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Review

Advancing Nigerian Indigenous Poultry Health and Production, Use of Probiotics as Viable Alternatives to Antibiotics: A Review

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Abstract

Poultry is a vital component of global meat production, with particular importance in Nigeria and Africa, as it promotes food security, economic growth, and rural livelihoods. Indigenous chickens, although less productive, are well adapted to local environments and provide significant socio-economic and nutritional benefits. The rising demand for animal protein and concerns over antimicrobial resistance (AMR) necessitate the development of sustainable alternatives to antibiotics in poultry production. Probiotics have emerged as effective feed additives that enhance gut health, immunity, nutrient absorption, and overall productivity. While extensively studied in commercial poultry, research on probiotics in Nigerian Indigenous Ecotype Chickens (NIECs) remains limited. Key challenges in indigenous poultry systems include low productivity, disease vulnerability, limited veterinary access, and environmental pressures. Addressing these requires improved management practices, infrastructure, veterinary support, and enabling policies. Multi-strain probiotics, particularly those containing *Lactobacillus*, *Bifidobacterium*, and *Bacillus* species, demonstrate promise in enhancing productivity, improving product quality, promoting environmental sustainability, and ensuring food safety. Focused research on local probiotic strains, field trials, farmer education, and policy support is crucial for harnessing the full benefits of probiotics and transforming indigenous poultry farming into a resilient and sustainable sector.

Keywords: antibiotic growth promoters; probiotics; microbiome; immunity; antimicrobial resistance

1. Introduction

Poultry is the world's most consistently consumed meat globally, valued for its cost-effectiveness, efficient production, short generation interval, and superior nutritive value. It is a form of high-quality protein and a source of the most essential amino acids and essential micronutrients, such as B vitamins and selenium. It has been demonstrated to improve muscle growth, immunity, and metabolic health, especially amid increasing demand for protein-based diets [1]. It is easier to manage and elicit low capital and operating costs than other types of livestock [2]. In Nigeria and Africa, animal husbandry is indispensable for human health, women's economic empowerment, and the resilience and environmental sustainability of rural communities [3].

With a growing population, the global demand for slaughtering and animal products, such as meat, milk, and eggs, is increasing, posing significant challenges to the livestock industry in keeping pace with this growing demand. The world's human population is growing significantly and is projected to reach 9.7 billion by 2050 [4]. Improving production efficiency in poultry and livestock is crucial for sustainably feeding an ever-growing population while also protecting animal and human welfare by reducing antibiotic use and promoting environmentally friendly and ethical farming practices [5]. The population of poultry in Africa by 2022 was approximately 2.4 billion, with Egypt leading at 300 million and Nigeria second at 249 million [6]. Hence, Nigeria, a major player in the industry, has a large poultry population, with the sector ranging from commercial to small-scale farm holdings, including indigenous and exotic breeds, and is distributed across various regions of the country.

The indigenous chickens are also referred to by various names in small-scale village, free-range, local, scavenging, family, or backyard production systems [7]. They are mostly unimproved and are characterized by low productivity but are majorly beneficial to rural society because of their hardiness and good adaptation to harsh environments and require little veterinary health care [7,8]. Although indigenous chickens are not selected for increased productivity, they are endowed with traits that render them well-adapted to harsh tropical environments. Native chickens consume a free-range, natural diet consisting of house scrapings, grazing grasses, seeds, insects, and nuts, supplemented with additional commercial feed [9]. They also have small eggs and a tenacious instinct to sit on and hatch them unaided. They are also highly resistant to diseases of local endemicity [10].

According to Kasimanickam et al. [11], administering antibiotics to poultry at subtherapeutic doses promotes growth, and this often leads to the emergence of antibiotic-resistant bacteria. Another drawback to this practice of administering antibiotics at subtherapeutic levels is the presence of drug residues in eggs and meat, which allows bacterial organisms to develop resistance to these antibiotics [12]. More often, withdrawal periods are not observed to avoid antibiotic residues in the meat and eggs that humans ingest, as they do not apply to meat-producing animals and their byproducts, which are meant for human consumption [13]. Due to their scavenging behavior, indigenous birds often encounter waste, sewage, and other contaminated materials, thereby increasing their susceptibility to infections caused by resistant bacteria, such as *E. coli* and *Campylobacter* [14]. Conversely, commercial birds are reared in controlled settings that implement biosecurity measures and vaccination protocols, which mitigate pathogen exposure; this environment allows for more precise administration of antibiotics under strict veterinary supervision [15].

The use of antibiotic growth promoters (AGPs) has been prohibited in most countries due to the growing problem of antibiotic resistance and antibiotic residues in poultry and livestock products, which pose a risk to human health. Antibiotics are also prohibited in most parts of the globe for use in animal husbandry at subtherapeutic levels. Their use is limited to cases prescribed by a veterinary surgeon for the treatment of confirmed clinical

cases. As the impending threat of AMR deepens, scientists must intensify their search for novel alternatives to traditional antimicrobials to maintain performance and protect the efficacy of existing therapies while acquiring justifiable solutions within a rapidly diminishing collection of practicable choices [16]. Diverse alternatives to AGPs have been tested as feed additives in poultry, yielding mixed results. In recent years, an array of innovative options for antibiotics, such as probiotics [17], prebiotics [18], postbiotics [19], phytochemicals [20], bacteriophages [21], bacteriocins [22], exogenous enzymes [23], vaccines, and antimicrobial peptides [24], have been developed as part of efforts to address AMR and AMU. Most promote growth, improve livestock productivity, and support animal and human health.

Probiotics, also known as direct-fed microbials (DFMs). They have attracted significant global interest in improving poultry health and performance, presenting a feasible alternative to antibiotic growth promoters in response to the growing demand for antibiotic-free and organic poultry. They are also gaining general recognition in the medical field for their varied health benefits and attaining notable success across sectors such as agriculture, biotechnology, and pharmaceuticals, owing to their preventive and therapeutic properties [25–27]. Integrating probiotics into animal diets has, therefore, increased growth, production efficiency, and disease resistance (immunity). It sustains the gut microbiota, which plays a critical function in poultry and livestock health and productivity. It does so by promoting beneficial bacteria, inhibiting pathogenic species, and enhancing more efficient nutrient digestion and absorption, host metabolism, and health in general [28–30].

Probiotics enhance nutrient digestion and absorption by augmenting the synthesis and action of digestive enzymes such as lipase, protease, and amylase. Probiotics are well-known for their wide range of health benefits, which largely depend on the bacterial strain, dose, and delivery volume, chicken genetics, inoculation site, concentration, dosage, and duration of administration [31,32]. There is a paucity of information on the use of probiotics in indigenous chickens in Nigeria. The objective of this review is to evaluate the potential of probiotics as sustainable alternatives to antibiotics in enhancing the health and productivity of Nigerian indigenous poultry. It is essential to conduct an appraisal using current literature and assess instances where probiotics have been utilized as supplements in chickens, particularly their impact on growth promotion and production performance, strengthening the gut microbiome and immune system, and improving meat quality. This should be performed while also considering the potential use in decreasing ammonia and greenhouse gas emissions.

2. An Overview of the Indigenous Poultry Industry in Nigeria

Indigenous poultry rearing presents exceptional opportunities for smallholder farmers, including women and children, to generate a profitable income and diversify their livelihoods, thereby contributing to poverty alleviation and economic empowerment. It is fundamental for food and nutrition security, as poultry products supply animal protein and essential micronutrients [33]. This type of farming is often more environmentally friendly than large commercial systems because it utilizes local resources, minimal infrastructure, and local breeds that thrive in harsh climates [34]. Local chicken meat is also regarded for its organoleptic properties, such as excellent taste, desirable flavor, and juicy tenderness [35]. It also boasts an impressive nutritional profile, rich in healthy protein and essential vitamins and minerals that support overall health. Compared to other traditional meat sources, indigenous chicken has a significantly lower percentage of saturated fat and cholesterol and a higher rate of unsaturated fatty acids, including oleic acid (a monounsaturated fatty acid, or MUFA) and total polyunsaturated fatty acids (PUFAs), which may be considered a heart-healthy option for health-conscious consumers [36].

Despite their multiple benefits, indigenous chickens are faced with numerous challenges by their keepers, which are attributed to the extensive management systems offered to them compared to exotic chicken breeds. However, malnutrition, inadequate extension services, and a lack of technical farming skills have been implicated in poor growth and development [37]. Bird keepers commonly keep these birds in small living quarters near them; this promotes exposure to various zoonoses, such as salmonellosis, chronic respiratory disease, and lousiness. On the other hand, such systems are also challenged by inadequate housing and food. Idiosyncrasies such as temperature fluctuations and extreme weather exacerbate these factors, which in turn influence the health and performance of these birds. Moreover, their relatively small body size, the number of flocks, and age variation within the flock decrease the overall level of meat production, and they have lower egg production, making them inefficient from a commercial standpoint [38]. Furthermore, disease control is one of the main challenges facing the poultry sector in Africa, specifically in smallholder production systems, as escalating production costs and a lack of sufficient vaccines limit farmers [39]. Free-range chickens are more prone to infections, such as Newcastle disease, coccidiosis, and fowl pox, disease vectors that distribute avian hemiparasites, resulting in increased morbidity and mortality risk. A low level of biosecurity, insufficient drugs, and the fact that smallholder farmers have little technical knowledge of how to prevent and control diseases further exacerbate the problem [40,41]. Vaccination programs in these systems are difficult to implement. Challenges include limited access to veterinary support services, difficulties in maintaining a cold chain to preserve vaccine efficacy, and inconsistent production and distribution of vaccines, particularly in resource-constrained countries [42]. Although indigenous chicken production practices could be sustainable, these challenges need to be addressed through innovative interventions, such as improved feeding and management practices, adopting the best biosecurity measures, and developing climate change adaptation technologies. These interventions are needed to contribute to increased productivity and income.

Antimicrobial Resistance

Antimicrobial resistance (AMR) has emerged as one of the most critical global public health emergencies, driven by the overuse and misuse of antimicrobial agents. This has led to a decrease in their capacity to tackle infections successfully. This top global health challenge is threatening the lives of millions of livestock and humans. Indigenous birds typically necessitate a higher quantity of antibiotics for the treatment of bacterial infections compared to commercially raised birds; this disparity is attributed mainly to their increased exposure to environmental pathogens and antibiotic-resistant strains. There are reports of free-ranging indigenous birds exhibiting AMR without being treated with antibiotics [43,44]. The detection of resistant genes may have resulted from environmental contamination. Antimicrobials, also known as antibiotics, have been recognized for decades for their ability to boost feed conversion efficiency, promote growth, prevent and treat animal diseases, and enhance productivity, thereby keeping pace with the demand for poultry meat and eggs. These antimicrobials are often administered in sub-therapeutic doses through animal feed, also to improve feed efficiency, leading to more significant mass gain and higher product yields [45,46]. This fosters a balanced gut microbiome and strengthens the immune system [47,48]. Collectively, these gains improve poultry's overall health, productivity, and profitability. The use of these drugs in animal husbandry dates to the mid-1940s, when the surge in antibiotic production for treating wounded soldiers during World War II made these medications widely available. This accessibility enabled their successful integration into veterinary practices, yielding extraordinary results [49]. However, the gains of employing antibiotics are becoming less clear as concerns grow over their prolonged

and inappropriate use as feed supplements, resulting in hazards of drug residues in animal products [50] and the development of antibiotic-resistant bacteria. For example, traces of antibiotics have been found in food items, raising potential health risks for consumers [51]. The detection of antibiotic residues in poultry meat and eggs poses substantial dangers to human health, including antibiotic sensitivities, allergic reactions, disturbances to the gut microbiota, increased bacterial resistance, and significant potential losses within the food chain [52]. Furthermore, long-term antibiotic use in poultry and livestock can disrupt the stability of intestinal microbiota, eventually impairing weight gain, survival rates, and feed efficiency [53,54].

The growing dissemination of antimicrobial-resistant bacteria from animals to humans, primarily through the consumption of animal products or direct contact, poses a substantial clinical risk due to the transmission of resistance genes. The increase in multidrug-resistant pathogens results from the inappropriate use of antibiotics in both veterinary and human medicine [55,56]. In addition, the use of antibiotics in food animals can lead to other food safety hazards, such as an increased incidence of allergic reactions, development of cancer, and carcinogenic and teratogenic outcomes in neonates and treatment failures in humans [57–59]. The growing challenge of antimicrobial resistance, resulting from indiscriminate or excessive use, is more prevalent in developing countries and poses considerable public health risks [60]. Resistant bacteria make simple infections harder to treat. This often leads to the need for more expensive alternatives if they are available, resulting in more devastating complications and resultant death. These drawbacks have led several countries worldwide to ban antibiotics at subtherapeutic doses in poultry and other food animals [61]. The prohibition on the use of antibiotics in poultry and livestock has led to increased morbidity and mortality, reduced feed intake and efficiency, and a resultant decrease in body weight. As a result of its use in human and veterinary practice and its consequent environmental contamination, AMR has now become the basis of the One Health Initiative, intricately linking the fields of agriculture, environment, and public health [62]. Consequently, an integrated global approach within these segments is required to tackle and effectively handle this growing menace. Across African countries, there is a prevalent misuse of antibiotics, inadequate antibiotic regulations, and a dearth of regional monitoring of AMR and antimicrobial usage (AMU) [63,64].

3. Biotics

In the gut health and nutrition perspective, "biotics", a collective noun, represents a class of supplements including prebiotics, probiotics, synbiotics, and postbiotics. These compounds promote the development and activity of beneficial gut bacteria, and as a result, these substances have lately been the core of vast research as prospective antibiotic substitutes in poultry and livestock production [65].

