia et al., 2017)
Citrus-thymol-carvacrol mix	Pigs	PFA3 (blend)	ADG ↑, Ig ↑	(Chang et al., 2022)
Black cumin	Broilers	10 g/kg	BWG ↑, FCR ↓, CBH ↑	(Ghasemi et al., 2014)
Propolis	Rabbits	150 mg/kg	Growth ↑, FCR ↓	(Shafiee et al., 2020)
Essential oils (oregano, citrus)	Broilers	125 ppm	BW ↑, FCR ↓, NDV Ab ↑	(Hong et al., 2012)
Achyranthes extract	Broilers	0.06%	BWG ↑ 5.7%	(Hossain et al., 2024)
Salix alba	Broilers	300 mg/kg BW	BW ↑, IL-2 ↑	(Kalia et al., 2021)
Phytoncide	Broilers	1 g/kg	BWG ↑, FCR ↓	(Li et al., 2015)
Polyherbal mix	Broilers	1 g/kg	ADG ↑, IgG ↑	(Liu et al., 2023)
Lycium barbarum polysaccharide	Broilers	2 g/kg	ADG ↑, Ig ↑	(Long et al., 2020)
Dialium guineense bark	Broilers	0.5 g/kg	BW ↑, FCR ↓	(Ogbuewu and Mbajiorgu, 2023)
Herbal blend (Aerva, Piper, etc.)	Broilers	1%	BW ↑, FCR ↓	(Oso et al., 2019)
Ajwain extract	Broilers	300 ppm	BW ↑, FCR ↓	(Saei et al., 2021)
Celery	Lambs	15 g/lamb/day	ADG ↑ 111 g/d, FCR ↓	(Hashem et al., 2017)
Cumin	Broilers	0.75%	BWG ↑, FCR ↓, Ig ↑	(Shafiee et al., 2020)
Fermented Chenopodium album	Broilers	4–8 g/kg	ADG ↑, FCR ↓, Ig ↑	(Xie et al., 2021)
PFA (commercial)	Cattle	—	ADG ↑ 1.31 kg/d	(Yang et al., 2023)

The ↓ symbol means there was a decrease, and the ↑ symbol means there was an increase.

21. IL-10 levels were lower in the 2 and 4 g/kg groups than in the control group on day 21, indicating modulation of immune activity.

3.2.2 Effect of some phytogenic feed additives on swine growth and immunomodulation

Chang et al (Chang et al., 2022). investigated the effects of five phytogenic feed additives on growth performance and immune responses in experimentally challenged weaned pigs with *Escherichia coli* F18. The additives included bitter citrus extract (PFA1), a microencapsulated blend of thymol and carvacrol (PFA2), a combination of bitter citrus extract, thymol and carvacrol (PFA3), a blend of grape seed, grape marc extract, green tea and hops (PFA4), and fenugreek seed powder (PFA5).). The trial spanned 21 days, comprising a 7-day preinoculation period and a 14-day post-inoculation period following three consecutive *E. coli* challenges. Compared to the positive control diet, supplementation with PFAs significantly improved ($P < 0.05$) the average daily gain (ADG) and the feed efficiency. Notably, pigs receiving PFA3 presented higher ($P < 0.05$) immunoglobulin G (IgG) and immunoglobulin A (IgA) concentrations at 7 days post-inoculation than did the controls, as shown in Table 5. Furthermore, tumor necrosis factor-α (TNF-α) levels were significantly reduced ($P < 0.05$) in all PFA-supplemented groups except PFA1 at 14 days post-inoculation, indicating anti-inflammatory effects. These results demonstrate that phytogenic

supplementation, particularly formulations containing citrus extracts, thymol, and carvacrol, can alleviate *E. coli*-induced growth suppression and enhance immune competence in weaned pigs.

3.2.3 Effect of some phytogenic feed additives on rabbit growth and immune response

Hashem et al (Hashem et al., 2017). evaluated the effects of two phytogenic feed additives, propolis and moringa roots, compared to vitamin E, on the growth performance and immune response of 150 growing V-line rabbits over a five-week feeding period. The diets included 150 mg/kg vitamin E (VE), 150 mg/kg propolis (LP), 300 mg/kg propolis (HP), 150 mg/kg moringa root (LM), 300 mg/kg moringa root (HM), or no additive (control). The live body weight was significantly greater ($P < 0.05$) in the VE, LP, and HP groups than in the control group, with intermediate values in the LM and HM groups. The average weekly weight gain was also greater in the VE, LP, HP, and HM groups than in the control, with corresponding improvements in the feed conversion ratio, particularly in the VE and LP groups. Compared to those in the control group, immune response indicators significantly ($P < 0.05$) increased the lymphocyte percentage and decreased the NLR in the LM and HM groups. In contrast, neutrophil percentages were reduced in the moringa-supplemented groups. Immunoglobulin G and M concentrations were not significantly affected by dietary

TABLE 5 Effects of phytogetic feed additives on the immune response.

Study (author, year)	Species	Phytogetic additive	Humoral immunity	Cell-mediated immunity
(Adeyemi et al., 2021)	Broiler	Mango leaf	IgM/IgA ↓	IL-10 ↑, TNF- α ↓
(Adil et al., 2024)	Broiler	Rosemary oil	IgG, IgM ↑, SRBC ↑	CBH ↑
(Chang et al., 2022)	Pig	PFA blends	IgG, IgA ↑	TNF- α ↓
(Ghasemi et al., 2014)	Broiler	Black cumin, synbiotic	SRBC ↑	CBH ↑
(Hashem et al., 2017)	Rabbit	Propolis, moringa	IgG, IgM ~ns	Lymphocyte % ↑
(Hong et al., 2012)	Broiler	Essential oils	NDV Ab ↑	DTH ↑
(Kalia et al., 2021)	Broiler	Salix alba	IL-2 ↑, IL-1 ↓	—
(Liu et al., 2023)	Broiler	Polyherbal mix	IgG ↑, IgA ↑	IFN- γ ↓
(Long et al., 2020)	Broiler	LBP	IgA, IgG ↑	—
(Shafiee et al., 2020)	Broiler	Cumin (0.75%)	SRBC titers ↑	CBH ↑
(Xie et al., 2021)	Broiler	FCAL	IgA, IgM ↑	IL-1 β , IL-8 ↓

1. IgG, IgA, IgM, and cytokines (IL-8, IL-10, IFN- γ , and TNF- α) are markers of humoral or cell-mediated immunity; ↑ indicates an increase, ↓ indicates a decrease, and ~ns indicates no significant change.

2. SRBC – Sheep red blood cell antibody titers (humoral immunity).

3. NDV Ab – Newcastle disease virus antibody titers.

4. CBH – Cutaneous basophil hypersensitivity (cell-mediated immunity).

5. DTH – Delayed-type hypersensitivity (cell-mediated immunity).

6. LBP – Lactobacillus-based probiotic.

7. FCAL – Fermented citrus and alfalfa leaf blend.

a. indicates a parameter not measured or reported.

8. The ↓ symbol means there was a decrease, and the ↑ symbol means there was an increase.

treatment. These findings suggest that propolis, especially at 150 mg/kg, can increase both growth efficiency and feed utilization, whereas moringa roots may modulate immune cell profiles without compromising growth.

3.2.4 Effect of some phytogetic feed additives on sheep growth and immunomodulation

Shaaban et al (Shaaban et al., 2021). investigated the inclusion of phytogetic feed additives thyme, celery, or their mixture, which significantly improved growth performance in Barki lambs compared to a control diet. Celery supplementation produced the highest final body weight (51.7 kg), total weight gain (32.1 kg), and average daily gain (111 g/d), representing increases of approximately 31%, 31%, and 30%, respectively, over those of the control. Thyme and the thyme-celery mixture also increased the growth parameters, resulting in final body weights of 48.1–48.7 kg and ADG values of 98–99 g/d. The feed conversion efficiency improved with the celery and salinomycin treatments, which presented the lowest feed conversion ratios (12.6–12.7 g feed/g ADG) compared with 15.3 g/g in the control.

