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Antibiotic-free poultry production for food security, food safety, and environmental stewardship

C.M. Mnisi[1#], I. Kumalo[1], S.R. Dibakoane[1,2], T. Mashiloane[1,2], M.S. Mthana[2], & V. Mlambo[1,2]

[1]Food Security and Safety Focus Area, Faculty of Natural and Agricultural Sciences, North-West University, Mafikeng Campus, Private Bag X 2046, Mmabatho 2745, South Africa
[2]School of Agricultural Sciences, Faculty of Agriculture and Natural Sciences, University of Mpumalanga, Cnr R40 and D725 Roads, Mbombela, 1200, South Africa

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Abstract

The use of antibiotic growth promoters (AGPs) in poultry production has raised concerns for human, animal, and environmental health owing to the development and spread of antimicrobial resistance. These concerns have triggered global efforts to decrease AGP use and have intensified calls for sustainable, antibiotic-free production. Antibiotic-free production aims to safeguard food security and safety while mitigating environmental risks; however, it faces challenges, including reduced productivity, increased disease susceptibility, and economic constraints. This systematic review assesses the current knowledge of AGPs and their alternatives in poultry production and identifies key research gaps. It examines the mechanisms through which AGPs promote growth and antimicrobial resistance, and the challenges and opportunities associated with antibiotic-free poultry systems, including regulatory and sustainability considerations. A total of 149 peer-reviewed articles published between 2005 and 2025 were identified following preferred reporting items for systematic reviews and meta-analyses guidelines. Evidence suggests that no single additive can consistently replace AGPs; rather, successful antibiotic-free production depends on integrated strategies targeting gut integrity, microbial ecology, and host immunity. Key inconsistencies in the literature include variable responses caused by diet composition, environmental conditions, and bird genetics, emphasising the need for mechanistic, systems-level approaches to optimise outcomes. Robust, scalable antibiotic-free systems will require coordinated advances in nutrition, management, and microbial modulation, supported by validation under commercial conditions. The transition from AGPs to sustainable, antibiotic-free poultry production requires coordinated action by researchers, policymakers, industry stakeholders, farmers, and consumers to establish resilient systems that deliver safe, high-quality products while promoting public health, food security, and environmental stewardship.

Keywords: antibiotics, environmental health, health care systems, natural additives, poultry, sustainable production

[#]Corresponding author: Kenny.mnisi@nwu.ac.za

Introduction

The global poultry industry continues to expand rapidly, making significant contributions to food and nutrition security and economic development in many nations. In 2022, global chicken meat production reached approximately 124 million tonnes, with further growth anticipated to meet rising consumer demand (Food and Agriculture Organization of the United Nations, 2022). To sustain this intensification, antibiotics have long been used for prophylactic, therapeutic, and growth-promoting purposes. While sub-therapeutic levels of antibiotics have traditionally improved bird health, feed efficiency, and growth performance (Rahman *et al.*, 2022; Eko *et al*., 2023), their indiscriminate use has generated unintended and far-reaching consequences. Foremost among these is the emergence of antibiotic-resistant bacteria, which can be transmitted to humans through poultry products, direct contact, or environmental exposure (Abreu *et al*., 2023). Antimicrobial resistance undermines the effectiveness of commonly used antibiotics in treating infections, complicating medical care and increasing healthcare costs (Heinemann *et al*., 2020). Residual antibiotics in poultry manure further exacerbate the problem, as they leach into soil and water systems, disrupt ecosystems, and promote resistance in non-target organisms (Yang *et al*., 2020). Collectively, these risks compromise food safety, public health, and environmental integrity, highlighting the need for sustainable alternatives to antibiotic-dependent systems (Muhammad *et al*., 2020; Gray *et al*., 2021).

In response, several high-income countries have restricted or banned the use of in-feed antibiotics, accelerating interest in antibiotic-free poultry production systems. These systems are designed to safeguard human health and environmental sustainability while ensuring food security. However, they also face challenges, including reduced productivity, higher disease risk, and economic constraints (Cervantes, 2015). Addressing these challenges requires a holistic approach that integrates improved management practices, enhanced biosecurity, vaccination, and the strategic use of natural antimicrobial or nutritional alternatives (Speksnijder *et al*., 2015; Abd El-Hack *et al*., 2022; Fonseca *et al*., 2024). Accordingly, this review examines the mechanisms by which antibiotic growth promoters (AGPs) enhance performance and drive antimicrobial resistance, while evaluating the challenges and opportunities of antibiotic-free poultry production systems, and considers the policy and sustainability frameworks required for their adoption. The aim is to provide insights that can guide the development of poultry production systems that promote food security, ensure food safety, and uphold environmental stewardship.

Methodology

An extensive systematic literature search was conducted using Google Scholar, Scopus, ScienceDirect, and PubMed. The search was conducted using two or more of the following keyword combinations: (1) *antibiotics*, *environmental health*, *natural additives*, *health care system*, *poultry*, and *sustainable production*; (2) *antibiotic evolution*, *anti-microbial growth promoters*, *poultry*, *multi-drug resistant pathogens*, and *antibiotic residues*; (3) *antibiotic residues*, *antimicrobial resistance*, *broilers*, *manure*, *poultry products*, and *food safety*; (4) *common antibiotic alternatives*, *challenges*, *limitations*, *applications*, and *poultry*; and (5) *bacteriophages*, *exogenous enzymes*, *phytobiotics*, *organic acids*, *essential oils*, and *poultry production systems.* The sequence of article identification, exclusion, screening, and inclusion steps is demonstrated by the preferred reporting items for systematic reviews and meta-analyses (PRISMA) protocol, as described by Page *et al*. (2021) (Figure 1). The inclusion criteria focused on peer-reviewed journal articles published between 2005 and 2025 that investigated the use of natural additives as in-feed strategies in place of synthetic antibiotics, and the spread and emergence of drug-resistant non-target organisms in poultry systems. The inclusion criteria also included papers that focused on the fate of synthetic antibiotic residues, the impacts of conventional antibiotics on non-target organisms, and the impacts of alternative natural antibiotics. However, papers that did not evaluate the use of natural antibiotic alternatives in place of synthetic antibiotics in poultry systems, as well as literature reviews, were excluded. As a result, 149 studies met the inclusion criteria and were used to develop the current systematic review.