3.1. Prebiotics

In recent years, prebiotics have garnered considerable attention due to their numerous benefits in enhancing the health of poultry and livestock. Prebiotics are non-digestible nutrients, specifically fermentable oligosaccharides (2–10 monosaccharide units), that have been demonstrated to favorably manipulate the composition and fermentation patterns of the gastrointestinal microbiota, facilitating the establishment of a healthy microbiota and regulating the host's immunity and metabolism [66,67]. Notable prebiotics include mannan oligosaccharide (MOS), galactooligosaccharides (GOSs), fructooligosaccharides (FOSs), and alginate oligosaccharide (AOS) [68,69]. Morgan [70] stated the requisites for qualifying prebiotics to include that they should not be metabolized in the upper gastrointestinal tract (GIT), they must operate as a selective nutrient for valuable microorganisms in the

gastrointestinal system, and they should initiate physiological reactions that offer benefits to the host. Fermentation products of prebiotics include short-chain fatty acids, principally volatile fatty acids (acetate, propionate, and butyrate) and lactic acid, which offer energy to the host and reduce gastrointestinal pH, thereby hindering the multiplication of acid-sensitive bacteria [71,72]. Therefore, integrating locally sourced prebiotic ingredients into poultry feed provides a sustainable and welfare-oriented approach to intensive farming. This strategy enhances animal performance and health outcomes, offering a cost-efficient and environmentally responsible alternative that advances the goal of a more resilient and ethical poultry industry. GIT is a complex, tube-like structure common to almost all species, with the small intestine functioning as a vital region accountable for the major digestion and assimilation of dietary nutrients [73].

3.2. Synbiotics

Synbiotics, which blend probiotics and prebiotics, deliver beneficial bacteria along with the nutrients they need; this combination helps enhance the survival and establishment of these helpful microbes in the gut [74]. A study by Hossain and his colleagues [75] confirmed that the effectiveness of synbiotics depends on various interconnected factors, including the exact dosages administered, routes of delivery, the specific combinations of prebiotic and probiotic strains, and the probiotic species used. They also stated that the breed and strain of the poultry, diet, location, levels of exposure to physiological stress, stocking densities, and ambient environmental temperatures impact the efficiency of synbiotics. Synbiotics, a synergistic combination of live probiotics and selectively utilized prebiotics, can be administered in ovo to poultry, enhancing gut colonization by beneficial bacteria and thereby improving digestion, health, and protection against pathogens [76].

Research on synbiotics has centered mainly on broiler and other commercial strains such as Arbor Acres and Ross 308 within broad poultry production contexts [77,78]. Although a few Nigerian reviews touch on probiotics, prebiotics, and postbiotics in the national poultry sector, no report has conducted direct comparative trials on synbiotics in indigenous breeds [79]. Notably, work on native Mandarah chicks in Egypt has tested different synbiotic administration routes, assessing outcomes in growth, gut morphology, and immune function [80]. While these findings come from outside Nigeria, the approach offers meaningful insight. Targeted trials on the country's own indigenous ecotypes remain a pressing need.

3.3. Postbiotics

Postbiotics, also known as pharmacobiotics, metabiotics, or heat-killed probiotics, are an emerging area of research and are gaining fast attention as they boost poultry and livestock health and production. They refer to metabolic byproducts or constituents obtained from probiotic bacteria that are less susceptible to various environmental factors, including temperature, pH, and processing methods [80], and they confer a spectrum of health and nutritional benefits to the host.

Supplementing diets with postbiotics has numerous benefits for the host, as it improves the architecture of intestinal villi, lowers the populations of Enterobacteriaceae, increases the fecal pH, and increases the number of lactic acid bacteria, leading to enhanced health and growth performance in broilers [81]. Chaney et al. [82] reported that incorporating *Saccharomyces cerevisiae* fermentation products in poultry feed might be a reliable approach for reducing the incidence of *Salmonella enterica* and improving food safety and overall poultry health. The intestinal microbiota produces postbiotics, such as Gamma-Aminobutyric Acid (GABA) from L-glutamic acid, short-chain fatty acids from carbohydrates, indole from amino acids, and polyphenolic acids from dietary sources;

these compounds are crucial for maintaining our bodies' balance and health [83,84]. These metabolites are products formed when gut bacteria ferment dietary components, playing a fundamental role in how the host's body interacts with the microbiome. For example, short-chain fatty acids (SCFAs) are synthesized by the host gut microbiota and are key players in managing insulin and glucose levels, inflammation, fat tissue development, and even certain cell growth [85]. This underscores their significance in various physiological processes. Some postbiotics have direct antimicrobial activities through the reinforcement of the gut barrier, competition for specific receptors required by pathogens, modulation of host gene expression, or even pH changes in the environment [86]. In other words, postbiotics are more stable, safer, fast-acting, and durable than probiotics [87]. Due to their resistance and effectiveness, they are a desirable option for various reasons, regardless of the presence of live bacteria.

Recent literature reveals only one Nigeria-based investigation into postbiotic and paraprobiotic supplementation, focusing solely on broiler chickens [88]. The study measured immune responses in commercially farmed flocks, offering no insight into the country's indigenous breeds. This gap underscores the importance of conducting robust, randomized trials that explore how postbiotics influence native ecotypes such as the Fulani, Ogun, and Yoruba, where breed-specific responses may hold valuable implications for poultry health and productivity.

3.4. Probiotics

The term "probiotic," derived from the Greek word meaning "for life," signifies non-pathogenic, live microorganisms (usually a culture of a single strain, or a mixture of different strains) that, when ingested in sufficient amounts (10^6–10^7 cfu/g), confer health benefits to the host via a symbiotic affiliation [89]. Probiotics are live microorganisms, typically bacteria and yeasts, that offer numerous health benefits to the host organism when consumed in sufficient amounts through food or supplements [90]. This represents a complete departure from the long-held misconception that all microorganisms are inherently harmful to livestock and humans. Over the years, the functional food sector has experienced a substantial increase in the promotion of probiotic-based products, primarily driven by growing consumer interest in dietary choices that offer enhanced physiological benefits [91]. Over the past decade and a half, probiotics have garnered significant attention for their therapeutic potential and have been extensively employed in treating a broad spectrum of pathological disorders. Probiotics have been associated with a wide range of health-enhancing effects, including but not limited to the following: enhancing lactose digestion for lactose-intolerant patients [92], regulating various types of cancer, especially colorectal cancer [93], and lowering blood cholesterol levels [94]. Additional benefits include reduction of blood glucose and cholesterol levels, reduction of obesity and hypertension, and resistance to allergens [95].

Dietary supplements, including probiotics, have become essential in poultry production. They stimulate optimal growth, efficient nutrient digestion and absorption, boost gut integrity, bolster immunity, and sustain a healthy balance of gut microbiota [96,97]. While the addition of probiotics to feed remains the most typical method of administration on poultry farms, a range of other delivery systems is also available; these include oral gavages (administered as drops or vaccines), aerosol sprays, granules, tablets, coated capsules, and sachets enclosing powdered preparations [98].

The sustenance of high feed efficiency is critical for the poultry industry's ability to fulfill the increasing global demand for poultry products. However, this is a significant challenge, as intensive bird production is highly susceptible to infectious disease outbreaks, particularly in areas facing shifting climatic conditions that aggravate vulnerability to

health-related disruptions [97]. The high cost of feed ingredients has consistently driven the price of livestock feeds to account for approximately 70% of the total cost of poultry production. Therefore, any measure that will reduce the price or quantity of this farm input would always be welcomed by farmers and make farming more sustainable. Optimizing conversion of feed to body weight is a critical determinant of commercial success in livestock production (there is a close relationship between profitability and efficiency of conversion of feed by the animal into live weight gain).

Current innovations have shown that probiotics promote human health and enhance food safety by eliminating harmful microorganisms and their toxins in food. The association between diet and gut microbiota has emerged as a significant focus for promoting animal and human health, with probiotic supplements gaining increasing acceptance as an efficient means of influencing the gut microbiome [99,100].

It has long been recognized that the variation in gut microbiota exerts a significant influence on host metabolism, nutrient digestion, growth performance, and the welfare of the host. Over the past few years, probiotics have been considered a safe and effective alternative to growth-promoting antibiotics in poultry production, attracting significant scientific and commercial attention due to their benefits in enhancing gut health and production performance, as well as combating antibiotic resistance in poultry [101]. Additionally, probiotics can react differently depending on the strain used and are susceptible to degradation when the temperature is unstable, making their effects unpredictable.

3.4.1. Characteristics of a Good Probiotic

An effective probiotic strain must be non-pathogenic, survive particularly under acidic and bile-rich conditions, have an elevated number of viable cells, demonstrate metabolic activity, and have a positive impact on the host's health. The ability to adhere to and colonize the mucosa of the digestive tract, improving the functions of the intestinal tract and retaining stability and viability throughout storage and field application [102,103]. A microbial strain can be deemed a probiotic if it meets specific, stringent safety and efficacy standards, comprising genetic stability, acid and bile resistance, gut adhesion, non-existence of pathogenicity, anti-genotoxic capacity, and lactic acid production [104]. It must also meet rigorous processing requirements, promote microbiota diversity, and have a reasonably brief reproductive cycle.

The mechanisms of action of probiotics are multifactorial and not fully characterized. However, they support the body by releasing antimicrobial compounds, competing with harmful microbes for space on the gut lining, reinforcing the intestinal barrier, and fine-tuning the immune system's responses. Probiotics exert their beneficial effects through several mechanisms, including the competitive exclusion of pathogens from adhesion sites, the manufacture of antimicrobial substances, the improvement of the intestinal mucosal barrier, the modulation of the immune system, and the production of neurotransmitters [76]. Recent findings corroborate that probiotic survival in the GIT is sometimes compromised by factors such as acidity, bile salts, oxygen, and processing stress [105,106]. This preceded the development of synbiotics (a mixture of probiotics and prebiotics) to improve microbial viability and efficacy and hamper the growth and multiplication of pathogenic species.

Probiotics' advantages stem from their distinct structural traits and ecological roles. Their presence strengthens the intestinal barrier, supports a diverse microbiota, and helps prevent the growth of harmful pathogens.

This review attempts to comprehensively investigate the potential roles of probiotics to improve food safety by eliminating bacterial, fungal, viral, and parasitic pathogens and neutralizing their toxins from meat and eggs. Furthermore, recent cases of probiotic commensals' antimicrobial activity in the body condition after ingesting contaminated

foods have also been summarized. These data show that different probiotics can inactivate pathogens and neutralize or detoxify various biological agents in food present in the host body following ingestion.

The most used probiotics are *Bacillus subtilis*, *Enterococcus faecium*, *Lactobacillus acidophilus*, *Bacillus amyloliquefaciens*, *Bacillus licheniformis*, *Lactobacillus plantarum*, *Lactobacillus casei*, *Lactobacillus rhamnosus*, *Lactococcus lactis*, *Pediococcus acidilactici*, *Bacillus coagulans*, *Bifidobacterium bifidum*, *Carnobacterium divergens*, *Lactobacillus delbrueckii*, *Lactobacillus farciminis*, *Lactobacillus fermentum*, *Lactobacillus paracasei*, and *Streptococcus salivarius* [107].

3.4.2. Role of Probiotics in Augmenting a Balanced Gut Microbiome and the Immune System

With the expansion of gut microbiota research, its pivotal influence on poultry health and growth is becoming increasingly evident, indicating that this microflora is an essential modulator in physiological development and the overall condition of poultry production systems. Recent studies have reported that optimal intestinal health in birds requires a balanced gut microflora to maintain a continuous interface with its host and harmonious coexistence [108]. A normal and healthy gut ecosystem of poultry is essential for its general health, nutrient digestion and absorption, immune system, and overall welfare performance. The microbiome encompasses a wide range of abundant microbiota (trillions of microorganisms) that have colonized a host and their bioactive products, nucleic acids, proteins, lipids, polysaccharides, and metabolites, which are formed through interactions with the host and affected by the environmental factors [109]. It is well established that gut microbiota diversity performs pivotal functions in host metabolism. It digests nutrients for growth, promotes gut microbiota diversity, eliminates pathogenic bacteria, enhances the intestinal barrier, maintains the immune system, and maintains the overall health of the host [31,110,111]. Any disruption of these could lead to health problems, which probiotics can help decipher. Enhancing gut health is essential for chickens to reach their genetic potential and achieve a low feed conversion ratio (FCR). Any compromise, mainly caused by enteric diseases, not only reduces performance but also has a direct and adverse effect on overall profitability [112]. Several advances can be made concerning preventing contaminated food by various pathogenic and toxigenic microorganisms. Numerous investigations have demonstrated that multiple probiotics, in addition to exerting beneficial effects on the health of hosts, can destroy or neutralize foodborne pathogens and their toxins in foods, thus improving food safety. Additionally, the differences in geography, age, sex, and feeding habits during the chicken's rearing influence the composition of the microbial population in the chicken's intestine, with significant potential effects on poultry health and productivity [113].

By regulating gut permeability through tight junctions, probiotics enhance the gut health of poultry. The tight junction protein complex controls ion movement, prevents pathogenic bacteria from passing between cells, and maintains intestinal epithelial integrity [114]. However, alterations in these proteins could lead to damage to the mucosal barrier, resulting in the translocation of pathogens within the intestinal epithelium. Maintaining the intestinal epithelium's integrity is crucial in poultry, as it serves as a selective barrier to limit the access of pathogenic organisms and toxins whilst allowing efficient nutrient absorption and utilization [115]. When disrupted due to factors such as enteric disease or inflammation caused by stress, this barrier can be associated with enhanced intestinal permeability, microbiota imbalance, and systemic inflammation, all of which have negative implications for growth, feed efficiency, and productivity [116,117]. In this sense, probiotics can help support or improve gut barrier function through various mechanisms, including the prevention of pathogenic bacteria and modulation of tight junction proteins. Thus, stabilized tight junction proteins shore up the epithelial barrier, protecting the host from

pathogen invasion into internal organs. This has resulted in comprehensive improvements in gut permeability and the suppression of pathogenic bacteria [112]. Probiotics play a crucial role in maintaining a balance in intestinal flora. They accomplish this by inhibiting the proliferation of detrimental bacteria and promoting the growth of beneficial microbes. This dual effect not only supports the intestinal barrier but also stimulates the immune response, resulting in superior growth performance and overall well-being in the animals. When provided at sufficient levels, probiotics can help establish a healthier microbial balance in the poultry gut, thereby improving digestion and supporting overall health, and providing a "shield" against harmful bacteria and pathogens [118]. Immunoglobulin G (IgG), the most abundant serum antibody comprising over 75% of blood antibodies, and secretory immunoglobulin A (sIgA), produced in the lamina propria, together play vital roles in systemic immunity and mucosal defense in the respiratory and gastrointestinal tracts [119,120]. This defensive layer efficiently blocks pathogens from attaching to cell surfaces, thereby significantly reducing the likelihood of infection and microbial invasion [121]. Ensuring a robust immune function is vital for the healthy development of chickens under all management systems.

