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Emerging functional feed additives for improving gut health, performance, and sustainability in broiler chickens: A review

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Abstract

The global poultry industry is undergoing a major transition toward antibiotic-free production systems due to increasing concerns regarding antimicrobial resistance, consumer demand for sustainable poultry products, and stricter regulatory frameworks. Consequently, functional feed additives have emerged as promising nutritional strategies for improving gut health, growth performance, nutrient utilization, and disease resilience in broiler chickens. This review critically synthesizes recent advances in emerging feed additives including β -glucans, β -mannanase enzymes, encapsulated multi-enzyme systems, probiotics combined with phytochemical compounds, precision biotics, and stimbiotics. Additionally, recent evidence regarding feeding behavior and feed intake dynamics is discussed as an important complementary aspect influencing feed efficiency and sustainability. β -glucans have demonstrated immunomodulatory and gut-protective effects, particularly under environmental stress conditions such as heat stress. β -mannanase supplementation improves nutrient digestibility and reduces intestinal viscosity by degrading non-starch polysaccharide. Nutrient availability and feed conversion efficiency is further enhanced by encapsulated enzyme technologies through improved enzyme stability and targeted gastrointestinal release. Probiotic herbal combinations have synergistic benefits on innate immunity, antioxidant status and growth performance. Precision biotics and stimbiotics are next generation microbiome-directed technologies that selectively modulate microbial metabolic pathways, especially short-chain fatty acid production, and have shown to improve intestinal resilience during enteric challenges such as necrotic enteritis. These additives together lead to increased productivity, reduced feed costs, reduced incidence of disease, and increased sustainability in poultry production systems. However, large research gaps remain to be filled, such as a lack of consistency across studies, poor validation in the field in the long term, and lack of full understanding of host-microbiome interactions. Further research should focus on integrative omics approaches, precision nutrition strategies, additive synergism and commercial scale validation to optimise the efficacy of functional feed additives in modern poultry production.

Keywords: precision biotics, stimbiotics, β -Glucans, encapsulated enzymes

1. Introduction

Broiler production is one of the fastest-growing areas in global livestock agriculture. It plays a crucial role in ensuring food security by providing affordable animal protein (Jie *et al.*, 2024) [4]. The rising global demand for poultry meat, combined with increasing feed costs and the need to reduce antibiotic use, has sped up the search for sustainable nutritional solutions. These solutions aim to maintain productivity and intestinal health in intensive production systems. In the past, antibiotic growth promoters (AGPs) were widely used to improve feed efficiency and control harmful bacteria in poultry. However, concerns about antimicrobial resistance have led to strict limits or outright bans on AGP use in many parts of the world (Hristakieva *et al.*, 2025; Bortoluzzi *et al.*, 2025) [3, 2]. This shift has resulted in more cases of intestinal issues such as necrotic enteritis, dysbiosis, and subclinical inflammation, all of which harm broiler performance and welfare. The gastrointestinal tract (GIT) serves not only as a digestive organ but also as an important part of the immune and metabolic systems. Gut integrity, microbial balance, nutrient

absorption, and immune strength are all closely linked factors that affect poultry productivity. New functional feed additives are increasingly being created to focus on these processes. They work by modifying gut microbiota, improving nutrient absorption, reducing oxidative stress, and strengthening the intestinal barrier. Recent advances in poultry nutrition have introduced several categories of innovative feed additives, including prebiotics, precision biotics, stimbiotics, phytochemicals, exogenous enzymes, encapsulated enzyme systems, and immunomodulatory polysaccharides such as β -glucans. These additives are designed not only to improve growth performance but also to support sustainable poultry production by reducing feed wastage, minimizing environmental nutrient excretion, and enhancing disease resilience. This review critically evaluates recent literature on emerging functional feed additives in broiler nutrition, focusing on their mechanisms of action, impacts on gut health and performance, and implications for sustainability in antibiotic-free poultry systems.

