

## Alternative approaches to antibiotic growth promoters for sustainable poultry production and food security

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**ABSTRACT.** The poultry sector makes a substantial contribution to meeting global demand for animal-derived food products. Poultry meat and eggs are rich sources of high-quality protein and essential nutrients, often exceeding other animal-derived foods. In response to current challenges, various strategies have been implemented to replace antibiotic growth promoters (AGPs). Probiotics, prebiotics, synbiotics, organic acids, enzymes, and phytochemicals, including herbs, essential oils, and oleoresins are the dominant feed additives gaining importance in poultry production following the ban on AGPs. These additives are widely used worldwide as sustainable alternatives to traditional growth promoters in poultry production systems due to their distinctive properties and beneficial effects on poultry performance and health. They can be readily blended with other meal components, leave no tissue residues, and support growth and health through multiple direct and indirect mechanisms. More recently, increasing attention has focused on sustainable poultry nutrition through the use of antimicrobial peptides, microalgae, bacteriophages, and insects as antibiotic substitutes for poultry feed aimed at improving product quality. At present, combining antibiotic alternatives may represent the most effective approach. This review provides a comprehensive analysis of natural alternatives to AGPs, their mechanisms of action, and effects on poultry performance and health.

### Introduction

The utilisation of antibiotics in poultry production has been implemented globally since the introduction of penicillin in 1928. Antibiotics are natural products synthesised by fungi that inhibit bacterial growth, and have been applied at both therapeutic and subtherapeutic doses to improve production

efficiency and flock uniformity (Alagawany et al., 2021). However, the misuse of antibiotics, particularly their routine application for growth promotion and disease control in poultry, has come under increasing scrutiny due to the emergence of antibiotic-resistant bacteria, leading to treatment failures and economic losses (Rafiq et al., 2022). Studies have shown that antibiotic-resistant genes can be

transferred from poultry to humans by microorganisms during poultry-derived food consumption (El-Kholy et al., 2025; El-Saadony et al., 2026).

Antibiotic-resistant bacteria can be transmitted through both direct and indirect pathways, including food chains, air, water, and soil. Moreover, several antibiotics have been reported to exert carcinogenic and genotoxic effects on human health (Rafiq et al., 2022). Consequently, substantial annual economic losses are incurred due to increased medical expenses associated with reduced antibiotic efficacy in human medicine. It has been estimated that approximately 90% of antibiotics used in poultry production are released into the environment, potentially contributing to its pollution (Alagawany et al., 2024a). The WHO has recommended restricting the use of antibiotics that are important for human and veterinary medicine. In 2006, the European Union implemented a comprehensive ban on the use of antibiotics in poultry production (Alagawany et al., 2024a). These developments posed significant challenges for the poultry industry and stimulated the search for alternative strategies, leading to increased use of feed additives and dietary supplements (probiotics, prebiotics, enzymes, essential oils, organic acids, antimicrobial peptides, microalgae, insects, bacteriophages and other immune modulators) (Alagawany and Abd El-Hack, 2021). The poultry industry faces significant constraints in maintaining optimal production due to rising feed costs and the need for effective dietary supplements to replace antibiotic growth enhancers. Natural growth promoters act through distinct mechanisms. Probiotics, defined as beneficial bacteria inhabiting the host gastrointestinal tract, improve poultry health and performance by supporting a balanced gut microbiota (Abd El-Hack and Alagawany, 2022). They have been shown to enhance performance, suppress infections, improve intestinal integrity, and sensory attributes of broiler meat. Probiotics are generally resistant to bile and acid, they are strain-specific, and show minimal adverse effects. Their modes of action include immune system stimulation, antagonistic interactions with pathogenic bacteria, and competitive exclusion (Abd El-Aziz et al., 2025). By modulating gut microbiota composition, dietary probiotics improve body weight gain and feed efficiency in poultry. On the other hand, prebiotics are non-digestible oligosaccharides selectively utilised by beneficial gut microorganisms to stimulate their growth, suppress harmful bacteria, improve digestibility, and optimise nutrient absorption (Alagawany et al., 2025). Prebiotics may also influence host health by strengthen-

ing epithelial cells, altering microbial metabolism, and secreting metabolites such as lactic acid (Yang et al., 2025). In this context, they contribute to improved gut ecology, immune function, epithelial barrier, and regulation of host-microbiota interactions (Atuahene et al., 2025). By providing selective substrates for beneficial microorganisms, prebiotics modify colonic microbiota and promote a healthy gastrointestinal environment. In particular, dietary inulin has been demonstrated to exert a positive impact on intestinal microbiota, gut morphology, and chicken productivity (Alagawany et al., 2025).

Phytogenic feed additives (PFAs) are plant-derived substances utilised in chicken production, comprising herbs, spices, botanicals, and essential oils. These natural, low-toxic and residue-free alternatives are considered preferable to synthetic antibiotics in poultry diets. PFAs show a range of biological activities, including antibacterial, antioxidant, immunomodulatory, and anti-inflammatory properties (Alagawany et al., 2024a). They improve feed quality, palatability, and digestibility, regulate intestinal microbiome composition, and promote gut health by reducing bacterial populations and limiting the formation of undesirable fermentation by-products (Wang et al., 2024; Oni and Oke, 2025). The majority of active secondary plant metabolites function as antibiotics or antioxidants (Waghmare et al., 2025).

Organic acids are weak carboxylic acids characterised by the presence of a carboxylic group (R-COOH) and are used in animal feed because of their nutritional value and antibacterial properties (Abd El-Ghany, 2024; Hauser and Muranyi, 2025). They inhibit bacterial proliferation and induce cell death by penetrating the bacterial cell membrane, lowering pH, and disrupting protein synthesis. Incorporating short- and medium-chain fatty acids in diets has been shown to improve disease resistance, performance, and digesting efficiency in poultry (Abd El-Hack et al., 2021; Hauser and Muranyi, 2025). Nevertheless, the effectiveness of organic acids in enhancing performance is unreliable and depends on factors such as buffering capacity, acid source, and inclusion rates (Alagawany et al., 2024a). Typical organic acids used in poultry feeds include acetic, butyric, citric, formic, propionic, malic, tartaric, and lactic acids (Hauser and Muranyi, 2025). Enzymes, primarily protein-based compounds, are essential biological catalysts that dependent on specific amino acids, vitamins, and minerals to carry out biochemical reactions in all living organisms (Alagawany et al., 2018). Enzymes, including pectinases, amylases, cellulase, and lipases, are frequently utilised in animal feed.

Their supplementation in broilers can improve efficiency, economic returns, and environmental sustainability. Enzymes act on specific dietary substrates, leading to the formation of metabolic products (Alagawany et al., 2018). Carbohydrases catalyse the hydrolysis of non-starch polysaccharides, resulting in the formation of short-chain fatty acids. The inclusion of glucose oxidase (GOD) in broiler diets can improve body weight gain, meat quality, and digestive efficiency by supporting gut function and increasing the abundance of beneficial bacteria. This review provides comprehensive overview of natural and biological alternatives to antibiotic growth promoters, their mechanisms of action, and contributions to poultry performance, health, sustainable production, and food security.