3.2.5 Effect of some phytogetic feed additives on the growth performance of beef cattle

Finally, Yanga et al (Yang et al., 2023). reported that dietary supplementation with a phytogetic feed additive (PFA) tended to improve the growth performance of crossbred Angus steers during a 110-day growing period. Steers receiving PFA had a final body weight of 415 kg compared to 403 kg in controls and achieved an overall average daily gain (ADG) of 1.31 kg/d versus 1.20 kg/d in the

controls, although these differences were not statistically significant compared to monensin (final BW = 422 kg; ADG = 1.38 kg/d). The gain-to-feed ratio (G: F) was greater for monensin (0.173) than for PFA (0.161) or the control (0.156), indicating a slightly greater feed efficiency with monensin. During the finishing phase (120 days), no significant differences were observed in ADG, G: F, or final BW among the PFA, monensin, and control treatments, although dry matter intake (DMI) was greater in the PFA group (10.2 kg/d) than in the monensin group (9.8 kg/d) but slightly lower than that in the control group (10.8 kg/d). In general, PFA moderately improved growth performance during the growth phase, suggesting that PFA has potential as a natural growth-promoting feed additive, although its effects on feed efficiency were less pronounced than those of monensin. Interestingly, the majority of the research on phytogetic feed for livestock production in this study was conducted in Asia, followed by Africa, with the lowest number of studies conducted in North America, as shown in Figure 2.

3.3 Assessment of risk of bias

The risk of bias in the six studies included in this review was systematically assessed via the SYRCLE risk of bias tool, as shown in Table 6 and Figure 3, which is specifically tailored for animal studies (Hooijmans et al., 2014). Overall, the studies demonstrated a low risk of bias for sequence generation and baseline characteristics, reflecting adequate randomization and comparability between experimental groups. Moderate to high risk was observed for allocation concealment and the blinding of caregivers and

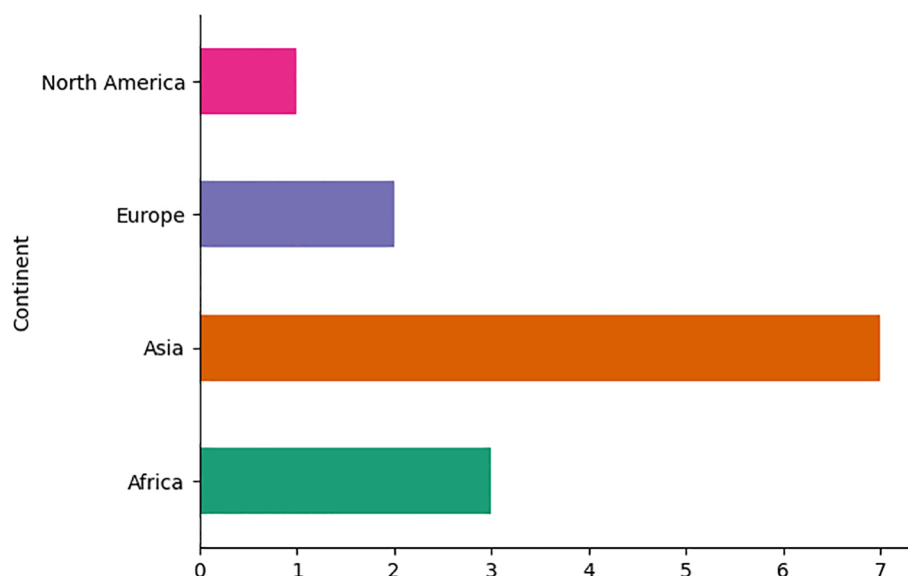


FIGURE 2

The number of included studies on phytogetic feed additives on each continent.

outcome assessors, particularly in studies involving nonbroiler species, indicating the potential for performance and detection bias. Random housing and outcome assessment were generally rated as moderate risk, whereas incomplete outcome data and selective reporting were considered low risk. In summary, the evidence is moderately reliable, with broiler studies yielding the most robust data, whereas findings from rabbits, lambs, and cattle should be interpreted cautiously owing to limitations in study design and blinding procedures.

4 Discussion

This systematic review demonstrated that phytogetic feed additives are being increasingly investigated as viable alternatives to antibiotic feed additives, which were historically used to increase growth and prevent disease in intensive livestock production (Wythe et al., 2023). This review highlights that the research landscape on phytogetic additives is heavily skewed toward broiler chickens, with 16 studies included in the review. In contrast, only one study was found for lambs, pigs, rabbits, and cattle. This bias reflects the global dominance of poultry production, which accounts for the fastest-growing and most affordable source of animal protein, particularly in low- and middle-income countries. Broilers also have a short life cycle (35–42 days), uniform genetics, and standardized management systems, making them highly suitable for controlled feeding trials where small differences in growth and immunity can be rapidly detected (Attia et al., 2017; Adeyemi et al., 2021; Liu et al., 2023, 16 –Xie et al., 2021).

Nevertheless, the inclusion of other livestock species, such as those other than broilers, underscores that PFAs are broadly applicable across different production systems. Each species,

however, exhibits unique digestive physiology and metabolic pathways that influence how phytogetic compounds are absorbed, metabolized, and expressed in terms of growth or immune outcomes. For example, in ruminants, the rumen microbiota may degrade or transform phytochemicals before they exert systemic effects, whereas in monogastric animals such as poultry and pigs, these compounds often act more directly within the gut (Lillehoj et al., 2018; Tedeschi et al., 2021). Similarly, rabbits, as hindgut fermenters, may respond differently to phytogetic supplementation than both ruminants and simple stomach species do (Assan, 2018). These differences highlight the importance of species-specific responses and the need for tailored formulations and dosages.

4.1 Impact on growth performance

Broilers are the most widely studied livestock species in relation to phytogetic feed additives, and numerous trials have reported meaningful improvements in growth performance when these compounds are included at appropriate levels, ref (Hong et al., 2012; Ghasemi et al., 2014; Li et al., 2015; Ahsan et al., 2018; Oso et al., 2019; Long et al., 2020; Shafiee et al., 2020; Kalia et al., 2021; Saei et al., 2021; Shaaban et al., 2021; Xie et al., 2021; Chang et al., 2022; Ogbuewu and Mbajorgu, 2023; Hossain et al., 2024) demonstrated that supplementation with blends of essential oils improved broiler body weight gain (BWG) by approximately 12.9% compared with that of unsupplemented controls while also reducing the feed conversion ratio (FCR) from 1.71 to 1.60. This improvement suggests that essential oils enhance digestive efficiency by stimulating enzymes and bile secretions, improving the gut microbial balance, and reducing oxidative stress, all of which translate into better nutrient absorption and feed utilization.

TABLE 6 Evaluation of risk of bias across studies.

Study	Species	1. Sequence eneration	2. Baseline characteristics	3. Allocation concealment	4.Random housing	5.Blinding of caregivers	6. Random outcome assessment	7. Blinding of outcome assessor	8.Incomplete outcome data	9.Selective reporting	10.Other bias
(Adeyemi et al., 2021)	Broilers	L	L	M	M	M	M	M	L	L	M
(Adil et al., 2024)	Broilers	L	L	M	L	L	L	L	L	L	M
(Ahsan et al., 2018)	Broilers	L	L	H	M	H	M	M	L	L	M
(Attia et al., 2017)	Broilers	L	L	M	M	M	M	M	L	L	M
(Chang et al., 2022)	Pigs	L	L	M	M	M	M	M	L	L	M
(Ghasemi et al., 2014)	Broilers	L	L	M	M	M	L	L	L	L	M
(Hashem et al., 2017)	Rabbits	L	L	H	M	H	M	M	L	L	M
(Hong et al., 2012)	Broilers	L	L	M	M	M	M	M	L	L	M
(Hossain et al., 2024)	Broilers	L	L	M	M	M	M	M	L	L	M
(Kalia et al., 2021)	Broilers	L	L	M	M	M	L	M	L	L	M
(Li et al., 2015)	Broilers	L	L	H	M	H	M	M	L	L	M
(Liu et al., 2023)	Broilers	L	L	M	M	M	M	M	L	L	M
(Long et al., 2020)	Broilers	L	L	M	M	M	L	L	L	L	M
(Ogbuewu and Mbajiorgu, 2023)	Broilers	L	L	H	M	H	M	M	L	L	M
(Oso et al., 2019)	Broilers	L	L	M	M	M	L	M	L	L	M

(Continued)