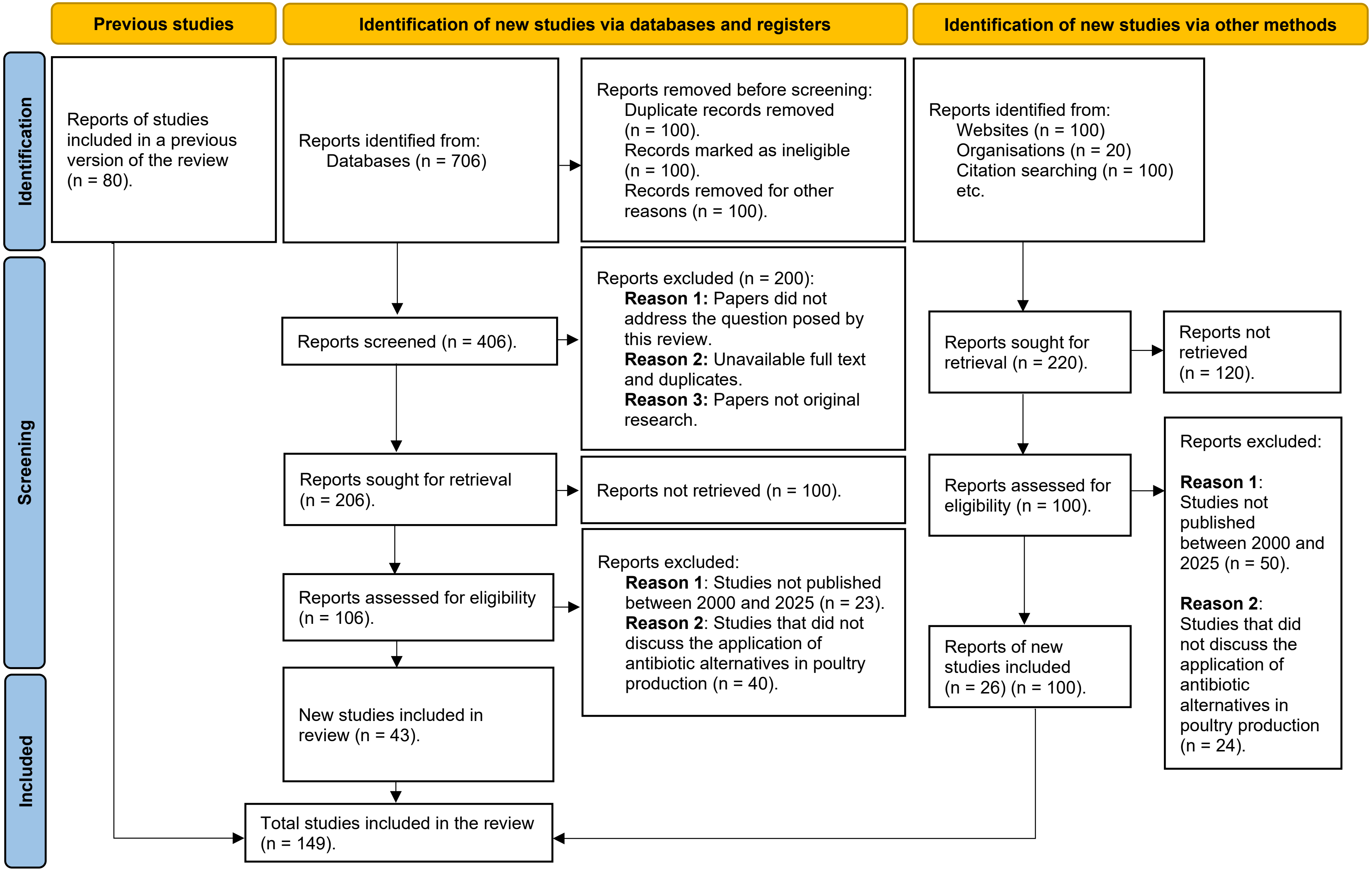

Figure 1 Preferred reporting items for systematic reviews and meta-analyses (PRISMA) flow diagram depicting the literature search and inclusion criteria used (Page *et al.*, 2021).

Antibiotic use in conventional poultry production

The evolution of antibiotic use in poultry farming

The rapid expansion of intensive poultry production has traditionally been supported by veterinary antibiotics used for prophylactic, subtherapeutic, and growth-promotion purposes (Fei *et al*., 2023). Intensive poultry farming, characterised by high stocking densities, has led to the proliferation of pathogens, resulting in the development of harmful diseases such as Gumboro, Newcastle, typhoid, and coccidiosis, among others (Owusu-Doubreh *et al*., 2023). However, since the discovery of the first and most common antibiotic (penicillin) by Alexander Fleming in 1928, several antibiotics (synthetic and natural) have been developed and are currently used to treat harmful pathogens in commercial birds (Lacroix *et al*., 2023). Over the past decades, more than 35 unique antimicrobial agents, including penicillin, cephalosporins, tetracyclines, chloramphenicol, macrolides, spectinomycin, lincosamide, sulphonamides, nitrofurans, nitroimidazoles, trimethoprim, polymyxins, quinolones, and macrocyclics (annamycins, glycopeptides, and aminoglycosides) have been successfully developed for use in commercial birds (Owusu-Doubreh *et al*., 2023). However, the use of synthetic antibiotics has been banned in several developed countries because of public concerns about the emergence of multidrug-resistant bacteria (Tabashsum *et al*., 2023). In 2006, the European Union banned the use of dietary antibiotics in food-producing animals as growth promoters and/or therapeutics (Roth *et al*., 2019). Subsequently, the United States Food and Drug Administration (FDA) also banned the use of antibiotics in animal production (Al-Khalaifah, 2018), intending to protect consumers from harmful antibiotic residues that could be transferred to animal food products.

Although several developed countries have considered banning antibiotic use in animal feeds, many developing nations, especially those in southern Africa and parts of Asia, continue to rely on them for improved production efficiency (Fei *et al*., 2023; Campagnano *et al*., 2024), despite increasing concerns regarding their impact on human and environmental health. Antibiotics are mostly used in broiler production in developing countries, and this use is characterised by limited controls and regulatory policies, raising serious public health concerns (Owusu-Doubreh *et al*., 2023). Therefore, sustainable antibiotic alternatives must be identified, evaluated, and adopted in poultry production (Al-Khalaifah, 2018). Alternative strategies may include vaccinations, bacteriophages (Tabashsum *et al*., 2023), probiotics, essential oils, organic acids, phytobiotics, plant-based synbiotics, and prebiotics, as well as antimicrobial peptides (Oladokun, 2020).

Benefits and unintended consequences of antibiotics

Traditionally, in-feed antibiotics are used to control, kill, or inhibit the proliferation of infectious diseases while promoting the growth and immune response of the animal (Al-Khalaifah, 2018). Table 1 summarises the major benefits of using antibiotics in conventional poultry production. The intensive nature of conventional poultry farming exposes birds to numerous harmful pathogens, leading to disease outbreaks (Tabashsum *et al*., 2023). Major poultry diseases, such as coccidiosis (*Eimeria* spp.), cause serious problems, including diarrhoea, decreased egg production, decreased feed conversion efficiency, reduced growth rates, and high mortality and morbidity rates (Owusu-Doubreh *et al*., 2023).

Table 1 Benefits of antibiotic-use in conventional poultry production

Benefits	References
Improved feed conversion ratio	Tabashsum *et al*. (2023)
Improved growth rate	Fei *et al*. (2023)
Inhibited pathogen proliferation	Roth *et al*. (2019); Lacroix *et al*. (2023)

Poultry producers have traditionally used antibiotics to manage diseases and poor productivity in intensively reared birds (Campagnano *et al*., 2024). However, these benefits are accompanied by several risks, including threats to environmental sustainability and animal welfare, the emergence of antibiotic-resistant pathogens, and the occurrence of antibiotic residues (Tabashsum *et al*., 2023). In humans, several health concerns have been raised regarding the use of antibiotics in poultry production. These include the emergence of drug-resistant bacteria, the intoxication of the normal intestinal microbiota, bone marrow depression, reproductive disorders, allergic reactions, and carcinogenic and mutagenic responses (Mohammadzadeh *et al*., 2022). Another challenge is the leaching of antibiotic residues into soil and water systems from poultry litter, urine, and contaminated feedstuffs, thereby indirectly contributing to the development of antimicrobial-resistant pathogens in the environment (Lacroix *et al*., 2023). Furthermore, disregarding recommended withdrawal periods leads to the transfer of synthetic drugs or metabolic residues from poultry meat and eggs to consumers, thus threatening human health (Mohammadzadeh *et al*., 2022). Current trends indicate that the continued use of antibiotics in animal production could result in approximately 10 million deaths per annum by 2050 (Hutchings & Truman, 2019).

Mechanisms of action of antibiotics

Antibiotics are chemical compounds produced by living organisms to suppress or terminate the growth of microorganisms (Owusu-Doubreh *et al*., 2023). These compounds are naturally occurring, semi-synthetic, or synthetic substances that exhibit antimicrobial activity (Roth *et al*., 2019). Although scientific evidence suggests that they help remodel microbial diversity and populations in the gastrointestinal tracts of animals (e.g. commercial birds) (Mehdi *et al.*, 2018), the mechanisms by which antibiotics exert their effects in poultry production remain incompletely understood. Table 2 summarises the possible modes of action of commonly used antibiotics in poultry production.

Inhibition of protein synthesis

Deoxyribonucleic acid (DNA) is a crucial prerequisite for protein synthesis, as it is translated into proteins at the ribosomal site (Abreu *et al*., 2023). Specifically, the ribosome translates DNA into messenger RNA (mRNA), which is then translated into a protein (Chaillou *et al*., 2014). Bacterial ribosomes are composed of three ribosomal RNA molecules (16S, 23S, and 5S rRNA) and more than 50 ribosomal proteins. These components assemble into two distinct subunits: the small 30S subunit and the large 50S subunit, which associate to form the functional 70S ribosome (Ramakrishnan, 2002). Protein synthesis is a highly regulated and coordinated process in which translation factors direct ribosomal activity through four sequential stages, namely, initiation, elongation, termination, and ribosome recycling (Lin *et al*., 2018). Selected antibiotics (aminocyclitol, amphenicols, macrolides, tetracyclines, and aminoglycosides) are added to poultry diets to inhibit the formation of bacterial proteins on the ribosomes, which may result in the death of infectious bacterial cells (Table 2).

Ribosomal inhibitors are among the most effective antimicrobial drugs and account for more than half of the veterinary medicines used to treat infections in animals (Abreu *et al*., 2023). These drugs work by stopping bacteria from making proteins, which are essential for their growth. For example, tetracyclines bind to bacterial ribosomes and block the entry of amino acids needed to make proteins, which stops protein production and slows or stops bacterial growth (Ramachanderan & Schaefer, 2021). Although tetracyclines and neomycin bind to similar sites on the ribosome, they inhibit protein synthesis in different ways (Lin *et al*., 2018). Tetracyclines prevent the building blocks of proteins from entering the ribosome, while neomycin interferes with their movement, causing errors in protein synthesis and eventually killing the bacterium (Hörömpöli *et al*., 2021).