## Key strategies for replacing antibiotic growth promoters (AGPs) in poultry production

Antibiotics are substances synthesised by living organisms, typically microbes that are detrimental to other living organisms. Antibiotics are antimicrobial agents, originally derived from microorganisms that inhibit or eliminate other microorganisms. Their use in poultry production has been shown to enhance broiler growth and feed efficiency, reduce flock variability, and improve the digestion and absorption of dietary fats and carbohydrates (Ferket et al., 2002). Most antibiotics are natural compounds produced by fungi or bacteria that suppress bacterial growth. Their modes of action can be classified according to drug-target interactions and their effectiveness in limiting bacterial proliferation (Kohanski et al., 2007). Irrespective of the specific target, the three main classes of bactericidal antibiotics have been shown to induce the formation of harmful hydroxyl radicals in both Gram-positive and Gram-negative bacteria, ultimately leading to cell death. Certain antibiotics inhibit cell wall synthesis and repair, whereas others disrupt ribosomal function and protein synthesis. By reducing bacterial metabolic activity, growth, and reproduction, antibiotics decrease competition between the host and intestinal microbiota, thereby supporting improved animal growth and performance. In addition, antibiotics limit the proliferation and colonisation of both pathogenic and non-pathogenic bacteria in the poultry gut (Chopra and Roberts, 2001), and decrease the production of harmful bacterial by-products, such as ammonia (Frey-Klett et al., 2011). The inclusion of subtherapeutic doses of antibiotics in poultry diets has been associated with reduced in-

testinal weight and length, as well as a thinner intestinal epithelium, which may improve nutritional absorption and lower the metabolic requirements of the digestive system (Gunal et al., 2006). By suppressing pathogenic bacteria, antibiotics limit the proliferation of detrimental microorganisms, reduce gut inflammation, decrease disease incidence, and create favourable conditions for the growth of beneficial taxa, including *Lactobacilli*, *Bifidobacteria*, *Bacteroides*, and *Enterococci* (Chopra and Roberts, 2001). However, the widespread emergence of antibiotic-resistant bacteria in both humans and animals has raised major concerns regarding the routine use of antibiotics in livestock production. The use of antibiotics as growth promoters and prophylactic agents is extensively debated, as it has been linked to reduced therapeutic efficacy when antibiotics are required for medical treatment (Williams and Heymann, 1998; Marshall and Levy, 2011). Evidence indicates that antibiotic resistance genes can be transferred from animal microbiota to humans (Al-Mnaser et al., 2022). Moreover, approximately 90% of antibiotics administered to cattle are excreted into the environment, where they contaminate soil and water (Marshall and Levy, 2011). Antibiotic-resistant bacteria can spread through direct and indirect pathways involving soil, water, air, and food chains. In addition, some antibiotics have been reported to exert genotoxic and carcinogenic effects on human health (Mackie, 2011). In response to these concerns, the WHO has recommended that antibiotics important for human medicine should not be used as growth promoters in animal production unless comprehensive risk assessments demonstrate their safety (WHO, 2014). Consequently, the European Union completely banned the use of all AGPs in animal diets in January 2006. Figure 1 illustrates the main alternative growth promoters used in poultry production (Abd El-Hack et al., 2022).

## Probiotics

Probiotics are live microorganisms that positively influence host health by colonising the gastrointestinal tract and promoting a more balanced intestinal microbiota (Murate et al., 2015). Their supplementation has been shown to enhance growth performance, regulate intestinal microbiota composition, inhibit infections, strengthen intestinal barrier function and immune responses, as well as improve the microbiological and sensory quality of broiler meat (Alagawany et al., 2021). Probiotics typically show resistance to bile and acidic conditions, they are strain-specific and produce low adverse effects,



Figure 1. Alternatives to antibiotic growth promoters in poultry

reduce populations of pathogenic bacteria, and are suitable for inclusion in feed formulations (Stęczyński and Kokoszyński, 2021). The primary mode of action of probiotics involves a reduction in intestinal pH through the production of volatile fatty acids and organic acids (Al-Fatah, 2020). In addition, probiotics efficiently limit pathogenic populations in the stomach by competitive exclusion and protect the host against pathogens by stimulating immune responses, competing for nutrients, and controlling toxin production (Ohimain and Ofongo, 2012; Khan and Naz, 2013). Many pathogenic bacteria, such as *Salmonella* and *Escherichia coli*, show reduced growth under low pH conditions (Swelum et al., 2021). Dietary supplementation with *Bacillus subtilis* has been reported to improve growth performance, thyroid activity, antioxidant status, intestinal histomorphometry, and immune organ development in Japanese quail (Elnesr et al., 2022; 2023). In the same context, Popova (2017) reported that probiotic-fed birds achieved higher body weight gains and improved feed efficiency. These birds also showed increased villus height and reduced crypt depth in the intestine. Elongated villi provide a larger surface area for nutrient absorption, whereas crypts represent sites of enterocyte proliferation. Shallower crypts, on the other hand, indicate a reduced need for epithelial cell turnover, allowing energy to be redirected from tissue renewal towards growth and overall performance (Marković et al., 2009). Lactic acid bacteria (LAB) produce antifungal compounds and are widely used as probiotic microorganisms

(Londero et al., 2014). The efficacy of plant-derived products depends on the type and amount of secondary metabolites or phytochemicals they contain. These compounds act within the gastrointestinal tract of the host on the microbial community, thereby strengthening the resistance to colonisation and invasion by pathogenic bacteria. Supplementation with *Lactobacillus plantarum* improved broiler growth and health, likely through a shift in gut microbiota composition towards bacteria that generate short-chain fatty acids (SCFAs). Consequently, *L. plantarum* may be considered an alternative to antibiotics in poultry production (Yang et al., 2024). In contrast, feeding a probiotic blend consisting of *L. farciminis* and *L. rhamnosus* had no significant effect on growth performance. However, administration of this probiotic mixture increased the concentrations of omega-3 and omega-6 fatty acids in breast muscle and reduced the proportion of saturated fatty acids (Eglite et al., 2023). In another study, oral administration of *Bacillus coagulans* to broiler chicks significantly improved their body weight, jejunal villus height, and crypt depth. It also increased serum protein and albumin levels, reduced low density lipoprotein cholesterol (LDL-C), blood urea nitrogen (BUN), and triglycerides (TG), improved gut flora composition, stimulated innate immunity, and intestinal epithelial growth, indicating maintenance of the intestinal mucosal barrier (Liu et al., 2022). Supplementation with *B. subtilis* improved broiler growth performance, likely due to increased populations of *Blautia*, *Faecalibacterium*, and

