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Public health risks associated with antibiotic residues in poultry food products

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ABSTRACT

Antibiotic residues in the poultry food products pose significant public health risks, contributing to the growing global challenge of antimicrobial resistance (AMR). This paper focuses on the public health risks associated with antibiotic residues in poultry food products. The study found that the routine use of antibiotics in poultry farming for growth promotion and disease prevention has resulted in the accumulation of residues in food products, which can lead to adverse health effects in consumers. These include allergic reactions, toxicity, disruption of gut microbiota, and the promotion of antibiotic-resistant bacteria. Long-term exposure to antibiotic residues, even at low levels, exacerbates these risks, impacting not only individual health but also broader public health systems. Regulatory frameworks, such as the establishment of maximum residue limits (MRLs) and stringent monitoring, are crucial for ensuring food safety. However, there is a pressing need for alternative strategies in poultry production that reduce reliance on antibiotics while maintaining animal health. Public education, antimicrobial stewardship, and sustainable farming practices are vital to mitigate the risks posed by antibiotic residues. The global effort to address AMR should involve coordinated actions among stakeholders, including policymakers, farmers, and healthcare providers, to protect both food safety and public health. Future research needs to prioritize the development of alternative therapeutics and innovative farming practices to minimize the presence of antibiotic residues in poultry products.

1. Introduction

Poultry farms are one of the important agricultural enterprises that supply high-quality animal protein. They offer a sustainable solution to meeting the growing demand for animal protein while reducing the environmental impact of agriculture [1,2]. These farms often use antibiotics to prevent disease and promote growth in their birds, but traces of these antibiotics can remain in the meat and eggs consumed by humans. Subtherapeutic doses of antibiotics are commonly used in poultry farming to promote growth, improve feed efficiency [3], and

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prevent disease. For instance, the use of antibiotics such as oxytetracycline and amoxicillin has been documented to improve weight gain in poultry [4]. However, the growth-promoting use of antibiotics has raised concerns regarding the long-term implications for both animal and human health, particularly in relation to antibiotic resistance [5,6]. The perception among farmers that antibiotics can secure higher productivity has perpetuated their use, despite emerging evidence of associated risks [7]. This could be due to the role in developing antibiotic-resistant bacteria, which can transfer to humans through the food chain or environmental pathways. Residual antibiotics in poultry products also pose potential risks to human health, including allergic reactions and disruption of gut microbiota.

Growing concern about antibiotic residues in food products has emerged as a significant public health issue. Residues can occur when antibiotics are not adequately cleared from the animal's system before slaughter, leading to their presence in meat and eggs consumed by humans [8]. Studies have shown that improper use of antibiotics in poultry can result in detectable levels of these substances in edible tissues, raising alarms about potential health risks for consumers [9]. The presence of antibiotic residues in food products not only poses direct health risks but also contributes to the broader issue of antimicrobial resistance (AMR), as the consumption of antibiotic-laden food can facilitate the transfer of resistant bacteria to humans [10].

Research indicates that the patterns of antibiotic use in poultry farming vary significantly across regions, influenced by factors such as local regulations, farmer knowledge, and economic considerations [11]. For example, studies in various countries have highlighted that antibiotics are often dispensed without veterinary oversight, leading to misuse and overuse [12]. This lack of regulation exacerbates the risk of developing antibiotic-resistant strains of bacteria, which can have dire consequences for both animal and human health [8,9]. The need for improved antibiotic stewardship in poultry farming is evident, as it can mitigate the risks associated with antibiotic residues and resistance.

The implications of antibiotic residues extend beyond individual health concerns, affecting public health systems at large [13]. The emergence of antibiotic-resistant infections has been recognized as a significant threat to global health [14], with poultry farming identified as a key contributor to this crisis [5,15]. Understanding the dynamics of antibiotic use in poultry farming is crucial for evaluating its impact on public health. The indiscriminate use of antibiotics has been linked to the emergence of multidrug-resistant bacteria, which can compromise the effectiveness of treatment options for human infections [9,16,17]. Furthermore, the environmental implications of antibiotic use, particularly through manure management practices, contribute to the dissemination of resistant bacteria in agricultural settings [10,18]. The World Health Organization (WHO) has emphasized the need for coordinated efforts to address antibiotic resistance, particularly in food-producing animals [15]. This calls for a comprehensive understanding of antibiotic use practices in poultry farming and the establishment of guidelines to ensure responsible use.

This study focuses on the critical issues surrounding antibiotic use in poultry farming, highlighting common antibiotics, mechanisms of residue accumulation, and regulatory standards. It examines the health implications of antibiotic residues, including the rise of antimicrobial resistance and associated health risks. Additionally, the paper emphasizes the importance of consumer awareness, detection methods, and recommendations for reducing public health risks related to antibiotic use in poultry.

2. Mechanisms of antibiotic residue accumulation in poultry food products

The accumulation of antibiotic residues in poultry food products is a significant concern for public health and food safety. Antibiotics are commonly used in poultry production for therapeutic purposes, growth promotion, and disease prevention. However, their extensive use raises the risk of residues remaining in meat and eggs, which can lead to adverse health effects in consumers, including allergic reactions and the development of antibiotic-resistant bacteria [19–21]. The mechanisms of accumulation are multifaceted, involving various factors such as the type of antibiotics used, administration routes, and production practices (Table 1).

