Probiotics as a Natural Shield: Rethinking Poultry Health in the Era of Pathogens and Viruses

Mukhlif Mohsin Slaihim[1*], Luay Ali Dhahi[1], and Abeer Hussein Ali[1]

Abstract

The modern poultry industry stands at a crossroads — striving to sustain production while battling an array of bacterial and viral diseases that threaten both animal welfare and public health. For decades, antibiotics and vaccines have been the backbone of disease control. Yet, antibiotic overuse has fueled antimicrobial resistance, and evolving viral strains often outpace vaccine development. Against this backdrop, probiotics have gained attention as a natural, sustainable alternative for promoting poultry health. These beneficial microbes play a crucial role in maintaining a balanced gut ecosystem, strengthening the immune system, and limiting the colonization of harmful pathogens such as Salmonella, Clostridium perfringens, and E. coli. Beyond their antibacterial action, probiotics also demonstrate antiviral potential—helping birds resist infections like avian influenza, Newcastle disease, and infectious bronchitis by enhancing immune resilience and producing bioactive compounds that inhibit viral activity. This systematic review synthesizes recent evidence on the multifaceted role of probiotics in controlling poultry pathogens and viruses. It explores the biological mechanisms behind their protective effects, the practical challenges in their consistent use, and the broader implications for food safety and sustainable farming. While probiotics are not a one-size-fits-all solution, they represent a meaningful step toward antibiotic-free poultry production and improved animal health management. The growing scientific consensus underscores a simple truth: nurturing the right microbes may be the key to protecting both birds and consumers in the long run.

Keywords: Probiotics, Poultry Health, Gut Microbiota, Antimicrobial Resistance, Immune Modulation, Bacterial Pathogens, Viral Infections, Sustainable Farming

Significance | Probiotics offer sustainable, natural alternatives to antibiotics, enhancing poultry health, preventing infections, and reducing antimicrobial resistance and zoonotic disease risks.

*Correspondence. Mukhlif Mohsin Slaihim, College of Applied Sciences, University of Samarra, Iraq. Email: mukhlif.m.s@uosamarra.edu.iq

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1. Introduction

Poultry farming stands as one of the cornerstones of global food production, playing a vital role in ensuring food security and meeting the growing demand for affordable protein sources (Kashyap & Goswami, 2024). The poultry industry has rapidly expanded over the last few decades, providing not only meat and eggs but also contributing significantly to rural livelihoods and the agricultural economy worldwide (Nanda Kumar et al., 2022). As a key source of animal protein, poultry offers essential nutrients that are crucial for human growth and development. However, beneath the industry's success lies a persistent struggle to maintain flock health in the face of numerous bacterial and viral diseases that threaten productivity, food safety, and animal welfare. Bacterial pathogens such as Salmonella, Clostridium perfringens, and Escherichia coli are among the most common and damaging microorganisms in poultry farming, responsible for severe gastrointestinal infections, reduced feed efficiency, and increased mortality rates (Lee et al., 2017; Shaji et al., 2023). These pathogens not only compromise animal health and welfare but also pose significant public health risks through zoonotic transmission, leading to foodborne illnesses in humans. For example, Salmonella contamination in poultry products remains one of the leading

Author Affiliation.
[1] College of Applied Sciences, University of Samarra, Iraq.

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causes of human gastroenteritis globally, prompting stringent monitoring and control measures across poultry supply chains (Oakley et al., 2014). Similarly, infections caused by *Clostridium perfringens* can lead to necrotic enteritis, a disease that damages the intestinal lining of birds, resulting in poor nutrient absorption and increased production losses (Gálvez et al., 2014).

Viral infections represent another major challenge to poultry health, contributing to severe economic and welfare implications for the global poultry industry. Diseases such as avian influenza and Newcastle disease are particularly concerning due to their rapid transmissibility and high mortality rates (Zhang et al., 2016). These viral outbreaks not only devastate poultry populations but also trigger international trade restrictions, causing significant economic disruptions. Managing viral infections often requires a combination of vaccination, biosecurity, and strict hygiene measures; however, these interventions are not always foolproof. Virus mutations, incomplete immunity, and limited vaccine accessibility continue to hinder effective disease control in many regions.