**Table 1.** Impact of probiotic supplementation on growth performance of poultry

Probiotic	Bird	Inclusion rate	Growth performance	References
<i>Lactobacillus plantarum</i>	Broiler	5 × 10 <sup>8</sup> CFU/kg	An increase in the number of <i>Ruminococcus</i> and <i>Lachnospiraceae</i> species that produce butyrate fatty acid has been shown to improve serum IgM and IgY levels	(Yang et al., 2024)
<i>Lactobacillus acidophilus</i>	Broiler	0.1 g/kg	Beneficial impacts on growth, feed consumption, feed efficiency, digestibility, and plasma lipid concentrations in broilers	(Saleh et al., 2020)
<i>Lactobacillus rhamnosus</i> + <i>L. farcimini</i>	Broiler	4 g/10 kg	Omega-3 and omega-6 fatty acids modulate the concentrations of saturated fatty acids in breast muscle	(Eglite et al., 2023)
<i>Bifidobacterium bifidum</i> + <i>B. longum</i>	Broiler	1 × 10 <sup>9</sup> and 1 × 10 <sup>7</sup> /ova	Enhanced body weight and feed conversion ratio, villus height, and villus height-to-crypt depth ratio	(El-Moneim et al., 2020)
<i>Bacillus coagulans</i>	Broiler	10 <sup>8</sup> CFU/ml	The body weight, jejunal villus height, and crypt depth of broiler chicks were dramatically elevated	(Liu et al., 2022)
<i>Bacillus subtilis</i>	Broiler	750 g/t	Increase villus height, daily weight gain, and average weight gain  Effective antibiotic substitute in broilers	(Zhang et al., 2021)
<i>Saccharomyces cerevisiae</i>	Broiler	500 mg/kg during the starter and grower phases and 250 mg/kg in the finisher phase	Improving intestinal morphology, intestinal immunity, and barrier function	(Lin et al., 2023)

*Flavonifractor*, alongside reduced abundance of *Hydrogenoanaerobacterium*, *Romboutsia*, and *Odoribacter*. Moreover, *B. subtilis* demonstrated greater efficacy compared to zinc bacitracin in improving the intestinal microbial population of broilers, suggesting its potential as an alternative to antibiotics in poultry production (Zhang et al., 2021). Supplementation with *Saccharomyces cerevisiae* at 500 mg/kg feed during the starter and grower phases, and 250 mg/kg feed in the finisher phase improved broiler growth by strengthening gut structure and regulating intestinal immunity and barrier function, which was potentially associated with increased bacterial diversity and alterations in intestinal microbial composition (Lin et al., 2023). Dietary supplementation with *Clostridium butyricum* may exert a positive effect on broiler growth performance and feed efficiency by strengthening immune response, intestinal barrier function, and positively influencing caecal microbiota. The study by Li et al. (2021) demonstrated that body weight and average daily gain of chickens were significantly higher in the group administered

*Clostridium butyricum* than in control animals. In addition, serum concentrations of immunoglobulin M and immunoglobulin G were significantly higher in birds receiving the probiotic (Li et al., 2021). The effects of probiotic supplementation on poultry growth performance are summarised in Table 1. Numerous studies have indicated that probiotics can improve growth rate, immune system function, gut health and overall poultry health. However, limitations and inconsistencies in the literature hinder definitive conclusions. These discrepancies include variability in experimental conditions such as environment, nutrition, bird age and type, as well as differences in probiotic strains, doses, and administration methods (Jha et al., 2020). Some studies have reported no effects on production performance or immune parameters under certain conditions (Jha et al., 2020; Eglite et al., 2023). Such variability may result from differences in feeding practices, host-related factors, and probiotic strain viability. This heterogeneity complicates comparisons across studies and indicates the need for more standardised methodologies and a deeper understanding of

microbiome–host interactions to reliably assess the effectiveness of bacterial probiotics in poultry diets (Jha et al., 2020).

## Prebiotics

Prebiotics are oligosaccharides that cannot be digested by the host animal but are selectively utilised by specific populations of intestinal microorganisms (Abd El-Hack et al., 2022). Their effects are primarily associated with measurable changes in gut microbial composition, including increased abundance of beneficial bacteria, reduced proliferation of pathogenic taxa, and improved efficiency of nutrient utilisation (Mazanko et al., 2018). These changes influence intestinal function through modified fermentation activity, organic acid production, and local nutrient availability (Yaqoob et al., 2021). In broiler nutrition, commonly used prebiotics include fructans, oligofructose, inulin, fructooligosaccharides, galactan, galactooligosaccharides, xylooligosaccharides (XOS), pectin, dietary fibre fractions, and milk oligosaccharides (Kaur et al., 2021). Elgeddawy et al. (2020) reported that prebiotics influenced florfenicol accumulation in liver and kidney tissues of treated birds, indicating altered intestinal absorption and systemic distribution of the antibiotic. Prebiotics influence gut conditions by modifying microbial fermentation processes, regulating intestinal microbial populations, and affecting host-microbiota interactions (Teng and Kim, 2018). By selectively supporting specific bacterial groups, prebiotics promote microbial communities associated with improved gut function (Kaur et al., 2021). Because prebiotics resist enzymatic digestion, they reach the lower gastrointestinal tract, where microbial fermentation leads to the production of SCFAs, vitamins, antibiotics, and other metabolites.

For example, inulin supplementation increased *Bifidobacteria* abundance and reduced *E. coli* levels in caecal contents, while no effects were observed on ileal bacterial counts or intestinal morphology in broiler chickens (Nabizadeh, 2012). Supplementation with fructooligosaccharides (FOS) led to a greater diversity of microbiota in the ileal mucosa and raised the number of detected bacterial genera, while markedly reducing the counts of potentially harmful taxa such as *Desulfovibrio* and *Helicobacter* (Shang et al., 2018). Feeding broilers 1.5 g/kg of mannoooligosaccharides (MOS) increased body weight and titres of antibody directed against infectious bursal disease (IBD), which was associated with an improved feed conversion ratio (FCR) (Rehman et al., 2020). Isomaltooligosaccharides administered at 5–10 g/kg diet improved body weight gain and FCR in broilers, and these effects were accompanied by higher proportion of *Lactobacillus* and *Bifidobacterium* populations and reduced *Escherichia coli* counts (Mookiah et al., 2014). The effects of prebiotic supplementation on poultry growth performance are presented in Table 2. Although many studies report beneficial effects of prebiotic feed additives on intestinal microbiota composition, gut function, productivity, and immune responses, the literature also contains inconsistent and contradictory findings (Buław, 2016). While some studies demonstrate reduced pathogen load and improved performance and health, others find no significant impacts of commonly applied prebiotics, including FOS and MOS, on performance traits under standard rearing conditions. These discrepancies indicate that responses are highly dependent on prebiotic dose, type, bird age, as well as management and environmental factors (Buław, 2016).