The moderate use of some selected antibiotics in poultry farming is essential for maintaining animal health but they can contributes to public health risks when residues remain in food products. Common antibiotics employed in poultry production include tetracyclines, sulfonamides, and fluoroquinolones. These antibiotics are favored for their efficacy in promoting growth and preventing disease outbreaks in flocks [22]. However, the misuse of these drugs, including off-label use and

Table 1
Possible implications of antibiotic use in poultry production across various dimensions.

Category	Details	Possible Implications
Common antibiotics used in poultry production	Tetracyclines (e.g., oxytetracycline), Penicillins (e.g., amoxicillin), Fluoroquinolones (e.g., enrofloxacin), Macrolides (e.g., tylosin), Sulfonamides and Aminoglycosides (e.g., gentamicin), Polypeptides (e.g., bacitracin) and Streptogramins (e.g., virginiamycin).	Promote growth and prevent diseases, contribute to the development of antibiotic-resistant bacteria, residue formation in meat and eggs and potential health risks like allergic reactions in consumers
Factors influencing presence of antibiotic residues in meat and eggs	Type of antibiotic, dosage and duration of use, withdrawal period compliance, health status of poultry, poultry farming practices (intensive vs. extensive) and environmental factors	Higher residue levels with improper dosage and non-adherence to withdrawal periods, intensive farming increases residue risks due to routine antibiotic use, and stress and illness in birds can affect residue metabolism
Routes of antibiotic administration	Feed: Antibiotics mixed with poultry feed	Feed: Widespread exposure leading to residues in tissues, eggs, and excreta
	Water: Antibiotics dissolved in drinking water Injections: Direct administration via intramuscular or subcutaneous routes	Water: Easily absorbed but inconsistent dosing in a flock Injections: Localized residues around injection sites
Residue formation during production, processing, and storage	Production: Antibiotics used for growth promotion or disease prevention	Residues can persist in muscle, liver, kidney, and eggs
	Processing: Minimal removal of residues unless specifically targeted	Processing methods (e.g., washing, freezing) have limited effects on reducing residues
	Storage: Residue stability in frozen or refrigerated products	Prolonged storage may not significantly degrade residues
Breakdown of residues in cooked vs. slightly cooked or undercooked poultry product consumption consumption	Cooking: High temperatures (boiling, grilling) can reduce or degrade some antibiotic residues	Possible partial breakdown of residues like tetracyclines Residues of heat-stable antibiotics (e.g., fluoroquinolones) may persist
	Undercooked Consumption: Consuming slightly cooked or undercooked poultry can result in exposure to higher residue levels	Higher risk of ingesting harmful residues

failure to adhere to withdrawal periods, significantly contributes to the presence of residues in poultry products [23,24]. For instance, studies have shown that a substantial percentage of poultry meat and eggs contain detectable levels of these antibiotics, highlighting the need for stringent monitoring and regulation [25].

Several factors influence the presence of antibiotic residues in poultry meat and eggs. These include the type of antibiotic administered, the dosage, the duration of treatment, and adherence to withdrawal periods before slaughter or egg-laying [23,24]. Additionally, farming practices, such as the use of medicated feed and water, can also impact residue levels. The lack of veterinary drug control and the prevalence of extra-label drug use have been identified as significant contributors to residue contamination [23]. Furthermore, environmental factors such as feed contamination and improper storage conditions can exacerbate the accumulation of residues [26].

Antibiotics can be administered to poultry through various routes, including feed, water, and injections [27–30]. Each method has implications for the absorption and subsequent accumulation of residues in edible tissues [31]. Feed and water are the most common routes, allowing for continuous exposure to antibiotics, which can lead to higher residue levels in meat and eggs [32]. Injections, while less common, can also result in significant residues if not managed properly, particularly if withdrawal periods are not observed [33–35]. The choice of administration route, therefore, plays a crucial role in determining the extent of residue accumulation.

The formation of antibiotic residues occurs during various stages of poultry production, processing, and storage. During production, the metabolism of antibiotics can lead to the formation of active and inactive metabolites, which may persist in tissues [36]. Processing methods, such as slaughtering and packaging, can also influence residue levels, as improper handling may lead to cross-contamination [37–39]. Furthermore, storage conditions, including temperature and duration, can affect the stability of antibiotic residues, potentially leading to increased concentrations over time [26].

The breakdown of antibiotic residues during cooking is an essential consideration for consumer safety. High-temperature cooking methods, such as boiling, grilling, or other forms of high-heat processing, can significantly reduce or degrade certain antibiotic residues present in poultry products [40,41]. This occurs because many antibiotics are heat-sensitive and undergo chemical breakdown when exposed to elevated temperatures. The thermal decomposition can alter the molecular structure of the antibiotic, rendering it inactive or transforming it into less harmful metabolites [40,41]. The extent of residue reduction depends on several factors, including the type of antibiotic, the cooking method, the duration of heat exposure, and the temperature achieved [41,42]. Studies have shown that antibiotics like tetracyclines and sulfonamides [36] are particularly prone to thermal degradation, while others may be more resistant [41,42]. Although high-temperature cooking can minimize the presence of these residues, it may not eliminate them entirely, especially if the initial concentration in the poultry product is high [40,41].