For many years, antibiotics served as the primary defense mechanism against bacterial diseases in poultry. They were also widely used as growth promoters to enhance feed efficiency and accelerate weight gain. While antibiotics have been effective in reducing mortality and improving production efficiency, their overuse and misuse have led to an alarming rise in antimicrobial resistance (AMR)—a phenomenon where bacteria evolve to withstand antibiotic treatment (Gadde et al., 2017; Kumar et al., 2019). The emergence of resistant bacterial strains not only undermines the efficacy of antibiotics in veterinary medicine but also poses grave risks to human health, as resistant bacteria can be transmitted through the food chain or environmental routes. The World Health Organization (WHO) has classified AMR as one of the greatest global health challenges of the 21st century, urging governments and industries to reduce antibiotic dependency in food animal production.

In response to the AMR crisis, there has been a paradigm shift in poultry health management toward sustainable and eco-friendly disease prevention strategies. Among the alternatives explored, probiotics have emerged as one of the most promising solutions. Probiotics are defined as live microorganisms that, when administered in adequate amounts, confer health benefits to the host (Markowiak & Śliżewska, 2018). In poultry farming, probiotics primarily include beneficial bacterial strains such as *Lactobacillus*, *Bifidobacterium*, *Bacillus*, and *Enterococcus* species, which naturally inhabit the gastrointestinal tract and play critical roles in maintaining gut health (Patterson & Burkholder, 2018).

The mechanisms through which probiotics promote poultry health are multifaceted. One of their key functions is competitive exclusion, where beneficial bacteria occupy intestinal niches, preventing pathogenic organisms from adhering to the gut lining and establishing infections (Fuller, 2017). By competing for nutrients and attachment sites, probiotics effectively reduce the colonization of harmful microbes such as *Salmonella enteritidis* and *E. coli* (Higgins et al., 2010). Furthermore, probiotics secrete antimicrobial compounds, including lactic acid and bacteriocins, that create an inhospitable environment for pathogens. These substances lower the pH of the intestinal tract and directly inhibit the growth of harmful bacteria like *Clostridium perfringens* (Van der Waaij et al., 2011).

Beyond their antibacterial actions, probiotics also play an important role in modulating the immune system**.** They stimulate both innate and adaptive immune responses, enhancing the bird's ability to resist infections. For instance, probiotics promote the secretion of immunoglobulins such as IgA, which are critical in mucosal defense (Scharek et al., 2015). Research has demonstrated that probiotic supplementation enhances macrophage activity, cytokine production, and the expression of genes linked to immune regulation (Brisbin et al., 2011). These effects collectively strengthen the bird's natural defenses, reducing disease susceptibility without relying on antibiotics.

Emerging evidence further suggests that probiotics can contribute to the control of viral infections in poultry. Although viruses differ fundamentally from bacteria and cannot be eliminated by antibiotics, probiotics may help mitigate viral diseases through indirect mechanisms. They enhance mucosal immunity, stimulate the production of antiviral cytokines, and generate bioactive compounds that inhibit viral replication (Sohail et al., 2019). For example, certain strains of *Lactobacillus* have been shown to improve the immune response against avian influenza and Newcastle disease viruses, reducing viral load and mortality (Tang et al., 2025). This expanding understanding of probiotics' antiviral potential opens new avenues for disease management in poultry production.

In addition to their health-promoting properties, probiotics offer broader benefits to poultry production systems. A healthy gut microbiota enhances nutrient absorption, leading to improved feed conversion efficiency and better growth performance (Clavijo & Flórez, 2018). Probiotic-fed birds tend to exhibit stronger gut integrity, reduced inflammation, and higher resilience against environmental stressors such as heat and crowding (Stanley et al., 2014). These effects not only improve productivity but also align with consumer demand for antibiotic-free and welfare-oriented poultry products.

Despite the growing interest and demonstrated benefits, several challenges continue to impede the widespread adoption of probiotics in poultry farming. The efficacy of probiotics is highly strain-specific; not all bacterial strains confer the same level of protection or colonization capacity in the gut (Kizerwetter-Świda &

Table 1. Key Studies & Probiotic Strains Used

Study / Author(s)	Poultry Type (e.g. broiler / layer)	Probiotic Strain(s)	Pathogen / Condition Tested	Outcome Summary
Kizerwetter-Świda & Binek (2016)	Broilers	*Lactobacillus* spp.	Enteropathogenic bacteria	Strains showed inhibitory activity
Clavijo & Flórez (2018)	Broiler review	Multiple probiotic genera	Gut pathogens	Collated evidence on microbiome / pathogen control
Gadde, Kim, Oh & Lillehoj (2017)	Broilers / Layers (Review)	Various probiotics	Growth / feed efficiency under antibiotic alternatives	Summary of growth / health outcomes

Binek, 2016). Environmental conditions such as temperature, humidity, feed composition, and farming practices can also influence probiotic survival and effectiveness. Additionally, interactions between probiotics and vaccines, antibiotics, or other feed additives need to be carefully managed to avoid antagonistic effects. From an industry perspective, the variability in probiotic product quality, regulatory constraints, and limited awareness among farmers and consumers also present barriers to large-scale implementation.