The region of the 30S ribosomal subunit encompassing helix 44 and its immediate surroundings is a major target for several classes of antibiotics, including tetracyclines and aminoglycosides (Lin *et al*., 2018). Streptomycin, an aminoglycoside, not only interacts with helix 44 but also contacts helix 18, helix 27, and ribosomal protein uS12. These interactions induce conformational changes in the conserved nucleotides A1492 and A1493 within the decoding centre (Rocha *et al*., 2021). The positively charged amino groups of streptomycin facilitate its binding to the negatively charged A-site cleft of the 30S subunit, thereby disrupting accurate decoding and inhibiting bacterial protein synthesis (Prabhu *et al*., 2022). Aminoglycoside antibiotics like paromomycin and gentamicin attach to a specific part of the bacterial ribosome and change its shape. This causes the ribosome to misread the genetic code, allowing the wrong amino acids to be added during protein synthesis. Consequently, alterations in the decoding centre substantially reduce translational fidelity, allowing promiscuous transfer RNA (tRNA) binding and impairing mRNA translocation (Parajuli *et al*., 2021). In addition to targeting the small subunit, certain aminoglycosides bind to the groove of helix 69 of the 23S rRNA within the large ribosomal subunit (Lin *et al*., 2018). This interaction distorts the inter-subunit bridge B2a, thereby disrupting subunit rotation and ribosome recycling (Parajuli *et al*., 2021). Hygromycin B, another aminoglycoside, does not promote miscoding but instead increases the affinity of tRNA for the A-site, and, similar to neomycin, inhibits tRNA translocation (Gonzalez *et al*., 1978).

Table 2 Selected medicinal antibiotics and their mechanisms of action in commercial birds

Class	Types	Mode of action	Reference
Aminoglycosides			
	Neomycin, canamycin, gentamycin, netilmicin.	Inhibit protein synthesis.	Owusu-Doubreh *et al*. (2023)
Aminocyclitol			
	Spectinomycin, apramycin.	Bacteriostatic and bactericidal, causing irreversible inhibition of protein synthesis.	Krause *et al*. (2016)
Amphenicols			
	Chloramphenicol, thiamphenicol, florfenicol.	Inhibit protein synthesis.	Zhou *et al*. (2023)
β-lactams			
	Amoxicillin (aminopenicillin), penicillin, cephalosporin, ampicillin, monobactam.	Prevent bacteria from building cell walls by weakening wall structure and blocking enzymes needed for cell wall formation, causing cell death.	Abbas *et al*. (2022)
Coccidiostats			
	Salinomycin, diclazuril, robenidine, lasalocid, toltrazuril, monensin, clopidol, ionophores.	Damage cell membranes, stopping energy production and preventing the uptake of essential vitamins, thereby causing cell death.	Martins *et al*. (2022)
Macrolide			
	Erythromycin, tylosin, spiramycin.	Inhibit protein synthesis.	Lin *et al*. (2007)
Nitrofurans			
	Furazolidone, furaltadone, nitrofurantoin, nitrofurazone.	Bacteriostatic or bactericidal (at high doses).	Vass *et al*. (2008)
Sulphonamides			
	Sulfacetamide, sulfamethoxazole, sulfadimidine, sulfadiazine, sulfafurazole.	Prevent microbes from making folic acid by competing with the substances needed to produce it.	Conde-Cid *et al*. (2020)
Tetracyclines			
	Chlortetracycline, tigecycline, minocycline, oxytetracycline.	Stop bacteria from synthesising proteins, slowing growth or causing cell death.	Ramachanderan & Schaefer (2021)
Fluoroquinolones/quinolones			
	Oxolinic acid, nalidixic acid, flumequine, enrofloxacin, norfloxacin.	Stop bacterial growth by blocking enzymes needed to copy, repair, and maintain DNA.	Aldred *et al*. (2014)

Inhibition of bacterial cell wall synthesis

Some antibiotics act by preventing the formation of cell walls (Table 2), thereby inhibiting the proliferation of non-beneficial microbes. Specifically, β-lactams (carbapenems, cephalosporins, penicillins, and monobactams) target the cell walls of bacterial pathogens, which are crucial for their viability and growth and the maintenance of cell shape (Keller & Dörr, 2023). These antibiotics target penicillin-binding proteins by inhibiting the synthesis of peptidoglycan (the primary cell wall polymer) in both Gram-negative and Gram-positive bacteria (Tooke *et al*., 2019). This causes several problems for bacterial cells. Firstly, no crosslinks will form, resulting in the breakdown of the emerging protein fibril networks. Secondly, this leads to cells entering a nefarious cycle of synthesising long, uncross-linked peptidoglycan strands, which are immediately destroyed by autolysins (lytic transglucosylases and endopeptidases). These enzymes are mostly active during rapid cell growth and elongation. As a result, cell growth is slowed and/or completely halted (Abbas *et al*., 2022).

Inhibition of nucleic acid replication, recombination, and repair

Fluoroquinolones (also referred to as quinolones) exert their antibacterial activity by inhibiting bacterial type II topoisomerases, specifically DNA gyrase and DNA topoisomerase IV, which are essential for DNA replication and chromosome segregation (Bush *et al*., 2020). These enzymes function by introducing transient double-stranded breaks in duplex DNA, passing an intact DNA segment through the break, and subsequently religating the cleaved strands to resolve topological constraints during DNA synthesis (Blondeau, 2004). Type II topoisomerases are indispensable for bacterial viability; however, their activity must be tightly regulated, as they can become cytotoxic if the balance between DNA cleavage and religation is disrupted (Pommier *et al*., 2010). Reduced gyrase-mediated DNA cleavage slows DNA replication and impairs cell growth, whereas insufficient topoisomerase IV activity prevents proper decatenation of daughter chromosomes, ultimately leading to cell death through mitotic failure. Conversely, excessive gyrase- or topoisomerase IV-mediated DNA cleavage can convert normally transient cleavage complexes into permanent double-stranded DNA breaks. Such lesions activate the SOS response and other DNA repair pathways and may culminate in bacterial cell death (Aldred & Kerns, 2014). Fluoroquinolones are broad-spectrum antibiotics effective against both Gram-positive and Gram-negative bacteria. They act by binding to DNA and to DNA gyrase or topoisomerase IV, thereby stabilising the enzyme-DNA cleavage complex and preventing DNA religation. This inhibition of DNA supercoiling and relaxation leads to the accumulation of lethal DNA breaks and ultimately results in bacterial cell death (Bush *et al*., 2020).

Reducing pathogenic microbial populations

The sustainability of poultry production is under threat owing to the emergence of several contagious diseases that must be addressed to ensure a sustainable enterprise. Coccidiosis is a major protozoan disease caused by *Eimeria* species that effects the economic viability of poultry production, with effects ranging from subclinical to fatal (Abebe & Gugsa, 2018). In commercial birds, physiological symptoms may include intestinal lesions, poor growth performance, and epidemic disorders such as mycoplasmosis, colibacillosis, and high mortality rates (Chapman *et al*., 2010). Broiler farmers use coccidiostats in poultry feeds to combat this disease and help maintain the health and well-being of their birds and, in some cases, improve feed conversion efficiency (Martins *et al*., 2022). Macrolides are antibiotics that inhibit bacterial growth by binding to bacterial ribosomes and interfering with protein synthesis (Lin *et al*., 2007).

Disruption of folic acid formation and competitive free amino acid uptake

Sulphonamides and trimethoprim are two important classes of antibiotics that inhibit folic acid synthesis and interfere with competitive free amino acid uptake (Table 2). Proteins present in poultry feedstuffs are complex macromolecules that must be enzymatically hydrolysed into free amino acids before absorption. When the dietary amino acid supply is inadequate, catabolic processes intensify, and endogenous body proteins are mobilised to meet metabolic demands (Kidd *et al*., 2021). This metabolic imbalance can be mitigated by supplementing free amino acids, which may suppress excessive protein catabolism by reducing catabolic enzyme activity (Hilliar *et al*., 2020). Therefore, increasing dietary methionine concentrations can enhance the intestinal transport and absorption of other essential amino acids, such as lysine and arginine, and improve the embryonic uptake of these amino acids from the egg (Sarsour & Persia, 2022; Yin *et al*., 2025). However, excessive methionine supplementation beyond recommended inclusion levels may lead to hyperhomocysteinemia, a metabolic condition associated with impaired renal function, pathological changes in arterial walls, and an increased risk of thromboembolic and cardiovascular disorders (Tombarkiewicz *et al*., 2024). In commercial poultry, elevated homocysteine concentrations are frequently linked to deficiencies in folic acid and vitamin B_6. Folic acid plays a critical role in homocysteine remethylation and is therefore a key limiting factor in maintaining amino acid homeostasis (Tombarkiewicz *et al*., 2024). Notably, sulphonamides and certain coccidiostats have been shown to inhibit folic acid synthesis while simultaneously influencing the uptake of essential amino acids, including lysine and arginine, which are required for optimal growth and development (Conde-Cid *et al*., 2020; Martins *et al*., 2022).