3. Health implications of antibiotic residues

The health implications of antibiotic and other chemical residues in food and the environment are multifaceted and increasingly concerning [43–46]. Antibiotic residues, which are remnants of medications used in livestock and agriculture, can lead to significant health risks for humans, primarily through the development of antibiotic resistance, allergic reactions, and disruptions to gut microbiota [47–50]. The presence of these residues in food products, such as meat and dairy, poses a direct threat to consumer health, necessitating a thorough examination of their implications [51]. Fig. 1 shows an overview of the health implications of antibiotic residues.

Antibiotic resistance is a critical public health issue that arises from the overuse and misuse of antibiotics in both human medicine and animal husbandry [52]. The continuous exposure of bacteria to low levels of antibiotic residues can lead to the development of antibiotic-resistant strains, complicating treatment options for infections in humans and animals alike [53,54]. This resistance not only diminishes the efficacy of existing antibiotics but also poses a risk of severe health outcomes, including increased morbidity and mortality rates associated with resistant infections [20,55]. The World Health Organization has highlighted antibiotic resistance as one of the top ten global public health threats, emphasizing the urgent need for effective strategies to mitigate this issue [56].

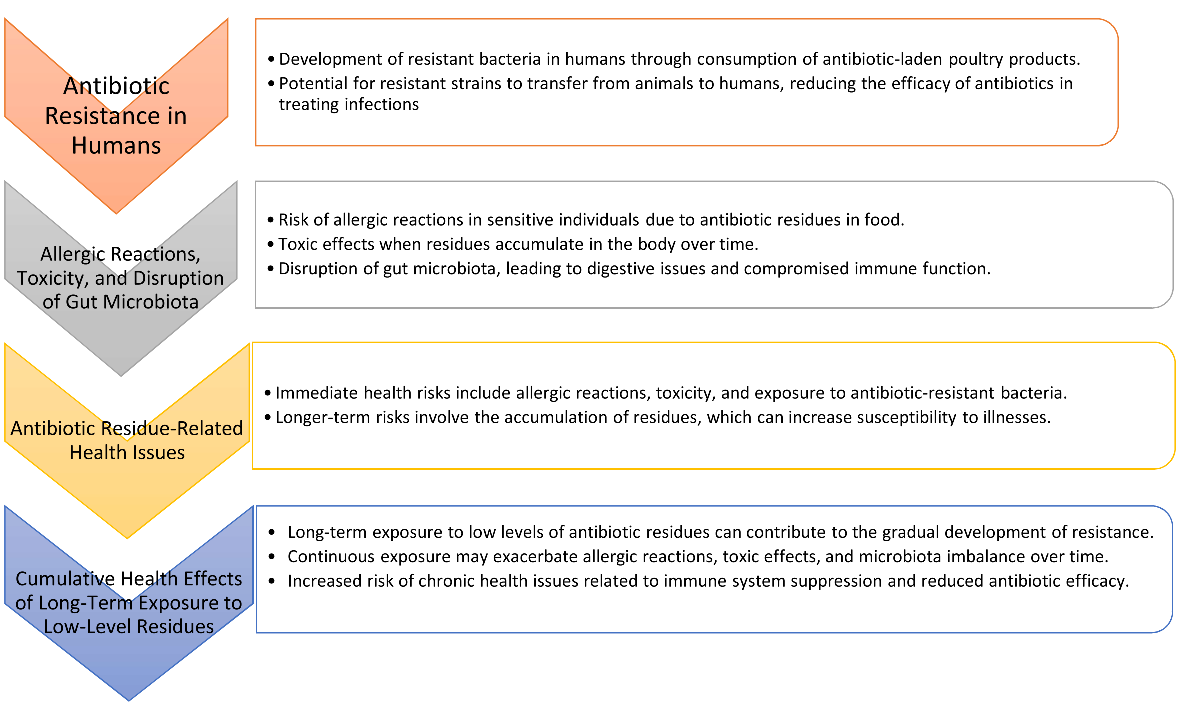

Fig. 1. Overview of the health implications of antibiotic residues.

The risks associated with antibiotic residues extend beyond resistance. They also include potential allergic reactions and toxicity. Consumption of food contaminated with antibiotic residues can trigger a range of allergic responses, from mild skin irritations to severe anaphylactic reactions [57,58]. For instance, certain antibiotics, such as penicillin, are well-known allergens, and their residues in food products can pose significant risks to sensitive individuals [59]. Additionally, antibiotic residues can disrupt the normal gut microbiota, leading to dysbiosis, which has been linked to various health issues, including gastrointestinal disorders and increased susceptibility to infections [60–63].

Studies have illustrated the real-world health implications of antibiotic residues [64,65]. For example, research conducted in India revealed detectable levels of antibiotic residues in river water, which were associated with the presence of antibiotic-resistant *Escherichia coli* [66]. This finding underscores the environmental transmission of resistance and highlights the potential for human exposure through contaminated water sources. Similarly, a study in Pakistan found antibiotic residues in beef samples, raising concerns about the health risks associated with the consumption of contaminated meat [67]. These case studies exemplify the broader public health implications of antibiotic residues in food and the environment.

Long-term exposure to low-level antibiotic residues can lead to cumulative health effects that may not be immediately apparent. Research indicates that chronic exposure to these residues can result in various adverse health outcomes, including carcinogenicity, neurotoxic effects, and disruption of the immune system [60]. The gradual accumulation of antibiotic residues in the body may also contribute to the development of chronic diseases, highlighting the need for ongoing monitoring and regulation of antibiotic use in agriculture and food production [68].