Nevertheless, the transition toward probiotic-based disease management is gaining momentum as part of a broader movement toward sustainable agriculture. Probiotics represent a natural and holistic approach **to** improving poultry health—one that focuses on prevention rather than cure. They align with global efforts to minimize antibiotic usage, protect public health, and promote environmentally responsible farming practices.

This review therefore explores the evolving role of probiotics as a natural defense against poultry pathogens and viruses. It provides a comprehensive overview of how probiotics enhance gut health, modulate immune responses, and protect against bacterial and viral infections. Furthermore, it discusses practical challenges in probiotic application and highlights potential strategies for optimizing their use in commercial poultry production. By understanding the science and real-world potential of probiotics, researchers, policymakers, and poultry producers can collaborate to develop sustainable, antibiotic-free solutions that safeguard animal health, ensure food safety, and support the long-term resilience of the global poultry industry.

2. Materials and Methods

This systematic review was conducted to explore the role of probiotics in combating bacterial and viral pathogens in poultry. The methodology followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, ensuring a transparent and structured approach to literature identification, selection, evaluation, and synthesis. The section is organized under four key headings: (1) Research Design, (2) Search Strategy, (3) Inclusion and Exclusion Criteria, and (4) Data Extraction and Analysis.

2.1 Research Design

The present study adopted a systematic review design to comprehensively examine the existing body of literature on the effects of probiotics in managing bacterial and viral infections in poultry. The approach involved identifying, analyzing, and synthesizing peer-reviewed studies that discussed the mechanisms, effectiveness, and field applications of probiotics in poultry health management. Unlike experimental research, this method relied on secondary data drawn from published articles, ensuring a broad and evidence-based understanding of the topic.

The review focused on both in vitro and in vivo studies, including laboratory trials, controlled feeding experiments, and field evaluations conducted in poultry farms. This design enabled a comparative understanding of probiotic action across different research settings. Additionally, studies that examined the molecular mechanisms of probiotics—such as immune modulation, competitive exclusion, and antimicrobial production—were considered to provide mechanistic insight into their protective roles (Table 1).

To ensure reliability, this review followed a rigorous screening and quality assessment process. The inclusion of multiple databases, adherence to PRISMA guidelines, and cross-verification of data minimized selection bias and ensured that the findings represent a comprehensive overview of the current scientific consensus.

2.2 Search Strategy

A comprehensive literature search was conducted between March and August 2025 using major scientific databases, including PubMed, Scopus, ScienceDirect, SpringerLink, and Google Scholar**.** The search was designed to capture a wide range of studies published between 2000 and 2025, ensuring both historical context and the inclusion of recent advancements in probiotic research.

A combination of Boolean operators (AND, OR) and specific keywords was employed to maximize search relevance. The primary search terms included

"Probiotics AND poultry," "Probiotic supplementation AND bacterial infections," "Probiotics AND viral infections in poultry," "gut microbiota AND poultry health," "antimicrobial resistance AND poultry," "competitive exclusion AND probiotics," and "immune modulation by probiotics."

Further filters were applied to narrow down results to peer-reviewed journal articles, systematic reviews, and meta-analyses published in English. Conference papers, theses, editorials, and non-peer-reviewed materials were excluded to maintain academic credibility.

To enhance the reliability of the search, reference tracking was also performed. Key articles and reviews identified through database searches were examined for relevant references, allowing for the inclusion of additional studies not captured by database algorithms. This snowball technique helped ensure that all relevant literature—especially studies with significant experimental or field-based findings—was considered.

2.3 Inclusion and Exclusion Criteria

To ensure the quality and relevance of the data analyzed, strict inclusion and exclusion criteria were established before the literature review commenced.