Recent in vivo results have emphasized the efficiency of *Lactobacillus* administration in remarkably reducing *Salmonella* colonization in a variety of species, including poultry, pigs, and mice, demonstrating that *Lactobacillus* administration is a biologic control method against enteric bacterial infections in avian and livestock [122,123]. The chicken gut microbiota represents a dynamic microbial community that is influenced by the age of the host, method of administration and route of infectious exposure, genotype, dietary inputs, and husbandry system. These factors collectively play roles in the stability and functionality of the gut ecosystem during the animal's life [92,124,125]. The enteric microbes inhabiting the GIT play a crucial role in nutrient and drug metabolism, detoxification, and prevention of pathogenic colonization, but they also contribute to the induction and regulation of significant aspects of the host's innate and adaptive immune response [126,127]. The gut microbiota, through interaction with the gut-associated lymphoid tissue (GALT), has a predominant influence on the development of the avian immune system. Probiotics boost both innate and adaptive defenses from the microflora by affecting the immune system, thereby enhancing resistance against infectious agents of the host [128].

GIT employs a combination of physical and immune defenses to confine its diverse microbial community to the gut lumen. The mucosal layers act as the principal endogenous defense system, capturing potential infectious agents and readily clearing them from the body through passage through the intestine [129]. Simultaneously, these mucus structures provide adhesion sites and metabolic substrates that allow bacteria to colonize and survive [130]. Disturbances in the gut microbiota (also known as dysbiosis) or its interaction with the immune system may adversely affect the health of the intestine and may arouse autoimmune diseases, which also highlights the significant role of the immune system in homeostasis of the host–microbe interaction and also the importance of keeping a microbial balance for immune homeostasis and the host's general well-being [131,132]. Alterations of the gut microbiota can be disrupted by antibiotic use, changes in diet, ageing, and infections, which can lead to potential discrepancies in pathogenic flora, inflammatory reactions, and metabolic diseases [131]. Therefore, interventions to maintain healthy microbiota are necessary to enhance chickens' immune response, health, and productivity. However, little is known about the microbiota of the Nigerian indigenous chickens. Nigerian indigenous chickens may differ from those of imported and exotic chickens in terms of their microbial composition and functional profiles, which could contribute to their edibility and potentially harbor unique probiotic strains with health benefits for the host. Therefore, there is a need to determine the gut microbiota composition of indigenous Nigerian chickens

and establish reference data for this purpose. This limits our ability to design probiotic interventions that target specific microbial imbalances or health challenges (Figure 1) [133].

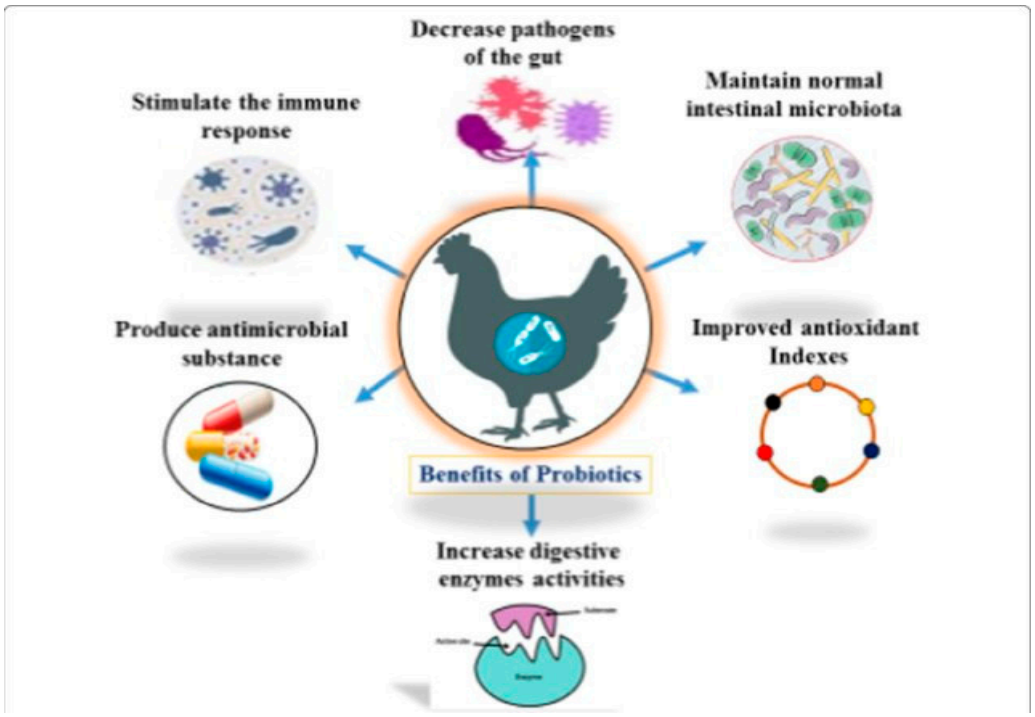


Figure 1. Illustrates the multifaceted benefits of probiotics in poultry. These include reducing gut pathogens, maintaining intestinal microbiota, improving antioxidant indexes, enhancing digestive enzyme activity, producing antimicrobial substances, and stimulating immune responses. Collectively, probiotics support better gut health, immunity, digestion, and oxidative balance, contributing to overall poultry health and performance. Source: Rajput et al. [133].

3.4.3. Role of Probiotics in Promoting Growth and Production Performance

Numerous studies have highlighted the beneficial roles of probiotics in improving growth performance and overall health status in laying birds and broilers. Incorporating probiotics into poultry diets has been demonstrated to increase feed conversion efficiency, feed quality, nutrient availability, boost body weight gain, and increase overall productivity, possibly attributed to improved nutrient digestibility [134,135]. This may be due to enhancing beneficial microbial populations, curbing pathogenic species, or bolstering intestinal barrier integrity, leading to a significant improvement of the host's health and resilience [136,137]. Multi-strain probiotic formulations may offer improved health benefits not only through their collective actions but also due to the precise ratio of each strain, enabling synergistic interactions such as enhanced gut adherence and pathogen suppression, while delivering diverse protective effects through various mechanisms of action [138,139].

Hens in the late laying stage, which accounts for approximately 50% of the production cycle, undergo physiological changes, including lowered nutrient absorption, reduced immune function, and disrupted lipid metabolism, collectively decreasing laying and egg quality [140]. This results in considerable economic losses for poultry farmers. Eggshell quality is one of the critical determinants of egg shelf life and marketability, with shell damage during handling, transport, and storage accounting for 6–10% of global losses, substantially affecting profitability [141]. Albumen height is a key marker of internal egg quality, indicating the freshness and general state of the egg white [142]. By modifying the gut microbiome, probiotics enhance nutrient bioavailability, enabling laying hens to efficiently meet the metabolic demands of eggshell formation, particularly during peak

production levels [143]. Carcass yield, along with breast and drumstick ratios, in part indicates broiler meat productivity and acts as an indirect measure of their overall growth productivity [144]. This leads to increased productivity, improved animal welfare, enhanced environmental sustainability, and greater farmer profitability. There is a synergy between intestinal microstructure and microbes that influences digestion and nutrient absorption, thereby regulating body weight and feed intake [145]. Villus height (VH) and crypt depth (CD) are essential markers of gut function; taller villi and shallower crypts signify improved nutrient absorption capacity and greater epithelial renewal, with less energy spent on cell production [146,147]. This ultimately sustains improved growth performance via an enlarged surface area for efficient nutrient uptake.

Recent histomorphometry analysis has confirmed that single or multiple probiotic supplementations often lead to an improved structure of the small intestine by increasing the villus height to crypt depth (VH:CD) ratio, boosting goblet cell density, and advancing the synthesis of Muc2, a fundamental constituent of the mucus layer [31]. Therefore, supplementing diets with probiotics considerably enhanced intestinal histomorphology in chickens and other livestock species. This is likely due to the probiotics' role in promoting villi cell repair, maturation, and metabolic activity. This aids in improved gut architecture and possibly enhanced nutrient absorption and overall well-being.

Zeng and co-researchers [148] documented that supplementing broiler feed with a blend of *Clostridium butyricum*, *Bacillus subtilis*, and *B. licheniformis* increased total and mean broiler body weight. Zou and his colleagues stated that carcass yield, along with proportions of breast and drumstick meat, partially shows broiler meat and growth performance [144]. Moreover, the authors demonstrated that supplementing diets with a 0.025% probiotic combination of *Bacillus subtilis*, *Clostridium butyricum*, and *Enterococcus faecalis* remarkably improved breast muscle fraction over the control group. Probiotic supplementation, therefore, leads to an improvement in feed conversion ratio (FCR) in poultry, suggesting that birds require less feed to attain target growth or egg production levels. This enhancement directly leads to a decrease in production costs and better economic returns for poultry operations [149]. Multi-strain combinations and behavior/welfare implications (e.g., stress mitigation) have not been explored in Nigerian breeds, even though recent global reviews have accentuated such effects.

3.4.4. The Role of Probiotics in Reducing Ammonia, Hydrogen Sulphide, and Greenhouse Gas Emissions

High-density poultry production not only leads to the generation of odorous volatile organic compounds and noxious gases (ammonia (NH_3), hydrogen sulphide (H_2S), and mercaptan) but also greenhouse gases such as methane (CH_4) and carbon dioxide (CO_2). Unwanted smells may occur with excessive NH_3 and H_2S gases. Odor generated from poultry and livestock waste decomposition is often associated with neighborhood complaints and social concerns; recently, the use of probiotics and microbial products has been used for odor alleviation associated with poultry and livestock management [150,151] (Figure 2).

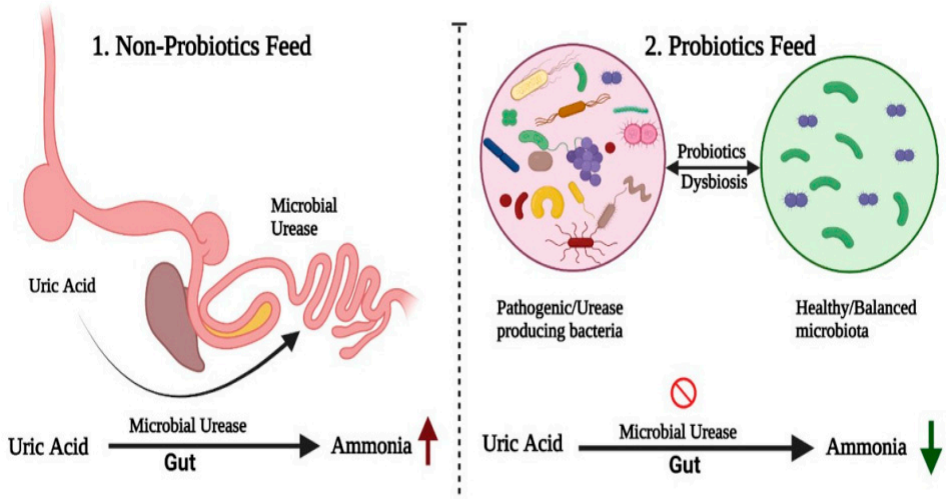


Figure 2. Comparison of non-probiotic and probiotic poultry feeds on gut microbiota and ammonia production. Non-probiotic feeding (**left**) increases gut urease activity, where pathogenic bacteria metabolize uric acid into excess ammonia, resulting in elevated levels (red upward arrow). In contrast, probiotic feeding (**right**) suppresses urease-producing bacteria, restores a balanced microbiota, and lowers ammonia generation (green downward arrow). This shift not only improves gut health but also reduces environmental ammonia load. Source: Khalid et al. [152].

In an in vitro study, Mi and his colleagues [153] indicated that the use of a microbial consortium, i.e., *Pichia guilliermondii* + *Bacillus subtilis* + *Lactobacillus plantarum* in a 1:2:1 ratio, resulted in reductions in NH_3 gas emissions by 46%, as revealed by its potential for mitigating the environmental impact in poultry production systems. Probiotic application led to a decrease in crude protein digestibility, pH, ammonium nitrogen, and valerate, as well as a reduction of urease and uricase activity. It also led to an increase in urea, purine trione, nitrate nitrogen, total volatile fatty acids, and acetate, indicating remarkable changes in nitrogen utilization and microbial fermentation [153]. Some recent research observed a reduction of fecal *E. coli* and *Salmonella*, increased *Lactobacillus*, a suppression of NH_3 and H_2S emissions in broiler feces because of probiotic supplementation, and a good connection between the amount of pathogenic bacteria and gas emissions in an experimental group of birds. A matter that hitherto gave support to some previous reports on associative relations between suppression of odor and microbial balance and nutrient utilization [100,154]. When human beings and other creatures encounter these gases, they cause pain and agitation, suppress appetite, and can also lead to chronic respiratory diseases. The addition of probiotics to poultry feed has been linked to a reduction in NH_3 and H_2S gas emissions. As probiotics in food improve digestion and nutrient absorption, fewer nutrients are available in manure for microbial action and decomposition [155].

3.4.5. Meat Quality

Meat quality is characterized by elements including lean to fat ratio as well as palatability features including visual appearance, odor, drip loss, color, texture, pH (acidity), water-holding capacity, fatty acid composition, tenderness, flavor, and juiciness [156,157]. Including probiotics in the diet is one of the strategic options for managing and improving the quality of meat from chickens, particularly broiler chickens. It serves to reduce the use of other additives and ingredients that affect animal health. At the same time, they contribute feed ingredients with good nutritional value, increasing the value of poultry products [18]. Several responses [158] were reported, including the effects of probiotics on carcass traits, such as fat deposition, meat quantity and quality, and some of these could be seen in Table 1 and Figure 3. The addition of probiotics to the diets of poultry animals

also improves the nutritional quality of poultry meat and reduces the chances of chronic diseases, such as obesity, cardiovascular diseases, and type 2 diabetes [159].

Table 1. Comparison of selected studies on the impact of probiotics on poultry performance parameters.