The environmental impact of antibiotic residues is significant, as they can contribute to the proliferation of resistant bacteria in ecosystems [69,70]. Antibiotic residues in the environment, such as in wastewater, soil, and water bodies, can select for and promote the spread of antibiotic-resistant bacteria and genes [71–73]. Studies have shown that the presence of antibiotic residues in hospital wastewater, agricultural runoff, and other sources can facilitate the persistence and horizontal gene transfer of antimicrobial resistance determinants [71,72]. This can lead to the emergence and dissemination of multidrug-resistant bacteria, posing a threat to both human and animal health.

The environmental reservoirs of antibiotic resistance genes can act as a source for the transfer of these genes to human pathogens, potentially compromising the effectiveness of antibiotics in clinical settings [73,74]. Factors such as improper disposal of antibiotics, lack of effective wastewater treatment, and the use of antibiotics in agriculture and aquaculture contribute to the accumulation of antibiotic residues in the environment [73,75]. The environmental impact of antibiotic residues is also significant, as they can contribute to the proliferation of resistant bacteria in ecosystems. Antibiotic residues released into the environment through agricultural runoff or improper disposal can lead to the selection of resistant strains in natural microbial communities [76]. This environmental reservoir of resistance can subsequently be transmitted to humans through the food chain, exacerbating the public health crisis associated with antibiotic resistance [68].

4. Public health threats and antibiotic resistance

Antimicrobial resistance has emerged as a critical public health threat. The WHO has classified AMR as one of the top global health challenges of the 21st century, with estimates suggesting that 1.27 million deaths were directly attributable to antibiotic resistance in 2019 alone, alongside an additional 4.95 million deaths linked to infections caused by resistant bacteria [77]. This alarming trend underscores the urgent need for comprehensive strategies to combat AMR, which is increasingly recognized as a multifaceted phenomenon influenced by various factors, including antibiotic residues in the environment, agricultural practices, and healthcare protocols [78]. Table 2 provides an overview of the possible implications of antibiotic residues on antimicrobial resistance and public health.

The role of antibiotic residues in the rise of AMR is particularly concerning. Antibiotic residues can persist in the environment, leading to the selection of resistant bacteria through environmental exposure. The presence of these residues in water sources, soil, and food products can facilitate horizontal gene transfer among bacteria, further propagating resistance traits [79]. This environmental contamination is often a result of agricultural practices where antibiotics are used not only for therapeutic purposes but also as growth promoters in livestock [80,81]. The indiscriminate application of antibiotics in agriculture significantly contributes to the development of antibiotic-resistant bacteria. This resistance emerges through various mechanisms, including horizontal gene transfer among bacterial populations, which can facilitate the spread of resistant strains from animals to humans [82]. Notably, antibiotic-resistant Campylobacter spp., commonly found in poultry, pose a serious threat to human health due to their association with foodborne illnesses [83,84]. The One Health approach underscores the necessity of addressing these interconnected health issues by integrating human, animal, and environmental health strategies to combat antibiotic resistance effectively.

Transmission of resistant bacteria from poultry and other livestock to humans is a significant pathway, through which AMR spreads. Studies have shown that antibiotic-resistant bacteria can be transferred to humans through direct contact with animals, consumption of contaminated food, or environmental exposure [78,85]. For instance, the prevalence of methicillin-resistant *Staphylococcus aureus* (MRSA) in livestock, particularly in poultry, poses a direct threat to public health as these bacteria can cause severe infections in humans [86]. The complex dynamics of this transmission underscore the need for integrated approaches that involve veterinary medicine, public health, and environmental management to mitigate the risks associated with AMR [85].

The global impact of AMR on healthcare systems is profound, leading to increased morbidity, mortality, and healthcare costs. Infections

Table 2
Possible implications of antibiotic residues on antimicrobial resistance and public health.

Category	Details	Implications
Role of antibiotic residues in the rise of AMR	Exposure to sub-therapeutic levels of antibiotics in poultry products, development of resistance mechanisms in bacteria, increase in resistant strains in the environment and non-compliance with withdrawal periods.	Amplifies the global AMR crisis, compromises antibiotic effectiveness, leading to treatment failures and increases healthcare costs due to complicated infections.
Transmission of resistant bacteria from poultry to humans	Ingestion of resistant bacteria via contaminated poultry, colonization of the human gut and direct contact with poultry or contaminated surfaces and horizontal gene transfer among bacteria.	Higher risk of difficult-to-treat infections, increased potential for outbreaks of resistant infections, and challenges in food safety and public health management.
Global impact of AMR on healthcare systems and disease treatment	Prolonged illnesses and increased healthcare costs, need for second-line or combination therapies that are more expensive, compromise of medical procedures reliant on effective antibiotics and increased burden on healthcare systems.	Strains healthcare infrastructure and resources, escalates public health concerns and reduces disease treatment efficacy and threatens surgical and therapeutic advancements.

caused by resistant bacteria often result in longer hospital stays, more complicated treatment regimens, and higher rates of treatment failure [87,88]. The economic burden associated with AMR is staggering, with estimates suggesting that the global economic losses could exceed $100 trillion if current trends continue [77]. Healthcare-associated infections (HAIs) caused by antibiotic-resistant organisms contribute significantly to this burden, with substantial costs related to prolonged hospitalizations and additional medical interventions [88]. The challenge of managing AMR necessitates a multifaceted response that includes improving infection prevention and control measures, optimizing antibiotic prescribing practices, and enhancing public awareness about the responsible use of antibiotics [89].