TABLE 6 Continued

Study	Species	1. Sequence eneration	2. Baseline characteristics	3. Allocation concealment	4.Random housing	5.Blinding of caregivers	6. Random outcome assessment	7. Blinding of outcome assessor	8.Incomplete outcome data	9.Selective reporting	10.Other bias
(Saei et al., 2021)	Broilers	L	L	M	M	M	L	M	L	L	M
(Shaaban et al., 2021)	Lambs	L	L	H	M	H	M	M	L	L	M
(Shafiee et al., 2020)	Broilers	L	L	M	M	M	L	L	L	L	M
(Xie et al., 2021)	Broilers	L	L	M	M	M	L	L	L	L	M
(Yang et al., 2023)	Cattle	L	L	H	M	H	M	M	L	L	M

4.1.1 Black cumin (*Nigella sativa*)

Ghasemi et al (Ghasemi et al., 2014). demonstrated that dietary inclusion of *Nigella sativa* (black cumin seed) significantly enhanced both growth performance and immune response in broiler chickens, with the 10 g/kg inclusion level (BS2) showing the most optimal effect. The observed increase in body weight gain (BWG) of approximately 110–150 g per bird and the improved feed conversion ratio (FCR) from 1.91 in the control to as low as 1.77 in the supplemented groups indicate a more efficient utilization of nutrients. Such outcomes are consistent with earlier reports that identified *N. sativa* as a potent phytogetic additive with bioactive constituents particularly thymoquinone, alkaloids, saponins, and essential oils known to exert antimicrobial, anti-inflammatory, and antioxidant effects (Ibrahim et al., 2022). The superior growth performance may be explained by enhanced gut health and better nutrient absorption, resulting from the modulation of intestinal microflora. Thymoquinone and other phenolic compounds suppress pathogenic bacteria such as *E. coli* and *Clostridium perfringens* while favouring beneficial bacteria like *Lactobacillus* spp., leading to improved gut morphology and villus height (Uttam, 2024). Improved gut integrity reduces energy loss from immune activation and promotes efficient digestion and assimilation of feed nutrients, ultimately supporting higher growth rates. The significant enhancement of immune indices, including the cutaneous basophil hypersensitivity (CBH) response and antibody titers against sheep red blood cells (SRBCs), further highlights the immunomodulatory role of *N. sativa*. The increased primary and secondary antibody titers observed in the probiotic and synbiotic groups, as well as the elevated CBH responses in the BS3 and synbiotic groups, suggest synergistic interactions between phytogetic compounds and microbial-based additives. Such combinations may promote both humoral and cell-mediated immunity by enhancing the functional activity of lymphocytes and macrophages [ref]. These findings support the growing consensus that phytogetic feed additives can serve as viable alternatives to antibiotic growth promoters (AGPs) in poultry production. The comparable performance of *N. sativa* to probiotic and synbiotic supplementation underscores its potential as a multifunctional additive that simultaneously promotes growth and health without contributing to antimicrobial resistance. However, the results also highlight that inclusion level is critical: the 10 g/kg dosage appeared optimal, while higher inclusion (20 g/kg) did not yield further improvement, likely due to dose-dependent metabolic effects or the presence of anti-nutritional factors.

4.1.2 Ajwain (*Trachyspermum ammi*)

Saei et al (Saei et al., 2021). evaluated the impact of *Trachyspermum ammi* (ajwain) extract on broiler performance and reported that moderate supplementation (300 ppm) significantly improved growth rate and final body weight compared with the control group, achieving values comparable to the antibiotic growth promoter Virginiamycin. The 300-ppm group reached an average final body weight of 2,763 g, representing about a 5% improvement over unsupplemented birds. In commercial



poultry production, even marginal gains of this magnitude translate into meaningful economic benefits through improved feed efficiency and higher market weights. The growth-promoting effects of ajwain extract are primarily attributed to its high concentrations of thymol and carvacrol, two phenolic compounds with well-documented antimicrobial, antioxidant, and digestive stimulant properties. These bioactive components enhance the activity of digestive enzymes such as amylase and protease, improving nutrient digestibility and absorption. Moreover, their antimicrobial effects help modulate the intestinal microbiota by suppressing pathogenic bacteria (*E. coli*, *Clostridium* spp.) and promoting beneficial species like *Lactobacillus* and *Bifidobacterium* (Shehata et al., 2022). The resulting improvement in gut health reduces nutrient competition and inflammatory stress, thereby supporting more efficient growth and feed utilization. Interestingly, the study observed that a higher dose (450 ppm) reduced both feed intake and final body weight, despite a numerically better feed conversion ratio (1.47). This suggests a dose-dependent response, where excessive levels of thymol may negatively affect feed palatability or cause mild gastrointestinal irritation. The comparable performance between the 300-ppm ajwain group and the Virginiamycin treatment highlights the potential of *T. ammi* extract as a natural alternative to antibiotic growth promoters (AGPs). In light of global restrictions on AGP

use, such phytogetic additives provide a sustainable, residue-free option for maintaining productivity and health in poultry systems. Future studies should focus on elucidating the precise mechanisms of thymol and carvacrol action, optimizing dosage formulations, and assessing long-term impacts on carcass traits, immune function, and production economics.

4.1.3 Tumeric (*Curcuma longa*)

Attia et al (Attia et al., 2017). demonstrated that turmeric (*Curcuma longa*) supplementation can enhance feed efficiency in broiler chickens, with the optimal response observed at 1 g/kg of diet. At this inclusion level, the feed conversion ratio (FCR) improved from 1.82 in the control to 1.68, comparable to the effects of mannan oligosaccharide (MOS) and oxytetracycline (OTC). Although the body weight gain did not differ significantly among treatments, birds fed turmeric at 1 g/kg achieved numerically higher gains (1833 g) than the control (1718 g), highlighting the additive’s potential to promote more efficient nutrient utilization rather than dramatically increasing growth rate. The improvement in FCR is largely attributed to curcumin, the primary bioactive compound in turmeric. Curcumin exhibits strong antioxidant, anti-inflammatory, and antimicrobial properties that enhance intestinal health and metabolic efficiency (Rahmani et al., 2018). By neutralizing reactive oxygen species and reducing

lipid peroxidation, curcumin helps preserve gut integrity, improving nutrient absorption and energy utilization (Platel and Srinivasan, 2004). Moreover, its antimicrobial action against enteric pathogens such as *E. coli* and *Clostridium perfringens* contributes to a healthier intestinal microflora, similar to the mechanism of antibiotic growth promoters but without their negative implications (Windisch et al., 2008). Interestingly, the study showed that higher turmeric inclusion (2 g/kg) did not enhance performance and even resulted in a slight reduction in feed efficiency (FCR = 1.83). This suggests a nonlinear, dose-dependent response, where excessive turmeric levels may negatively affect palatability or interfere with nutrient metabolism (Rajput et al., 2013). Such findings highlight the importance of optimizing dosage levels to achieve the balance between bioactivity and feed intake. The comparable EPEI values between turmeric (279) and MOS (303) treatments further suggest that turmeric may serve as a viable natural alternative to synthetic antibiotics and prebiotics. This aligns with the growing interest in phytogetic feed additives as sustainable growth promoters that improve efficiency and health while meeting consumer demand for antibiotic-free poultry products. Future research should investigate the synergistic effects of turmeric with other phytogetic compounds or probiotics and explore its long-term effects on carcass composition, immunity, and product quality.

4.1.4 *Lycium barbarum* polysaccharide

Long et al (Long et al., 2020). demonstrated that dietary supplementation with *Lycium barbarum* polysaccharides (LBP) significantly enhanced growth performance and immune function in broiler chickens, particularly at an inclusion level of 2,000 mg/kg. Broilers receiving this level achieved a 7.4% increase in average daily gain (ADG) and an improved feed conversion ratio (FCR) from 1.68 in the control to 1.57, indicating more efficient feed utilization. These improvements suggest that LBP exerts both nutritional and physiological benefits that contribute to enhanced productivity and overall health. The positive effects of LBP can be largely attributed to its bioactive polysaccharide components, which possess potent antioxidant, immunomodulatory, and prebiotic properties (Jia et al., 2020; Liang et al., 2022). LBP enhances intestinal integrity and microbial balance by stimulating the proliferation of beneficial bacteria such as *Lactobacillus* spp. and *Bifidobacterium* spp., thereby improving nutrient absorption and reducing intestinal inflammation (Yin et al., 2021). These effects may explain the reduced FCR and higher ADG observed in LBP-supplemented groups. The dose-dependent responses observed, where 2,000 mg/kg yielded optimal results while higher levels (4,000 mg/kg) offered no additional benefits, highlight the importance of optimal inclusion rates. Excessive supplementation might exceed physiological needs or lead to metabolic inefficiencies. The findings by Long et al (Long et al., 2020). affirm that *Lycium barbarum* polysaccharides can serve as an effective phytogetic growth promoter, improving both performance and immune competence. These results support the broader view that plant-derived polysaccharides can replace synthetic growth enhancers in sustainable and antibiotic-free livestock production systems.