Probiotic Strains	Health/Performance Effects	Reference
Lactobacillus reuteri	Early supplementation improves microbial diversity, increases beneficial microbes, reduces pathogen levels, and lowers disease susceptibility (up to 6 weeks of age).	[148,160]
Bacillus subtilis, Clostridium butyricum, *Enterococcus faecalis*	Supplementation increases the thymus and bursa of Fabricius relative to body weight (by 29.3%), indicating enhanced humoral and cellular immune responses and improved overall immunity.	[100,161]
Multi-strain probiotics (unspecified)	Enhance immune responses, increase lysozyme activity, and boost IgA, IgG, IgM, and T-lymphocyte activity in intestinal mucosa.	[99,162]
Bifidobacterium spp., *Lactobacillus casei* (0.5%)	Improve intestinal mucosa, inhibit harmful bacteria from spreading, and significantly increase egg production.	[163]
Bacillus subtilis	Increased egg production, improvements in egg weight, shell thickness, and Haugh unit, increased egg freshness and quality	[164]
Bacillus subtilis, *Enterococcus faecium*	Enhance feed intake and conversion efficiency; improve growth and egg production.	[165]
Bacillus subtilis, yeast cell wall components	Improve egg weight, shell thickness, yolk pigmentation, albumen height, and Haugh unit.	[166]
Clostridium butyricum, *B. subtilis*	Improve the villus height to crypt depth ratio; better nutrient absorption.	[167]
Enterococcus lactis	Enhances nutrient absorption, growth, egg production, feed conversion, and calcium/phosphorus metabolism (notably during late laying).	[168,169]
Lactobacillus rhamnosus	Improves egg-laying performance, feed-to-egg ratio, and eggshell strength.	[170]
Pediococcus acidilactici	Maintains laying rate and feed efficiency when the metabolizable energy in the diet is reduced.	[140]
Saccharomyces cerevisiae	An increase in hen-day egg performance and a reduction in circulating cholesterol, mitigate oxidative stress.	[171]
Multi-strain preparation probiotics	Improved body weight gain, feed conversion ratio, reduced cholesterol, increased HDL content, lowered LDL, lower total triglycerides, meat yield, Increased meat protein in broilers	[172]
Bacillus-based probiotics	Decreased abdominal fat and improved fatty acid composition with increased unsaturated fatty acids in broilers.	[173]
Bacillus-based probiotics	Improved hen-day egg production and average egg weight, especially at higher dosages.	[174]

Iakubchak et al. [175] found improvement in carcass associated with muscle accretion due to probiotics, resulting in better formation of muscle tissue and, consequently, better growth performance. According to a study by Ivanovic [176], treatment by some probiotics in the diets of 42-day-old Arbour Acres broilers in comparison to control led to a higher moisture level and lower fat and protein content of drumstick meat. This indicates a possible difference in the composition of the meat, provoked by the probiotic supplementation. All researchers found that meat from animals supplemented with probiotics was less moist and had a higher crude protein content, which is probably due to an increase in protein synthesis. High moisture levels are usually associated with poor meat quality; thus,

this change in the meat composition suggests an upgrade in the overall quality of the FS products [177–179].

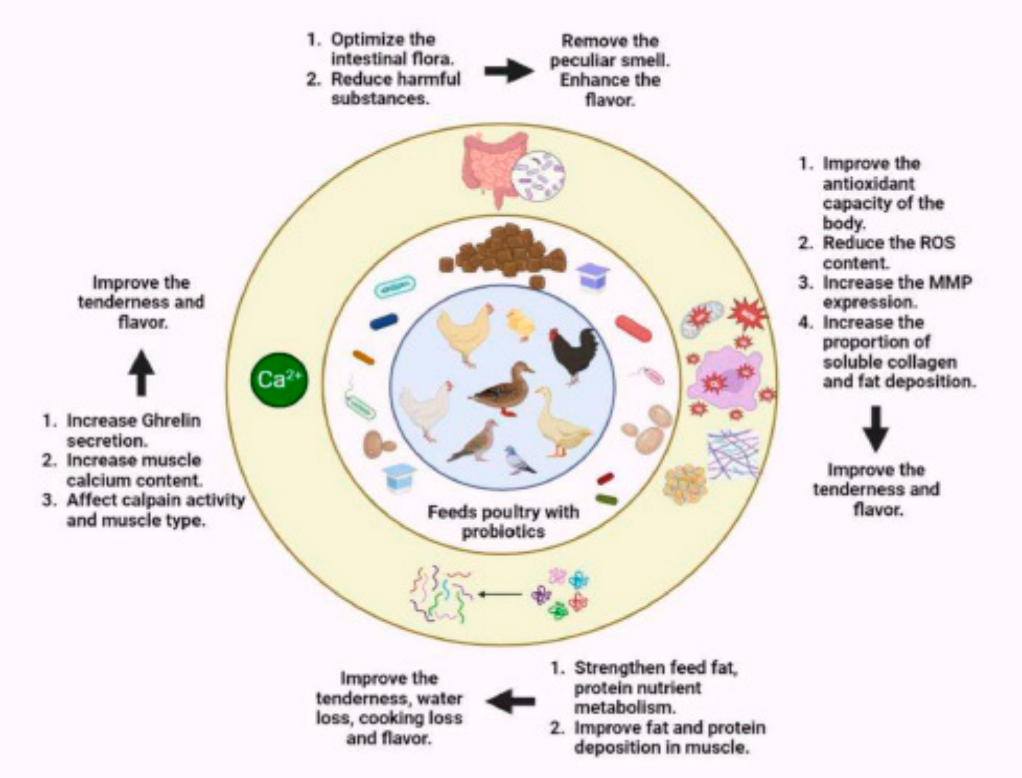


Figure 3. Illustrates how feeding poultry with probiotics enhances meat quality. Probiotics optimize gut flora, reduce harmful substances, boost antioxidant capacity, regulate calcium, and improve nutrient metabolism. These actions increase muscle calcium, collagen, and fat deposition, reduce reactive oxygen species (ROS), and enhance ghrelin secretion. Overall, probiotics improve tenderness, water retention, and flavor, and reduce cooking loss in poultry meat. Source: Dong et al. [158].

3.4.6. Impact of Probiotics on Stress Management in Poultry

Livestock and poultry are continuously exposed to a variety of environmental factors, including high stocking density, poor handling and transportation, disease outbreaks, feed changes and restrictions, high ammonia buildup, and temperature extremes. These have a profound impact on the profile and integrity of the gut microbiome [180] and subsequently affect the health, performance, and overall productivity of chickens. The absence of sweat glands, the presence of thermally insulating plumage, and a relatively high body mass-to-surface area ratio render poultry particularly susceptible to a range of environmental stressors [181].

Emerging research suggests that as global temperatures continue to rise, the negative impact of oxidative stress on the health and performance of poultry and livestock will become increasingly pronounced [182]. Studies have established a link between heat-induced oxidative damage and impaired growth metrics in avian species [183,184]. Probiotics are effective interventions for reducing stress in poultry by rebalancing the gut microbiota, modulating the hypothalamic–pituitary–adrenal (HPA) axis, and regulating the microbiota–gut–brain axis. Heat stress in chickens triggers the HPA axis and increases corticosterone concentrations, which may compromise intestinal health [78]. Probiotics are known to modulate the composition of the gut microbiota by regulating pathogenic bacteria and promoting the growth of beneficial bacteria, thereby contributing to the improvement of intestinal integrity. This will result in better gut health, as well as increased resistance to

stress-induced disruptions. Probiotics may influence the HPA axis by reducing systemic levels of circulating inflammatory cytokines and microbial antigens, thereby guarding against neuroinflammation [185]. This balance modulates the stress response in chickens, promoting overall chicken health. The microbiota–gut–brain axis is an ancient bidirectional signaling system that connects the gut microbiota and the central nervous system. Probiotics modulate this axis through metabolites, including short-chain fatty acids, which serve as an energy source for intestinal cells, and exert anti-inflammatory effects in the intestinal tract, as well as influence neurotransmitters [186], potentially affecting mood and behavior. This interaction could facilitate a decrease in stress-like behaviors and an improvement in welfare in poultry. The use of probiotics in poultry feeding has been reported to alleviate negative behaviors associated with stress, such as aggression and feather pecking, and to enhance productivity. *Bacillus subtilis* addition resulted in lower levels of aggressive behavior, as observed in laying hens subjected to a social challenge [187]. Hence, probiotic supplementation in feed leads to improved animal welfare, reduced stress, and better productivity in poultry and other animals.

4. Challenges, Specific Knowledge Gaps, and Future Research

The increasing risk of antimicrobial resistance and the growing demand for safe, residue-free animal products have driven attention toward the potential use of probiotics as alternatives to AGPs in the poultry industry. This is also the case for Nigerian indigenous poultry, which is a significant contributor to the livelihoods and food security of rural and semi-urban households.

The potential of probiotics to improve growth performance, feed utilization, and production in poultry has been extensively explored. In indigenous breeds, they ensure the integrity of the intestine by stimulating the balanced growth of the intestinal microflora, improving nutrient absorption and intestinal immunoregulation. For instance, some studies have reported that including probiotics in the diet of chickens can lead to an increase in carcass yield and meat quality, resulting from reduced fat deposition and improved muscle texture and taste characteristics, which are increasingly sought after by modern consumers. However, these should be investigated in Nigerian local chickens.

In the context of environmental concerns, organic acids act as probiotics and can help mitigate the emission of noxious gases such as ammonia and hydrogen sulphide associated with poultry waste. Probiotics, by enhancing gut fermentation processes, decrease nitrogenous excretion, thereby reducing the production of greenhouse gases and contributing to the sustainability of poultry production systems.

Notwithstanding the encouraging advantages, several challenges limit the acceptance of probiotics in Nigeria. Among them is the significant lack of indigenous poultry gut ecology-adapted strains. Furthermore, there are limited locally based breed-specific studies on the efficacy and safety of commercial probiotic strains. Poor farmer knowledge, a lack of generic standards governing regulatory conduct, and restricted access to affordable and quality-controlled products are additional constraints that prohibit the practical application.

Further studies are needed to focus on the isolation and characterization of indigenous probiotic strains, which can adapt promptly to local poultry genotypes and conditions. Multi-local field studies on performance, gut microbiota modulation, and eco-environmental impact are needed under both semi-intensive and extensive husbandry conditions. Integrated extension strategies for disseminating recommendations and promoting farmers' adoption also need to be developed and strengthened.

5. Conclusions

The Nigerian Indigenous Ecotype Chicken (NIEC) plays a vital role in rural food systems, livelihoods, and cultural traditions. Though they exhibit lower productivity compared to commercial breeds, their resilience to local environmental stressors and disease makes them indispensable to sustainable poultry systems in Nigeria. However, the growing demand for animal protein, coupled with rising concerns about antimicrobial resistance (AMR), highlights the urgent need for viable, sustainable alternatives to antibiotics.

Probiotics have emerged as promising feed additives that enhance gut health, immunity, and nutrient utilization, contributing to improved performance and food safety. Yet, while extensive research has focused on their use in commercial poultry, application in NIEC remains limited. To ensure effective adoption, probiotic strategies must be tailored to the genetic and microbial profiles of indigenous breeds.

Key priorities moving forward include the isolation and characterization of probiotic strains native to the NIEC gastrointestinal tract, which could offer more context-specific benefits. Additionally, cost-subsidized field deployment of validated probiotic products is crucial to encourage widespread adoption among smallholder farmers. Government policy support is equally vital, particularly in the form of funding for local research, regulation of probiotic products, and integration of probiotics into national livestock health strategies.

An integrated, locally driven approach that combines scientific research, practical field application, farmer education, and institutional backing will be essential to unlocking probiotics' full potential in enhancing Nigeria's indigenous poultry sector's health, resilience, and productivity.

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References

1. Sharma, P.; Vidyarthi, V.K. Impact of microplastic intake via poultry products: Environmental toxicity and human health. *J. Hazard. Mater. Adv.* **2024**, *14*, 100426. [CrossRef]
2. Mnisi, C.M.; Mlambo, V.; Montso, P.K.; Manyeula, F.; Kumanda, C.; Moreki, J.C. Nutraceuticals as components of sustainable poultry production systems for food and nutrition security in Africa: A review. *Agric. Food Secur.* **2024**, *13*, 24. [CrossRef]
3. Djikeng, A.; Olori, V.E.; Houaga, I.; Aggrey, S.E.; Mwai, O.; Ibeagha-Awemu, E.M.; Mrode, R.; Chagunda, M.G.G.; Tiambo, C.K.; Rekaya, R.; et al. The African Animal Breeding Network as a pathway towards genetic improvement of livestock. *Nat. Genet.* **2025**, *57*, 498–504. [CrossRef]
4. United Nations. 9.7 Billion on Earth by 2050, But Growth Rate Slowing, Says New UN Population Report | UN News. 2019. Available online: https://news.un.org/en/story/2019/06/1040621 (accessed on 6 April 2025).