Through informed community engagement, public education is pivotal in combating AMR. Many individuals remain unaware of the mechanisms behind antibiotic resistance and its health implications [90]. Educational campaigns that highlight the dangers of antibiotic misuse are critical for fostering responsible medication practices [91]. Research indicates that personalized messaging, which underscores the risks associated with unnecessary antibiotic use, can effectively alter public behavior. Furthermore, the integration of social networks in health communication enhances the dissemination of vital information, particularly in communities with historical mistrust [92]. Effective public health strategies must also involve collaboration between health authorities and community leaders to ensure message credibility and relevance. Ultimately, a multifaceted approach that combines personalized education, community engagement, and strategic messaging is essential for reducing AMR and promoting public health [93]. Furthermore, engaging the public in discussions about AMR can empower individuals to take an active role in combating this issue, fostering a culture of responsible antibiotic use [94,95].

Antimicrobial activity is important to maintain the health of the plants, animals and human beings as well [96–100]. Various natural products have shown unique antimicrobial activities [101–103]. Antimicrobial resistance poses a significant threat to global health systems and requires immediate attention [104]. The implementation of robust antimicrobial stewardship programs is essential for optimizing antibiotic usage in healthcare settings. These programs focus on ensuring that antibiotics are prescribed judiciously, thereby minimizing unnecessary exposure to these medications. By selecting the appropriate antibiotics for specific infections, healthcare providers can enhance treatment efficacy and patient outcomes. Moreover, reducing unnecessary antibiotic prescriptions decreases the selective pressure that contributes to the development of resistant bacterial strains [89]. This proactive approach not only benefits individual patients but also safeguards public health by curbing the spread of AMR. Continuous surveillance of antibiotic resistance patterns is crucial for adapting treatment guidelines and informing public health strategies effectively [78,85]. Ultimately, integrating antimicrobial stewardship with sustainable farming practices can further mitigate the risks associated with antibiotic residues in the environment.

5. Regulatory frameworks and guidelines

The regulatory frameworks and guidelines surrounding antibiotic use in food products are critical for ensuring food safety and public health. Antibiotic residues in food can lead to adverse health effects, including allergic reactions and the development of antibiotic-resistant bacteria, which pose significant risks to human health. As such, various international and local regulations have been established to set Maximum Residue Limits (MRLs) for antibiotics in food products. The Codex Alimentarius, established by the Food and Agriculture Organization (FAO) and the WHO, provides international food safety standards, including MRLs for various substances, including antibiotics [105,106]. These guidelines are essential for harmonizing food safety regulations across countries and ensuring that food products are safe for consumption [107–109]. Fig. 2 shows an overview of a possible framework for managing antibiotic residues in food production.

In addition to international regulations, many countries have implemented their own local regulations to control antibiotic residues in food. For instance, the European Union has strict regulations regarding the use of antibiotics in livestock, prohibiting the use of certain antibiotics as growth promoters and establishing stringent MRLs for antibiotic residues in food products [110]. Similarly, the United States has enacted the Animal Drug Availability Act, which regulates the use of antibiotics