4.1.5 Polyherbal blends

Polyherbal mixtures have demonstrated significant potential to enhance growth performance in poultry, largely due to the synergistic interactions among their bioactive components. Liu et al (Liu et al., 2023). reported that supplementation of a polyherbal mixture (PHM) containing *Portulaca oleracea*, *Radix Sophora flavescens*, *Thalictrum glandulosissimum*, *Terra flava usta*, and *Pogostemon cablin* improved both final body weight and average daily gain in yellow-feathered broilers compared with a basal diet. Similarly, Oso et al (Oso et al., 2019). found that inclusion of a phytogetic blend (PB) consisting of *Aerva lanata*, *Piper betle*, *Cynodon dactylon*, and *Piper nigrum* resulted in higher body weight gain (2,167.8 g/bird) and improved feed conversion ratio (FCR = 1.47), comparable to or better than the antibiotic-supplemented group. The consistent improvement in feed efficiency (0.05–0.10 FCR reduction) and growth rate (4–6% higher ADG) observed across both studies underscores the capacity of polyherbal formulations to enhance nutrient utilization and metabolic efficiency. The inclusion of diverse plant compounds—such as flavonoids, alkaloids, and terpenoids may stimulate digestive enzyme activity, improve intestinal morphology, and balance gut microflora, thereby facilitating better nutrient absorption. These mechanisms contribute to the observed increases in body weight and feed efficiency, positioning polyherbal additives as effective natural growth promoters capable of replacing conventional antibiotics in poultry diets.

4.1.6 Phytogetic feed additive blends

Ahsan et al (Ahsan et al., 2018). reported that supplementation of a commercial phytogetic feed additive (PFA) at 100–150 mg/kg did not significantly affect body weight gain, feed intake, or feed conversion ratio (FCR) in Ross 308 broilers over a 42-day trial. Final body weights ranged narrowly from 2808 g (PFA125) to 2893 g (control), and FCR varied slightly from 1.77 to 1.83 across treatments, indicating negligible impact of the tested PFA levels on growth performance. These findings highlight that not all commercial phytogetic formulations produce measurable performance gains at low to moderate inclusion levels. Similar observations have been reported by Ogbuwu and Mbajorgu (2023), who found that while feed intake increased with higher phytogetic doses, FCR worsened, suggesting compromised nutrient utilization. This pattern reflects a dose–response relationship, where moderate supplementation may be beneficial, but excessive or suboptimal inclusion can disrupt digestive processes or metabolic balance, limiting efficiency. The lack of significant improvement in Ahsan et al (Ahsan et al., 2018). may also be attributable to factors such as PFA composition, bioactive concentration, feed matrix interactions, or the health status of birds, which can influence the efficacy of phytogetic additives. It underscores the importance of optimizing inclusion levels and matching specific phytogetic formulations to production goals, rather than assuming uniform benefits across all commercial products.

In pigs, Chang et al (Chang et al., 2022). demonstrated that phytogetic feed additives (PFAs), particularly multicomponent blends containing bitter citrus extract, thymol, and carvacrol

(PFA3), significantly improved average daily gain (ADG) and feed efficiency in weaned pigs subjected to *E. coli* F18 challenge. These findings highlight the context-dependent efficacy of PFAs: while effects may be modest in healthy pigs, their benefits are most pronounced under pathogen-induced stress, where growth suppression is a common consequence. The observed improvements likely result from enhanced nutrient digestibility, modulation of gut microbiota, and maintenance of intestinal barrier integrity, which collectively support better feed utilization and growth despite infectious challenges. The results suggest that phytogetic blends can function as natural growth promoters, particularly in environments where pigs are exposed to microbial or environmental stressors, potentially reducing production losses associated with enteric infections.

In cattle's, Yanga et al (Yang et al., 2023). reported supplementation of crossbred Angus steers with a phytogetic feed additive (PFA) moderately improved growth performance during a 110-day growing phase. Steers receiving PFA achieved an average daily gain (ADG) of 1.31 kg/d compared with 1.20 kg/d in the control group. Although these differences were not statistically significant and were slightly lower than monensin-supplemented steers (ADG = 1.38 kg/d), the data suggest that PFAs can support consistent growth during early development (Yang et al., 2023). The diminished response during the finishing phase indicates that phytogetic additives may exert their greatest effects during periods of rapid lean tissue deposition, when nutrient partitioning favours muscle accretion over fat deposition. This aligns with previous observations in ruminants where bioactive plant compounds, such as essential oils, polyphenols, or saponins, primarily influence rumen fermentation and nutrient utilization during the growth phase rather than later finishing stages (Patra, 2011). Feed efficiency, as measured by gain-to-feed ratio (G:F), improved modestly in PFA-supplemented cattle (0.161) relative to controls (0.156) but remained lower than that achieved with monensin (0.173). This suggests that while PFAs may enhance nutrient utilization to a degree, they do not yet match the efficiency of established ionophore growth promoters. Nevertheless, the moderate improvements observed, coupled with higher dry matter intake (DMI) in PFA-fed steers (10.2 kg/d), indicate that these natural additives can contribute to sustained growth performance while addressing consumer demand for antibiotic- and chemical-free beef production. The findings underscore the potential of PFAs as complementary feed additives, particularly during growth stages, and highlight the need for further research to optimize formulations and inclusion rates to achieve feed efficiency comparable to synthetic additives.

4.1.7 Celery and thyme

Shaaban et al (Shaaban et al., 2021). demonstrated that supplementation of Barki lambs with phytogetic feed additives, specifically celery, thyme, or their mixture, significantly enhanced growth performance compared with controls. Lambs receiving celery achieved the highest final body weight (51.7 kg), total weight gain (32.1 kg), and average daily gain (ADG; 111 g/d), representing increases of approximately 30–31% over the control

group (ADG = 85 g/d). Thyme and the thyme-celery mixture also improved growth, with ADG values of 98–99 g/d and final weights of 48.1–48.7 kg. These results indicate that certain phytogetic additives can substantially accelerate growth rates in small ruminants, likely by enhancing nutrient digestibility and optimizing metabolic efficiency during the growth phase. Feed conversion efficiency was markedly improved in lambs supplemented with celery, achieving an FCR of 12.6 g feed/g ADG compared with 15.3 g/g in the control group. This improvement is comparable to effects observed with synthetic growth promoters such as monensin, suggesting that phytogetics may exert similar functional benefits. The underlying mechanisms likely include enhanced rumen fermentation, with better fibre digestion and volatile fatty acid production, reduction of methane losses, and increased energy capture from fibrous feeds. Additionally, the bioactive compounds in celery and thyme, such as phenolics, flavonoids, and essential oils, may exert antimicrobial and antioxidant effects, improving gut health and nutrient absorption, which collectively support improved growth performance and feed utilization.

4.1.8 Propolis and moringa

Hashem et al (Hashem et al., 2017). reported that supplementation of V-line rabbits with propolis (150–300 mg/kg) or moringa roots (150–300 mg/kg) improved growth performance compared with controls. Rabbits receiving propolis, particularly at 150 mg/kg, achieved significantly higher live body weight and average weekly gain, along with improved feed conversion ratios (FCR). Moringa-supplemented groups showed intermediate growth gains, indicating that the effects on weight gain were less pronounced than those of propolis or vitamin E. These results suggest that phytogetic additives can enhance growth efficiency and feed utilization in hindgut fermenters, likely by stabilizing caecal fermentation, improving fibre digestibility, and supporting optimal nutrient absorption. The positive effects of propolis, a bioactive-rich additive containing flavonoids and phenolics, may also be attributed to its antimicrobial and antioxidant properties, which reduce gut microbial imbalances and oxidative stress, indirectly supporting growth.