5. Ponnampalam, E.N.; Holman, B.W.B. Sustainability II: Sustainable animal production and meat processing. In *Lawrie's Meat Science*; Elsevier: Amsterdam, The Netherlands, 2023; pp. 727–798. [CrossRef]
6. Galal, S. Livestock Population of Major Species in Africa as of 2022. Available online: https://www.statista.com/statistics/1290023/livestock-population-in-africa/ (accessed on 30 May 2025).
7. Manyelo, T.G.; Selaledi, L.; Hassan, Z.M.; Mabelebele, M. Local Chicken Breeds of Africa: Their Description, Uses and Conservation Methods. *Animals* **2020**, *10*, 2257. [CrossRef]
8. Rachman, M.P.; Bamidele, O.; Dessie, T.; Smith, J.; Hanotte, O.; Gheyas, A.A. Genomic analysis of Nigerian indigenous chickens reveals their genetic diversity and adaptation to heat-stress. *Sci. Rep.* **2024**, *14*, 2209. [CrossRef] [PubMed]
9. Pewan, S.B.; Yibis, G.G.; Danbirni, S.; Nyam, P.P.; Tahir, I.; Mbap, S.T. Effects of seasons on haematologic and serum biochemical profiles of indigenous chickens in Shendam, Plateau State, Nigeria. *Niger. J. Anim. Sci.* **2019**, *21*, 77–84.
10. Ikpeme, E.; Ekerette, E.E.; Job, I.E.; Umoyen, A.J.; Osim, P.B.; Ozoje, M.O. Genetic relationship among three Nigerian chicken (*Gallus gallus*) genotypes based on cytochrome-b of mitochondrial DNA. *Asian J. Anim. Sci.* **2020**, *15*, 35–42. [CrossRef]
11. Kasimanickam, V.; Kasimanickam, M.; Kasimanickam, R. Antibiotics use in food animal production: Escalation of antimicrobial resistance: Where are we now in combating AMR? *Med. Sci.* **2021**, *9*, 14. [CrossRef]
12. Dokuta, S.; Yadoung, S.; Hongjaisee, S.; Khamnoi, P.; Manochomphu, S.; Chuttong, B.; Hongsibsong, S. Seasonal Determination of Antibiotic-Resistant Microorganisms and Ciprofloxacin Residues in Pork and Chicken Meats Collected from Fresh Markets in Chiang Mai, Northern Thailand. *Foods* **2025**, *14*, 174. [CrossRef]
13. Cortés-Avizanda, A.; Blanco, G.; De Vault, T.L.; Markandya, A.; Virani, M.Z.; Donázar, J.A. Supplementary feeding and endangered avian scavengers: Benefits, caveats and controversies. *Front. Ecol. Environ.* **2016**, *14*, 191–199. [CrossRef]
14. Liu, T.; Shao, Y.; Pang, X.; Liu, Y.; Mo, X.; Chen, Z.; Lu, X. Intestinal microbiota and high-risk antibiotic resistance genes in wild birds with varied ecological traits: Insights from opportunistic direct sampling in Tianjin, China. *Environ. Res.* **2023**, *263*, 120040. [CrossRef] [PubMed]
15. Ndahi, M.D.; Hendriksen, R.; Helwigh, B.; Card, R.M.; Fagbamila, I.O.; Abiodun-Adewusi, O.O.; Ekeng, E.; Adetunji, V.; Adebiyi, I.; Andersen, J.K. Determination of antimicrobial use in commercial poultry farms in Plateau and Oyo States, Nigeria. *Antimicrob. Resist. Infect. Control.* **2023**, *12*, 30. [CrossRef]
16. Cullen, L.; Neale, D.; Kinchin, H. Exploring perceptions of bacteriophage use in the UK across the One Health spectrum: A roundtable discussion. *Sustain. Microbiol.* **2024**, *1*, qvae030. [CrossRef]
17. Tran, C.; Horyanto, D.; Stanley, D.; Cock, I.E.; Chen, X.; Feng, Y. Antimicrobial Properties of *Bacillus* Probiotics as Animal Growth Promoters. *Antibiotics* **2023**, *12*, 407. [CrossRef] [PubMed]
18. Dong, S.; Li, L.; Hao, F.; Fang, Z.; Zhong, R.; Wu, J.; Fang, X. Improving quality of poultry and its meat products with probiotics, prebiotics, and phytoextracts. *Poult. Sci.* **2024**, *103*, 103287. [CrossRef] [PubMed]
19. Saeed, M.; Afzal, Z.; Afzal, F.; Khan, R.U.; Elnesr, S.S.; Alagawany, M.; Chen, H. Use of postbiotic as growth promoter in poultry industry: A review of current knowledge and future prospects. *Food Sci. Anim. Resour.* **2023**, *43*, 1111. [CrossRef]
20. Obianwuna, U.E.; Chang, X.; Oleforuh-Okoleh, V.U.; Onu, P.N.; Zhang, H.; Qiu, K.; Wu, S. Phytobiotics in poultry: Revolutionizing broiler chicken nutrition with plant-derived gut health enhancers. *J. Anim. Sci. Biotechnol.* **2024**, *15*, 169. [CrossRef]
21. Olorundare, O.O.; Zrelovs, N.; Kabantiyok, D.; Svanberga, K.; Jansons, J.; Kazaks, A.; Agada, G.O.; Agu, C.G.; Morenikeji, O.R.; Oluwapelumi, O.A.; et al. Isolation and Characterization of a Novel Jumbo Phage HPP-Temi Infecting *Pseudomonas aeruginosa* Pa9 and Increasing Host Sensitivity to Ciprofloxacin. *Antibiotics* **2024**, *13*, 1006. [CrossRef]
22. Lipilkina, T.A.; Xu, C.; Barbosa, M.d.S.; Khramova, V.N.; Shebeko, S.K.; Ermakov, A.M.; Ivanova, I.V.; Todorov, S.D. Beneficial and Safety Properties of a Bacteriocinogenic and Putative Probiotic *Latilactobacillus sakei* subsp. *sakei* 2a Strain. *Foods* **2024**, *13*, 3770. [CrossRef]
23. Cowieson, A.J.; Kluenter, A.M. Contribution of exogenous enzymes to potentiate the removal of antibiotic growth promoters in poultry production. *Anim. Feed Sci. Technol.* **2019**, *250*, 81–92. [CrossRef]
24. Marquardt, R.R.; Li, S. Antimicrobial resistance in livestock: Advances and alternatives to antibiotics. *Anim. Front.* **2018**, *8*, 30–37. [CrossRef] [PubMed]
25. Barman, I.; Seo, H.; Kim, S.; Rahim, M.A.; Yoon, Y.; Hossain, M.S.; Shuvo, S.H.; Song, H.Y. Isolation of New Strains of Lactic Acid Bacteria from the Vaginal Microbiome of Postmenopausal Women and their Probiotic Characteristics. *Curr. Microbiol.* **2025**, *82*, 76. [CrossRef]
26. Jan, T.; Negi, R.; Sharma, B.; Kour, D.; Kumar, S.; Rai, A.K.; Rustagi, S.; Singh, S.; Sheikh, M.A.; Kumar, K.J.B. Diversity, distribution and role of probiotics for human health: Current research and future challenges. *Biocatal. Agric. Biotechnol.* **2023**, *53*, 102889. [CrossRef]
27. Ebeid, T.A.; Al-Homidan, I.H.; Fathi Moataz, M. Physiological and immunological benefits of probiotics and their impacts in poultry productivity. *World's Poult Sci. J.* **2021**, *77*, 883–899. [CrossRef]
28. Halder, N.; Sunder, J.; De, A.K.; Bhattacharya, D.; Joardar, S.N. Probiotics in poultry: A comprehensive review. *J. Basic Appl. Zool.* **2024**, *85*, 23. [CrossRef]

29. Shehata, A.A.; Yalçın, S.; Latorre, J.D.; Basiouni, S.; Attia, Y.A.; Abd El-Wahab, A.; Visscher, C.; El-Seedi, H.R.; Huber, C.; Hafez, H.M.; et al. Probiotics, Prebiotics, and Phytogenic Substances for Optimizing Gut Health in Poultry. *Microorganisms* **2022**, *10*, 395. [CrossRef]
30. Lan, R.; Tran, H.; Kim, I. Effects of probiotic supplementation in different nutrient density diets on growth performance, nutrient digestibility, blood profiles, faecal microflora and noxious gas emission in weaning pig. *J. Sci. Food Agric.* **2017**, *97*, 1335–1341. [CrossRef]
31. Herich, R.; Szabóová, R.; Karaffová, V.; Racines, M.P.; Šefcová, M.A.; Larrea-Álvarez, M. A Narrative Review on the Impact of Probiotic Supplementation on Muscle Development, Metabolic Regulation, and Fiber Traits Related to Meat Quality in Broiler Chickens. *Microorganisms* **2025**, *13*, 784. [CrossRef]
32. Leão, A.P.A.; Alvarenga, R.R.; Zangeronimo, M.G. In Ovo Inoculation of Probiotics for Broiler Chickens: Systematic Review and Meta-Analysis. *Anim. Feed Sci. Technol.* **2021**, *280*, 115080. [CrossRef]
33. Grace, D.; Knight-Jones, T.J.D.; Melaku, A.; Alders, R.; Jemberu, W.T. The Public Health Importance and Management of Infectious Poultry Diseases in Smallholder Systems in Africa. *Foods* **2024**, *13*, 411. [CrossRef] [PubMed]
34. Wong, J.T.; de Bruyn, J.; Bagnol, B.; Grieve, H.; Li, M.; Pym, R.; Alders, R.G. Small-scale poultry and food security in resource-poor settings: A review. *Glob. Food Secur.* **2017**, *15*, 43–52. [CrossRef]
35. Odah, E.O.; Daikwo, S.I.; Mbap, S.T.; Okpanachi, U. Phenotypic characterization of local chickens (gallus gallus domesticus) in Bekwarra Cross River State, Nigeria. *JSM Vet. Med. Res.* **2019**, *2*, 1–7.
36. Sokoya, O.O.; Babajide, J.M.; Shittu, T.A.; Sanwo, K.A.; Adegbite, J.A. Chemical and colour characterisation of breast meat from FUNAAB indigenous and Marshall broiler chickens. *Trop. Anim. Health Prod.* **2019**, *51*, 2575–2582. [CrossRef]
37. Yakubu, A.; Dahloum, L.; Gimba, E.G. Smallholder cattle farmers' breeding practices and trait preferences in a tropical guinea savanna agro-ecological zone. *Trop. Anim. Health Prod.* **2019**, *51*, 1497–1506. [CrossRef] [PubMed]
38. Desta, T.T. Indigenous village chicken production: A tool for poverty alleviation, the empowerment of women, and rural development. *Trop. Anim. Health Prod.* **2021**, *53*, 337. [CrossRef]
39. Adesola, R.O.; Idris, I.; Bakre, A.A. Implementation of national poultry improvement plan in poultry disease control in Africa: Current perspectives, challenges, and prospects. *Bull. Natl. Res. Cent.* **2025**, *49*, 10. [CrossRef]
40. Matloa, T.; Erasmus, R.; Ledwaba, M.B.; Malatji, D.P. Avian haemosporidian parasites affecting non-descript village chickens in Africa. *Trop. Anim. Health Prod.* **2025**, *57*, 28. [CrossRef]
41. Enahoro, D.; Galiè, A.; Abukari, Y.; Chiwanga, G.H.; Kelly, T.R.; Kahamba, J.; Massawe, F.A.; Mapunda, F.; Jumba, H.; Weber, C.; et al. Strategies to upgrade animal health delivery in village poultry systems: Perspectives of stakeholders from Northern Ghana and Central Zones in Tanzania. *Front. Vet. Sci.* **2021**, *8*, 611357. [CrossRef] [PubMed]
42. Ouma, E.A.; Kankya, C.; Dione, M.; Kelly, T.; Enahoro, D.; Chiwanga, G.; Abukari, Y.; Msoffe, P.; Kayang, B.B.; Zhou, H. Poultry health constraints in smallholder village poultry systems in Northern Ghana and Central Tanzania. *Front. Vet. Sci.* **2023**, *10*, 1159331. [CrossRef] [PubMed]
43. Agusi, E.R.; Kabantiyok, D.; Mkpuma, N.; Atai, R.B.; Okongwu-Ejike, C.; Bakare, E.L.; Budaye, J.; Sule, K.G.; Rindaps, R.J.; James, G.K.; et al. Prevalence of multidrug-resistant *Escherichia coli* isolates and virulence gene expression in poultry farms in Jos, Nigeria. *Front. Microbiol.* **2024**, *15*, 1298582. [CrossRef] [PubMed]
44. Mazhar, S.H.; Li, X.; Rashid, A.; Su, J.; Xu, J.; Brejnrod, A.D.; Su, J.-Q.; Wu, Y.; Zhu, Y.-G.; Zhou, S.G.; et al. Co-selection of antibiotic resistance genes, and mobile genetic elements in the presence of heavy metals in poultry farm environments. *Sci. Total Environ.* **2021**, *755*, 142702. [CrossRef] [PubMed]
45. Andrew Selaledi, L.; Mohammed Hassan, Z.; Manyelo, T.G.; Mabelebele, M. The Current Status of the Alternative Use to Antibiotics in Poultry Production: An African Perspective. *Antibiotics* **2020**, *9*, 594. [CrossRef]
46. Manyi-Loh, C.; Manphweli, S.; Meyer, E.; Okoh, A. Antibiotic use in agriculture and its consequential resistance in environmental sources: Potential public health implications. *Molecules* **2018**, *23*, 795. [CrossRef]
47. Gadde, U.; Kim, W.H.; Oh, S.T.; Lillehoj, H.S. Alternatives to antibiotics for maximizing growth performance and feed efficiency in poultry: A review. *Anim. Health Res. Rev.* **2017**, *18*, 26–45. [CrossRef]
48. Rushton, J. Anti-microbial use in animals: How to assess the trade-offs. *Zoonoses Public Health* **2015**, *62*, 10–21. [CrossRef] [PubMed]
49. Van, T.T.H.; Yidana, Z.; Smooker, P.M.; Coloe, P.J. Antibiotic use in food animals in the world with focus on Africa: Pluses and minuses. *J. Glob. Antimicrob. Resist.* **2020**, *20*, 170–177. [CrossRef] [PubMed]
50. Ronquillo, M.G.; Hernandez, J.C.A. Antibiotic and synthetic growth promoters in animal diets: Review of impact and analytical methods. *Food Control* **2017**, *72*, 255–267. [CrossRef]
51. Oladeji, O.M.; Mugivhisa, L.L.; Olowoyo, J.O. Antibiotic Residues in Animal Products from Some African Countries and Their Possible Impact on Human Health. *Antibiotics* **2025**, *14*, 90. [CrossRef] [PubMed]
52. Lateefat, H.M.; Olaniyi, O.A.; Misbahu, G.; Raimi, O.M. A wake-up call: Determination of antibiotics residue level in raw meat in abattoir and selected slaughterhouses in five local government in Kano State, Nigeria. *bioRxiv* **2022**. [CrossRef]