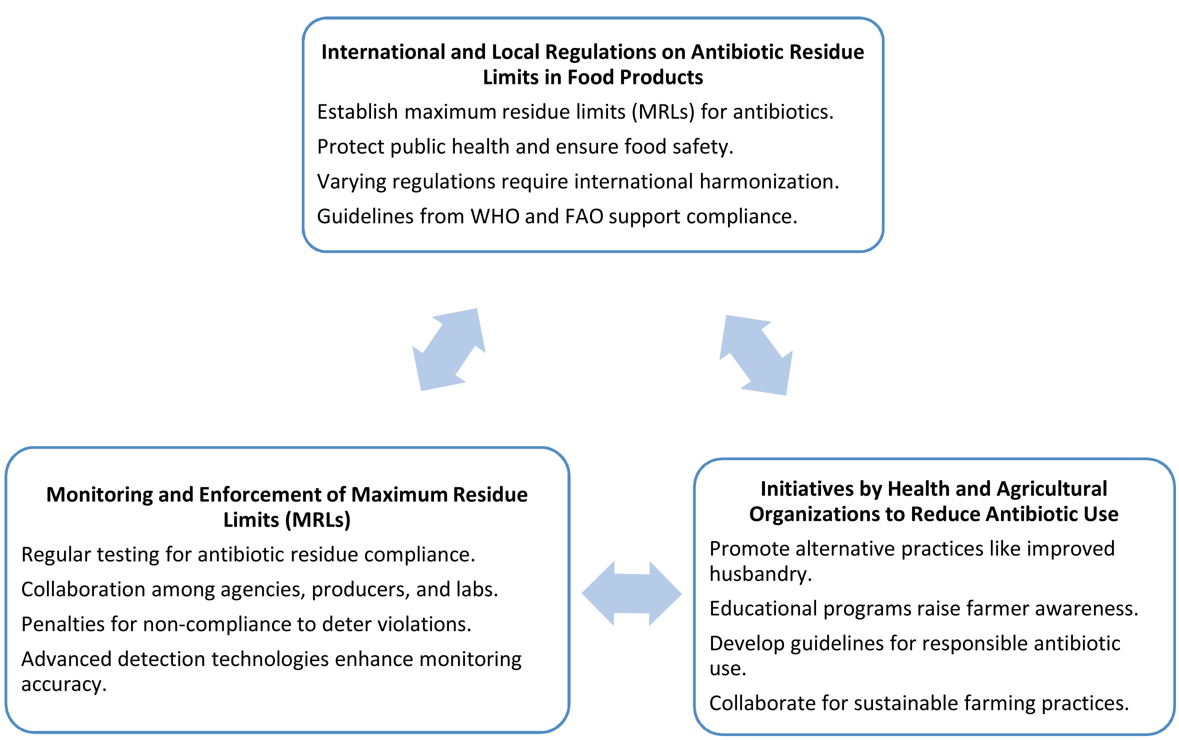

Fig. 2. Possible framework for managing antibiotic residues in food production.

in food animals and mandates withdrawal periods to ensure that antibiotic residues do not exceed established limits before animals are slaughtered for food [111]. These regulatory frameworks are crucial for protecting consumers from the potential health risks associated with antibiotic residues in food.

Monitoring and enforcement of MRLs are vital components of these regulatory frameworks. Effective monitoring systems are necessary to ensure compliance with established limits and to detect any violations promptly. For example, in Denmark, the implementation of the "yellow card initiative" has led to biannual audits of veterinary practices and a significant reduction in antibiotic use in food animal production [112]. This initiative relies on a comprehensive database that tracks antibiotic prescriptions, allowing for targeted enforcement actions against non-compliance. Similarly, in Vietnam, monitoring programs have been established to test for antibiotic residues in aquaculture products, ensuring that they meet safety standards before reaching consumers [113]. These monitoring efforts are essential for maintaining food safety and public health [114,115].

Health and agricultural organizations have also initiated various programs to reduce antibiotic use in food production. The World Organization for Animal Health (OIE) and the FAO have launched initiatives aimed at promoting responsible antibiotic use in livestock and reducing the reliance on antibiotics for growth promotion [116]. These organizations advocate for the adoption of alternative practices, such as improved animal husbandry and biosecurity measures, to minimize the need for antibiotics in food animal production. Additionally, the use of probiotics and other non-antibiotic feed additives has gained traction as a means to enhance animal health and growth performance without the associated risks of antibiotic use [117,118]. Such initiatives are crucial for addressing the growing concerns regarding antibiotic resistance and ensuring sustainable food production practices [119,120].

The impact of antibiotic use in agriculture extends beyond food safety; it also has significant implications for environmental health. Antibiotic residues can contaminate soil and water systems, leading to the proliferation of antibiotic-resistant bacteria in the environment [121]. Studies have shown that the application of manure containing antibiotic residues can contribute to the selection of antibiotic-resistant genes in agricultural soils, posing risks to both human health and ecosystem integrity [122]. Therefore, regulatory frameworks must also address the environmental aspects of antibiotic use in agriculture to mitigate these risks effectively.

In addition to regulatory measures, public awareness and education play a crucial role in reducing antibiotic use in food production. Farmers and veterinarians must be educated about the risks associated with inappropriate antibiotic use and the importance of adhering to established guidelines. For instance, in the UK, educational campaigns have been implemented to promote responsible antibiotic use in livestock farming, resulting in a significant reduction in antibiotic consumption [123]. Such initiatives are essential for fostering a culture of responsible antibiotic use within the agricultural sector.

The economic implications of antibiotic regulations are also noteworthy. Farmers may face increased costs associated with compliance with MRLs and the adoption of alternative practices to reduce antibiotic use. However, studies have shown that the long-term benefits of reducing antibiotic use, such as improved animal health and reduced healthcare costs associated with antibiotic resistance, can outweigh these initial costs [112]. Therefore, it is essential for policymakers to consider the economic impacts of regulatory measures while promoting public health and environmental sustainability.

The global nature of food production and trade necessitates international cooperation in establishing and enforcing antibiotic regulations. The Codex Alimentarius plays a vital role in facilitating this cooperation by providing a platform for countries to discuss and harmonize food safety standards, including those related to antibiotic residues [105]. International organizations like the WHO and FAO are pivotal in promoting sustainable antibiotic practices in agriculture [124]. Their collaborative initiatives address the pressing issue of antibiotic resistance, which threatens global food safety [125]. By implementing comprehensive strategies, these organizations aim to mitigate the risks associated with antibiotic misuse in livestock, thereby safeguarding public health. Such efforts are crucial for ensuring that antibiotics remain effective against infections in both humans and animals, preserving their efficacy for future generations.

6. Detection and management of antibiotic residues

The detection and management of antibiotic residues in poultry products is a critical issue that has garnered significant attention due to its implications for public health and food safety. Antibiotic residues can result from the therapeutic and prophylactic use of antibiotics in poultry farming, leading to potential health risks for consumers. Various methods have been developed to detect these residues, including chemical and microbiological assays, which are essential for ensuring the safety of poultry products. For instance, microbiological inhibition tests are commonly employed for preliminary screening of antibiotic residues, as they are simple, cost-effective, and capable of processing multiple samples simultaneously [126,127]. These methods can identify the presence of antibiotics in poultry tissues, thereby helping to mitigate the risks associated with their consumption. Table 3 shows an overview

Table 3
Strategies for managing antibiotic residues in poultry farming.