4.2 Impact on the immune response

Phytogetic feed additives exert profound effects on immune modulation in broilers, with evidence spanning anti-inflammatory responses, humoral immunity, cell-mediated immunity, and immune organ development. One of the most consistent findings is the capacity of PFAs to shift cytokine expression toward an anti-inflammatory profile.

4.2.1 Mango leaf

Adeyemi et al (Adeyemi et al., 2021). demonstrated that mango leaf (ML) supplementation exerts a strong immunomodulatory effect in broilers. Proinflammatory cytokines, interleukin-1 β (IL-1 β) and tumor necrosis factor- α (TNF- α), were markedly

reduced by up to 68% and 61%, respectively indicating a suppression of inflammatory processes that could otherwise lead to tissue damage and increased metabolic costs. Concurrently, the anti-inflammatory cytokine interleukin-10 (IL-10) increased threefold, suggesting enhanced immune regulation and tolerance. Interestingly, humoral immune markers, including immunoglobulins IgM and IgA, were decreased (46–70% and 65–85%, respectively), suggesting that ML supplementation selectively modulates cell-mediated and regulatory immune pathways rather than enhancing antibody-mediated immunity. This targeted immune modulation may allow broilers to allocate more energy toward growth and tissue deposition while maintaining sufficient immune protection against pathogens. These findings highlight mango leaves as potent natural immunomodulators, capable of reducing excessive inflammatory responses and promoting immune homeostasis, which is particularly valuable in intensive poultry systems where chronic stress and inflammation can impair productivity.

4.2.2 *Salix alba*

Kalia et al (Kalia et al., 2021). demonstrated that supplementation of broilers with *Salix alba* leaf extract, particularly at 300 mg/kg body weight, positively modulated immune function under high-altitude cold-stress conditions. Birds in the *Salix* 300 group exhibited increased plasma interleukin-2 (IL-2) concentrations (9.22 pg/mL vs. 8.51 pg/mL in controls), indicating enhanced T-cell proliferation and adaptive immune activity. At the same time, proinflammatory cytokines IL-1 and IL-6 were reduced (6.24 and 7.89 pg/mL vs. 6.46 and 8.26 pg/mL in controls), suggesting a suppression of excessive inflammatory responses. These findings highlight that *Salix alba* extract can promote immune homeostasis by dampening unnecessary inflammation while sustaining adaptive immune competence. Such immune modulation is particularly valuable under high-altitude or environmental stress conditions, where chronic inflammation can compromise growth and health. The bioactive compounds in *S. alba*, including flavonoids and phenolics, are likely responsible for its antioxidant and immunomodulatory effects, supporting both the innate and adaptive arms of the immune system.

4.2.3 Nano- encapsulated rosemary essential oil (N-REO)

Adil et al (Adil et al., 2024). demonstrated that supplementation of broilers with nanoprotected rosemary essential oil (N-REO), particularly at 200 mg/kg, significantly enhanced both humoral and cell-mediated immunity. Humoral immune responses were strengthened, as evidenced by increased serum immunoglobulin concentrations IgG rose from 316 mg/mL in controls to 368 mg/mL, and IgM increased from 580 mg/mL to 653 mg/mL. Anti-sheep red blood cell (SRBC) antibody titers also improved from 5.52 log₂ in the control group to 6.49 log₂ in the high-N-REO group, indicating enhanced systemic antibody-mediated immunity. Cell-mediated immunity was similarly augmented, with the cutaneous basophil hypersensitivity (CBH) response increasing from 1.34 mm

in controls to 1.76 mm in high-N-REO birds. Additionally, the relative weights of immune organs, such as the bursa of Fabricius, were slightly higher in supplemented birds, suggesting improved lymphoid organ development and overall immune competence. These findings suggest that nanoencapsulation enhances the bioavailability and stability of rosemary essential oil, allowing its bioactive compounds phenolics, flavonoids, and terpenoids—to effectively stimulate both adaptive and innate immune responses. Consequently, N-REO at 200 mg/kg not only supports a robust systemic and mucosal immune response but may also serve as a natural alternative to conventional antibiotics in broiler production.

4.2.4 Black cumin

Ghasemi et al (Ghasemi et al., 2014). demonstrated that supplementation with black cumin seeds (*Nigella sativa*), probiotics, and synbiotics positively modulated immune responses in broiler chickens. The cutaneous basophil hypersensitivity (CBH) response to phytohemagglutinin-P, an indicator of cell-mediated immunity, was significantly higher in birds receiving high-dose black cumin (BS3) and synbiotics (0.77 mm and 0.75 mm, respectively) compared with controls (0.59 mm), suggesting enhanced T-cell-mediated immune function. Humoral immunity was also improved, as evidenced by elevated primary antibody titers against sheep red blood cells (SRBCs) in the probiotic (6.65 log₂) and synbiotic (6.83 log₂) groups, with comparable increases in secondary antibody titers. These results indicate that black cumin and synbiotic supplementation can enhance both adaptive immune responses and vaccine responsiveness, potentially improving disease resistance in broilers. The immune-stimulating effects of black cumin are likely attributable to its bioactive compounds, including thymoquinone, which possess antioxidant, antimicrobial, and immunomodulatory properties, supporting both innate and adaptive immunity. Black cumin and synbiotics can serve as natural immunostimulants, complementing growth-promoting effects and contributing to improved health status in intensive poultry production systems.

4.2.5 Cumin

Shafiee et al (Shafiee et al., 2020). demonstrated that dietary supplementation with 0.75% cumin (*Cuminum cyminum*) significantly enhanced both humoral and cell-mediated immunity in broiler chickens. Humoral immunity, measured via sheep red blood cell (SRBC) titers, increased from 4.25 log₂ in controls to 6.25 log₂ in cumin-supplemented birds, indicating a stronger systemic antibody-mediated response. Cell-mediated immunity was also markedly improved. The cutaneous basophil hypersensitivity (CBH) response, a proxy for T-cell activity, nearly doubled in the cumin group (987 μm) compared with controls (519 μm), reflecting enhanced T-cell reactivity and adaptive immune competence. This suggests that cumin supplementation stimulates the cellular arm of immunity, which is critical for defence against intracellular pathogens and for mounting an effective response to immunological challenges. The immunostimulatory effects of cumin are likely mediated by its bioactive compounds, including essential oils, flavonoids, and phenolics, which possess antioxidant,

antimicrobial, and immunomodulatory properties. These compounds can enhance lymphocyte proliferation and improve overall immune organ function, contributing to better immune resilience in broilers. Shafiee et al (Shafiee et al., 2020). highlight that cumin serves as a natural immune enhancer, supporting both humoral and cell-mediated responses and providing a potential alternative to in-feed antibiotics in poultry production.

4.2.6 *Lycium barbarum* polysaccharides

Long et al (Long et al., 2020). provided further evidence that *Lycium barbarum* polysaccharides significantly increase the serum IgA and IgG levels, indicating the broad-spectrum strengthening of antibody-mediated immunity in broilers. The marked elevation in serum immunoglobulins (IgA and IgG) following *Lycium barbarum* polysaccharide (LBP) supplementation, as reported by Long et al (Long et al., 2020), highlights the compound's potent immunomodulatory properties. Immunoglobulins serve as critical components of the adaptive immune system, and their upregulation suggests that LBP enhances both mucosal and systemic immunity in broiler chickens. IgA is the principal antibody at mucosal surfaces, particularly within the intestinal tract, where it forms the first line of immune defence by neutralizing pathogens and preventing microbial adherence to epithelial cells. The observed increase in serum IgA concentration (0.481–0.489 mg/mL versus 0.384 mg/mL in the control) suggests that LBP may stimulate gut-associated lymphoid tissue (GALT), thereby reinforcing intestinal barrier function and reducing pathogen translocation across the epithelium (Yin et al., 2021). A more robust mucosal immune response supports gut integrity, minimizes inflammation, and promotes an optimal environment for nutrient absorption—all of which contribute to improved feed efficiency and growth performance. Similarly, the significant elevation in IgG levels (0.798–0.889 mg/mL versus 0.749 mg/mL in the control) reflects enhanced systemic immune protection. IgG antibodies circulate throughout the bloodstream, recognizing and neutralizing antigens such as bacteria and viruses. This indicates that LBP may activate B-lymphocyte proliferation and antibody production, possibly through modulation of cytokine signalling pathways and macrophage activation (Zhao et al., 2021). Immune stimulation increases the bird's resistance to infections and reduces the metabolic costs associated with immune suppression or subclinical disease challenges. The combined rise in IgA and IgG levels demonstrates that LBP not only fortifies local intestinal immunity but also strengthens systemic defence mechanisms, enhancing the bird's overall immune resilience. This dual immunostimulatory effect may explain the improved performance parameters observed in LBP-treated groups. Consequently, *Lycium barbarum* polysaccharides emerge as promising natural immunomodulators capable of replacing antibiotic growth promoters, supporting both health and productivity in poultry production systems.