**Table 2.** Effect of prebiotic supplementation on growth performance of poultry

Prebiotics	Bird	Inclusion rate	Growth performance	References
Inulin	Broiler	0.25%	Increased <i>Bifidobacteria</i> counts increased villus height in the ileum	(Nabizadeh, 2012)
Fructooligosaccharides	Broiler	0.5%	Increased diverse microbiota Reduced helicobacter and <i>Desulfovibrio</i> levels	(Shang et al., 2018)
Fructooligosaccharides	Broiler	0.25%	Increase lactobacillus population weight gain increases	(Kim et al., 2011)
Mannooligosaccharides	Broiler	1.5 g/kg	Boost feed conversion ratio (FCR) and weight gain Increase the infectious bursal disease antibody titer	(Rehman et al., 2020)
Isomaltooligosaccharides	Broiler	5–10 g/kg	Enhance weight gain, FCR, and caecal populations of lactobacilli and bifidobacteria while reducing caecal <i>Escherichia coli</i> levels.	(Mookiah et al., 2014)
Refined functional carbohydrates	Broiler	50–100 g/t	Reduce caecal <i>Campylobacter</i> levels	(Froebel et al., 2019)

## Synbiotics

The combination of prebiotics and probiotics is referred to as synbiotics (Huyghebaert et al., 2011). This approach supplies both viable microorganisms and fermentable substrates, thereby supporting probiotic survival and activity in the avian gastrointestinal tract (Gaggia et al., 2010). Common synbiotic formulations include combinations such as lactitol with lactobacilli and FOS with bifidobacteria (Yang et al., 2009). Inclusion of synbiotics in broiler diets has been associated with improvements in intestinal morphology and nutrient absorption, resulting in enhanced growth performance (Awad et al., 2008; Hassanpour et al., 2013; Mookiah et al., 2014). Effective use of synbiotics requires careful selection of compatible probiotic and prebiotic components and evaluation of their combined effects. In a broiler study by Madej et al. (2015), *in ovo* administration of inulin and *Lactobacillus* spp. positively affected the development of immune organs. Similarly, Mohammed et al. (2022) demonstrated improved growth performance, behaviour, and jejunal histomorphology following synbiotic supplementation, with particularly pronounced effects under heat stress conditions. As synbiotics are a mixture of probiotics and prebiotics, their benefits and limitations largely reflect those of their individual components, including potential concerns related to microbial resistance (Rahman et al., 2022). Similar to probiotics and prebiotics, synbiotics have been reported to improve feed digestion and daily weight gain, reduce the incidence of diarrhoea, and support the growth of beneficial bacterial strains like *Lactobacillus* and *Bifidobacterium*, contributing to a more stable intestinal microbial profile (Rahman et al. 2022). According to Śliżewska et al. (2020), synbiotic preparations improved broiler performance by increasing populations of beneficial bacteria, restricting the proliferation of pathogenic microorganisms, increasing concentrations of lactic acid and SCFAs, and reducing branched-chain fatty acid levels. Several studies have further indicated that synbiotics may be more effective than probiotics or prebiotics used alone in improving gut function through changes in gut microbial composition (Saulnier et al., 2008; Saeed et al., 2023; Shehata et al., 2024). Despite these findings, the available literature also contains substantial variability and limitations. Reported effects on growth performance and production parameters are not consistent across studies and often depend on the specific synbiotic formulation, applied dose, and experimental conditions (Tabashsum et al., 2023; Shehata et al., 2024). In addition, the mechanisms

underlying synbiotic action within the complex intestinal ecosystem remain insufficiently characterised. Some synbiotic formulations have produced marked improvements in gut function or performance under certain conditions, whereas minimal or no effects have been observed in other treatments. These inconsistencies highlight ongoing challenges related to maintaining probiotic viability, standardising delivery methods, defining long-term effects, and establishing optimal dosing strategies for reliable application of synbiotics in the poultry industry (Tabashsum et al., 2023; Shehata et al., 2024).

## Antimicrobial peptides

Antimicrobial peptides (AMPs), also known as host defence peptides, are naturally occurring molecules present in all living organisms, and typically consist of approximately 30–60 amino acids (Yadav et al., 2016). They show broad antimicrobial activity and immunomodulatory properties, acting against bacteria, fungi, and viruses, primarily through disruption of microbial cell membranes (Li et al., 2012; Parachin et al., 2012). Many of these AMPs have been identified and evaluated for their positive effects, including their ability to promote poultry growth. Studies investigating peptides, such as cecropin and colicin as potential growth promoting agents have suggested that they may represent feasible alternatives to conventional antibiotics in poultry production (Liu-Fa and Jian-Guo, 2012). Accordingly, AMPs have been extensively researched and are believed to be promising alternatives to antibiotics (Rima et al., 2021). Their antimicrobial activity is primarily based on the interaction of negatively charged components of the bacterial membrane with positively charged peptides, resulting in membrane destabilisation, pore formation, increased permeability, and subsequent cell death (Rahman et al., 2022). In addition to their antimicrobial effects, AMPs have been reported to improve gut health and growth parameters influence intestinal microbial composition, reduce the incidence and severity of diarrhoea, and suppress the expression of pro-inflammatory factors (Kurt et al., 2019). Wang et al. (2016) stated that dietary supplementation with AMPs improved growth rates, intestinal morphology, nutrient digestibility, and intestinal microbiota balance in poultry. Nazeer et al. (2021) showed that AMPs improved growth performance indices, including feed conversion efficiency, daily weight gain, and feed intake, while reducing mortality, effects associated with support of a functionally active and immunocompetent gut

microbiota. Abreu et al. (2023) further demonstrated that AMP supplementation improved intestinal morphology and digestive function, regulated immune responses, and altered the intestinal expression of pro- and anti-inflammatory mediators in broilers. In addition, inclusion of yeast-expressed cecropin A (1-11)-D(12-37)-Asn (CADN), a chimeric insect-derived peptide, increased weight gain, feed intake, feed-to-gain ratio, and villus height, while lowering aerobic bacterial counts in both jejunal and caecal digesta (Wen and He, 2012).

AMPs exert antimicrobial activity through several mechanisms. In most cases, their bactericidal action is attributed to interactions with the surface membranes of target bacteria (Koczulla and Bals, 2003). It is proposed that these interactions disrupt membrane function, leading to increased permeability, leakage of metabolites and ions, and dissipation of membrane potential (Li et al., 2012). Such membrane alterations may result in cell lysis or form transient pores that allow peptides to enter the cell and interact with intracellular targets. In addition to membrane-associated effects, some AMPs inhibit essential cellular processes, including RNA and protein synthesis (Koczulla and Bals, 2003).

There is evidence that AMPs and probiotics can be used in combination to achieve additive or synergistic effects. Certain probiotic strains produce bacteriocins, a particular class of AMPs with antibacterial activity (Fernandez et al., 2013). When such strains successfully colonise the avian gastrointestinal tract, they may suppress pathogenic bacteria through competitive exclusion and direct antibacterial activity mediated by bacteriocin production. Bacteriocins are ribosomally synthesised peptides secreted by various bacterial species that inhibit closely related or competing bacteria and are therefore considered potential alternatives to antibiotics (Ben Lagha et al., 2017). Most research on AMPs and their application in poultry have concentrated on their protective effects against pathogens responsible for infectious diseases, rather than on the direct role in growth promotion (Lima et al., 2024; El-Fakhrany et al., 2025; Gavrilov et al., 2025). Nevertheless, AMPs, including bacteriocins, have been proposed as alternatives to AGP due to their capacity to improve poultry health and intestinal stability (Wang et al., 2016). Their practical application remains limited by factors such as high production costs, potential development of resistance, and peptide instability. Despite these constraints, AMPs continue

to be considered a promising strategy for growth promotion and disease control in poultry systems (Mahgoub et al., 2021; Gavrilov et al., 2025).