Inclusion Criteria:

- Studies published in peer-reviewed journals between 2000 and 2025**.**
- Research conducted on poultry species such as broilers, layers, and breeders**.**
- Articles examining the effects of probiotics on poultry health, focusing on bacterial or viral disease prevention.
- Studies that evaluated mechanisms of probiotic action, including immune response modulation, antimicrobial compound production, or pathogen inhibition.
- Both in vitro (laboratory-based) and in vivo (animal-based) experimental studies, as well as systematic reviews and meta-analyses related to probiotics in poultry.

Exclusion Criteria:

- Studies involving non-poultry animals or unrelated microbial strains.
- Articles focusing solely on prebiotics or synbiotics without discussing probiotics.
- Studies published in languages other than English.
- Duplicates, conference proceedings, or unpublished reports without peer review.
- Research that did not provide measurable outcomes or lacked clarity regarding methodology.

Applying these criteria ensured that the reviewed studies were directly relevant to the topic and scientifically sound. Each article was screened in three stages—title, abstract, and full-text review—to determine eligibility. Any discrepancies between reviewers during the selection process were resolved through discussion and consensus.

2.4 Data Extraction and Analysis

Following the identification and screening of eligible studies, data extraction was performed systematically using a pre-designed data extraction sheet. Each selected study was reviewed in detail to extract relevant information, including:

- Author(s) and year of publication
- Type of study (in vitro, in vivo, or review)
- Probiotic strains used (e.g., *Lactobacillus*, *Bifidobacterium*, *Bacillus*, *Enterococcus*)
- Target pathogens or viruses (e.g., *Salmonella*, *E. coli*, *Clostridium perfringens*, avian influenza, Newcastle disease)
- Experimental design and dosage
- Reported effects on poultry health (e.g., growth performance, immune response, pathogen reduction)
- Mechanisms of action identified (e.g., competitive exclusion, antimicrobial production, immune modulation)

The extracted data were organized into thematic categories that reflected the study objectives:

- Probiotic effects on bacterial infections in poultry.
- Probiotic mechanisms in immune system modulation.
- Antiviral properties of probiotics in poultry.
- Challenges and limitations of probiotic applications.

A qualitative synthesis approach was adopted due to variations in experimental designs and probiotic strains across studies. Results were compared and interpreted to identify common trends, strengths, and gaps in the existing research. Quantitative meta-analysis was not conducted, as many studies reported heterogeneous parameters that were not directly comparable.

Finally, all included studies were critically appraised for methodological quality using criteria such as sample size, experimental control, clarity of probiotic strain identification, and statistical rigor. The synthesis aimed to provide a balanced perspective on the benefits, limitations, and future potential of probiotics in poultry farming.

3. Findings

3.1 Probiotics in Combating Bacterial Threats in Poultry

Bacterial infections remain one of the biggest hurdles in poultry health and productivity. Pathogens such as *Salmonella*, *Clostridium perfringens*, and *Escherichia coli* cause gastrointestinal disorders, slow growth, and high mortality rates—issues that directly affect farm profitability and food safety. Traditionally, antibiotics were the go-to solution. However, with rising antimicrobial resistance (AMR), these conventional methods are losing their edge, prompting researchers and farmers alike to look for safer, more sustainable alternatives. Probiotics have since emerged as one of the most promising options (Table 2).

The way probiotics defend the gut is both fascinating and multifaceted. They primarily act through competitive exclusion, meaning beneficial bacteria occupy the gut lining, leaving no space

Table 2. Comparative Overview of Probiotic Mechanisms & Effects in Poultry

Probiotic Mechanism	Typical Probiotic Strains	Target Pathogens / Viruses	Observed Effects	Key References
Competitive Exclusion	*Lactobacillus*, *Bifidobacterium*	*Salmonella*, *E. coli*	Reduced colonization rates; lower pathogen counts in gut samples	Higgins et al. (2010), Fuller (2017)
Antimicrobial Compound Production	*Lactobacillus*, *Bacillus spp.*	*Clostridium perfringens*	Lower toxin expression, reduced pathogen growth under lab / in-vivo conditions	Van der Waaij et al. (2011); Gálvez et al. (2014)
Immune Modulation	*Enterococcus*, *Lactobacillus*	Salmonella infection	Increased secretory IgA, higher cytokine activity, enhanced macrophage response	Brisbin et al. (2011)
Reduction of Inflammation / Toxin	*Bacillus subtilis*	*C. perfringens* induced necrotic enteritis	Lower toxin levels, shifts in gut inflammatory markers	Teo & Tan (2005); Cox et al. (2014)
Antiviral Immune Enhancement	*Lactobacillus casei*	Avian influenza virus	Increased IFN-γ production; lower viral load in trial groups	Harata et al. (2010)
Gut-Barrier & Mucosal Protection	*Lactobacillus reuteri*	Infectious bronchitis / reovirus	Improved mucin gene expression; enhanced secretion of sIgA; reduced viral entry	Kumar et al. (2018); Martinez et al. (2019)