53. Abbas, W.; Bi, R.; Hussain, M.D.; Tajdar, A.; Guo, F.; Guo, Y.; Wang, Z. Antibiotic Cocktail Effects on Intestinal Microbial Community, Barrier Function, and Immune Function in Early Broiler Chickens. *Antibiotics* **2024**, *13*, 413. [CrossRef]
54. Ire, F.S.; Njoku, T.T.; Ahaotu, I.; Maduka, N. Bioefficacy performance and meat quality of a commercial feed supplemented with probiotics on broilers. *Sci. Afr.* **2024**, *23*, 213–230.
55. Nagpala, M.J.; Mora, J.F.; Pavon, R.D.; Rivera, W.L. Genomic characterization of antimicrobial-resistant Salmonella enterica in chicken meat from wet markets in Metro Manila, Philippines. *Front. Microbiol.* **2025**, *16*, 1496685. [CrossRef]
56. Danaei, B.; Sarmastzadeh, T.; Khalili, F.; Yazarlou, F.; Centis, R.; D'Ambrosio, L.; Sotgiu, G.; Migliori, G.B.; Nasiri, M.J. The battle against colistin-resistant *E. coli* and the need for a one health approach. *New Microbes New Infect.* **2023**, *54*, 101161. [CrossRef]
57. Bacanlı, M.G. The two faces of antibiotics: An overview of the effects of antibiotic residues in foodstuffs. *Arch. Toxicol.* **2024**, *98*, 1717–1725. [CrossRef]
58. Ghimpețeanu, O.M.; Pogurschi, E.N.; Popa, D.C.; Dragomir, N.; Drăgotoiu, T.; Mihai, O.D.; Petcu, C.D. Antibiotic Use in Livestock and Residues in Food—A Public Health Threat: A Review. *Foods* **2022**, *16*, 1430. [CrossRef]
59. Lhermie, G.; Grohn, Y.T.; Raboisson, D. Addressing antimicrobial resistance: An overview of priority actions to prevent suboptimal antimicrobial use in food-animal production. *Front. Microbiol.* **2016**, *7*, 2114. [CrossRef]
60. Sardar, D.; Afsana, S.; Habib, A.; Hossain, T. Dietary effects of multi-strain probiotics as an alternative to antibiotics on growth performance, carcass characteristics, blood profiling and meat quality of broilers. *Vet. Integr. Sci.* **2025**, *23*, 255–267. [CrossRef]
61. Murungi, M.; Vudriko, P.; Ndagije, H.B.; Kesi, D.N.; Serwanga, A.; Rajab, K.; Manirakiza, L.; Waswa, J.P.; Kasujja, H.; Barigye, M.; et al. National-Level Consumption of Antimicrobials in the Veterinary Sector in Uganda: A Report on Analysis of Import Data for 2021. *Antibiotics* **2025**, *14*, 150. [CrossRef]
62. Odey, T.O.J.; Tanimowo, W.O.; Afolabi, K.O.; Jahid, I.K.; Reuben, R.C. Antimicrobial use and resistance in food animal production: Food safety and associated concerns in Sub-Saharan Africa. *Int. Microbiol.* **2024**, *27*, 1–23. [CrossRef]
63. Craig, J.; Hiban, K.; Frost, I.; Kapoor, G.; Alimi, Y.; Varma, J.K. Comparison of national antimicrobial treatment guidelines, African Union. *Bull. World Health Org.* **2022**, *100*, 50. [CrossRef] [PubMed]
64. Gulumbe, B.H.; Haruna, U.A.; Almazan, J.; Ibrahim, I.H.; Faggo, A.A.; Bazata, A.Y. Combating the menace of antimicrobial resistance in Africa: A review on stewardship, surveillance and diagnostic strategies. *Biol. Proced. Online* **2022**, *24*, 19. [CrossRef] [PubMed]
65. Tukaram, N.M.; Biswas, A.; Deo, C.; Laxman, A.J.; Monika, M.; Tiwari, A.K. Effects of paraprobiotic as replacements for antibiotic on performance, immunity, gut health and carcass characteristics in broiler chickens. *Sci. Rep.* **2022**, *12*, 22619. [CrossRef]
66. Akhavan, N.; Hrynkiewicz, K.; Thiem, D.; Randazzo, C.; Walsh, A.M.; Guinan, K.J.T.J.; Stadnicka, K. Evaluation of probiotic growth stimulation using prebiotic ingredients to optimize compounds for in ovo delivery. *Front. Microbiol.* **2023**, *14*, 1242027. [CrossRef]
67. Cunningham, M.; Azcarate-Peril, M.A.; Barnard, A.; Benoit, V.; Grimaldi, R.; Guyonnet, D.; Holscher, H.D.; Hunter, K.; Manurung, S.; Obis, D.; et al. Shaping the future of probiotics and prebiotics. *Trends Microbiol.* **2021**, *29*, 667–685. [CrossRef]
68. Teng, P.Y.; Kim, W.K. Roles of prebiotics in intestinal ecosystem of broilers. *Front. Vet. Sci.* **2018**, *5*, 245. [CrossRef]
69. Xing, M.; Cao, Q.; Wang, Y.; Xiao, H.; Zhao, J.; Zhang, Q.; Ji, A.; Song, S. Advances in research on the bioactivity of alginate oligosaccharides. *Mar. Drugs* **2020**, *18*, 144. [CrossRef] [PubMed]
70. Morgan, N.K. Advances in prebiotics for poultry: Role of the caeca and Oligosaccharides. *Anim. Prod. Sci.* **2023**, *63*, 1911–1925. [CrossRef]
71. Liu, L.; Li, Q.; Yang, Y.; Guo, A. Biological Function of Short-Chain Fatty Acids and Its Regulation on Intestinal Health of Poultry. *Front. Vet. Sci.* **2021**, *8*, 736739. [CrossRef]
72. Ríos-Covián, D.; Ruas-Madiedo, P.; Abelardo, M.; Gueimonde, M.; Reyes-Gavilán, C.G.d.L.; Salazar, N. Intestinal short-chain fatty acids and their link with diet and human health. *Front. Microbiol.* **2016**, *7*, 185. [CrossRef]
73. Shini, S.; Bryden, W.L. Probiotics and gut health: Linking gut homeostasis and poultry productivity. *Anim. Prod. Sci.* **2021**, *62*, 1090–1112. [CrossRef]
74. Jiang, S.; Mohammed, A.; Jacobs, J.; Cramer, T.; Cheng, H. Effect of synbiotics on thyroid hormones, intestinal histomorphology, and heat shock protein 70 expression in broiler chickens reared under cyclic heat stress. *Poult. Sci.* **2020**, *99*, 142–150. [CrossRef]
75. Hossain, H.; Nuradji, H.; Miah, M.Y.; Islam, M.N.; Siddiqui, M.S.I. Impact of synbiotic on growth performance, histo-architectural modulation of lymphoid organ, hematology, blood biochemistry and humoral immune response in naked neck chicken. *Trop. Anim. Health Prod.* **2025**, *57*, 4. [CrossRef]
76. Bueno, D.J.; Latorre, J.D.; Shehata, A.A.; Eisenreich, W.; Tellez, G. Strategies to attack pathogenic avian microorganisms: From probiotics to postbiotics. *Ger. J. Vet. Res.* **2024**, *4*, 95–118. [CrossRef]
77. Youssef, I.M.; Elsherbeni, A.I.; Almuraee, A.A.; Nass, N.M.; Beyari, E.A.; Alshammarii, N.M.; Abdel-Ghany, A.M.; Ahmed, E.S.G.; Nasr, S.; Youssef, K.M.; et al. Influence of using synbiotics by various routes on Mandarah male chicks: Intestinal bacterial counts, gut morphology and histological status. *Poult. Sci.* **2024**, *103*, 103601. [CrossRef]

78. Sayed, Y.; Hassan, M.; Salem, H.M.; Al-Amry, K.; Eid, G.E. Probiotics/prebiotics effect on chicken gut microbiota and immunity in relation to heat-stress and climate-change mitigation. *J. Therm. Biol.* **2025**, *129*, 104097. [CrossRef]
79. Olowoyeye, J.C. Biotics as Sustainable Alternatives to Antibiotics in Nigerian Poultry Farming. *Asian J. Food Res. Nutr.* **2025**, *4*, 522–533. [CrossRef]
80. Hossain, M.I.; Mizan, M.F.R.; Roy, P.K.; Nahar, S.; Toushik, S.H.; Ashrafudoulla, M.; Jahid, I.K.; Lee, J.; Ha, S.D. Listeria monocytogenes biofilm inhibition on food contact surfaces by application of postbiotics from Lactobacillus curvatus B.67 and Lactobacillus plantarum M.2. *Food Res. Int.* **2021**, *148*, 110595. [CrossRef]
81. Urban, J.; Kareem, K.Y.; Atanasov, A.G.; Matuszewski, A.; Bień, D.; Ciborowska, P.; Rygało-Galewska, A.; Michalczuk, M. Postbiotics, a natural feed additive for growth performance, gut microbiota and quality of poultry products. *Curr. Res. Biotechnol.* **2024**, *8*, 100247. [CrossRef]
82. Chaney, W.E.; Naqvi, S.A.; Gutierrez, M.; Gernat, A.; Johnson, T.J.; Petry, D. Dietary Inclusion of a *Saccharomyces cerevisiae*-Derived Postbiotic Is Associated with Lower *Salmonella enterica* Burden in Broiler Chickens on a Commercial Farm in Honduras. *Microorganisms* **2022**, *10*, 544. [CrossRef]
83. Diez-Gutiérrez, L.; San Vicente, L.; Barrón, L.J.R.; del Carmen Villarán, M.; Chávarri, M. Gamma-aminobutyric acid and probiotics: Multiple health benefits and their future in the global functional food and nutraceuticals market. *J. Funct. Foods* **2020**, *64*, 103669. [CrossRef]
84. Chaluvadi, S.; Hotchkiss, A.T.; Yam, K.L. Gut microbiota: Impact of probiotics, prebiotics, synbiotics, pharmabiotics, and postbiotics on human health. In *Probiotics, Prebiotics, and Synbiotics: Bioactive Foods in Health Promotion*; Academic Press: Cambridge, MA, USA, 2015; pp. 515–523. [CrossRef]
85. Żółkiewicz, J.; Marzec, A.; Ruszczyński, M.; Feleszko, W. Postbiotics—A Step Beyond Pre- and Probiotics. *Nutrients* **2020**, *12*, 2189. [CrossRef]
86. Khodaii, Z.; Ghaderian, S.M.H.; Natanzi, M.M. Probiotic Bacteria and their Supernatants Protect Enterocyte Cell Lines from Enteroinvasive Escherichia coli (EIEC) Invasion. *Int. J. Mol. Cell. Med.* **2017**, *6*, 183–189. [PubMed]
87. Otto, J.R.; Mwangi, F.W.; Pewan, S.B.; Holman, B.W.B.; Malau-Aduli, A.E.O. Emerging applications of postbiotics to sustainable livestock production systems. *Aust. J. Agric. Vet. Anim. Sci.* **2025**, *1*, 100002.
88. Danladi, Y.; Teck, C.H.; Hooi, L.F. Effect of supplementation of postbiotics and pararobiotics on the immune response of broiler chickens. *Niger. J. Anim. Prod.* **2024**, 1311–1316. [CrossRef]
89. Çam, G.; Akın, N.; Konak Göktepe, Ç.; Demirci, T. Pea (*Pisum sativum* L.) pod powder as a potential enhancer of probiotic *Enterococcus faecium* M74 in ice cream and its physicochemical, structural, and sensory effects. *J. Sci. Food Agric.* **2023**, *103*, 3184–3193. [CrossRef]
90. Latif, A.; Shehzad, A.; Niazi, S.; Zahid, A.; Ashraf, W.; Iqbal, M.W.; Rehman, A.; Riaz, T.; Aadil, R.M.; Khan, I.M.; et al. Probiotics: Mechanism of action, health benefits and their application in food industries. *Front. Microbiol.* **2023**, *14*, 1216674. [CrossRef] [PubMed]
91. Wieërs, G.; Belkhir, L.; Enaud, R.; Leclercq, S.; Philippart de Foy, J.M.; de Timary Dequenne, I.; Cani, P.D. How probiotics affect the microbiota. *Front. Cell. Infect. Microbiol.* **2020**, *9*, 454. [CrossRef]
92. Rasinkangas, P.; Forssten, S.D.; Marttinen, M.; Ibarra, A.; Bothe, G.; Junnila, J.; Uebelhack, R.; Donazzolo, Y.; Ouwehand, A.C. *Bifidobacterium animalis* subsp. lactis Bi-07 supports lactose digestion in vitro and in randomized, placebo- and lactase-controlled clinical trials. *Am. J. Clin. Nutr.* **2022**, *116*, 1580–1594. [CrossRef]
93. Sałański, P.; Kowalczyk, M.; Bardowski, J.K.; Szczepankowska, A.K. Health-Promoting nature of *Lactococcus lactis* IBB109 and *Lactococcus lactis* IBB417 strains exhibiting proliferation inhibition and stimulation of interleukin-18 expression in colorectal cancer cells. *Front. Microbiol.* **2022**, *13*, 822912. [CrossRef]
94. Wang, S.; Ren, H.; Zhong, H.; Zhao, X.; Li, C.; Ma, J.; Gu, X.; Xue, Y.; Huang, S.; Yang, J.; et al. Combined berberine and probiotic treatment as an effective regimen for improving postprandial hyperlipidemia in type 2 diabetes patients: A double blinded placebo controlled randomized study. *Gut Microbes* **2022**, *14*, 2003176. [CrossRef]
95. Zommiti, M.; Feuilloley, M.G.J.; Connil, N. Update of Probiotics in Human World: A Nonstop Source of Benefactions till the End of Time. *Microorganisms* **2020**, *8*, 1907. [CrossRef]
96. Kabir, S.L. Dietary probiotics in poultry: A game-changer for growth, immunity, and microbiota balance. *Asian J. Med. Biol. Res.* **2025**, *11*, 1–4. [CrossRef]
97. Diaz Carrasco, J.M.; Casanova, N.A.; Fernández Miyakawa, M.E. Microbiota, Gut Health and Chicken Productivity: What Is the Connection? *Microorganisms* **2019**, *7*, 374. [CrossRef]
98. Krysiak, K.; Konkol, D.; Korczyński, M. Overview of the Use of Probiotics in Poultry Production. *Animals* **2021**, *11*, 1620. [CrossRef] [PubMed]
99. Fusco, V.; Wu, R.; Zhang, W.; Zhai, Q. Editorial: Role of probiotics and probiotics' metabolites in food and intestine. *Front. Microbiol.* **2023**, *14*, 1183550. [CrossRef]