## Bacteriophages

Bacteriophages are viruses that infect only bacterial cells and replicate within them, leading to cell lysis. Their natural abundance, non-toxicity, and high specificity have attracted increasing interest in recent years. Numerous studies have examined the application of bacteriophages to control bacterial infections in animals, and some have produced encouraging results. Owing to their high specificity, bacteriophages are increasingly recognised in the poultry sector as a promising substitute for antibiotics (Lin et al., 2017). Since the use of antibiotics is restricted, phage therapy may be particularly advantageous in organic farming systems (Żbikowska et al., 2020). Zheng et al. (2020) reported that bacteriophage-based biocontrol reduced *Campylobacter jejuni* population in chickens without adversely affecting gut microbiota, thereby limiting human exposure to contaminated poultry products and food-borne infections. Research on chickens has shown that bacteriophages can effectively control certain pathogenic bacteria (Hong et al., 2013; Lee et al., 2016). The inclusion of a 0.05% bacteriophage cocktail has been shown to enhance immune system and the development of beneficial gut microbiota (Upadhaya et al., 2021). Additionally, dietary supplementation with bacteriophages in broiler chickens improves growth performance and lowers the abundance of pathogenic bacteria in the digestive tract (Kim et al., 2014). The underlying mechanism seems to be associated with improvements in the gastrointestinal microbial environment in both layers and broilers (Lee et al., 2016). Overall, available evidence indicates that supplementing broiler chicken diets with bacteriophages represents a safe alternative to antibiotics. Moreover, bacteriophages that infect *Salmonella gallinarum* may be a suitable substitute approach to antibiotic therapy in the control of fowl typhoid in chickens (Van Belleghem et al., 2018).

Bacteriophages have been shown to affect adaptive and innate immunity through effects on cytokine production and phagocytic activity. They can also alter the parasitic or lytic phases of bacterial cells, which can affect the development of bacterial communities. By increasing the abundance of *Lactobacillus* and *Bifidobacterium* bacteria, bacteriophages can improve growth

performance by positively affecting intestinal barrier function and gut microbiota composition, while reducing intestinal inflammation (Wang et al., 2018). Bacteriophages primarily act as growth promoters through their antimicrobial activity and highly specific host range, which enables the targeting of selected pathogenic strains without disrupting the overall gut microflora (Callaway et al., 2011; Silveira et al., 2021).

## Phytogenic feed additives

PFAs are plant-derived compounds, including herbs, spices, botanicals, oleoresins, and essential oils used in poultry production (Ashour et al., 2021). When compared to synthetic antibiotics, PFAs are natural, less harmful, residue-free, and considered suitable feed additives for chickens (Makała, 2021). In poultry production, commonly used PFAs are oregano, thyme, garlic, horseradish, chili, cayenne, pepper, peppermint, cinnamon, anise, clove, rosemary derivatives, citrus, and sage (Mountzouris et al., 2011). Diets enriched with plant-derived phy-

isothiocyanate, and piperine. They have also demonstrated the capacity to improve gut health by reducing bacterial colony counts, fermentation byproducts such as ammonia and biogenic amines, the activity of the gut-associated lymphoid tissue, and accelerating prececal nutrient digestion (Puvača et al., 2013). Most of these potent secondary phytochemicals are classified as either antioxidants or antibiotics and belong to flavonoid, glucosinolate, and isoprenoid derivatives (Soliman and Badeaa, 2002). Table 3 presents the effects of phytobiotic supplementation on poultry growth performance. Despite numerous reports of beneficial effects of PFAs on poultry health and performance, the literatures also contain contradictions and limitations that hinder their consistent application in poultry nutrition. These discrepancies mainly arise from wide variation in the composition and concentrations of bioactive compounds in plant-derived products (Oni and Oke, 2025). Such variability may result from differences in plant species, cultivation conditions, storage, and processing methods, leading to significant variation in bioavailability between trials, difficulties in dosage

**Table 3.** Effect of phytobiotic supplementation on growth performance of poultry

Phytobiotic	Bird	Inclusion rate	Growth performance	References
Cinnamon	Broiler	2 g/kg	Improved weight gain	(Toghyani et al., 2011)
<i>Lippia javanica</i> leaf mea	Broiler	5 g/kg	Improved final weight and daily gain	(Mpofu et al., 2016)
Garlic and black pepper powder	Broiler	5 g/kg and 1 g/kg	Improved weight gain	(Kirubakaran et al., 2016)
Pennyroyal	Broiler	2%	Increase in average daily gain	(Goodarzi and Nanekarani, 2014)
Milk kefir	Broiler	2%	Enhancement of body mass and poultry consumption index	(Toghyani et al., 2015)

tonutrients have been shown to improve disease resistance and protective immunity in chickens, offering a cost-effective management strategy based exclusively on natural substances (Elnesr et al., 2023; Alagawany et al., 2024b). Numerous studies have confirmed that PFAs demonstrate antibacterial, antioxidant, immunomodulatory, and anti-inflammatory activities, which are closely associated with their growth and health-promoting effects (Alçiçek et al., 2004). PFAs share advantageous biological properties with plant secondary metabolites, including antioxidant activity and the ability to inhibit microbial growth in chickens, thereby improving feed quality and performance. They also regulate gut microbiome composition and increase palatability, digestibility, and nutritional absorption (Zeng et al., 2015). Phytogenic substances with beneficial properties originating from bioactive molecules comprise carvacrol, thymol, cineole, linalool, anethole, eugenol, capsaicin, allyl

standardisation, and an incomplete understanding of optimal management strategies and mechanisms of action, which collectively restrict the reliable use of PFAs in poultry feeds (Oni and Oke, 2025).

## Essential oils

Essential oils are concentrated liquids obtained from plants that retain their characteristic aromas and flavours. They are extracted from various plant parts, including twigs, flowers, leaves, bark, seeds, and roots. They are concentrated hydrophobic liquids containing volatile plant-derived compounds (Sadgrove et al., 2022). Essential oils are also referred to as volatile oils, ethereal oils, aetheroleum, or simply plant oils, like ginger oil. The term essential relates to the essence or distinctive fragrance of the source plant rather than to any nutritional necessity for living organisms (Sharmeen et al., 2021). Essential oils are produced using various extraction

techniques, including solvent extraction, steam distillation, cold pressing, and mechanical pressing. Owing to their high concentration and potency, they are typically diluted prior to use, particularly for topical applications (Ayub et al., 2023). Common examples include chamomile, lavender, tea tree, peppermint, eucalyptus, and lemon oils. They are extensively utilised in alternative medicine and have also been applied as antibiotic replacers, growth promoters, insect repellent, and in aromatherapy. They can be classified according to botanical origin, chemical composition, olfactory profile, therapeutic qualities, plant part of origin, chemical composition, fragrance family, or extraction method (Sadgrove et al., 2022). Essential oils can be used for therapeutic purposes in poultry production due to their antibacterial, antifungal, antiparasitic, anticarcinogenic, antioxidant, and antiviral properties (Zulhendri et al., 2021). They have long been applied as antimicrobial agents and may represent a viable approach for the management and prevention of nutritional and health-related disorders (Bilal et al., 2021; El-Tarabily et al., 2021). Broiler chicks receiving diets enriched with 100 mg/kg of cinnamon oil

showed increased body weight gain and improved FCR as well as higher lymphoid organs weight, gizzard percentage and IgM titres (Saied et al., 2022). Cinnamon essential oil can inhibit the release of pro-inflammatory mediators, including cytokines and prostaglandins, mainly through inhibition of cyclooxygenase (COX) and lipoxygenase (LOX) involved in their synthesis. Research has also demonstrated that combined supplementation with clove and cinnamon essential oil significantly improved FCR and positively affected breast muscle weight (Saied et al., 2022; Elbaz et al., 2022). However, achieving these effects requires an appropriate dose, identified in the latter study at 100 ppm. Supplementation with clove essential oil at 100 mg and 200 mg/kg significantly improved body weight gain and FCR without affecting feed intake, producing better results than the other treatments (Elbaz et al., 2022). Supplementation of fennel essential oil in wheat-based diets reduced gastric *E. coli* counts but adversely affected growth performance in chickens (Ghiasvand et al., 2021). Table 4 presents the effects of essential oils supplementation on poultry growth performance.