4.2.7 Essential oil

Hong et al (Hong et al., 2012). demonstrated that supplementation of broilers with an essential oil blend (oregano, anise, and citrus peel) at 125 ppm significantly enhanced both

humoral and cell-mediated immunity. Humoral responses were evidenced by higher Newcastle disease virus (NDV) antibody titers ($10.44 \log_2$) compared with the antibiotic group ($9.06 \log_2$), indicating a stronger systemic antibody-mediated response. Sheep red blood cell (SRBC) antibody titers were also improved, suggesting that essential oils can support broad-spectrum humoral immunity. Cell-mediated immunity was similarly augmented, with the delayed-type hypersensitivity (DTH) response increasing from 1.03 mm in controls to 1.57 mm in the essential oil group. This reflects enhanced T-cell reactivity and improved adaptive cellular immune competence. The essential oil blend likely exerts these effects through its bioactive compounds, including thymol, carvacrol, and flavonoids, which possess antioxidant, antimicrobial, and immunomodulatory properties. These compounds may stimulate lymphocyte proliferation and promote the development of immune organs, thereby contributing to overall immune resilience. The findings indicate that essential oils not only match or exceed antibiotic growth-promoting effects but also enhance immune function by simultaneously stimulating humoral and cellular pathways, supporting balanced and effective immune defence in broilers.

4.2.8 Polyherbal mixtures

Beyond growth enhancement, polyherbal mixtures exert profound effects on the immune competence of broilers. Liu et al (Liu et al., 2023). observed that PHM supplementation significantly increased the spleen index, serum immunoglobulin G (IgG), and jejunal secretory immunoglobulin A (sIgA) concentrations, indicating activation of both systemic and mucosal immunity. The elevated sIgA levels suggest improved gut immune defence, which is critical for maintaining intestinal barrier integrity and preventing pathogen colonization. In contrast, higher IgG concentrations reflect strengthened systemic immunity, enhancing the bird's ability to respond to infections and maintain overall health status. Furthermore, Liu et al (Liu et al., 2023). reported that PHM supplementation increased interleukin-4 (IL-4) and reduced interferon-gamma (IFN- γ) concentrations, suggesting a shift toward a Th2-dominant immune profile. This modulation promotes antibody-mediated (humoral) immunity while mitigating excessive inflammation, allowing for more efficient nutrient allocation toward growth. Such immune balancing reduces metabolic stress and may explain the simultaneous improvements in performance metrics.

4.2.9 Propolis and moringa

Hashem et al (Hashem et al., 2017). observed significant modulation of immune parameters in rabbits fed moringa root supplements. Lymphocyte percentages increased, while neutrophil-to-lymphocyte ratios (NLR) decreased, indicating enhanced immune competence and reduced systemic inflammatory stress. Neutrophil percentages were correspondingly reduced, suggesting a shift toward adaptive immunity without compromising growth performance. However, serum immunoglobulin G (IgG) and M (IgM) concentrations were not significantly altered, indicating that the immunomodulatory effects were primarily cell-mediated rather

than humoral. These findings highlight that moringa roots may provide functional immune support, strengthening the rabbit's resilience to stressors and potential infections, which is particularly valuable in intensive production systems where immune challenges are common.

4.2.10 Phytogetic feed additive blends

Beyond growth performance, PFAs exerted significant immunomodulatory and anti-inflammatory effects. Pigs receiving PFA3 exhibited elevated serum immunoglobulin G (IgG) and immunoglobulin A (IgA) concentrations 7 days post-inoculation, indicating enhanced systemic and mucosal immunity (Chang et al., 2022). These immune responses improve the animal's ability to neutralize pathogens and maintain gut integrity. Additionally, tumor necrosis factor- α (TNF- α) levels were significantly reduced in most PFA-supplemented groups at 14 days post-inoculation, reflecting anti-inflammatory activity. Lower inflammatory signalling likely reduces metabolic energy diversion toward immune activation, allowing more resources to be directed toward growth and tissue deposition.

4.3 Implications

In poultry production, phytogetic feed additives have been identified as effective alternatives to antibiotics. The evidence in the included studies demonstrates consistent improvements in growth performance, feed efficiency, and immune function, making them particularly suited to the intensive broiler industry, where antibiotic reduction is most urgent (Hong et al., 2012; Ghasemi et al., 2014; Li et al., 2015; Attia et al., 2017; Ahsan et al., 2018; Oso et al., 2019; Long et al., 2020; Shafiee et al., 2020; Adeyemi et al., 2021; Kalia et al., 2021; Saei et al., 2021; Xie et al., 2021; Liu et al., 2023; Ogbuewu and Mbajorgu, 2023; Adil et al., 2024; Hossain et al., 2024), whereas only one is focused on pigs (Chang et al., 2022), rabbits (Hashem et al., 2017) and lambs (Shaaban et al., 2021). However, the challenge lies not in proving efficacy but in defining optimal combinations and dosages. Many phytoGENICS, such as turmeric, black cumin, and essential oils, show strong results individually, but variability in outcomes highlights the need for standardized formulations and precise inclusion levels to ensure reliable field performance (Ghasemi et al., 2014; Attia et al., 2017; Adil et al., 2024). In swine and rabbit production, the benefits of PFAs appear to be most pronounced under disease-challenge conditions (Hashem et al., 2017; Chang et al., 2022). A study revealed that immune-enhancing effects, such as improved IgG and IgA and reduced proinflammatory cytokines, translate into performance gains when animals face infections such as *E. coli* (Chang et al., 2022). This suggests that in these species, PFAs may function not only as growth enhancers but also as health stabilizers, reducing morbidity and mortality in intensive systems where infectious pressure is high. Their value may therefore be greatest in contexts where antibiotic-free systems must still maintain resilience against disease outbreaks. For ruminants, an evidence base is still lacking. Early trials suggested improvements in growth

and general health, but the effects on feed efficiency remain inconsistent compared with those of conventional ionophores such as monensin (Shaaban et al., 2021; Yang et al., 2023). This is likely due to rumen metabolism, which can degrade or transform phytochemicals before they exert systemic effects. To maximize the impact on cattle and small ruminants, long-term studies are needed to capture subtle changes in growth, immunity, and methane emissions (Shaaban et al., 2021; Yang et al., 2023). For the feed industry, the key insight is that blended formulations outperform single compounds. Combinations such as citrus + thymol + carvacrol or multitherbal mixtures consistently have synergistic effects on both growth and immune outcomes (Oso et al., 2019; Chang et al., 2022; Liu et al., 2023). This suggests that the future of phytoGENICS lies not in single additive solutions but in strategically designed blends that balance antimicrobial, antioxidant, and immunomodulatory properties. This approach mirrors the complexity of antibiotics but leverages natural compounds in a way that reduces resistance risk and enhances sustainability.

4.4 Limitations of the study

While this systematic review offers important insights into the effects of phytogetic feed additives on growth and immune responses in livestock from 2010–2024, several limitations should be acknowledged. First, the selection of databases may have restricted the comprehensiveness of the review. Only seven major databases were searched—Scopus, ScienceDirect, Web of Science, and EBSCOhost (Academic Search Ultimate, AGRICOLA, and MEDLINE with Full Text)—which, although extensive, may have excluded other relevant sources containing additional studies in this field. Second, only studies published in English were considered, introducing potential language bias and possibly omitting relevant evidence published in other languages. Third, studies published before 2010 were not included, which may have overlooked earlier but still informative research on phytogetic feed additives. To mitigate these limitations, future reviews should consider expanding database coverage, including non-English publications, and incorporating earlier studies to provide a more comprehensive synthesis of the evidence.