β -Glucans as Immunomodulatory and Gut-Protective Additives

β -glucans are soluble non-starch polysaccharides derived from yeast, fungi, cereals, and bacteria that have attracted considerable attention due to their immunomodulatory and prebiotic properties (Abuajamieh *et al.*, 2025) ^[1]. Their role in enhancing intestinal integrity and stress tolerance is particularly relevant in modern poultry systems exposed to environmental and physiological stressors. Heat stress is recognized as a major challenge in broiler production, causing impaired feed intake, compromised intestinal integrity, oxidative stress, and reduced growth performance. Abuajamieh *et al.* (2025) ^[1] demonstrated that dietary β -glucan supplementation significantly improved feed intake, average daily gain, and intestinal morphology in broilers subjected to acute cyclic heat stress. Supplementation with 3 g/kg β -glucan reduced rectal temperature and enhanced villus height, villus width, and intestinal surface area under heat stress conditions. The beneficial effects of β -glucans are largely mediated through modulation of intestinal immunity and microbiota. β -glucans enhance the proliferation of beneficial microbial populations while suppressing pathogenic bacteria such as *Escherichia coli*. Additionally, they stimulate the secretion of glucagon-like peptide-2 (GLP-2), which supports epithelial regeneration and reduces gut permeability (Abuajamieh *et al.*, 2025) ^[1]. Another important mechanism involves the reduction of circulating lipopolysaccharides and inflammatory mediators during stress conditions. By preserving intestinal barrier integrity and limiting endotoxin translocation, β -glucans may reduce systemic inflammation and improve metabolic efficiency. Despite promising outcomes, variability exists regarding optimal inclusion levels and source-specific efficacy of β -glucans. Differences in molecular structure, solubility, and extraction methods may contribute to inconsistent responses among studies. Further research is needed to establish standardized dosage recommendations and evaluate long-term effects under commercial production conditions.

β -Mannanase and Non-Starch Polysaccharide Degradation

Non-starch polysaccharides (NSPs) present in corn–soybean meal diets can impair nutrient utilization by increasing digesta viscosity and encapsulating nutrients within plant cell walls. β -mannans, in particular, act as anti-nutritional factors and can stimulate unnecessary immune responses that divert energy away from growth (Nusairat *et al.*, 2024) ^[6]. β -mannanase enzymes hydrolyze β -mannans into smaller oligosaccharides, thereby reducing intestinal viscosity and improving nutrient accessibility. Nusairat *et al.* (2024) ^[6] demonstrated that supplementation of β -mannanase at 60–90 U/g significantly improved body weight gain, feed conversion ratio, and metabolizable energy in broilers fed energy-reduced diets. Importantly, β -mannanase supplementation also reduced intestinal lesion scores and digesta viscosity, indicating improved gut health and nutrient absorption. These findings suggest that NSP degradation not only enhances digestive efficiency but also alleviates inflammatory stress associated with immune stimulation by β -mannans. The economic significance of β -mannanase supplementation is substantial because it enables

formulation of lower-energy diets without compromising performance. This contributes directly to sustainability by reducing dependence on costly energy-rich feed ingredients. However, enzyme efficacy may depend on dietary composition, feed processing conditions, and bird age. Furthermore, synergistic interactions with other carbohydrases and microbiome-targeted additives require additional investigation.