Development of antibiotic-resistant bacteria

Poultry production systems are widely recognised as high-risk environments for the development, emergence, and dissemination of antimicrobial-resistant bacterial strains, largely due to the persistent and often intensive use of antibiotics (Abreu *et al.*, 2023; Owusu-Doubreh *et al*., 2023). Bacteria can acquire resistance to therapeutic antibiotics through three primary mechanisms: (1) by pumping the drug out of the cell, resulting in a reduced intracellular concentration of the drug; (2) by chemically breaking the drug down; and (3) by modifying the drug target to prevent effective interaction (Lin *et al*., 2018). For example, bacteria often become resistant to tetracyclines by acquiring new genes that help them expel the antibiotic from the cell, protect the ribosome from the antibiotic, or degrade the antibiotic, making the treatment less effective (Ramachanderan & Schaefer, 2021). Consequently, antibiotic-resistant genes enable pathogenic microbes to thrive in the presence of antibiotics (Cornejo *et al*., 2020), undermining the efficacy of antibiotics and further exacerbating farmers' production costs. When commercial birds are administered antibiotics, antimicrobial-resistant bacteria tend to replicate and outcompete non-resistant strains, owing to the complex interrelationship between the host, environment, and microbes (Scicchitano *et al*., 2024). During the slaughter of birds or the processing of poultry products, antimicrobial-resistant bacteria can contaminate food and be transferred to consumers (Punchihewage-Don *et al*., 2022). Accordingly, the use of antibiotics leads to the emergence of antibiotic-resistant bacteria, which pose a threat to environmental, animal, and human health (Lacroix *et al*., 2023). In developing countries, antibiotics are often administered by non-specialist personnel, whereas in developed countries, where their use is permitted, the rules are stricter, often requiring a specialist to administer the medication to the birds. The administration of antibiotics by non-specialist personnel may lead to prolonged and excessive antibiotic dosages, potentially resulting in the development of drug-resistant bacteria (Mohammadzadeh *et al*., 2022).

Antibiotic residues in poultry meat and eggs

The use of antibiotics by poultry farmers is driven by the need to improve broiler meat and egg production by supporting and enhancing disease prevention, growth rates, and feed conversion ratios (Mehdi *et al*., 2018). However, the deposition of toxic antibiotic residues in broiler meat and egg products is a significant problem in poultry production, largely due to the indiscriminate use of antibiotics in poultry farming, and is widely linked to adverse health impacts in humans (Cornejo *et al*., 2020). The threat of antibiotic residues in poultry products is a global challenge (Owusu-Doubreh *et al*., 2023). Worldwide, intake of antibiotic residues by both humans and livestock is estimated to range from 1×10^5 to 2×10^5 tonnes (Mehdi *et al*., 2018). Antimicrobial drug residues in food products occur when recommended withdrawal periods are not observed or when unlicensed medicinal antimicrobials are used (Owusu-Doubreh *et al*., 2023).

Broiler chickens are reared worldwide because of their short growth cycles and low-fat composition (Haque *et al*., 2020). The potential of medicinal drug deposition in animal tissues depends on pharmacokinetic factors, such as metabolism, absorption, distribution, and excretion in the bird (Owusu-Doubreh *et al*., 2023). For example, residues of ciprofloxacin, enrofloxacin, oxytetracycline, doxycycline, and amoxicillin were detected in various poultry tissues (liver, thigh muscle, and breast muscle) in southern Asia (Sarker *et al*., 2018). Similarly, residues of ciprofloxacin and oxytetracycline were detected in chicken breast meat in East Africa (Ahmed & Gareib, 2016). In Nepal, broilers were analysed for antibiotic residues and tested positive for enrofloxacin, ciprofloxacin, streptomycin, and chloramphenicol (Prajapati *et al*., 2018).

In layer hens, the concentrations and deposition patterns of antibiotic residues are influenced by the drug composition in the diet, egg development, the nature of the egg compartment, the hen's physiology, and the physicochemical properties of the antibiotics used (Owusu-Doubreh *et al*., 2023). Once the drug has been administered to the birds, the antimicrobial compounds can be absorbed and transported in the bloodstream, where they reach the ovaries (Muaz *et al*., 2018). Antibiotic residues can accumulate in egg yolk or white, potentially harming consumers' health (Cornejo *et al*., 2020). For example, tetracyclines have been reported to interfere with tooth development in children. This is also the case with β-agonists, such as clenbuterol, which can result in food poisoning and muscle tremors, palpitations, and tachycardia (Haque *et al*., 2020). Quinolone residues have been found to produce joint injuries, allergic reactions, DNA damage, and other genotoxic effects in humans (Fei *et al*., 2023).

Impact of antibiotics on non-target organisms

Poultry litter and urine are increasingly recognised as a significant source of antibiotic residues in the environment, leading to the emergence of antimicrobial-resistant bacteria and resistant genes. Organisms such as houseflies tend to act as vectors of antibiotic resistance because of their unrestricted access to poultry manure (Graham *et al*., 2009). An investigation into the excretion rates of common antibiotics through poultry litter revealed that the excretion rates of major antibiotics, namely lincosamide, tetracycline, macrolide, sulphonamide, and fluoroquinolone, were 60%, 75%–80%, 50%–90%, 80%–90%, and 90%, respectively (Rashid *et al*., 2023). Nevertheless, poultry litter is considered a valuable organic fertiliser for organic farming owing to its essential nutrients and mineral elements, which can improve the chemical and physical properties of agricultural land (Rashid *et al*., 2023). Unfortunately, the presence of a high concentration of unmetabolised antibiotics in poultry litter, leading to soil and water pollution, is inevitable (Rashid *et al*., 2023), and this affects non-target organisms, including humans, plants, insects, and other animals. For example, antibiotic residues in the soil profile can negatively affect plants that absorb contaminated water from the environment. These residues degrade and/or transform into several toxic compounds, and they also migrate to neighbouring agricultural lands through surface runoff and percolation into underground aquifers (Rashid *et al*., 2023). This is a serious problem because residues are eventually stored in various plant tissues and organs, inevitably resulting in the unintended exposure of consumers and wildlife to antibiotics (Haque *et al*., 2020).

Nutritional strategies to minimise or eliminate antibiotic use

Consumer concerns and pressure regarding the harmful effects of antibiotic use have led to the search for strategies to minimise or eliminate antibiotic use in poultry production. These strategies are designed to reduce mortality rates and enhance poultry gut microflora, productivity, and food safety without the use of antibiotics. These strategies can generally be grouped into antibiotic alternatives and nutritional management practices.

Nutritional management

To reduce disease susceptibility and strengthen the immune system in poultry, it is essential to provide balanced nutrition tailored to birds' specific nutrient requirements. Optimal nutrition plays a crucial role in supporting immune responses, as nutrient deficiencies or imbalances can compromise immunity and increase susceptibility to infections (Adedokun & Olojede, 2019). For example, dietary vitamin E, selenium, and zinc have been shown to enhance immune defences by stimulating immune cell activity and antibody production in ducks (He *et al*., 2013), geese (Fu *et al*., 2022), and broiler chickens (Hafez *et al*., 2020). Similarly, amino acids such as methionine and lysine are crucial for maintaining mucosal barrier integrity and the overall health of immune tissues (Konieczka *et al*., 2022; Gong *et al*., 2023), thereby reducing disease incidence and the need for antibiotics.

In addition to meeting nutrient requirements, feed producers can also adopt alternative strategies such as incorporating fermented energy or protein sources into poultry diets. Fermented feed ingredients can help promote a healthy gut microbiota, improve gut integrity, and enhance immunity, further reducing reliance on antibiotics in poultry production systems.

Alternatives to in-feed antibiotics

The poultry industry has increasingly adopted antibiotic-free management practices and interventions to address challenges posed by antibiotic resistance and the demand for ethically produced poultry products. The use of these antibiotic alternatives has been found to improve performance, feed efficiency, and the health of poultry without compromising product quality or causing antimicrobial resistance-related challenges. The influence and potency of these antibiotic alternatives, including prebiotics, probiotics, and organic acids, are presented and summarised in Table 3.