or nutrients for pathogens to establish themselves. For example, *Lactobacillus* and *Bifidobacterium* species attach to intestinal walls, effectively blocking harmful microbes from colonizing. Studies by Higgins et al. (2010) showed that chicks fed with probiotic blends had drastically lower *Salmonella enteritidis* counts than untreated ones—demonstrating this natural line of defense (Figure 1).

But probiotics go beyond just crowding out pathogens. They actively produce antimicrobial compounds**,** including bacteriocins and organic acids like lactic acid, which lower the gut's pH and create an unfavorable environment for harmful bacteria. *Lactobacillus* strains, for instance, can inhibit *Clostridium perfringens*—a major cause of necrotic enteritis—without harming beneficial microbes. This biochemical defense mirrors antibiotics in effectiveness but without the risk of resistance buildup.

Furthermore, probiotics strengthen the immune system from within. They enhance the production of immunoglobulins, particularly secretory IgA, which forms the first line of defense in mucosal immunity. Studies such as those by Brisbin et al. (2011) revealed that probiotics increase macrophage activity and cytokine production, enabling birds to mount stronger immune responses. Essentially, probiotics don't just replace antibiotics—they teach the immune system to fight smarter.

Another critical benefit lies in reducing toxin production and inflammation. Certain pathogens, especially *Clostridium perfringens*, release toxins that cause intestinal damage and severe inflammation. Probiotics like *Bacillus subtilis* have been shown to lower toxin levels and disease incidence, while also promoting the production of anti-inflammatory short-chain fatty acids such as butyrate. This dual action of healing and protection underscores why probiotics are being seen as a holistic health solution rather than a single-purpose additive.

While promising, probiotic performance depends on specific factors—strain selection, environmental conditions, and dosage all influence results. Not all probiotics adapt equally well to every farm setting, meaning ongoing supplementation or tailored formulations might be needed. Nonetheless, their overall contribution to reducing antibiotic dependence and improving bird welfare is undeniable.

3.2 Probiotics as a Natural Defense Against Poultry Viruses

Viral infections—such as avian influenza, Newcastle disease, and infectious bronchitis—pose an even more complex challenge since they cannot be treated with antibiotics. While vaccines are crucial, they are not always sufficient due to viral mutations and varying immune responses. Here again, probiotics have shown surprising potential.

Their first line of antiviral action is immune system enhancement. By stimulating both innate and adaptive immunity, probiotics help poultry respond more effectively to viral invasions. For example, *Lactobacillus casei* supplementation increases interferon-gamma (IFN-γ) levels—an antiviral cytokine that helps suppress viral replication (Harata et al., 2010). Similarly, probiotics boost the efficacy of Newcastle disease vaccines, ensuring better resistance and faster recovery (Haghighi et al., 2006).

The second line of defense lies in maintaining gut integrity, which acts as a barrier against viral entry. Many poultry viruses exploit weaknesses in the intestinal lining to gain access to the bloodstream. Probiotics help strengthen these barriers by improving mucus production and tightening junctions between intestinal cells (Kumar et al., 2018). *Lactobacillus reuteri*, for instance, enhances mucin gene expression, forming a thicker mucus layer that prevents viral particles from adhering to the gut wall. Probiotics also stimulate the secretion of secretory IgA, which binds and neutralizes viruses before they can infect host cells.