Category	Key aspects	Points	Implications
Methods for detecting antibiotic residues	Chemical assays	Chromatography for precise residue quantification.	Ensures compliance with safety standards and regulations.
	Microbiological assays	Bioassays to assess antibiotic activity.	Identifies active residues that may pose health risks.
	Immunoassays	ELISA for rapid antibiotic screening.	Allows for quick testing, improving food safety.
	Screening tests	Rapid tests for on-site detection.	Facilitates immediate detection and corrective actions.
Best practices for preventing residue accumulation	Adhere to withdrawal periods	Follow antibiotic administration guidelines.	Reduces risk of residues in meat and eggs.
	Implement good management practices	Enhance biosecurity and flock health.	Minimizes disease occurrence, decreasing antibiotic use.
	Monitor usage	Keep accurate antibiotic usage records.	Promotes responsible antibiotic use and accountability.
	Educate staff	Train on responsible antibiotic use.	Increases awareness of residue risks among farm personnel.
Alternatives to antibiotics in poultry farming	Probiotics	Use beneficial bacteria for gut health.	Supports animal health without antibiotic dependence.
	Vaccination	Prevent diseases, reducing antibiotic use.	Reduces disease incidence and promotes animal welfare.
	Phytobiotics	Plant-based additives for growth promotion.	Enhances growth and health without antibiotics.
	Nutritional Strategies	Optimize feed for better health.	Improves overall flock health and productivity.

of the strategies for managing antibiotic residues in poultry farming.

In addition to microbiological assays, chemical methods such as enzyme-linked immunosorbent assays (ELISA) and chromatographic techniques are also utilized for more precise quantification of antibiotic residues in poultry products [128,129]. These advanced techniques provide a higher sensitivity and specificity compared to traditional microbiological methods, allowing for the detection of lower concentrations of residues. For example, studies have shown that ELISA can effectively detect residues of various antibiotics, including tetracyclines and macrolides, in chicken tissues [128,130]. The combination of these detection methods is crucial for comprehensive monitoring of antibiotic residues in poultry, ensuring compliance with established maximum residue limits (MRLs) set by regulatory bodies [129].

To prevent the accumulation of antibiotic residues in poultry products, best practices for poultry farmers are essential. One significant practice is adhering to the recommended withdrawal periods after antibiotic treatment, which is the time required for the drug to be eliminated from the animal's system before slaughter [23,131]. Failure to observe these periods can lead to violative levels of residues in meat and eggs, posing health risks to consumers [23,132]. Furthermore, educating farmers about the proper use of antibiotics and the importance of veterinary oversight can significantly reduce the indiscriminate use of these drugs, which is often driven by a lack of knowledge and access to veterinary services [133,134]. Implementing strict monitoring and record-keeping practices can also help farmers track antibiotic usage and ensure compliance with safety standards.

In addition to these practices, the adoption of alternatives to antibiotics in poultry farming is gaining traction as a means to reduce reliance on these drugs and minimize the risk of residue accumulation. Probiotics, for instance, have been shown to improve gut health and enhance the immune response in poultry, thereby reducing the need for antibiotic interventions [135]. Vaccination programs are another effective strategy, as they can prevent diseases that would otherwise necessitate antibiotic treatment [136,137]. The integration of these alternatives not only promotes animal health but also contributes to the overall sustainability of poultry farming by reducing the environmental impact associated with antibiotic use.

Moreover, the use of prebiotics and phytogenics has emerged as a promising approach to enhance poultry health and performance without the use of antibiotics. These natural compounds can improve gut microbiota balance and enhance nutrient absorption, leading to better growth rates and feed efficiency [129]. Research indicates that incorporating such alternatives can significantly reduce the incidence of infections in poultry, thereby decreasing the need for antibiotic treatments [138]. This shift towards alternative strategies aligns with global efforts to combat antibiotic resistance and promote responsible antibiotic use in agriculture.

The public health implications of antibiotic residues in poultry products cannot be overstated. The presence of these residues in food can lead to adverse health effects, including allergic reactions and the development of antibiotic-resistant bacteria [132,139]. The WHO has recognized antibiotic resistance as a major global health challenge, emphasizing the need for effective monitoring and management strategies [129]. As such, regulatory frameworks must be strengthened to ensure that poultry products meet safety standards and do not pose risks to consumers.

7. Addressing the adverse consequences of antibiotic residues by safeguarding One Health and exploring natural alternatives

7.1. The adverse consequences of antibiotic residues on One Health

The presence of antibiotic residues in food products of animal origin poses significant threats to public health and the environment [140,141]. These residues can have direct toxic effects on consumers, leading to adverse health outcomes such as carcinogenicity, mutagenicity, nephropathy, hepatotoxicity, bone marrow toxicity, and allergic reactions [140,142]. Moreover, the transfer of antibiotic-resistant bacteria (ARB) and antibiotic-resistant genes (ARGs) from animals to humans through the food chain is a major concern [124,141,143].

Epidemiological studies have linked early-life exposure to antibiotics through the food supply chain or drinking water to an increased risk of childhood obesity [141,144]. Antibiotic residues can also disrupt the gut microbiome, leading to metabolic disorders and other long-lasting effects [144]. Furthermore, the presence of antibiotic residues in milk and dairy products can inhibit the growth of starter cultures used in fermentation processes, causing economic losses for the dairy industry [145,146].