100. Brito Sampaio, K.; Fusco, V.; de Brito Alves, J.L.; Leite de Souza, E. Chapter 1—Probiotics: Concepts, evolution, and applications. In *Probiotics for Human Nutrition in Health and Disease*; Leite de Souza, E., de Brito Alves, J.L., Fusco, V., Eds.; Academic Press: Cambridge, MA, USA, 2022; ISBN 9780323899086.
101. Idowu, P.A.; Mpofu, T.J.; Magoro, A.M.; Modiba, M.C.; Nephawe, K.A.; Mtileni, B. Impact of probiotics on chicken gut microbiota, immunity, behavior, and productive performance—A systematic review. *Front. Anim. Sci.* **2025**, *6*, 1562527. [CrossRef]
102. Al-Shawi, S.G.; Dang, D.S.; Yousif, A.Y.; Al-Younis, Z.K.; Najm, T.A.; Matarneh, S.K. The Potential Use of Probiotics to Improve Animal Health, Efficiency, and Meat Quality: A Review. *Agriculture* **2020**, *10*, 452. [CrossRef]
103. Ezema, C. Probiotics in animal production: A review. *J. Vet. Med. Anim. Health* **2013**, *5*, 308–316.
104. de Melo Pereira, G.V.; de Oliveira Coelho, B.; Magalhães Júnior, A.I.; Thomaz-Soccol, V.; Soccol, C.R. How to select a probiotic? A review and update of methods and criteria. *Biotechnol. Adv.* **2018**, *36*, 2060–2076. [CrossRef]
105. Sarita, B.; Samadhan, D.; Hassan, M.Z.; Kovaleva, E.G. A comprehensive review of probiotics and human health-current prospective and applications. *Front. Microbiol.* **2025**, *15*, 1487641. [CrossRef]
106. Mazziotta, C.; Tognon, M.; Martini, F.; Torreggiani, E.; Rotondo, J.C. Probiotics mechanism of action on immune cells and beneficial effects on human health. *Cells* **2023**, *12*, 184. [CrossRef]
107. Marková, K.; Kreisinger, J.; Vinkler, M. Are there consistent effects of gut microbiota composition on performance, productivity and condition in poultry? *Poult. Sci.* **2024**, *103*, 103752. [CrossRef]
108. Dinalli, V.P.; Costa, M.C.; Venâncio, E.J.; Filho, J.A.B.; Bessegatto, J.A.; Holkem, A.T.; Alfieri, A.A.A.; da Silva, C.A.; Oba, A. Impact of *Chlorella vulgaris* and probiotic supplementation on performance, immunity and intestinal microbiota of broiler chickens. *PLoS ONE* **2025**, *20*, e0313736. [CrossRef]
109. Berg, G.; Rybakova, D.; Fischer, D.; Cernava, T.; Vergès, M.C.C.; Charles, T.; Chen, X.; Cocolin, L.; Eversole, K.; Corral, G.H.; et al. Microbiome definition re-visited: Old concepts and new challenges. *Microbiome* **2020**, *8*, 103. [CrossRef]
110. Prajapati, K.; Bisani, K.; Prajapati, H.; Prajapati, S.; Agrawal, D.; Singh, S.; Saraf, M.; Goswami, D. Advances in probiotics research: Mechanisms of action, health benefits, and limitations in applications. *Syst. Microbiol. Biomanufacturing* **2024**, *4*, 386–406. [CrossRef]
111. Wang, Y.; Sun, J.; Zhong, H.; Li, N.; Xu, H.; Zhu, Q.; Liu, P. Effect of probiotics on the meat flavour and gut microbiota of chicken. *Sci. Rep.* **2017**, *7*, 6400. [CrossRef] [PubMed]
112. Emami, N.K.; Calik, A.; White, M.B.; Kimminau, E.A.; Dalloul, R.A. Effect of Probiotics and Multi-Component Feed Additives on Microbiota, Gut Barrier and Immune Responses in Broiler Chickens During Subclinical Necrotic Enteritis. *Front. Vet. Sci.* **2020**, *7*, 572142. [CrossRef]
113. Rychlik, I. Composition and Function of Chicken Gut Microbiota. *Animals* **2020**, *10*, 103. [CrossRef] [PubMed]
114. Khan, S.; Moore, R.J.; Stanley, D.; Chousalkar, K.K. The gut microbiota of laying hens and its manipulation with prebiotics and probiotics to enhance gut health and food safety. *Appl. Environ. Microbiol.* **2020**, *86*, e00600-20. [CrossRef]
115. Bist, R.B.; Bist, K.; Poudel, S.; Subedi, D.; Yang, X.; Paneru, B.; Mani, S.; Wang, D.; Chai, L. Sustainable poultry farming practices: A critical review of current strategies and future prospects. *Poult. Sci.* **2024**, *103*, 104295. [CrossRef]
116. Park, I.; Lee, Y.; Goo, D.; Zimmerman, N.P.; Smith, A.H.; Rehberger, T.; Lillehoj, H.S. The effects of dietary Bacillus subtilis supplementation, as a alternative to antibiotics, on growth performance, intestinal immunity, and epithelial barrier integrity in broiler chickens infected with Eimeria maxima. *Poult. Sci.* **2020**, *99*, 725–733. [CrossRef]
117. Ritzi, M.M.; Abdelrahman, W.; Mohnl, M.; Dalloul, R.A. Effects of probiotics and application methods on performance and response of broiler chickens to an *Eimeria* challenge. *Poult. Sci.* **2014**, *93*, 2772–2778. [CrossRef]
118. Jha, R.; Das, R.; Oak, S.; Mishra, P. Probiotics (Direct-Fed Microbials) in Poultry Nutrition and Their Effects on Nutrient Utilization, Growth and Laying Performance, and Gut Health: A Systematic Review. *Animals* **2020**, *10*, 1863. [CrossRef]
119. Zhen, R.; Feng, J.; He, D.; Chen, Y.; Chen, T.; Cai, W.; Xiong, Y.; Qiu, Y.; Jiang, Z.; Wang, L.; et al. Effects of Niacin on Resistance to Enterotoxigenic *Escherichia coli* Infection in Weaned Piglets. *Front. Nutr.* **2022**, *9*, 865311. [CrossRef]
120. Gondim, D.R.; Cecilia, J.A.; Rodrigues, T.N.B.; Vilarrasa-García, E.; Rodríguez-Castellón, E.; Azevedo, D.C.S.; Silva, I.J., Jr. Protein Adsorption onto Modified Porous Silica by Single and Binary Human Serum Protein Solutions. *Int. J. Mol. Sci.* **2021**, *22*, 9164. [CrossRef]
121. Yangbo, J.; Weiqiang, H.; Qihang, Z.; Lin, L.; Jie, Z.; Yongfu, C. Inactivated Lactiplantibacillus plantarum Ps-8 enhances growth performance and intestinal health in broiler chickens via gut microbiota and serum metabolite modulation. *Poult. Sci.* **2025**, *104*, 105611. [CrossRef]
122. Rodríguez-Sorrento, A.; Castillejos, L.; López-Colom, P.; Cifuentes-Orjuela, G.; Rodríguez-Palmero, M.; Moreno-Muñoz, J.A.; Martín-Orúe, S.M. Effects of *Bifidobacterium longum* subsp. infantis CECT 7210 and *Lactobacillus rhamnosus* HN001, combined or not with oligofructose-enriched inulin, on weaned pigs orally challenged with *Salmonella typhimurium*. *Front. Microbiol.* **2020**, *11*, 2012. [CrossRef] [PubMed]

123. Tsuruda, C.T.; Souza, P.C.D.; Nishio, E.K.; Almeida, R.S.; Panagio, L.A.; Baptista, A.A.S.; Garcia, S.; Pinheiro, D.O.; Araújo, E.J.A.; Chue-Gonçalves, M.; et al. Lactobacillus rhamnosus V5 prevents Salmonella enterica serovar typhimurium invasion in cell culture and mice infection. *Microbiol. Res. J. Int.* **2020**, *30*, 44–57. [CrossRef]
124. Borda-Molina, D.; Vital, M.; Sommerfeld, V.; Rodehutscord, M.; Camarinha-Silva, A. Insights Into Broilers' Gut Microbiota Fed with Phosphorus, Calcium, and Phytase Supplemented Diets. *Front. Microbiol.* **2016**, *7*, 228625. [CrossRef]
125. Xu, Y.; Yang, H.; Zhang, L.; Su, Y.; Shi, D.; Xiao, H.; Tian, Y. High-Throughput Sequencing Technology to Reveal the Composition and Function of Cecal Microbiota in Dagu Chicken. *BMC Microbiol.* **2016**, *16*, 259. [CrossRef] [PubMed]
126. Magne, F.; Gotteland, M.; Gauthier, L.; Zazueta, A.; Pesoa, S.; Navarrete, P.; Balamurugan, R. The firmicutes/bacteroidetes ratio: A relevant marker of gut dysbiosis in obese patients? *Nutrients* **2020**, *12*, 1474. [CrossRef]
127. Jandhyala, S.M.; Talukdar, R.; Subramanyam, C.; Vuyyuru, H.; Sasikala, M.; Reddy, D.N. Role of the normal gut microbiota. *World J. Gastroenterol.* **2015**, *21*, 8836–8847. [CrossRef] [PubMed]
128. Bemark, M.; Pitcher, M.J.; Dionisi, C.; Spencer, J. Gut-associated lymphoid tissue: A microbiota-driven hub of B cell immunity. *Trends Immunol.* **2024**, *45*, 211–223. [CrossRef]
129. Broom, L.J.; Kogut, M.H. The role of the gut microbiome in shaping the immune system of chickens. *Vet. Immunol. Immunopathol.* **2018**, *204*, 44–51. [CrossRef] [PubMed]
130. Zhang, Q.; Eicher, S.D.; Applegate, T.J. Development of intestinal mucin 2, IgA, and polymeric Ig receptor expressions in broiler chickens and Pekin ducks. *Poult. Sci.* **2015**, *94*, 172–180. [CrossRef]
131. Gyawali, I.; Zhou, G.; Xu, G.; Li, G.; Wang, Y.; Zeng, Y.; Li, J.; Zhou, J.; Zhu, C.; Shu, G.; et al. Supplementation of microencapsulated probiotics modulates gut health and intestinal microbiota. *Food Sci. Nutr.* **2023**, *11*, 4547–4561. [CrossRef] [PubMed]
132. Zheng, D.; Liwinski, T.; Elinav, E. Interaction between microbiota and immunity in health and disease. *Cell Res.* **2020**, *30*, 492–506. [CrossRef]
133. Rajput, D.S.; Zeng, D.; Khalique, A.; Rajput, S.S.; Wang, H.; Zhao, Y.; Sun, N.; Ni, X. Pretreatment with probiotics ameliorates gut health and necrotic enteritis in broiler chickens, as a substitute to antibiotics. *AMB Express* **2020**, *10*, 220. [CrossRef]
134. Ayalew, H.; Zhang, H.; Wang, J.; Wu, S.; Qiu, K.; Qi, G.; Tekeste, A.; Wassie, T.; Chanie, D. Potential feed additives as antibiotic alternatives in broiler production. *Front. Vet. Sci.* **2022**, *9*, 916473. [CrossRef]
135. Korver, D.R. Intestinal Nutrition: Role of Vitamins and Biofactors and Gaps of Knowledge. *Poult. Sci.* **2022**, *101*, 101665. [CrossRef]
136. Sachdeva, A.; Tomar, T.; Malik, T.; Bains, A.; Karnwal, A. Exploring probiotics as a sustainable alternative to antimicrobial growth promoters: Mechanisms and benefits in animal health. *Front. Sustain. Food Syst.* **2025**, *8*, 1523678. [CrossRef]
137. Grozina, A.A.; Ilina, L.A.; Laptev, G.Y.; Yildirim, E.A.; Ponomareva, E.S.; Filippova, V.A.; Tyurina, D.G.; Fisinin, V.I.; Kochish, I.I.; Griffin, D.K.; et al. Probiotics as an Alternative to Antibiotics in Modulating the Intestinal Microbiota and Performance of Broiler Chickens. *J. Appl. Microbiol.* **2023**, *134*, lxad213. [CrossRef]
138. Adli, D.N.; Sholikin, M.M.; Sitaresmi, P.I.; Ani Nurgiartiningsih, V.M.; Crooijmans, R.P. Dose-Dependent Effects of Probiotics on the Reproductive Performance, Egg Characteristics, and Seminal Traits of Broiler Breeders: A Model-Based Meta-Analysis. *J. Anim. Physiol. Anim. Nutr.* **2025**, 1–19. [CrossRef]
139. McFarland, L.V. Efficacy of single-strain probiotics versus multi-strain mixtures: Systematic review of strain and disease specificity. *Dig. Dis. Sci.* **2021**, *66*, 694–704. [CrossRef] [PubMed]
140. Liu, L.; Zhang, G.; Qu, G.; Liu, B.; Zhang, X.; Li, G.; Jin, N.; Li, C.; Bai, J.; Zhao, C. Effects of dietary Lactobacillus rhamnosus GG supplementation on the production performance, egg quality, eggshell ultrastructure, and lipid metabolism of late-phase laying hens. *BMC Vet. Res.* **2023**, *19*, 150. [CrossRef]
141. Wang, Y.; Zhang, C.; Chen, X.; Zheng, A.; Liu, G.; Ren, Y.; Chen, Z. Dietary supplementation of compound probiotics to improve performance, egg quality, biochemical parameters and intestinal morphology of laying hens. *Front. Vet. Sci.* **2024**, *11*, 1505151. [CrossRef] [PubMed]
142. Chang, X.; Wang, B.; Zhang, H.; Qiu, K.; Wu, S. The change of albumen quality during the laying cycle and its potential physiological and molecular basis of laying hens. *Poult. Sci.* **2024**, *103*, 104004. [CrossRef] [PubMed]
143. Dangsawat, O.; Rattanawut, J.; Srisawat, T.; Sowanpreecha, R.; Tang Phuc Khang, L.; Srinual, O.; Hung, N.D.; Do-Hyung, K.; Husna, N.N.; Dwinanti, S.H.; et al. *Bacillus aryabhattai* CKNJh11 as a promising probiotic improves growth performance and egg quality in laying hens. *Sci. Rep.* **2025**, *15*, 13659. [CrossRef]
144. Zou, Q.; Fan, X.; Xu, Y.; Wang, T.; Li, D. Effects of dietary supplementation probiotic complex on growth performance, blood parameters, fecal harmful gas, and fecal microbiota in AA+ male broilers. *Front. Microbiol.* **2022**, *13*, 1088179. [CrossRef]
145. Shi, N.; Li, N.; Duan, X.; Niu, H. Interaction between the gut microbiome and mucosal immune system. *Mil. Med. Res.* **2017**, *4*, 14. [CrossRef]
146. Lee, A.R.; Kim, S.H.; Kim, S.K. Effects of supplementation with a novel strain of *Paenibacillus konkukensis* on laying performance, tibial characteristics, and caecal microbiota in laying hens. *Ital. J. Anim. Sc.* **2025**, *24*, 827–841. [CrossRef]