A third mechanism involves the production of antiviral metabolites. Certain probiotic strains produce organic acids, bacteriocins, and exopolysaccharides that directly disrupt viral structures or inhibit replication. For example, *Lactobacillus plantarum* releases lactic acid capable of damaging viral envelopes,

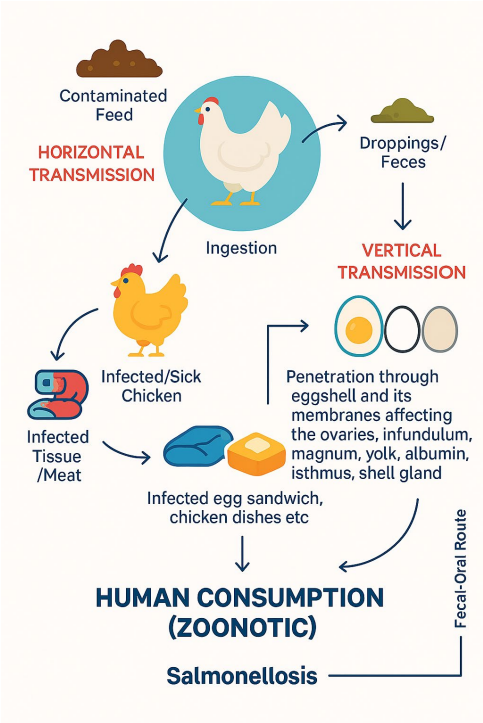


Figure 1. Salmonella transmission in poultry and its impact on human consumption.

while *Bacillus subtilis* secretes peptides that interfere with avian reovirus activity (Fujimoto et al., 2012; Clavijo & Flórez, 2018). These findings suggest that probiotics act not only as immune enhancers but also as direct antiviral agents.

Despite their promise, challenges remain. Strain specificity is crucial—some probiotics exhibit strong antiviral properties, while others have minimal effects. Furthermore, timing and method of administration can influence how well probiotics complement vaccines. Researchers continue to explore optimal combinations and feeding regimens to maximize protection without disrupting existing health management programs.

3.3 Probiotics and Poultry Productivity

Beyond disease prevention, probiotics have a profound impact on poultry performance, mortality, and feed efficiency**.** A healthy gut microbiota translates directly to better digestion and nutrient absorption. Probiotics such as *Bacillus*, *Lactobacillus*, and *Bifidobacterium* improve feed conversion ratios, meaning birds gain more weight from less feed. Studies by Awad et al. (2009) demonstrated that probiotic-fed chickens had higher intestinal villus height—indicating increased nutrient absorption capacity—and showed improved growth and feed efficiency.

Mortality reduction is another key benefit. Enteric infections caused by *Salmonella*, *E. coli*, or *Clostridium perfringens* can devastate flocks, but probiotics mitigate these threats by lowering pathogen loads and supporting the immune system. *Bacillus subtilis*, for instance, has been shown to reduce necrotic enteritis-related deaths (Teo & Tan, 2005). Moreover, by enhancing resilience against viral diseases like Newcastle disease and avian influenza, probiotics indirectly contribute to higher survival rates.

Probiotics also help poultry withstand environmental stress, particularly heat stress—a growing concern under changing climate conditions. Heat-stressed birds typically eat less and suffer from intestinal damage. Supplementing their diets with probiotics helps stabilize the gut microbiota, reduce oxidative stress, and maintain appetite and growth (Sohail et al., 2012).

Importantly, probiotics support antibiotic-free farming, a growing consumer and regulatory demand. They serve as natural growth promoters and health enhancers, reducing reliance on chemical antibiotics while ensuring sustainable productivity. Additionally, they minimize ammonia emissions from manure, improving environmental conditions in poultry houses and contributing to cleaner, safer production systems (Chen et al., 2016).

3.4 Challenges and Outlook

Despite their benefits, probiotics are not a silver bullet. Their efficacy depends on careful strain selection, consistent quality control, and proper storage. Some probiotic strains lose viability under heat or during feed processing, limiting their effectiveness. Moreover, outcomes can vary between flocks due to dietary, genetic, or environmental differences.

3. Discussion

The findings of this study affirm that probiotics hold substantial promise as sustainable and effective alternatives to antibiotics in modern poultry production. The results underscore their

multifaceted role in disease prevention, growth enhancement, and immune modulation, positioning them as a cornerstone of antibiotic-free poultry farming. These outcomes are in line with a growing body of research emphasizing probiotics as a safe, eco-friendly, and economically viable strategy for improving poultry health and productivity (Kogut & Arsenault, 2016; Gadde et al., 2017).