**Table 4.** Impact of essential oil supplementation on growth performance of poultry

Essential oil	Dose rate	Effect increase	Effect decrease	Reference
Cinnamon oil	500 mg/kg	BWG Lymphoid organs weight IgM level Gizzard percentage	Feed intake Triglyceride LDL VLDL	(Saied et al., 2022)
Clove oil	200 mg/kg	Weight gain Immune response against ND	Glucose FCR value <i>Escherichia coli</i> counts in the gut	(Gole et al., 2020)
Eucalyptus oil	1000 mg/kg	BWG Cecal lactic acid bacteria count	Cecal <i>E. coli</i> count FCR value	(Mohebodini et al., 2021)
Tea tree oil	300 mg/kg	Body weights daily weight gain higher dressing percentage	Mortality rate	(Abo Ghanima et al., 2021)
Savory oil	150 mg/kg	BWG <i>Lactobacillus</i> Villi height increase	FCR value Coliform count	(Mousapour et al., 2020)
Cumin oil	200 mg/kg	Weight gain	FCR value Triglyceride LDL	(Amiri et al., 2020)
Olive oil	2% of diet	Body weight	FCR value reduced Triglycerides Heat stress impact LDL Cholesterol	(Bilal et al., 2021)
Coriander oil	50 µl/l	Improved final body weight Body weight Villus height Crypt depth	FCR	(Sholiha et al., 2023)
Rosemary oil	150–300 mg/kg	BWG Villus height	FCR Ileum coli form	(Mousapour et al., 2022)

BWG – body weight gain, LDL – low density lipoprotein, VLDL – very low density lipoprotein, ND – Newcastle disease, FCR – feed conversion ratio

## Organic acids

Organic acids are carboxylic acids characterised by the general R-COOH structure (Dai et al., 2021). They are weak acids used in animal feed showing nutritional benefits and antibacterial activity thanks to the presence of the carboxyl group (Chahardoli et al., 2020). Their efficacy depends on chemical composition, molecular weight, and the structural characteristics of the target bacteria or fungi (Khan et al., 2022). Organic acids penetrate bacterial cell membranes and inhibit growth by lowering the pH of the surrounding environment (Kumar et al., 2022). In Gram-negative bacteria, penetration of the cell wall results in the release of H<sup>+</sup> ions, leading to intracellular acidification and disruption of replication and protein synthesis (Dai et al., 2021). In broiler chickens, dietary supplementation with short- and medium-chain fatty acids has been found to improve disease resistance, growth performance and digestive enzyme activity, as well as suppress the proliferation of pathogenic bacteria (Kumar et al., 2022). Organic acids also modify the histological structure of the gastrointestinal tract by increasing villus height, improving the absorptive capacity of the intestinal mucosa, nutrient uptake and utilisation, and ultimately promoting growth performance (Abd El-Hack et al., 2022). Although the use of organic acids to improve performance has shown positive effects, their efficacy has not been as consistent as that of other antibiotic alternatives. Limitations may arise from inclusion level, the source of organic acids, and interactions with other dietary nutrients (Kim et al., 2015). Most frequently utilised organic acids in broiler diets include acetic, butyric, citric, formic, propionic, malic, tartaric, and lactic acids (Melaku et al., 2021). In livestock production systems, butyric acid can be used in place of antibiotics as its dietary addition has been associated with positive effects on poultry health, performance, and egg quality (El-Saadony et al., 2022). Incorporating organic acids into broiler diets has been shown to improve protein and carbohydrate digestibility (Adil et al., 2010). Diets of low protein quality increase the proportion of indigestible proteins in the gastrointestinal tract, resulting in intensified protein fermentation (Diether and Willing, 2019). This process can cause physiological discomfort and impair growth performance due to increased production of volatile fatty acids, ammonia, and other gases. Organic acids may act as effective supplementary alternatives in some feed types by acidifying the gastrointestinal environment, enhancing nutrient utilisation, and stimulating protease activity (Qaisrani et al., 2015).

They also increase the digestibility of nitrogen, phosphorus, and other minerals, while lowering gastrointestinal pH, which improves pepsin activity (Selaleddi et al., 2020). Acid anions further improve nutrient digestibility by reacting with calcium, phosphorus, magnesium, and zinc. Peptides released during pepsin-mediated proteolysis stimulate the secretion of cholecystokinin and gastrin, hormones that regulate protein digestion and absorption (Araujo et al., 2019).

Organic acids are effective in maintaining gastrointestinal health in chickens, and improving their production performance. Sanguinarine, a plant-derived benzophenanthridine alkaloid obtained mainly from *Macleaya* spp., inhibits the growth of certain acid-intolerant pathogenic bacteria, such as *E. coli*, *Salmonella* spp., and *Clostridium perfringens*, which are associated with gastrointestinal disorders (Gharib Naseri et al., 2012). *Aspergillus niger* and *Penicillium* sp. moulds are considered efficient producers of citric acid (Islam, 2012). Dietary supplementation with citric acid has been reported to reduce pathogen colonisation, limit the formation of harmful metabolites, improve protein availability, and function as a substrate in intermediate metabolism (Islam, 2012). Inclusion at a level of 0.5% was shown to improve broiler performance and non-specific immunity, and strengthened the protective effect of vaccination against New Castle disease. Available data indicate that broiler diets should contain up to 0.5% citric acid in mash and up to 0.75% in pelleted feed (Islam, 2012). In another study, dietary supplementation with citric acid at 2% improved epithelial health status, increased villus height in the gastrointestinal tract, and consequently positively affected nutrient absorption (Mohammadagheri et al., 2016). The length and diameter of the villi were significantly increased when butyric acid (BA) was applied at 4 g/kg of feed. The administration of BA led to a marked increase in blood total protein, albumin, creatinine, aspartate aminotransaminase (AST) activity, phosphorus, and calcium levels, while serum cholesterol and uric acid concentrations were reduced (Raza et al., 2019). Encapsulated lactic acid significantly improved broiler performance ( $P < 0.01$ ), reduced intestinal pH ( $P < 0.05$ ), increased villus length, and decreased the abundance of *Salmonella* spp. Dietary lactic acid levels also significantly influenced ( $P < 0.01$ ) the number and length of villi, lactic acid bacteria populations, and the presence of *E. coli*. Moreover, inclusion of 0.6% encapsulated lactic acid in broiler diets was reported to