5 Conclusion

Phytogetic feed additives are promising alternatives to antibiotics, enhancing growth and immune function across livestock, particularly in broilers. They reduce proinflammatory cytokines, increase antibody and lymphocyte activity, and support overall health. Optimal dosing is crucial, as excessive inclusion can impair feed efficiency, and evidence in ruminants remains limited. Blended formulations of complementary phytochemicals often provide synergistic benefits, outperforming single additives. Collectively, PFAs offer a sustainable strategy for antibiotic-free livestock production, improving productivity while maintaining immune resilience and animal welfare.

Author contributions

OI: Conceptualization, Formal analysis, Resources, Supervision, Validation, Visualization, Writing – review & editing. ZN: Data curation, Formal analysis, Investigation, Methodology, Software, Writing – original draft. IJ: Resources, Supervision, Validation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

- Adetunji, A. O., Price, J., Owusu, H., Adewale, E. F., Adesina, P. A., Saliu, T. P., et al. (2025). Mechanisms by which phytochemicals enhance livestock reproductive health: current insights and future directions. *Front. Veterinary Sci.* 12. doi: 10.3389/fvets.2025.1568577
- Adeyemi, K. D., Olanrewaju, S. M., Adewunmi, P. S., and Abdulqadir, Z. (2021). Mango leaf and synthetic additives in broiler diet: impact on growth, cecal microbiota, immunity, blood chemistry, and meat quality. *J. Saudi Soc. Agric. Sci.* 20, 482–489. doi: 10.1016/j.jssas.2021.05.005
- Adil, S., Banday, M. T., Wani, M. A., Hussain, S. A., Shah, S., Sheikh, I. D., et al. (2024). Nanoprotected form of rosemary essential oil has a positive influence on blood biochemistry parameters, hematological indices, immune-antioxidant status, intestinal microbiota and histomorphology of meat-type chickens. *Poultry Sci.* 103, 104309. doi: 10.1016/j.psj.2024.104309
- Ahsan, U., Kuter, E., Raza, I., Köksal, B. H., Cengiz, Ö., Yıldız, M., et al. (2018). Dietary supplementation of different levels of phytochemical feed additive in broiler diets: the dynamics of growth performance, cecal microbiota, and intestinal morphometry. *Braz. J. Poultry Sci.* 20, 737–746. doi: 10.1590/1806-9061-2017-0698
- Assan, N. (2018). Plant based feed additives (phytochemical) as a primary solution to an antibiotic free nutritional program and feeding strategy in rabbit production. *Sci. J. Anim. Sci.* 7, 493–503. doi: 10.14196/sjas.v7i3.2521
- Attia, Y. A., Addeo, N. F., Bovera, F., Abd AlHack, M. E., AlBanoby, M. A., Alhotan, R. A., et al. (2025). *Phytochemical Substances as Novel Feed Supplements and Their Application in Livestock Nutrition. In Phytochemical and Phytochemical as Alternative Feed Additives for Animal Production* (United Arab Emirates: Bentham Science Publishers), 4–18. doi: 10.2174/9789815322767125010005
- Attia, Y. A., Al-Harthi, M. A., and Hassan, S. S. (2017). Turmeric (*Curcuma longa* Linn.) as a phytochemical growth promoter alternative for antibiotic and comparable to mannan oligosaccharides for broiler chicks. *Rev. mexicana Cienc. pecuarias* 8, 11–21. doi: 10.22319/rmcp.v8i1.4309
- Chang, S. Y., Song, M. H., Lee, J. H., Oh, H. J., Kim, Y. J., An, J. W., et al. (2022). Phytochemical feed additives alleviate pathogenic *Escherichia coli*-induced intestinal damage through improving barrier integrity and inhibiting inflammation in weaned pigs. *J. Anim. Sci. Biotechnol.* 13, 107. doi: 10.1186/s40104-022-00750-y
- Ghasemi, H. A., Kasani, N., and Taherpour, K. (2014). Effects of black cumin seed (*Nigella sativa* L.), a probiotic, a prebiotic, and a synbiotic on growth performance, immune response, and blood characteristics of male broilers. *Livestock Sci.* 164, 128–134. doi: 10.1016/j.livsci.2014.03.014
- Hashem, N. M., Abd El-Hady, A. M., and Hassan, O. A. (2017). Inclusion of phytochemical feed additives comparable to vitamin E in diet of growing rabbits: Effects on metabolism and growth. *Ann. Agric. Sci.* 62, 161–167. doi: 10.1016/j.aos.2017.11.003
- Hong, J. C., Steiner, T., Aufy, A., and Lien, T. F. (2012). Effects of supplemental essential oil on growth performance, lipid metabolites and immunity, intestinal characteristics, microbiota and carcass traits in broilers. *Livestock Sci.* 144, 253–262. doi: 10.1016/j.livsci.2011.12.008
- Hooijmans, C. R., Rovers, M. M., De Vries, R. B., Leenaars, M., Ritskes-Hoitinga, M., and Langendam, M. W. (2014). SYRCLE's risk of bias tool for animal studies. *BMC Med. Res. Method.* 14, 43. doi: 10.1186/1471-2288-14-43
- Hossain, M. M., Cho, S., and Kim, I. H. (2024). *Achyranthes japonica* extract as phytochemical feed additive enhanced nutrient digestibility and growth performance in broiler. *J. Anim. Sci. Technol.* 66, 471. doi: 10.5187/jast.2023.e56
- Ibrahim, D., Shahin, S. E., Alqahtani, L. S., Hassan, Z., Althobaiti, F., Albogami, S., et al. (2022). Exploring the interactive effects of thymol and thymoquinone: moving toward an enhanced performance, gross margin, immunity and *Aeromonas sobria* resistance of Nile Tilapia (*Oreochromis niloticus*). *Animals* 12, 3034. doi: 10.3390/ani12213034
- Jia, R., Cao, L., Xu, P., Jeney, G., Yin, G., and Zhang, J. (2020). Lycium barbarum polysaccharides enhance growth and immunity by regulating gut microbiota and metabolism in broilers. *Poultry Sci.* 99, 5233–5243. doi: 10.1016/j.psj.2020.07.015
- Kalia, S., Bharti, V. K., Giri, A., Malairaman, U., Biswas, A., and Kumar, B. (2021). Effect of *Salix alba* leave extract on growth performance, antioxidant level and immune status of broiler chickens reared at high altitude cold desert. *Biologia* 76, 3003–3015. doi: 10.1007/s11756-021-00795-w
- Li, H. L., Zhao, P. Y., Lei, Y., Hossain, M. M., and Kim, I. H. (2015). Phytoncide, phytochemical feed additive as an alternative to conventional antibiotics, improved growth performance and decreased excreta gas emission without adverse effect on meat quality in broiler chickens. *Livestock Sci.* 181, 1–6. doi: 10.1016/j.livsci.2015.10.001
- Liang, X., Zhang, X., Zhou, J., and Liu, Z. (2022). Effects of Lycium barbarum polysaccharides on intestinal morphology, antioxidant status, and performance in poultry: A meta-analysis. *Animals* 12, 1779. doi: 10.3390/ani12141779
- Lillehoj, H., Liu, Y., Calsamiglia, S., Fernandez-Miyakawa, M. E., Chi, F., Cravens, R. L., et al. (2018). Phytochemicals as antibiotic alternatives to promote growth and enhance host health. *Veterinary Res.* 49, 76. doi: 10.1186/s13567-018-0562-6
- Liu, M., Zhou, J., Li, Y., Ding, Y., Lian, J., Dong, Q., et al. (2023). Effects of dietary polyherbal mixtures on growth performance, antioxidant capacity, immune function and jejunal health of yellow-feathered broilers. *Poultry Sci.* 102, 102714. doi: 10.1016/j.psj.2023.102714
- Long, L. N., Kang, B. J., Jiang, Q., and Chen, J. S. (2020). Effects of dietary Lycium barbarum polysaccharides on growth performance, digestive enzyme activities, antioxidant status, and immunity of broiler chickens. *Poultry Sci.* 99, 744–751. doi: 10.1016/j.psj.2019.10.043
- Manchee, L. (2018). Alternative uses to ionophores in the feedlot industry. *A Rep. Nuffield Aust. Farming Scholars Nuffield Aust. Project* 1604, 50.