Encapsulated Multi-Enzyme Technologies

In traditional dietary supplement of enzymes for poultry, two factors, i.e., enzyme stability to feed processing conditions and *in vivo* activity in gastrointestinal tract (GIT) have remained as limiting factors. Now, encapsulating techniques of enzymes have appeared as the new technologies for protecting enzymes and targeted release into intestine. Rafeeq and Zia (2026) ^[7] evaluated the effects of using Encapsulated mixture of protease, lipase, cellulase and amylase in diets of broiler. They concluded that dietary inclusion of ECSEM in broiler diets, had enhanced body weight gain, decreased feed to gain ratio, increased carcass traits and improved nutritional value of ingredients. The supplemented diets have increased the digestibility of CP, CF and EE as well as decreased that of CA in comparison with ECSE. Encapsulation offered multiple advantages over conventional supplementation of enzyme. Enzymes entrapped into protected forms were more stable to heat denaturation in pellet processing. And they could survive to activity in the guts. Also, controlled release of enzyme and substrates and efficient utilization of nutrients were improved due to the encapsulation. A mixture of multiple enzymes could satisfy the need of coordinated degradation of complicated substances into simple ones. Each enzyme could perform the degradation of protein (proteases), fiber (cellulases), fats (lipases) and carbohydrates (amylases). The overall benefit in terms of economic and environmental sustainability could include reducing cost, increasing retention of nutrients, and reducing excretion of N and P into the environment. However, it still needs economic analysis and large commercial studies to validate encapsulation technologies in the poultry industry.

Probiotics and Phytogetic Additives: Synergistic Effects on Immunity and Performance

Probiotics and phytogetic feed additives are widely recognized as natural alternatives to antibiotics due to their antimicrobial, antioxidant, and immunomodulatory properties. Increasing evidence suggests that combining probiotics with medicinal herbs may produce synergistic effects on broiler health and productivity. Hristakieva *et al.* (2025) ^[3] demonstrated that supplementation with probiotics combined with milk thistle, nettle, and dandelion significantly improved growth performance, blood biochemical parameters, and innate immune responses in broilers. Birds receiving combined supplementation exhibited increased complement activation, lysozyme activity, and beta-lysine levels, indicating enhanced innate immunity. The probiotic strains used in the study, primarily *Lactobacillus* spp. and *Kluyveromyces lactis*, likely contributed to microbiota stabilization and pathogen inhibition. Meanwhile, phytogetic compounds provided antioxidant and anti-inflammatory effects through bioactive

metabolites such as flavonoids, polyphenols, and silymarin. Phytogenic additives may also stimulate digestive enzyme secretion and improve feed palatability, thereby indirectly enhancing feed intake and nutrient utilization. The observed improvements in blood lipid and protein profiles further indicate beneficial metabolic effects. Although combined probiotic-herbal supplementation appears promising, substantial variability exists among studies due to differences in plant composition, extraction methods, microbial strains, and inclusion rates. Standardization of phytogenic formulations remains a major challenge for commercial application.

Precision Biotics and Microbiome Metabolic Engineering

Recent advances in microbiome science have shifted nutritional strategies from simple microbial modulation toward targeted manipulation of microbial metabolic pathways. Precision biotics represent a new generation of feed additives specifically designed to influence microbiome metabolism rather than merely altering microbial composition. Bortoluzzi *et al.* (2025) [2] investigated glycan-based precision biotics in broilers challenged with necrotic enteritis and reported significant improvements in growth performance, feed conversion ratio, lesion scores, and mortality reduction. Precision biotic supplementation increased the abundance of short-chain fatty acid (SCFA)-producing bacteria, including *Faecalibacterium* species, and enhanced propionate and butyrate metabolic pathways. SCFAs play critical roles in enterocyte energy metabolism, intestinal barrier integrity, immune modulation, and anti-inflammatory signaling. Enhanced SCFA production contributes to faster intestinal recovery following enteric damage and improved resilience against pathogens such as *Clostridium perfringens*. Unlike conventional prebiotics, precision biotics are selected based on their ability to direct specific microbial metabolic functions. This represents a major conceptual shift toward precision microbiome engineering in poultry nutrition. The integration of metagenomics and metabolomics in these studies provides mechanistic insight into host-microbiome interactions. However, challenges remain regarding the reproducibility of microbiome responses across different environments, genetics, and management systems.