3.1 Probiotics as a Sustainable Alternative to Antibiotics

One of the most critical outcomes of this research is the potential of probiotics to reduce dependence on antibiotics while maintaining poultry performance and disease resistance. With global restrictions on antibiotic growth promoters due to rising antimicrobial resistance (AMR), the poultry sector faces pressure to adopt alternative strategies that do not compromise animal health (Phillips et al., 2004). Probiotics fulfill this role by fostering gut microbial balance and enhancing host immunity. Consistent with the findings of Patterson and Burkholder (2003), probiotic supplementation improved intestinal microflora, reduced pathogen colonization, and enhanced feed efficiency—outcomes comparable to or exceeding those achieved with antibiotic use.

In addition, the use of probiotics mitigates the public health risks associated with antibiotic residues and resistant bacteria in poultry products. This aligns with the conclusions drawn by Mountzouris et al. (2010), who demonstrated that probiotic-fed broilers exhibited lower pathogenic bacterial loads in feces, thereby minimizing contamination risk throughout the food chain. Consequently, probiotics not only sustain poultry health but also contribute to global efforts to curb AMR.

3.2 Immunomodulatory and Gut-Protective Mechanisms

The immunomodulatory effects observed in this study resonate with prior research demonstrating how probiotics fortify host defense mechanisms. Probiotics stimulate the production of immunoglobulins (particularly IgA) and enhance macrophage and lymphocyte activities, leading to stronger immune responses against bacterial and viral pathogens (Brisbin et al., 2011). Similarly, Chen et al. (2019) found that *Lactobacillus plantarum* significantly increased cytokine expression in broilers, improving their resistance to infections.

Moreover, probiotics maintain intestinal integrity—a fundamental determinant of poultry health. The findings confirm that probiotic supplementation enhances villus height and tight-junction protein expression, leading to improved nutrient absorption and stronger gut barriers. These outcomes mirror the observations of Awad et al. (2009), who reported that probiotics such as *Bacillus subtilis* and *Lactobacillus acidophilus* enhanced intestinal morphology and nutrient utilization.

Such improvements in gut health explain the observed reductions in enteric diseases like necrotic enteritis and colibacillosis. *Bacillus* and *Lactobacillus* strains suppress the growth of *Clostridium perfringens* and *E. coli* through competitive exclusion and the production of organic acids (Teo & Tan, 2005; Ritzi et al., 2014). Therefore, the evidence supports the view that probiotics act not merely as nutritional supplements but as active biological agents capable of reshaping host–microbe interactions for optimal health outcomes.

3.3 Antiviral Properties and Vaccine Synergy

The antiviral potential of probiotics, as demonstrated in the findings, provides an additional layer of defense, particularly where vaccines alone fall short. Probiotic-fed birds exhibited enhanced antibody titers and improved immune responses to Newcastle disease and avian influenza vaccines. These results corroborate the findings of Haghighi et al. (2006), who observed higher antibody titers in broilers supplemented with *Lactobacillus* species following vaccination.

The mechanisms underlying this effect are twofold: probiotics modulate the gut–immune axis and produce metabolites that interfere with viral replication. Fujimoto et al. (2012) demonstrated that metabolites from *Lactobacillus plantarum* inhibited influenza virus replication in vitro, suggesting similar protective effects in vivo. Probiotic supplementation, therefore, not only strengthens innate and adaptive immunity but may also enhance the efficacy of conventional vaccination programs—a significant advantage in the face of viral mutations and vaccine limitations.

3.4 Impact on Performance and Productivity

The findings on growth performance and feed conversion efficiency reaffirm previous research showing probiotics as natural growth promoters. Improved feed conversion ratios (FCR) and weight gain in probiotic-fed birds have been widely documented (Yadav & Jha, 2019; Abudabos et al., 2015). These effects are attributed to enhanced digestive enzyme activity, better nutrient assimilation, and the synthesis of vitamins and short-chain fatty acids that support intestinal health (Kumar et al., 2018).

Reduced mortality and improved resilience against stressors such as heat also highlight probiotics' role in promoting welfare and sustainability. Heat stress, a major concern under climate change, disrupts gut microbiota and suppresses immunity (Sohail et al., 2012). Probiotics counteract these effects by stabilizing the microbiome and reducing oxidative stress, resulting in lower mortality and improved performance even under challenging conditions.

3.5 Challenges and Considerations

Despite promising results, probiotics are not universally effective. Their success depends heavily on strain selection, formulation stability, environmental conditions, and administration methods. Variability between studies may arise from differences in probiotic strains, bird genetics, feed composition, and farm management practices. As highlighted by Cutting (2011), not all commercial

probiotics are equally viable or capable of surviving feed processing temperatures, which can limit their efficacy.