- Memar, M. Y., Raei, P., Alizadeh, N., Aghdam, M. A., and Kafil, H. S. (2017). Carvacrol and thymol: strong antimicrobial agents against resistant isolates. *Rev. Res. Med. Microbiol.* 28, 63–68. doi: 10.1016/j.rmmr.2017.06.001
- Mills, J., and Driscoll, M. (2022). The hidden health impacts of industrial livestock systems: transforming livestock systems for better human, animal and planetary health. Available online at: <https://www.worldanimalprotection.org/globalassets/pdfs/reports/english/hidden-health-impacts.pdf> (Accessed August 24 2025).
- Ogbuwu, I. P., and Mbajorgu, C. A. (2023). Dietary Dialium guineense stem-bark supplementation improves growth performance and hemato-biochemical characteristics of broiler chickens. *Heliyon* 9. doi: 10.1016/j.heliyon.2023.e17341
- Oso, A. O., Suganthi, R. U., Reddy, G. M., Malik, P. K., Thirumalaisamy, G., Awachat, V. B., et al. (2019). Effect of dietary supplementation with phyto-genic blend on growth performance, apparent ileal digestibility of nutrients, intestinal morphology, and cecal microflora of broiler chickens. *Poultry Sci* 98, 4755–4766. doi: 10.3382/ps/pez191
- Ostojić Andrić, D., Hristov, S., Stanković, B., Petrović Caro, V., Pajić, M., Nikšić, D., et al. (2023). “Medicinal and aromatic plants in livestock farming: A promising approach for boosting health and performance,” in *Proceedings of 14th International Symposium “Modern Trends In Livestock Production”* (Institute for Animal Husbandry, Belgrade-Zemun, Serbia), 460–475. Available online at: https://www.google.com/search?q=http://istocar.bg.ac.rs/PDF/Proceedings_14_MTLIP_2023.pdf (Accessed August 24 2025).
- Platel, K., and Srinivasan, K. (2004). Digestive stimulant action of spices: A myth or reality? *Indian J. Med. Res.* 119, 167–179.
- Puvača, N., Milenković, J., Galonja Coghill, T., Bursić, V., Petrović, A., Tanasković, S., et al. (2021). Antimicrobial activity of selected essential oils against selected pathogenic bacteria: *In vitro* study. *Antibiotics* 10, 546. doi: 10.3390/antibiotics10050546
- Rahmani, A. H., Alsahli, M. A., Aly, S. M., and Khan, M. A. (2018). Role of curcumin in disease prevention and treatment. *Advanced Biomed. Res.* 7, 1–13. doi: 10.4103/abr.abr_147_17
- Rajput, N., Muhamma, N., Yan, R., Zhong, X., and Wang, T. (2013). Effect of dietary supplementation of curcumin on growth performance, intestinal morphology, and nutrient utilization of broiler chickens. *J. Poultry Sci* 50, 44–52. doi: 10.2141/jpsa.0120056
- Rethlefsen, M. L., Kirtley, S., Waffenschmidt, S., Ayala, A. P., Moher, D., Page, M. J., et al. (2021). PRISMA-S: an extension to the PRISMA statement for reporting literature searches in systematic reviews. *Systematic Rev.* 10, 39. doi: 10.1186/s13643-020-01542-z
- Saei, S., Di Rosa, A. R., Rasouli, B., Seidavi, A., Chiofalo, V., Liotta, L., et al. (2021). Ajwain (*Trachyspermum copticum*) extract in broiler diets: effect on growth performance, carcass components, plasma constituents, immunity and cecum microflora. *Ital. J. Anim. Sci* 20, 842–849. doi: 10.1080/1828051X.2021.1926347
- Salim, H. M., Huque, K. S., Kamaruddin, K. M., and Haque Beg, A. (2018). Global restriction of using antibiotic growth promoters and alternative strategies in poultry production. *Sci Prog.* 101, 52–75. doi: 10.3184/003685018X15173975498947
- Shaaban, M. M., Kholif, A. E., Abd El Tawab, A. M., Radwan, M. A., Hadhoud, F. I., Khattab, M. S. A., et al. (2021). Thyme and celery as potential alternatives to ionophores use in livestock production: their effects on feed utilization, growth performance and meat quality of Barki lambs. *Small Ruminant Res.* 200, 106400. doi: 10.1016/j.smallrumres.2021.106400
- Shafiee, M., Akbari, M. R., Asadi-Khoshoi, E., Bahadoran, S., and Hassanpour, H. (2020). Growth performance, nutrients digestibility, immune system, and blood parameters in broiler chickens fed on diets supplemented with cumin (*Cuminum cyminum*) or black cumin (*Bunium persicum*) seed powders. *Poultry Sci.* 8(2):223–231. doi: 10.22069/psj.2020.18155.1601
- Shehata, A. A., Yalçın, S., Latorre, J. D., Basiouni, S., Attia, Y. A., El-Wahab, A. A., et al. (2022). Probiotics, prebiotics, and phyto-genic substances for modulation of gut microbiota and immune system in poultry. *Front. Veterinary Sci* 9. doi: 10.3389/fvets.2022.887715
- Tedeschi, L. O., Muir, J. P., Naumann, H. D., Norris, A. B., Ramírez-Restrepo, C. A., and Mertens-Talcott, S. U. (2021). Nutritional aspects of ecologically relevant phytochemicals in ruminant production. *Front. Veterinary Sci* 8. doi: 10.3389/fvets.2021.628445
- Uttam, M. T. M. (2024). Effect Of Dietary Supplementation Of Black Cumin (*Nigella Sativa*) And Garlic (*Allium Sativum* L.) Powder On Growth Performance And Carcass Parameters Of Broilers. Available online at: <https://krishikosh.egranth.ac.in/handle/1/5810214843> (Accessed August 24 2025).
- Windisch, W., Schedle, K., Plitzner, C., and Kroismayr, A. (2008). Use of phyto-genic products as feed additives for swine and poultry. *J. Anim. Sci* 86, E140–E148. doi: 10.2527/jas.2007-0459
- Wu, G., Fanzo, J., Miller, D. D., Pingali, P., Post, M., Steiner, J. L., et al. (2014). Production and supply of high-quality food protein for human consumption: sustainability, challenges, and innovations. *Ann. New York Acad. Sci.* 1321, 1–19. doi: 10.1111/nyas.12500
- Wythe, L. A., Dittoe, D. K., and Ricke, S. C. (2023). “Advancements in Poultry Nutrition and Genetics, the Role of Antibiotic Growth Promoters, and the Introduction of Feed Additive Alternatives,” in *Direct-Fed Microbials and Prebiotics for Animals: Science and Mechanisms of Action* (Springer International Publishing, Cham), 59–79. doi: 10.1007/978-3-031-40512-9_4
- Xie, M., Wang, R., Wang, Y., Liu, N., and Qi, J. (2021). Effects of dietary supplementation with fermented *Chenopodium album* L. @ on growth, nutrient digestibility, immunity, carcass characteristics and meat quality of broilers. *Ital. J. Anim. Sci* 20, 2063–2074. doi: 10.1080/1828051X.2021.1996289
- Yahfoufi, N., Alsadi, N., Jambi, M., and Matar, C. (2018). The immunomodulatory and anti-inflammatory role of polyphenols. *Nutrients* 10, 1618. doi: 10.3390/nu10111618
- Yang, W. Z., Lima, P. M. T., Ramirez, S., Schwandt, E., and McAllister, T. A. (2023). Effects of a phyto-genic feed additive on growth performance, feed intake, and carcass traits of beef steers. *Appl. Anim. Sci* 39, 423–432. doi: 10.15232/aas.2023-02421
- Yin, G., Zhang, J., Li, Y., and Zhang, S. (2021). Dietary supplementation of Lycium barbarum polysaccharides enhances growth, immune response, and intestinal health in broilers. *Front. Veterinary Sci* 8. doi: 10.3389/fvets.2021.654392
- Zhao, X., Wang, C., Zhang, Y., and Chen, G. (2021). Immunomodulatory effects of Lycium barbarum polysaccharides and their role in oxidative stress reduction in poultry. *Int. J. Biol. Macromolecules* 184, 917–925. doi: 10.1016/j.ijbiomac.2021.06.062