Bacteriophages

Bacteriophages are viruses that selectively target and infect bacteria. Bacteriophages active against infections are primarily found in environments where their host bacteria are prevalent, such as farms. They affect the immune system by influencing how immune cells respond to infections, and they can also alter the balance and activity of gut bacteria (Yang *et al*., 2020). By influencing bacterial community formation and phases, they also support bacterial colonisation and enhance disease resistance in various body sites (Rahman *et al*., 2022). The mechanisms of action of bacteriophages involve attaching to and colonising receptors on bacterial cell surfaces, injecting their genetic material, and utilising the bacterial cell's machinery to produce new phages. The newly formed phages will cause the bacterial cells to lyse, releasing new phages to infect other bacteria. Bacteriophages are desirable because they can maintain a balanced gut microbiota population by targeting specific harmful bacteria, without destroying beneficial strains. Bacteriophages have been shown to reduce *Salmonella* colonisation and infection rates in Ross 308 broilers (Dlamini *et al*., 2023) and colibacillosis occurrence in Cobb 500 broilers (Huff *et al*., 2004). Other studies have demonstrated that bacteriophages reduce the incidence of *Salmonella enterica* serovar Enteritidis shedding in quails (Ahmed & Gareib, 2016). Although bacteriophages have shown potential as a viable antibiotic alternative, their adoption and use in the poultry industry remain limited because of high production costs, the need for specialised and skilled personnel, a lack of policy direction, and host specificity.

Table 3 Effects of replacing in-feed antibiotics with potential alternatives in poultry

Ingredient	Antibiotic	Species	Results	Reference
150 mg/kg arabinoxylanase	200 mg/kg virginiamycin	Ross 385 chickens	Comparable growth performance; liver and caecum weights; duodenum, jejunum, and ileum length; and villi width.	Parsaie *et al*. (2007)
0.25% fructo-oligosaccharide (FOS) and 0.05% mannan-oligosaccharide (MOS)	6 mg/kg avilamycin	Ross 308 chickens	No significant differences between control and supplemented groups in overall feed intake, feed conversion efficiency (FCE), and mortality. FOS and MOS increased the diversity of the *Lactobacillus* community in the ileum.	Kim *et al*. (2011)
500 mg/kg formic acid	125 mg/kg enramycin	Cobb 400 chickens	Comparable body weight gain, FCE, serum biochemistry, and *Clostridium* count.	Pathak *et al*. (2017)
0.45 g/kg thymol	0.20 g/kg Avilamycin	Ross 308 chickens	Comparable FCE, carcass yield, serum total antioxidant capacity, thiobarbituric acid reactive substances, villus height, and villus width.	Abudabos *et al*. (2018)
0.20 g/kg blend of plant extracts	0.10 g/kg Avilamycin	Ross 308 chickens	Plant extracts improved body weight gain and FCE. Comparable carcass yield, internal organ weight, serum biochemistry, and meat quality.	Aljumaah *et al*. (2020)
2000 mg/kg benzoic acid and 300 mg/kg amylase	40 mg/kg zinc bacitracin	Lingnan broiler chickens	Benzoic acid, amylase, and zinc bacitracin caused similar growth performance. Benzoic acid and amylase enhanced antioxidant capacity, nutrient digestion, and gut microbiota composition.	Wang *et al*. (2020)
1 g/L probiotics and 1.2 g/L synbiotics	100 mg/ml ciprofloxacin	Lohman broiler chickens	Probiotics and synbiotics had positive effects on body weight, FCE, and haemato-biochemical profile.	Khalil *et al*. (2021)
0.05% bacteriophage	0.025% Avilamax®	Ross 308 chickens	Bacteriophage improved body weight gain, and bursa and spleen weight.	Upadhaya *et al*. (2021)
400 g/tonne sweet chestnut wood extract	150 g/tonne Flavomycin®	Cobb 500 chickens	Sweet chestnut wood extract increased crude protein and fibre digestibility and slaughter weights, with no improvement in serum biochemistry.	Zaikina *et al*. (2022)
0.175 g/kg *Salmonella*-specific phage cocktail	0.5 g/kg zinc bacitracin	Ross 308 chickens	Comparable FCE, haemato-biochemical indices, carcass yield, and meat quality.	Dlamini *et al*. (2023)

Exogenous enzymes

Enzymes produced through bacterial and fungal fermentation are primarily used as feed additives to enhance the feed conversion efficiency of poultry (Andrew Selaledi *et al*., 2020). These enzymes improve bird performance by reducing digesta viscosity, facilitating digestion and nutrient absorption, and increasing feed intake (Gadde *et al*., 2017). The enhanced feed digestibility observed in birds fed enzyme-containing diets is attributed to the ability of enzymes to break down fibre, reduce feed viscosity, and regulate gut microbiota by destroying the cell wall, disrupting its integrity, and releasing the nutrients bound within (Gadde *et al*., 2017; Andrew Selaledi *et al*., 2020). The mechanisms and modes of action of enzymes are linked to their hydrolytic properties, which enable them to access and degrade the matrix of biologically active components, including cytosolic spaces and cell walls (Streimikyte *et al*., 2022). The efficacy of enzymes is influenced by feed composition, moisture content, and gut conditions, including pH.

Organic acids

Organic acids are carbon-based compounds that play an important role in maintaining gut health in poultry (Yang *et al*., 2020; Tian *et al*., 2021). Their primary mode of action involves lowering the gastrointestinal tract pH, thereby enhancing starch stability, protein utilisation, and feed conversion efficiency by improving nutrient digestion and increasing protease activity. In addition, organic acids suppress pathogenic bacteria such as *Escherichia coli* and *Salmonella*, while promoting beneficial bacteria, particularly *Lactobacillus* species in the ileum, resulting in improved growth performance (Nava *et al*., 2009). Although the beneficial effects of organic acids in poultry production are well documented, their precise mechanisms of action remain incompletely understood. Moreover, their efficacy is influenced by several factors, including dosage, gut environment, and the specific type of organic acid used. Therefore, further research is required to elucidate their mechanisms of action, determine optimal inclusion levels, and identify the most effective organic acids for poultry nutrition.

Phytobiotics

Phytobiotics such as spices, natural compounds, and herbs offer health benefits when incorporated into the diet (Yang *et al*., 2016; Tian *et al*., 2021; Abd El-Hack *et al*., 2022). The mechanisms by which phytobiotics improve gut health and bird performance include their antioxidant and antimicrobial properties, enhanced palatability, improved digestion, growth promotion, and improved overall gut health (Andrew Selaledi *et al*., 2020; Abd El-Hack *et al*., 2022). The antimicrobial activity of phytobiotics is attributed to bioactive compounds that disrupt the metabolic pathways of pathogenic bacteria. The reduction and destruction of pathogenic bacteria result in a healthy gut lining, improved growth performance, and reduced incidence of diseases such as necrotic enteritis, without compromising meat quality (Li *et al*., 2015; Das *et al*., 2020). However, the efficacy of phytobiotics may vary, owing to differences in plant chemical composition, processing techniques, and environmental factors.

Essential oils

Essential oils are concentrated plant extracts that possess characteristic scents, which are attributed to the presence of aromatic compounds and active ingredients. These oils are typically obtained from bark, flowers, leaves, peels, and/or seeds through processes such as cold pressing or solvent extraction. These oils are gaining traction in the poultry industry because of their antimicrobial, antioxidant, anti-inflammatory, and digestion-enhancing properties. Essential oils disrupt cell membranes and suppress the growth of pathogenic bacteria, leading to a healthy gut microbiota composition (Angane *et al*., 2022). Furthermore, essential oils protect the intestinal lining and gut integrity by reducing oxidative stress and neutralising free radicals. Moreover, the decrease in pathogenic bacterial populations indicates that organic acids can lower bacterial loads in poultry.

Prebiotics, probiotics, and synbiotics

Prebiotics are components of foods that escape digestion in the gastrointestinal tract and are fermented by probiotic species such as *Bifidobacterium* and *Lactobacillus* in the large intestine. Prebiotics are fermented by gut microbes to produce short-chain volatile fatty acids (SCVFAs) such as acetate, propionate, and butyrate, which reduce the pH and eliminate harmful gut microbiota (Yaqoob *et al*., 2021). The fermentation of prebiotics and production of SCVFAs play a critical role in maintaining a balanced gut microbiome and upregulating favourable immune responses, thereby maintaining health and product quality. Short-chain volatile fatty acids also play a critical role in maintaining gut barrier function by preventing harmful microbiota from attaching to the gut lining and by inhibiting toxin production. Some studies have demonstrated that the incorporation of prebiotics, such as oligosaccharides, upregulates the immune responses of Cobb 500 chickens (Murarolli *et al*., 2014), while other studies have demonstrated that prebiotics (mannan oligosaccharides, virginiamycin, and bacitracin) had similar effects to conventional dietary interventions in terms of weight gain and carcass yield (Baurhoo *et al*., 2009). This demonstrates that prebiotics are suitable alternatives to antibiotics in the poultry industry.