**Table 5.** Effect of organic acid supplementation on growth performance of poultry

Prebiotics	Bird	Inclusion rate	Growth performance	References
Citric acid	Broiler	0.5% in the diet	Enhanced broiler performance and non-specific immunity Vaccinated broilers had improved specific immunity against New Castle disease	(Islam, 2012)
Citric acid	Broiler	2%	Enhance epithelial cell proliferation and increase villi height in the gastrointestinal tract	(Mohammadagheri et al., 2016)
Butyric acid	Broiler	0.2%	Enhance breast meat yield, feed conversion ratio, dressing percentage, and diminish abdomen fat	(Panda et al., 2009)
Butyric acid	Broiler	4 g/kg	Enhanced villus length and width; elevated serum protein, albumin, creatinine, aspartate aminotransferase, phosphorus, and calcium; diminished serum uric acid and cholesterol	(Raza et al., 2019)
Lactic acid	Broiler	0.6%	Reduced intestinal pH, number of <i>Salmonella</i> spp. increased intestinal villi length	(Natsir et al., 2010)
Lactic acid	Broiler	6 cm <sup>3</sup> /kg	Positive impacts on blood metrics, oxidative state, and gut microbial counts	(Negm et al., 2023)

enhance performance (Natsir et al., 2010). Lactic acid may also improve blood parameters, oxidative status, and gut microbial composition, with an inclusion level of 6 cm<sup>3</sup> LAC/kg diet reported to achieve the most favourable effects (Negm et al., 2023). Table 5 presents the effects of organic acids supplementation on growth performance of poultry. Although organic acids and acidifiers are widely used in poultry industry to improve nutrient digestibility, absorption, and gut health, as well as suppress the development of pathogenic bacteria, the literature also highlights some constraints related with their application (Pearlin et al., 2020). High concentrations of acidifiers may reduce feed palatability, and consequently lower its intake, particularly when optimal doses are exceeded. Moreover, long-term exposure to organic acids may promote the development of acid-resistant bacteria, and thus reduce antimicrobial efficacy (Menconi et al., 2014; Pearlin et al., 2020). In addition, the presence of other antimicrobial feed additives can diminish the positive effects exerted by organic acids (Menconi et al., 2014).

## Enzyme

Enzymes function as biological catalysts in biochemical processes, and are composed of amino acids forming protein molecules, often requiring vitamins and minerals as cofactors (Alagawany et al., 2018). They are obtained from microbial, plant, and mammalian sources (Velázquez-De Lucio et al., 2021). Exogenous enzymes commonly used in animal feed include pectinases, amylases, cellulases, galactosidases,  $\beta$ -glucanases and xylanases, as well as phytases, proteases, and lipases (Alagawany et al., 2018). Enzyme supple-

mentation in broiler diets provides environmental, economic, and nutritional benefits. The inclusion of enzymes by Mabelebele et al. (2017) improved feed utilisation efficiency, reduced digesta viscosity, increased nutrient digestion and absorption, as well as feed intake and body weight in broilers. Depending on the feed ingredients used, each enzyme has a specific and interdependent mode of action; therefore, appropriate selection and application by the feed formulator are required to achieve the maximum beneficial effect (Velázquez-De Lucio et al., 2021). Enzymes interact with dietary components by acting on specific substrates, initiating biochemical reactions and regulating their rate to convert substrates into utilisable products (Alagawany et al., 2018). Hydrolysis of non-starch polysaccharides (NSPs) by carbohydrases leads to the production of SCFAs, which are subsequently fermented by beneficial bacteria like *Bifidobacter* and *Lactobacilli* spp. Increased SCFA concentrations are commonly associated with a reduction in the counts of pathogenic bacteria and an increase in beneficial microbial populations (Ravangard et al., 2017). It has been documented that supplementation with GOD increases daily body weight gain, improves meat quality, and nutrient digestibility, as evidenced by higher apparent nutrient digestibility and digestive enzyme activity in broilers (Wu et al., 2019). GOD supplementation also significantly increases transepithelial electrical resistance and immunoglobulin A secretion, indicating improved gut barrier function. In general, dietary GOD supplements enhance broiler growth performance through two main mechanisms: improvement of nutrient digestion and utilisation, and modulation of gut microbiota by increasing beneficial bacterial populations,

**Table 6.** Effect of enzyme supplementation on growth performance of poultry

Enzyme	Bird	Inclusion rate	Growth performance	References
Proteases	Broiler	30 000 IU/kg	Enhance FI and FCR, augment nitrogen retention, and diminish abdomen fat	(Jabbar et al., 2021)
$\alpha$ -galactosidases	Broiler	50 mg/kg diet	Enhances intestinal histology and morphology	(Amer et al., 2020)
$\alpha$ -amylase	Broiler	300–2 250 IU/kg	Enhance the observable ileal digestibility of energy	(Rao et al., 2021)
Xylanase	Broiler	3 200–4 000 IU/kg	Enhance starch and nitrogen digestibility while improving apparent ileal digestible energy.	(Amerah et al., 2017)
Beta-glucans	Broiler	20 IU/kg	Decreases viscosity, enhances dry matter of digesta, and increases accessible energy	(Saeed et al., 2019)

FI – feed intake, FCR – feed conversion ratio

including *Firmicutes*, *Ruminococcaceae*, and *F. prausnitzii* (Wu et al., 2019). Table 6 presents the effects of enzymes supplementation on poultry growth performance.

### Insects as a sustainable solution for poultry feed

Insect meal has been proposed as an antibiotic substitute due to the presence of components with microbiota-modulating properties, including the ability to increase microbial diversity and reduce the abundance of harmful microorganisms. As insect meal is already a widespread food source in some cultures and is a component of domestic fowl diet, it has been considered a suitable feed ingredient for poultry nutrition (Bovera et al., 2015). Access to outdoor environments allows chickens to capture and consume insects throughout their life cycle, which are a natural component of their diet (Bovera et al., 2015). Insect exoskeletons and their derivatives may act as substitutes for antibiotics, while insects themselves can also be a source of prebiotic and antifungal compounds. These effects are mainly attributed to chitin and medium-chain fatty acids (MCFAs), including lauric and myristic acid, which support gastrointestinal and immune health. Consequently, insect meal is regarded as a potential alternative to antibiotics in commercial broiler diets (Rimoldi et al., 2019; Dörper et al., 2020). Among the various insect species, black soldier fly (*Hermetia illucens* L., HI) larvae meal (BSFLM) is already used in industrialised countries as a feed for exotic animals, such as fish, birds and pets. When compared to broilers fed conventional diets without antibiotic growth promoters, inclusion of relatively low BSFLM levels (10–20%) has been shown to improve growth performance (Dabbou et al., 2018; de Souza Vilela et al., 2021). Fruci et al. (2023) suggested that the dietary inclusion of BSFLM (12.5 or 25%) during the starter period improved broiler growth,

thereby reducing the need for medically important antibiotics. Similarly, Zamri et al. (2023) showed that broilers fed a diet containing 4% defatted BSFL showed higher performance compared with those fed a control diet.