Stimbiotics and Intestinal Barrier Function

Stimbiotics are a relatively new class of non-digestible, fermentable additives designed to stimulate fiber-degrading microbiota and enhance fermentation activity at low inclusion rates. Lee *et al.* (2023) [5] evaluated stimbiotic supplementation in broilers challenged with necrotic enteritis and observed significant improvements in growth performance, intestinal morphology, microbial balance, and inflammatory markers. Stimbiotic supplementation increased villus height and villus height-to-crypt depth ratio while reducing serum endotoxin levels and pro-inflammatory cytokines such as TNF- α . Interestingly, stimbiotic supplementation alone produced effects comparable to complex additive blends containing essential oils, probiotics, and enzymes. This suggests that targeted stimulation of fiber-fermenting bacteria may represent an efficient strategy for improving intestinal resilience. The

proposed mechanism involves enhancement of microbial fermentation and production of beneficial metabolites, particularly SCFAs. Improved microbial ecology subsequently strengthens intestinal barrier integrity and reduces pathogen proliferation. Despite promising results, the distinction between prebiotics and stimbiotics remains an area of ongoing debate. Further mechanistic studies are required to clarify their unique functional characteristics and optimal application strategies.

Feed Intake Dynamics and Nutritional Sustainability

Beyond feed additives themselves, understanding feeding behavior and feed intake dynamics is increasingly important for optimizing feed efficiency and sustainability in broiler production. Jie *et al.* (2024) [4] identified three distinct feed intake patterns in broilers: continuous increase, plateau, and decline patterns. Birds exhibiting continuously increasing feed intake demonstrated superior growth performance and feed conversion efficiency compared with birds showing declining intake patterns. These findings highlight the importance of appetite regulation and nutrient utilization during late-stage growth. Functional feed additives capable of preserving appetite and intestinal functionality under stress conditions may therefore have substantial impacts on production efficiency. Integration of feeding behavior data with nutritional interventions may enable development of precision feeding systems tailored to individual physiological responses. Such approaches could improve nutrient efficiency while reducing feed waste and environmental impact.

Discussion

Emerging functional feed additives are transforming poultry nutrition by targeting intestinal health, microbial metabolism, immune function, and nutrient digestibility. Collectively, the reviewed studies demonstrate consistent improvements in growth performance, feed efficiency, gut integrity, and disease resilience. Nevertheless, several important challenges remain unresolved. First, considerable variability exists among studies due to differences in additive formulations, bird genetics, environmental conditions, diet composition, and experimental models. Standardization of methodologies and additive characterization is therefore essential. Second, most studies are conducted under controlled experimental conditions rather than commercial-scale production systems. Field validation under diverse management and environmental conditions is needed to determine practical efficacy and economic feasibility. Third, mechanistic understanding of host-microbiome interactions remains incomplete. Advances in metagenomics, transcriptomics, metabolomics, and artificial intelligence-driven nutritional modeling will likely accelerate the development of next-generation precision nutrition strategies. Future research should also focus on synergistic combinations of additives. For example, integrating enzymes with microbiome-targeted additives may improve substrate availability for beneficial bacteria, thereby amplifying SCFA production and gut health benefits. Additionally, sustainability assessments should extend beyond growth performance to include environmental indicators such as nitrogen excretion, carbon footprint, and resource utilization efficiency.

Conclusion

Functional feed additives represent a critical component of sustainable, antibiotic-free broiler production systems. β -glucans, β -mannanase, encapsulated enzymes, probiotics combined with phytogetic compounds, precision biotics, and stimbiotics each provide distinct yet complementary mechanisms for improving gut health, nutrient utilization, immune competence, and production efficiency. Among these technologies, microbiome-directed approaches such as precision biotics and stimbiotics appear particularly promising due to their ability to selectively modulate microbial metabolism and intestinal resilience. Meanwhile, enzyme technologies and immunomodulatory additives continue to play essential roles in enhancing digestive efficiency and stress tolerance. Although substantial progress has been made, future advances will depend on integrating nutritional science with systems biology, microbiome engineering, and precision livestock management. Such multidisciplinary approaches will be essential for optimizing poultry productivity while meeting global demands for sustainability, animal welfare, and reduced antibiotic dependence.

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