As live microorganisms, probiotics are acid-resistant, making them suitable for enhancing poultry gut health and overall well-being (Abreu *et al*., 2023). Probiotics attach to the lining of the intestines, forming a barrier that prevents pathogenic bacteria from adhering to the gut wall and invading intestinal cells (competitive exclusion). This leads to a balanced gut microbiome, which, in turn, enhances the growth, digestion, nutrient uptake, and immunity of poultry (Bortoluzzi *et al*., 2019; Vieco-Saiz *et al*., 2019). Furthermore, some studies have demonstrated that probiotics can reduce the stress of densely stocked poultry, while improving carcass traits, intestinal morphology, and growth performance (He *et al*., 2019; Agustono *et al*., 2022). The combination of probiotics and prebiotics (synbiotics) enhances the survival of beneficial microbes in the gut, resulting in a greater impact compared to when they are used separately. Synbiotics increase the production of both lactic acid and SCVFAs (Markowiak-Kopeć *et al*., 2022).

Comparative effectiveness of in-feed antibiotic alternatives

As shown in Table 3, direct comparisons between in-feed antibiotics and antibiotic alternatives remain limited, largely owing to differences in poultry species/strains, dosage levels, and experimental designs used across studies. Nevertheless, several studies have attempted to evaluate the comparative effectiveness of in-feed antibiotic alternatives in poultry nutrition. However, the findings are often inconsistent. For instance, Abd El-Ghany *et al*. (2022) compared probiotics, postbiotics, and amoxicillin in broiler chickens challenged with *Clostridium perfringens*. Their results indicated that postbiotics improved immune response and gut health relative to the other treatments. Similarly, supplementation with organic acids has been reported to significantly reduce the enteric *C. perfringens* population while improving feed conversion efficiency and intestinal morphology. In contrast, Shah *et al*. (2025) compared a synbiotic to an AGP under a necrotic enteritis challenge and found that neither synbiotics nor the AGP significantly improved the growth performance of broiler chickens. Likewise, Tumpa *et al*. (2024) evaluated the effectiveness of probiotics, organic acids, exogenous enzymes, and phytogenics, and reported that organic acids produced the most favourable overall growth performance outcomes of the alternatives tested. These contrasting findings suggest that in-feed antibiotic alternatives do not consistently outperform AGPs, particularly under severe disease challenge conditions. Consequently, Mohite *et al*. (2021) investigated the effects of single additives versus combined feed additives (prebiotics, probiotics, and organic acids) in Giriraja chicken. Their results indicated that multi-additive strategies were more effective than single additives, highlighting the potential benefits of synergistic combinations of antibiotic alternatives in poultry diets. Despite these potential benefits, the use of some in-feed antibiotic alternatives, such as phytobiotics and enzymes, may be limited by their rapid degradation in the gut before reaching their target site. To enhance their stability and efficacy, advanced delivery technologies such as nano-encapsulation should be employed to protect active compounds until they reach their intended site of action.

There is currently limited information available on the effectiveness of in-feed antibiotic alternatives in terms of reducing or eliminating antibiotic resistance genes. Nevertheless, some studies have reported the presence of antibiotic resistance genes in antibiotic-free poultry production systems (Liu *et al*., 2020; Farooq *et al*., 2022; Baker *et al*., 2023). This observation suggests that resistance genes may already be widespread in poultry production environments and may not be solely associated with the current use of antibiotics. In addition, resistant bacteria can potentially be transmitted vertically from breeder flocks to newly hatched chicks. Therefore, further research is required to determine whether in-feed antibiotic alternatives can effectively reduce or eradicate antibiotic resistance genes within poultry production systems.

Sustainable antibiotic-free poultry production systems

Sustainability is a multipronged phenomenon that encompasses environmental, social, and economic well-being. In poultry production, the adoption of alternative management practices and therapeutic interventions, such as bacteriophages, enzymes, phytogenics, plant extracts, and probiotics, can be used to replace antibiotics and contribute positively to environmental sustainability (Kithama *et al*., 2021). These management practices have been used to support gut health, growth performance, nutrient digestion and uptake, and product quality. Furthermore, social sustainability is concerned with enhancing the welfare of birds and workers (Fernandes *et al*., 2021). The enhancement of poultry welfare can be achieved through the optimisation of stocking densities and the rearing of strains with excellent feed efficiencies and high stress tolerance levels (Bessei, 2006). Moreover, the social sustainability of alternative poultry production systems can be achieved by reskilling and upskilling producers and workers in sustainable management practices that require minimal antibiotic interventions (Chah *et al*., 2022). One of the criticisms levelled against antibiotic-free production systems is that they lack economic viability because of the high cost of production inputs (e.g. probiotics) (Cervantes, 2015). To mitigate these challenges, poultry producers can utilise locally available resources as feed (inexpensive feed sources) and therapeutics, while maintaining birds at optimal stocking densities (Alber *et al*., 2019; Li *et al*., 2019; Zou *et al*., 2020).

Lessons learnt

While positive outcomes of antibiotic-free poultry production abound, there is a need for a closer analysis of possible unintended consequences in animal and human health, food security, and the cost of production. Notable successes in public health and agriculture have been achieved by reducing antibiotic use by 56% between 2007 and 2012 in the Netherlands (Speksnijder *et al*., 2015). This change was driven by the recognition of increased antimicrobial resistance risks, highlighted by the presence of pathogens such as *Staphylococcus aureus*. The reduction was the result of a collaborative effort involving government regulation, veterinary oversight, and stakeholder engagement within the livestock sector (Speksnijder *et al*., 2015). This initiative promotes healthier livestock and safer consumer products, serving as a model for global agriculture that demonstrates the effectiveness of combined efforts in sustainable farming practices. The Netherlands continues to aim for a 70% reduction, inspiring other nations to adopt similar approaches in combating antimicrobial resistance (Hesp *et al*., 2019; Wallinga *et al*., 2022). In contrast to this success story, when chicken litter samples from conventional farms (with antibiotics) and antibiotic-free farms in the Abruzzi region of Italy were screened for antibiotic-resistant genes (Farooq *et al*., 2022), the authors noted higher tetracycline antibiotic resistance from the antibiotic-free farms.

Akter *et al*. (2023) examined management practices crucial to the success of antibiotic-free poultry production, including brooding, housing, feed and water management, lighting, and stringent biosecurity measures, in Bangladesh. The authors found a benefit-to-cost ratio of 1.40, indicating a 40% return on investment, which they attributed to reduced mortality rates, higher market prices for safe broiler meat, and consumers' willingness to pay more for healthier, antibiotic-free poultry products. Hence, marketing strategies that highlight the health benefits of antibiotic-free poultry products can enhance their market potential. However, challenges such as high feed costs, limited availability of day-old chicks, and a lack of training and infrastructure were still prevalent (Hennessey *et al*., 2021). Thus, improving local feed production, expanding hatchery facilities, and training farmers to sustain and scale the antibiotic-free poultry industry in Bangladesh were recommended (Akter *et al*., 2023).

In recent years, the performance of sustainable poultry farms across Africa has been inconsistent, despite the adoption of innovative strategies that minimise antibiotic usage. One commendable approach has been the use of natural additives such as probiotics, prebiotics, and phytochemicals in poultry diets (Andrew Selaledi *et al*., 2020). For instance, a study conducted on several farms in Kenya demonstrated that birds reared with antibiotic alternatives showed fewer signs of disease and exhibited better growth rates than those on traditional antibiotic-based regimens (Kiambi *et al*., 2021). This shift promotes healthier poultry populations and aligns with global trends aimed at reducing antibiotic resistance.

Additionally, improvements in sanitary conditions and farm biosecurity measures have played a crucial role in mitigating the spread of infectious diseases among poultry, further reducing dependence on antibiotics. Enhanced cleaning protocols, better ventilation systems, and strict visitor controls are among the biosecurity measures that have been effectively implemented. Such practices have been observed in Nigeria (Agada *et al*., 2014) and Ghana (Andoh *et al*., 2016), where farms adopting these measures reported a dramatic decrease in on-farm mortalities and disease outbreaks. However, Bamidele *et al*. (2022) evaluated faecal samples from conventional farms and farms using ethnoveterinary medicine in Nasarawa State, Nigeria, and reported increased streptomycin antibiotic resistance in samples from the ethnoveterinary medicine farms. This raises concerns about the effectiveness of alternative farming systems in reducing antibiotic resistance in global poultry production.