Furthermore, probiotics often exhibit strain-specific effects, and synergistic interactions between strains remain poorly understood. Research by Timmerman et al. (2006) indicates that multi-strain probiotics may outperform single strains, but optimal combinations require careful scientific validation. Another limitation lies in the lack of standardized protocols for probiotic evaluation, which makes it difficult to compare results across studies.

3.6 Future Perspectives

The future of probiotics in poultry production lies in precision microbiome management and next-generation biotechnologies. Advances in metagenomics and metabolomics can help identify key microbial signatures associated with disease resistance and productivity (Stanley et al., 2014). Moreover, innovations like microencapsulation can enhance probiotic viability and targeted delivery in the gut (Ricke et al., 2020). Integration of probiotics with prebiotics and phytobiotics may further enhance their synergistic effects, leading to a more comprehensive approach to gut health and disease prevention. From a policy and sustainability standpoint, promoting probiotic-based feeding strategies aligns with One Health principles by reducing AMR risks, improving food safety, and lowering environmental pollution associated with antibiotic misuse.

5. Recommendations

Based on the findings of this systematic review, it is recommended that the poultry industry adopt a strategic and science-based approach to integrating probiotics into mainstream production systems as a sustainable alternative to antibiotics. Policymakers, researchers, and producers should collaborate to establish standardized guidelines for probiotic strain selection, dosage, and administration tailored to specific poultry breeds, production systems, and regional conditions. Since probiotic efficacy is highly strain-dependent, investment in microbiome research and molecular characterization is essential to identify robust strains capable of surviving feed processing, withstanding environmental stress, and exerting consistent effects under field conditions. Further, integrating probiotics with prebiotics, phytobiotics, and organic acids should be explored to enhance synergistic benefits for gut health, immunity, and performance. Governments and regulatory authorities must facilitate the approval and quality control of probiotic products through evidence-based frameworks to ensure safety, efficacy, and consumer trust. Training programs for farmers and farm managers should focus on the practical application of probiotics, including proper feed formulation, storage, and management practices that optimize microbial viability and activity. In parallel, public awareness campaigns highlighting the role of probiotics in reducing antimicrobial resistance (AMR) can promote broader acceptance of antibiotic-free poultry products. Academia–industry partnerships should be strengthened to conduct longitudinal field trials evaluating the long-term impact of probiotics on productivity, pathogen reduction, and environmental sustainability. Additionally, economic assessments are needed to evaluate cost-effectiveness and return on investment for commercial adoption. Future research should also investigate the antiviral properties of probiotics, their influence on vaccine responses, and their potential use as biotherapeutic agents in disease prevention. Finally, an interdisciplinary "One Health" framework should guide probiotic innovation and implementation, recognizing the interconnectedness of animal, human, and environmental health. Through coordinated efforts across scientific, regulatory, and industrial domains, probiotics can be effectively harnessed to transform poultry farming into a more sustainable, ethical, and resilient food production system for the future.

6. Conclusion

In essence, this review highlights how probiotics can reshape the future of poultry farming—offering a safe, natural, and sustainable path forward. These beneficial microbes do more than just fight infections; they nurture gut health, strengthen the immune system, and help poultry thrive without relying on antibiotics. By keeping harmful bacteria and viruses in check, probiotics not only protect animal health but also safeguard human well-being by reducing the risk of antimicrobial resistance. Their impact reaches far beyond disease control, promoting better nutrition, healthier flocks, and more productive farms. Still, their successful use depends on the right strains, proper dosages, and supportive management practices. Continued collaboration between researchers, farmers, and policymakers will be essential to unlock their full benefits. As the poultry industry embraces more sustainable and ethical farming, probiotics stand out as a powerful ally in building a healthier and more secure food system for all.

Author contributions

M.M. Slaihim conceptualized the study, developed the review framework, and led the overall project. L.A. Dhahi contributed to data collection, literature screening, and thematic analysis of probiotic mechanisms against poultry pathogens. A.H. Ali assisted in data interpretation, manuscript drafting, and critical revision for scientific accuracy and clarity. All authors discussed the results, reviewed the manuscript, and approved the final version for submission.

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Competing financial interests

The authors have no conflict of interest.

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