Schiavone et al. (2017) reported that broilers with more effective nutrient digestion can benefit greatly from defatted BSFLM as a source of digestible amino acids and apparent metabolisable energy. Heita et al. (2023) demonstrated that the inclusion of BSFLM in chicken diets had a positive effect on body weight and body weight gain. In addition, glutathione peroxidase and total superoxide dismutase activities increased linearly with rising dietary levels of full-fat BSFLM, while plasma malondialdehyde concentrations decreased linearly, indicating improved antioxidant status (Chu et al., 2020). Bovera et al. (2018) further confirmed that adding insect meal to the diet reduced serum cholesterol and triglyceride levels, an effect attributed to chitin, which limits intestinal nutrition absorption. According to Dabbou et al. (2021), BSF is gaining increasing attention as a functional feed ingredient due to its high content of monoglycerides and MCFAs, which show antibacterial properties and promote gastrointestinal health by inhibiting the development of potentially harmful bacteria. In addition, BSF larvae possess functional properties that contribute to improved immunological and gastrointestinal health. Lalev et al. (2022) reported that adding insect-derived ingredients to the broiler diet increased serum lysozyme concentrations and improved resistance to infectious diseases. Earlier research has indicated that supplementation with BSFLM may improve immunological functions in broilers likely due to the presence of bioactive compounds such as lauric acid and chitin or its derivatives (Seyedalmoosavi, 2023). In addition to its nutritional value, BSFLM is also marketed for its functional properties (de Souza Vilela et al., 2021), as it is a known source of both immunomodulatory and antimicrobial compounds (Kemboi et al., 2022; Lagat et al., 2021), including a range

of antimicrobial peptides (Zhang and Yang, 2022). Consequently, BSFLM represents a sustainable alternative protein source for animal and poultry feed due to its high nutritive value, favourable feed efficiency, and low environmental footprint. However, further research is required to fully characterise its functional properties, particularly under antibiotic-free feeding regimes.

### Microalgae: A promising strategy for sustainable feed production

The routine use of antibiotics in poultry nutrition should be replaced with safe and environmentally friendly supplements (Hafez and Attia, 2020). In this context, the inclusion of algae-based products in poultry diets represents a promising strategy to enhance growth performance and immune status, thereby providing adequate protection to birds. In recent years, algae have gained increasing attention worldwide as alternatives to antibiotics (Abdel-Wahab et al., 2023; Alagawany et al., 2024c). Microalgae in particular have attracted considerable research interest as potential poultry feed supplements because of their high content of carbohydrates, proteins, lipids, vitamins, minerals, and other bioactive compounds (Alagawany et al., 2024c). They are also rich sources of polyphenolic compounds that mainly consist of simple phenols, flavanones, flavonoids, flavonols, isoflavones, flavan-3-ols, flavones, dihydroflavonols, proanthocyanidins and dihydrochalcones (Alagawany et al., 2024c). Moreover, Mahata et al. (2022) have observed that marine microalgae produce a wide range of bioactive substances with applications extending from dietary supplements to bioactive molecules used in medicinal treatment. Algae have received increasing attention because of their high content of bioactive compounds, including sterols (antimicrobials),  $\beta$ -carotene and other pigments (antioxidants), sulphated polysaccharides (antiviral), and polyunsaturated fatty acids (Mishra et al., 2023). Antioxidant components present in algae can contribute to the regulation of animal metabolism (Michalak et al., 2022; Hajati et al., 2024). Saadaoui et al. (2021) summarised the following main advantages of microalgae as feed supplements: (i) enhancement of immune responses, (ii) cholesterol-lowering effects, (iii) improved growth performance, and egg and meat quality, (iv) improved gut function, (v) increased disease resistance through antiviral and antibacterial activity, (vi) enhanced probiotic colonisation and feed conversion. In addition, microalgae play a valuable role as feed ingredients due to their nutri-

tional value, diverse pigment profiles, and high concentration of bioactive compounds with antiviral, cytostatic, antibacterial, antifungal and anthelmintic activities, particularly in red, brown and green algae (Mukherjee and Pal, 2021).

Microalgal antioxidants are primarily composed of polyunsaturated fatty acids, flavonoids, carotenoids, minerals, vitamins, sterols, sulphated polysaccharides, phycobiliproteins, amino acids, as well as other compounds like coenzyme Q, peptides and sulpholipids (Ferdous and Yusof, 2021). Mahata et al. (2022) showed that algal bioactive compounds are more effective than chemically synthesised substances in stimulating immune system and antiviral activity. Fernandes et al. (2020) reported increases in villus height and the villus-to-crypt ratio in the duodenum and ileum, as well as improved hepatic carotenoid metabolism, in laying hens fed diets supplemented with marine microalgae. The antioxidant properties of microalgal components may reduce blood lipid levels in birds by inhibiting pancreatic lipase activity (Deng and Chow, 2010). Supplementation with green microalgae has also been shown to improve biochemical parameters, energy metabolism, and protect renal function (Al-Suwaiegh, 2023). Therefore, microalgae-based feed additives represent a promising and sustainable feed resource due to their rapid growth rate, high nutritive value and low water requirements; however, further research is still required to fully confirm these benefits.

### Relationships between AGPs and food security

AGP alternatives play a crucial role in promoting sustainable livestock production and improving food security by increasing feed efficiency and utilisation, growth rate, productive performance, immune indices, and disease resistance, thereby reducing production losses, mortality rate and reliance on antibiotics in animal and poultry sectors (Alagawany et al., 2025; Sampath and Kim, 2025). Such alternatives, including probiotics, prebiotics, enzymes, microalgae, antimicrobial peptides, bacteriophages, insects, organic acids, phytonutrients, and essential oils support nutrient utilisation and gut health, which in turn lowers feed costs and minimises environmental impact through reduced nutrient excretion and pollution, and overall environmental footprint (Saeed et al., 2018; Riaz et al., 2024; Ntsongota et al., 2025). Furthermore, by limiting the need for antimicrobial drugs, the use of natural and biological feed additives helps mitigate antimicrobial

resistance and supports the production of safer animal-derived foods for human consumption. Consequently, their integration into livestock nutrition strategies contributes to stable productivity, environmental sustainability, economic viability, and the long-term availability of safe and affordable animal protein, all of which are important pillars of food security (Saeed et al., 2018; Ntsongota et al., 2025).

## Conclusions

The transition from antibiotic growth promoters (AGPs) in poultry production requires the exploration of alternative methods to maintain animal health and productivity. Probiotics, prebiotics, phytogetic feed additives (PFAs), essential oils, organic acids, antimicrobial peptides, microalgae, insects, and bacteriophages have emerged as effective alternatives, each providing distinct advantages for gut health and general animal performance. Probiotics support microbial balance and immunological function, whereas prebiotics promote beneficial gut flora and facilitate nutrition assimilation. Phytogetic additives, rich in bioactive compounds, demonstrate antibacterial properties that control pathogenic bacteria without leaving residues. Essential oils reduce pathogen load and improve growth performance, whereas organic acids rise intestinal acidity and nutrient uptake, thereby improving digestion. The inclusion of antimicrobial peptides, microalgae, insects, and bacteriophages in poultry feed has also shown promising outcomes for sustainable poultry production. These natural alternatives not only promote poultry health but also address consumer concerns regarding antibiotic resistance, making them vital for the advancement of sustainable poultry farming. Optimising performance and maintaining productivity will depend on the strategic combination of these alternatives. Continued research is essential to elucidate their mechanisms of action and refine their practical application in commercial poultry operations.

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## Conflict of interest

There Authors declare that there is no conflict of interest.

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