Quality assurance

Monitoring in sustainable poultry production systems involves the systematic gathering, analysis, and interpretation of data on antimicrobial use and resistance, with the aim of guiding policy, public health responses, and global efforts through surveillance and trend analysis (Rahman *et al*., 2022). Certification programmes are structured efforts to promote and verify the reduction of antimicrobial use in animal agriculture, setting specific standards and guidelines to curb the spread of antimicrobial resistance (Haque *et al*., 2020). These programmes typically involve standard development, compliance monitoring, certification, training, and continuous improvement processes.

Sanders *et al*. (2020) proposed a monitoring and certification programme for sustainable poultry farms, aiming to combat antimicrobial resistance by providing precise data on antimicrobial use at the farm level. By adopting methodologies from existing systems, monitoring enables accurate tracking, analysis, and benchmarking of antimicrobial use, guiding farmers toward reduced, responsible antibiotic use. Certified farms that demonstrate low antimicrobial use are recognised, thereby promoting sustainable practices and enhancing consumer trust (Hedman *et al*., 2020). Sanders *et al*. (2020) leveraged transparent reporting and harmonised analysis based on insights from 38 antimicrobial use monitoring systems across 16 countries, ensuring comparability and clarity in the results. Such a structured approach supports broader initiatives to reduce antimicrobial use, benefits public health, and advances animal welfare, setting a standard in the poultry industry.

Subsequently, research by George & George (2023) demonstrated how advanced monitoring systems on poultry farms can reduce antibiotic use by automating environmental controls and health monitoring. Artificial intelligence systems detect health issues early, reducing the need for pharmaceutical interventions and supporting antibiotic-free poultry production. This approach aligns with certification programmes focused on sustainable farming practices, establishing new industry standards for health and efficiency (George & George, 2023). By adopting these technologies, farms can enhance animal welfare, improve profitability, and meet certification criteria for reduced antibiotic usage.

Consumer trust and transparency

Consumer trust and transparency refer to the critical relationship and open communication between poultry producers and consumers regarding the methods and practices used to rear poultry without antibiotics (Sanders *et al*., 2020). This concept is particularly significant for marketing poultry products to health-conscious, environmentally aware consumers who prioritise animal welfare and sustainable agricultural practices. A study by Garcez de Oliveira Padilha *et al*. (2021) highlighted a gap in Australian consumers' understanding of sustainable poultry farming, particularly regarding antibiotic use and the environmental impacts of production. Consumers often equate higher prices with greater sustainability and make incorrect assumptions based on sustainability labels (Garcez de Oliveira Padilha *et al*., 2021). This misperception highlights the need for clearer labelling and improved education to help consumers make informed choices about the sustainability of chicken products, particularly regarding antibiotic stewardship. Garcez de Oliveira Padilha *et al*. (2021) suggested that improving transparency in labelling could bridge the trust gap between consumers and producers. By offering clearer, more accurate sustainability credentials, the poultry industry can ensure that consumer purchases align more closely with their sustainability values, encouraging more informed decisions and supporting broader sustainable practices across the industry. Similarly, Ritter (2021) highlighted consumer confusion caused by the plethora of ambiguous meat labels and proposed a new labelling initiative rooted in One Health principles. This approach emphasises transparency and educates consumers about antibiotic stewardship practices in poultry farming, aiming to reduce antimicrobial resistance. The proposed labels would detail the measures farms take to minimise antibiotic use, fostering consumer trust and encouraging sustainable practices that align with broader public health and environmental goals.

Consumer trust in sustainable poultry farming is significantly influenced by transparency about antibiotic use. Barrett *et al*. (2021) reported that 77.1% of consumers are concerned about antimicrobial use in poultry production, primarily because of concerns about human health and animal welfare, although this is not directly linked to fears of antimicrobial resistance. This discrepancy suggests a need for clearer communication from farms about their antibiotic policies, aligning with consumer expectations and building trust. The authors noted that consumer concerns are influenced by demographic factors, including gender, age, income, and education. However, current research methods, which are primarily quantitative and use indices such as willingness-to-pay studies, may not fully capture the complexity of consumer decision-making. The authors suggest that incorporating qualitative research could offer deeper insights into consumer behaviours and preferences, potentially guiding poultry producers to better meet market demands and enhance industry sustainability.

Quality and safety of poultry products

Nutritional quality

In recent years, the poultry industry has undergone a significant shift towards antibiotic-free production, driven by consumer demand for higher animal welfare standards and concerns about antibiotic resistance. Guaragni *et al*. (2020) examined the use of 25 mg inulin/kg as a replacement for 4.4 mg lincomycin/kg in Cobb 500 chickens challenged with 1.0 mL of *C. perfringens* (4.0×10^8 colony-forming units/mL) at day 21. Their results showed no variation in breast meat pH, colour, tenderness, cooking loss, water-holding capacity, thiobarbituric acid reactive substances (TBARS), glutathione S-transferase, superoxide dismutase, or catalase activity. Similarly, the replacement of 15 mg virginiamycin/kg with 400 mg/kg of an essential oil blend (60% cinnamon, 30% oregano, and 10% limestone as carrier) in Ross 308 chickens resulted in comparable breast meat tenderness, cooking loss, TBARS, crude protein, lipids, moisture, and mineral content (Bosetti *et al*., 2020). Supplementation with antibiotic alternatives better meets customer needs for safer, sustainable, and ethically produced food than antibiotic-reliant chicken farming, which raises concerns about drug residues and antibiotic resistance.

When antibiotic-free and conventional broiler meat are compared, the nutritional quality in terms of the protein, vitamin, and mineral content remains largely the same. However, antibiotic-free broiler meat is perceived as healthier because it lacks antibiotic residues; these residues may contribute to the development of antibiotic resistance and negatively impact human health. Consequently, while the basic nutritional properties, such as the protein content, remain largely unaffected, the presence/absence of antibiotic residues is a major difference and has a significant impact on consumer and environmental health.

Antibiotic residues

Antibiotic residues in poultry meat and eggs are a significant concern for food safety and public health (Mund *et al*., 2017). Residues can persist in meat and eggs after poultry are treated with antibiotics, potentially leading to human exposure when these products are consumed (Muaz *et al*., 2018). Regulatory bodies, such as the European Union and the FDA, have established maximum residue limits (MRLs) for antibiotics in food products to ensure their safety for consumption. These MRLs vary by antibiotic, but are generally set at levels deemed safe based on toxicological assessments (Muaz *et al*., 2018). Oyedeji *et al*. (2021) found that the concentrations of tylosin, sulfadimethoxine, enrofloxacin, and sulfamerazine residues in imported and local frozen meat and gizzards of broiler chickens and turkeys exceeded MRLs. This implies that these producers did not observe recommended withdrawal periods before slaughtering poultry treated with antibiotics, thereby exposing consumers to potentially harmful antibiotic residues. The presence of antibiotic residues above these limits poses a significant human health risk, underscoring the importance of strict adherence to withdrawal periods and proper management practices in poultry production.

The presence of antibiotic residues in food can directly affect consumer health in several ways. Firstly, even at low levels, these residues can cause allergic reactions in sensitive individuals, including skin rashes, respiratory distress, and gastrointestinal disturbances (Barrett *et al*., 2021). Additionally, the consumption of poultry products containing antibiotic residues has been linked to the development of human antibiotic-resistant bacteria (Mund *et al*., 2017). These bacteria can transfer resistance genes to other bacteria in the human gut, potentially leading to infections that are more difficult to treat (McInnes *et al*., 2020). Consequently, minimising antibiotic residues in poultry products is crucial for protecting consumer health and mitigating the risks associated with antibiotic resistance.

Health benefits

Sustainable poultry farming is generally associated with enhanced animal welfare standards, thereby suggesting healthier birds and better products. Birds raised without the need for routine antibiotics are generally managed using good husbandry practices and/or antibiotic alternatives. The preference for sustainable poultry products reflects growing consumer demand for natural and organic products, which are believed to be safer and more nutritious. The market trend towards cleaner labels, which eschew chemical additives and pharmaceuticals, is based on the perception supported by some studies (Barrett *et al*., 2021; Ritter, 2021) that these products are healthier.