147. Muneeb, M.; Khan, E.U.; Ali, M.; Suleman, M.; Shaheen, M.S.; Zafar, M.S.; Ahmad, S. Effects of replacing antibiotics with probiotics and antimicrobial peptides on performance, gut health, carcass traits, meat quality, and welfare in broilers infected with *Eimeria* and *Clostridium perfringens*. *Trop. Anim. Health Prod.* **2025**, *57*, 184. [CrossRef]
148. Zeng, X.; Li, Q.; Yang, C.; Yu, Y.; Fu, Z.; Wang, H.; Fan, X.; Yue, X.; Xu, Y. Effects of *Clostridium butyricum*- and *Bacillus* spp.-Based Potential Probiotics on the Growth Performance, Intestinal Morphology, Immune Responses, and Caecal Microbiota in Broilers. *Antibiotics* **2021**, *10*, 624. [CrossRef] [PubMed]
149. Naeem, M.; Bourassa, D. Probiotics in Poultry: Unlocking Productivity Through Microbiome Modulation and Gut Health. *Microorganisms* **2025**, *13*, 257. [CrossRef] [PubMed]
150. Kim, J.-A.; Bayo, J.; Cha, J.; Choi, Y.J.; Jung, M.Y.; Kim, D.-H.; Kim, Y.; Du, C. Investigating the probiotic characteristics of four microbial strains with potential application in feed industry. *PLoS ONE* **2019**, *14*, e0218922. [CrossRef]
151. Kalus, K.; Opaliński, S.; Maurer, D.; Rice, S.; Koziel, J.A.; Korczyński, M.; Dobrzański, Z.; Kołacz, R.; Gutarowska, B. Odour reducing microbial-mineral additive for poultry manure treatment. *Front. Environ. Sci. Eng.* **2017**, *11*, 7. [CrossRef]
152. Khalid, A.; Khalid, F.; Mahreen, N.; Hussain, S.M.; Shahzad, M.M.; Khan, S.; Wang, Z. Effect of Spore-Forming Probiotics on the Poultry Production: A Review. *Food Sci. Anim. Resour.* **2022**, *42*, 968–980. [CrossRef]
153. Mi, J.; Chen, X.; Liao, X. Screening of single or combined administration of probiotics to reduce ammonia emissions from laying hens. *Poult. Sci.* **2019**, *98*, 3977–3988. [CrossRef] [PubMed]
154. Misiukiewicz, A.; Gao, M.; Filipiak, W.; Cieslak, A.; Patra, A.K.; Szumacher-Strabel, M. Review: Methanogens and methane production in the digestive systems of non-ruminant farm animals. *Animals* **2021**, *15*, 100060. [CrossRef]
155. Adamu, G.; Hassim, H.A.; Kumar, P.; Sazili, A.Q.; Mohd Zainudin, M.H. Controlling odour emissions in poultry production through dietary interventions: Prospects and challenges. *World's Poult. Sci. J.* **2024**, *80*, 1101–1122. [CrossRef]
156. Pewan, S.B.; Otto, J.R.; Huerlimann, R.; Budd, A.M.; Mwangi, F.W.; Edmunds, R.C.; Holman, B.W.B.; Henry, M.L.E.; Kinobe, R.T.; Adegboye, O.A.; et al. Genetics of Omega-3 Long-Chain Polyunsaturated Fatty Acid Metabolism and Meat Eating Quality in Tattykeel Australian White Lambs. *Genes* **2020**, *11*, 587. [CrossRef]
157. FAO. Food and Agriculture Organization of the United Nations. Meat Quality 2014. Available online: http://www.fao.org/ag/againfo/themes/en/meat/quality_meat (accessed on 12 April 2025).
158. Mohammed, A.A.; Zaki, R.S.; Negm, E.A.; Mahmoud, M.A.; Cheng, H.W. Effects of dietary supplementation of a probiotic (*Bacillus subtilis*) on bone mass and meat quality of broiler chickens. *Poult. Sci.* **2021**, *100*, 100906. [CrossRef]
159. Das, A.K.; Nanda, P.; Madane, P.; Biswas, S.; Das, A.; Zhang, W.; Lorenzo, J.M. A comprehensive review on antioxidant dietary fibre enriched meat-based functional foods. *Trends Food Sci. Technol.* **2020**, *99*, 323–336. [CrossRef]
160. Franco, L.; Boulianne, M.; Parent, E.; Barjesteh, N.; Costa, M.C. Colonization of the Gastrointestinal Tract of Chicks with Different Bacterial Microbiota Profiles. *Animals* **2023**, *13*, 2633. [CrossRef]
161. Rubio, L.A. Possibilities of early life programming in broiler chickens via intestinal microbiota modulation. *Poult. Sci.* **2019**, *98*, 695–706. [CrossRef] [PubMed]
162. Al-Yemni, A.H.; Al-Abdullatif, A.A.; Attia, Y.A.; Hussein, E. Effects of different dietary levels of blue lupine (*Lupinus angustifolius*) seed meal with or without probiotics on the performance, carcass criteria, immune organs, and gut morphology of broiler chickens. *Front. Vet. Sci.* **2020**, *7*, 124. [CrossRef]
163. Neveling, D.P.; van Emmenes, L.; Ahire, J.J.; Pieterse, E.; Smith, C.; Dicks, L.M.T. Effect of a Multi-Species Probiotic on the Colonisation of Salmonella in Broilers. Probiotics Antimicrob. *Proteins* **2020**, *12*, 896–905. [CrossRef]
164. Shanmugasundaram, R.; Markazi, A.; Mortada, M.; Ng, T.T.; Applegate, T.J.; Bielke, L.R.; Syed, B.; Pender, C.M.; Curry, S.; Murugesan, G.R.; et al. Research Note: Effect of synbiotic supplementation on caecal Clostridium perfringens load in broiler chickens with different necrotic enteritis challenge models. *Poult. Sci.* **2020**, *99*, 2452–2458. [CrossRef]
165. Lokapirnasari, W.P.; Pribadi, T.B.; Al Arif, A.; Soeharsono, S.; Hidanah, S.; Harijani, N.; Najwan, R.; Huda, K.; Wardhani, H.C.P.; Rahman, N.F.N.; et al. Potency of probiotics *Bifidobacterium* spp. and *Lactobacillus casei* to improve growth performance and business analysis in organic laying hens. *Vet. World* **2019**, *12*, 860–867. [CrossRef]
166. Tsai, M.-Y.; Shih, B.-L.; Liaw, R.-B.; Chen, W.-T.; Lee, T.-Y.; Hung, H.-W.; Hung, K.-H.; Lin, Y.-F. Effect of Dietary Supplementation of *Bacillus subtilis* TLRI 211-1 on Laying Performance, Egg Quality and Blood Characteristics of Leghorn Layers. *Anim. Biosci.* **2023**, *36*, 609–618. [CrossRef]
167. Saili, T.; Aka, R.; Auza, F.A.; Salido, W.L.; Sari, A.M.; Napirah, A. Production Performance of Local Village Chicken Fed by Agriculture By-Product Supplemented with Herbal Probiotics and Mud Clams Extract (*Polymesoda erosa*) in Kendari-South-East Sulawesi. *J. Peternak. Indones.* **2019**, *21*, 327. [CrossRef]
168. Gao, H.; Xiao, J.; Zhang, Q.; Man, H.; Tang, X.; Wang, Z.; Fang, R.; Jiang, S. Effect of supplementation continuously in pullet and early lay period with *Bacillus subtilis* and yeast cell wall on the intestinal morphology, bone parameters, and egg quality of hens. *Front. Vet. Sci.* **2025**, *12*, 1584627. [CrossRef]

169. Khogali, M.K.; Wen, K.; Jauregui, D.; Malik, H.E.; Liu, L.; Zhao, M.; Gong, D.; Geng, T. Probiotics-induced changes in intestinal structure and gut microbiota are associated with reduced rate of pimpled eggs in the late laying period of hens. *J. Poult. Sci.* **2022**, *59*, 206–222. [CrossRef] [PubMed]
170. Liu, L.; Liu, C.; Wang, H.; Tang, H.; Chen, Z.; Dou, X.; Cheng, J.; Li, Z.; Wang, Z.; Mei, Y.; et al. Probiotic potential of enterococcus lactis in improving egg production and quality in quails during late egg-laying period. *Poult. Sci.* **2025**, *104*, 104765. [CrossRef]
171. Ezema, C.; Eze, D.C. Probiotic effect of yeast (*Saccharomyces cerevisiae*) on hen-day egg performance, serum and egg cholesterol levels in laying chicken. *Pak. J. Nutr.* **2015**, *14*, 44–46. [CrossRef]
172. Hossain, M.T.; Sardar, D.; Afsana, S.; Datta, M.; Habib, M.A. Comparative analysis between multi-strain probiotics and antibiotic as starter feed supplement of poultry on growth performance, serum metabolites and meat quality. *Vet. Anim. Sci.* **2024**, *24*, 100346. [CrossRef]
173. Tang, X.; Liu, X.; Liu, H. Effects of Dietary Probiotic (*Bacillus subtilis*) Supplementation on Carcass Traits, Meat Quality, Amino Acid, and Fatty Acid Profile of Broiler Chickens. *Front. Vet. Sci.* **2021**, *8*, 767802. [CrossRef]
174. Tajudeen, H.; Ha, S.H.; Hosseindoust, A.; Mun, J.Y.; Park, S.; Park, S.; Choi, P.S.; Hermes, R.G.; Taechavasonyoo, A.; Rodriguez, R.; et al. Effect of dietary inclusion of Bacillus-based probiotics on performance, egg quality, and the faecal microbiota of laying hens. *Anim. Biosci.* **2024**, *37*, 689–696. [CrossRef]
175. Iakubchak, O.M.; Vivych, A.Y.; Hryb, J.V.; Danylenko, S.H.; Taran, T.V. Production and Meat Quality of Broiler Chickens with the Use of a Probiotic Complex of Bifidobacteria and Lactobacilli. *Regul. Mech. Biosyst.* **2024**, *15*, 477–482. [CrossRef]
176. Ivanović, S.; Baltić, M.Ž.; Popov-Raljić, J.; Pisinov, B.; Maslić-Strižak, D.; Stojanović, Z.; Pavlović, I. The effect of different probiotics on broiler meat quality. *Afr. J. Microbiol. Res.* **2012**, *6*, 937–943. [CrossRef]
177. Begdildayeva, N.; Karahan, A.G.; Kondybayev, A.; Kudaibergenova, A.; Nurgazina, A.; Akhmetsadykov, N.; Ospanova, A.; Akhmetsadykova, S.; Wang, D.Y. Probiotics effects on the growth performance and meat quality of broiler chickens. *Anim. Prod. Sci.* **2024**, *64*, AN23424. [CrossRef]
178. Freitas, A.S.; Carvalho, L.M.; Soares, A.L.; Oliveira, M.E.S.; Madruga, M.S.; Neto, A.C.S.; Carvalho, R.H.; Ida, E.I.; Shimokomaki, M. Pale, soft and exudative (PSE) and dark, firm and dry (DFD) meat determination in broiler chicken raised under tropical climate management conditions. *Int. J. Poult. Sci.* **2017**, *16*, 81–87. [CrossRef]
179. Sharipova, A.; Khaziev, D.; Kanareikina, S.; Kanareikin, V.; Rebezov, M.; Kazanina, M.; Andreeva, A.; Okuskhanova, E.; Yessimbekov, Z.; Bykova, O. The effects of a probiotic dietary supplementation on the amino acid and mineral composition of broilers meat. *Annu. Res. Rev. Biol.* **2017**, *21*, 1–7. [CrossRef]
180. Jadhav, V.V.; Han, J.; Fasina, Y.; Harrison, S.H. Connecting gut microbiomes and short chain fatty acids with the serotonergic system and behavior in *Gallus gallus* and other avian species. *Front. Physiol.* **2022**, *13*, 1035538. [CrossRef]
181. Bernabucci, U. Climate change: Impact on livestock and how can we adapt. *Anim. Front.* **2019**, *9*, 3–5. [CrossRef]
182. Chen, S.; Yong, Y.; Ju, X. Effect of heat stress on growth and production performance of livestock and poultry: Mechanism to prevention. *J. Therm. Biol.* **2021**, *99*, 103019. [CrossRef] [PubMed]
183. Oni, A.I.; Abiona, J.A.; Fafiolu, A.O.; Oke, O.E. Early-age thermal manipulation and supplemental antioxidants on physiological, biochemical and productive performance of broiler chickens in hot-tropical environments. *Stress* **2024**, *27*, 2319803. [CrossRef] [PubMed]
184. Kikusato, M.; Xue, G.; Pastor, A.; Niewold, T.A.; Toyomizu, M. Effects of plant-derived isoquinoline alkaloids on growth performance and intestinal function of broiler chickens under heat stress. *Poult. Sci.* **2021**, *100*, 957–963. [CrossRef]
185. Aydin, S.S.; Hatipoglu, D. Probiotic strategies for mitigating heat stress effects on broiler chicken performance. *Int. J. Biometeorol.* **2024**, *68*, 2153–2171. [CrossRef]
186. Verma, A.; Inslicht, S.S.; Bhargava, A. Gut-Brain Axis: Role of Microbiome, Metabolomics, Hormones, and Stress in Mental Health Disorders. *Cells* **2024**, *13*, 1436. [CrossRef]
187. Hu, J.; Chen, H.; Cheng, H.W. Effect of direct-fed microbials, Bacillus subtilis, on production performance, serotonin concentrations and behavioral parameters in a selected dominant strain of white leghorn hens. *Int. J. Poult. Sci* **2018**, *17*, 106–115. [CrossRef]

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