Challenges for antibiotic-free poultry production and future directions

Cost of production

The biggest challenge in antibiotic-free poultry production systems is cost management. Antibiotic-free production systems may require more feed and space, and longer rearing times, than conventional production systems (Cervantes, 2015). This will result in higher market costs and, consequently, increase the prices of meat and eggs in retail markets (Tabashsum *et al*., 2023). Furthermore, the use of alternative therapeutics may decrease broiler growth performance and compromise meat quality (Lillehoj *et al*., 2018). Some studies have suggested that composite therapy can have the same effect as antibiotics; however, composite therapeutics (synbiotics) are more expensive as they combine therapeutics from different sources (Tabashsum *et al*., 2023). Bacteriophages and vaccines have been proposed as interventions to treat diseases such as coccidiosis (Smith, 2019). However, the challenge with these interventions is that they target a specific pathogen and do not offer cross-protection against multiple pathogens (Tabashsum *et al*., 2023). Probiotics and prebiotics have thus been proposed as a solution. Probiotics and prebiotics protect against disease by modulating the gut microbiota, triggering host immune responses, and producing metabolites such as SCVFAs (Cervantes, 2015; Van Wagenberg *et al*., 2020). However, their mechanisms of action and delivery methods, as well as the interactions between the gut microbiota and probiotics in humans, have not been fully explored (Van Wagenberg *et al*., 2020). Prebiotics may be the most feasible as they are abundant in cost-effective food sources such as unripe banana flour.

The use of alternative therapeutics is expected to increase production costs, as some studies have suggested that alternative medications are more expensive than antibiotics (Cervantes, 2015; Ray *et al*., 2019; Van Wagenberg *et al*., 2020). Ray *et al*. (2019) demonstrated that using probiotics as therapeutics to control *Campylobacter* in broiler chickens is relatively expensive. Some studies have suggested that recommended dosage levels in poultry should be 1%–10% (Van Wagenberg *et al*., 2020; Tukaram *et al*., 2022), as dosages above this level incur a higher cost with no added benefit for growth, gut health, immunity, and product quality in chickens. Studies investigating optimal dosage levels for various chicken breeds (layers and broilers) may thus be required.

Increased production costs lead to higher market prices for poultry products (Kato *et al*., 2022). The Economic Research Division of the United States of America found that organic eggs were twice as expensive as conventional eggs, and it was suggested that products labelled as ‘raised without antibiotics’ (RWA) command a premium in the market and therefore sell at higher prices (Zaheer, 2015). Given that the price of RWA foods has increased by 20% per annum since 1990 (Centner, 2016), most consumers in the developing world may become food insecure if this trend continues. Eggs and meat serve as cheap sources of high-quality protein for most consumers in the developing world, particularly those with low incomes (Zaheer, 2015). Hence, the increase in organic or RWA meat and eggs may leave consumers in low-income brackets food- and nutrient-insecure, as they will not be able to afford these premium poultry products.

Fraudulent marketing practices

The advent of RWA poultry products has increased fraudulent marketing and product labelling practices in the food industry, as producers seek to capitalise on the higher profit margins associated with the premium prices of RWA products (Peacock, 2013). Because of their prolonged rearing times and lower stocking densities, broiler chickens reared in antibiotic-free production systems require more feed to reach market weight (El Jeni *et al.*, 2021). The costs and demands of feeding these birds increase significantly as farmers must support a large number of birds for a prolonged period; consequently, most studies have suggested that antibiotic-free production systems have higher production costs than conventional production systems (Kato *et al.*, 2022). In addition, antibiotic-free production systems such as free-range systems incur substantial losses of animal stock owing to predation and parasite infestations caused by the consumption of infested feed (El Jeni *et al.*, 2021).

To support the global take-off and mainstreaming of natural additives in poultry diets, private and public stakeholders should collectively invest in the development and dissemination of inexpensive, locally available, and scalable natural additives, suited to peri-urban and rural poultry feed processing contexts. Farmers should prioritise the upscaling of selected natural feed additives. Agricultural extension agents/institutions and feed manufacturers should promote awareness and knowledge sharing to enable smallholder farmers and feed manufacturers to adopt sustainable, climate-resilient substitutes for antibiotics. Local governments should focus on framework policies that incentivise the large-scale adoption and use of locally available natural additives in place of synthetic antibiotics to reduce/eliminate over-dependence on imported conventional synthetic antibiotics.

Inappropriate feed formulations

The nutritional composition of the feedstuffs used in antibiotic-free production systems, particularly in free-range systems, is often unknown and variable because of its agricultural origin (Mallick *et al.*, 2020; Alhotan, 2021). This makes it difficult for nutritionists to formulate balanced rations, as they do not know the nutritional composition of the individual feed sources; hence, the animals' nutritional requirements may not be met. Furthermore, manufacturing may require the establishment of novel analytical procedures and production lines, which will incur additional costs and necessitate the upskilling of farmers. The use of alternative feedstuffs such as rapeseed, barley, rye, and legumes in antibiotic-free production systems may also be limited by the high fibre and antinutrient contents of these products, which reduce the bioavailability of nutrients for digestion (Alhotan, 2021; Seidavi *et al.*, 2021; Singh & Kim, 2021).

The provision of nutritionally imbalanced diets/rations results in prolonged rearing times due to impaired and sub-optimal biophysical processes (Ravindran, 2013; Yadav, 2022). Chickens will not extract nutrients at a similar level to those fed well-balanced feeds, leading to poor growth and development. The chickens must therefore remain in the production cycle for longer to reach their desired marketable state (Mallick *et al.*, 2020; Alhotan, 2021).

Ineffective antibiotic alternatives

Probiotics, prebiotics, and nucleotides have been used as alternative therapeutics to antibiotics (Ray *et al.*, 2019; Van Wagenberg *et al.*, 2020). However, some studies have argued that alternative therapeutics, when used as single agents, are less effective than antibiotics (Tabashsum *et al.*, 2023). Furthermore, the mechanisms of action and methods of delivery, as well as the interactions between the gut microbiota and probiotics, and the secondary responses they induce, remain unknown, likely because of their complexity. Moreover, some of these therapeutics, such as bacteriophages, cannot offer cross-pathogen protection (Tabashsum *et al.*, 2023). This means that if chickens are infected by non-targeted pathogens, they will not be protected.

Further studies are needed to investigate consumers', farmers', and feed manufacturers' perceptions of the use of natural antibiotic alternatives in poultry production systems. Researchers often focus on the impacts of substitute natural additives (e.g. bacteriophages, exogenous enzymes, organic acids, phytobiotics, essential oils, and biotics), while overlooking how feed manufacturers, farmers, and consumers perceive the use of in-feed antibiotics compared with antibiotic-free chickens. In addition, further studies should investigate the development of standard optimal inclusion levels for alternative antibiotic types and their synergic effects. The effects of various feed formulation techniques (e.g. extrusion, high-temperature processing, boiling, and soaking) on plant-based feed ingredients also warrant further study. These processing techniques may affect the heat stability of plant-based natural additives, potentially altering their mechanistic effects in feed. Additional studies should also investigate the long-term effects of natural additives on gut microbial viability.

Conclusions and recommendations

The transition toward antibiotic-free poultry production represents both a scientific and practical challenge, requiring a shift from reliance on single-function interventions to integrated, systems-based approaches. While a variety of feed additives have demonstrated potential to improve gut health, immune function, and growth performance, the evidence also indicates that their efficacy is highly variable and often insufficient to fully replicate the multifunctional benefits historically provided by AGPs. This variability reflects the complex and dynamic nature of the gut ecosystem, where outcomes are shaped by interactions between the diet, microbiota, host physiology, and environmental stressors. Consequently, antibiotic-free production cannot be achieved by directly substituting antibiotics with individual additives, but rather through coordinated strategies that enhance gut integrity, stabilise microbial communities, and support host resilience. Among the available approaches, combinations of functional feed additives, coupled with improved management practices, appear most promising for achieving consistent performance under commercial conditions. However, significant gaps remain, particularly in understanding the mechanisms underpinning additive efficacy, the conditions under which they fail, and their long-term impacts on animal health and productivity.

Future research should prioritise mechanistic studies linking microbial modulation to host responses, the development of standardised evaluation frameworks, and validation in realistic production environments. Ultimately, the success of antibiotic-free poultry systems will depend on integrating nutritional, microbial, and management interventions into coherent strategies that balance productivity, animal welfare, and public health considerations.

Authors' contributions

C.M.M. was responsible for conceptualisation, writing of the manuscript, and validation. I.K., R.S.D., and T.M. wrote the initial draft of this manuscript. M.S.M. wrote, validated, and finalised the manuscript. V.M. conceptualised, wrote, and validated the manuscript. All authors have read and approved the finalised manuscript.

Conflict of interest declaration

The authors declare no conflicts of interest.

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