The widespread use of antibiotics in food-producing animals has contributed to the emergence and spread of antibiotic resistance, which is a global threat to public health [124,143]. The One Health approach, which recognizes the interconnectedness of human, animal, and environmental health, is crucial in addressing this issue [147,148]. Comprehensive and integrated measures, including monitoring and regulating antibiotic residues, are necessary to ensure food safety, combat infectious diseases, and preserve the efficacy of antibiotics for future generations [124,143].

7.2. Natural alternatives to antibiotics for healthy food

In order to address the adverse consequences of antibiotic residues and the growing threat of antibiotic resistance, researchers have explored natural alternatives to antibiotics for use in food production. Except the photocatalytic method [149–151], one promising solution is the use of biochar, a carbon-rich material derived from the pyrolysis of organic matter [152,153]. Studies have demonstrated that biochar can effectively remove or reduce the contaminating effects of antibiotic residues, antibiotic resistance genes, and other contaminants in soil and water [154].

The use of biochar in the food supply chain can help mitigate the transfer of antibiotic residues and resistant bacteria, contributing to the overall improvement of food safety and public health [154]. Additionally, the use of biochar is in line with the principles of a circular economy and sustainable development [155,156], as it provides an eco-friendly and cost-effective solution for the removal of these contaminants [154].

Other natural alternatives, such as the use of essential oils [157], plant-derived compounds [158–160], and bacteriophages, are also being explored as potential replacements for antibiotics in animal husbandry and food production [161,162]. These natural compounds have shown promising results in inhibiting the growth of pathogenic bacteria without contributing to the development of antibiotic resistance.

By adopting a comprehensive approach that combines the monitoring and regulation of antibiotic residues with the implementation of natural alternatives, the food industry and regulatory bodies can work towards ensuring the safety and sustainability of the food supply, while also addressing the pressing issue of antibiotic resistance [124,143].

8. Recommendations for reducing public health risks

The reduction of public health risks associated with antibiotic use in poultry farming is critical, especially in light of the rising concerns over AMR. The implementation of effective policy recommendations is essential to mitigate these risks. One significant approach is to enhance the regulation of antibiotic use in poultry farming, which can be achieved through the establishment of stringent guidelines and monitoring systems. Studies indicate that the indiscriminate use of antibiotics in poultry is often driven by inadequate veterinary services and self-medication practices among farmers [133,163]. By instituting comprehensive surveillance systems to monitor antibiotic access and usage, policymakers can significantly reduce the prevalence of antibiotic-containing agents in poultry farming [163].

Furthermore, education plays a vital role in changing farmers' attitudes towards antibiotic use. Research shows that improving literacy on biosecurity and poultry management standards can lead to a decrease in antimicrobial use [164]. This educational initiative should be coupled with the promotion of best practices throughout the poultry value chain, which can help farmers adopt more responsible antibiotic use behaviors [164]. Additionally, the involvement of veterinarians in the decision-making process regarding antibiotic prescriptions is crucial, as their expertise can guide farmers towards more judicious use of these medications [163].

Encouraging sustainable farming practices is another vital recommendation for reducing public health risks [165,166]. Sustainable agriculture not only minimizes the reliance on antibiotics but also promotes overall farm health and productivity. The exploration of alternatives to antibiotics, such as probiotics and phytochemicals, has gained traction as effective strategies to enhance poultry health without contributing to AMR [167,168]. Implementing these alternatives can help maintain animal productivity while reducing the environmental impact associated with antibiotic use [98]. Moreover, integrating sustainable practices into poultry farming can lead to improved biosecurity measures, which are essential for preventing the spread of pathogens [169].

The adoption of sustainable farming practices can also be supported through financial incentives and educational programs tailored to specific farming contexts [170]. Governments should consider offering subsidies or tax breaks to farmers who implement sustainable practices, as this can encourage a shift away from conventional methods that rely heavily on antibiotics [171]. Additionally, agricultural extension services should focus on disseminating knowledge about sustainable practices, emphasizing their long-term benefits for both farmers and public health [172,173].

Strengthening food safety monitoring systems is crucial in ensuring that poultry products are safe for consumption and free from antibiotic residues [174–176]. Enhanced monitoring can help identify and mitigate risks associated with antibiotic use in poultry farming. For instance, the establishment of robust testing protocols for antibiotic residues in poultry products can help safeguard public health by ensuring that contaminated products do not enter the food supply [177]. Moreover, integrating food safety monitoring with existing public health frameworks can facilitate a more comprehensive approach to managing AMR risks [178].

Furthermore, the role of environmental factors in the emergence and spread of AMR cannot be overlooked [179]. Research indicates that antibiotic-resistant bacteria can persist in the environment, particularly in agricultural settings where antibiotics are used extensively [177]. Therefore, implementing environmental management practices, such as proper wastewater treatment and disposal, is essential to prevent the contamination of agricultural land and water sources with antibiotic residues. This approach not only protects public health but also promotes sustainable agricultural practices.

The collaboration between various stakeholders, including farmers, veterinarians, policymakers, and public health officials, is essential for the successful implementation of these recommendations. A multidisciplinary approach can facilitate the sharing of knowledge and resources, leading to more effective strategies for reducing antibiotic use in poultry farming [180]. Additionally, fostering partnerships between research institutions and the agricultural sector can promote the development of innovative solutions to combat AMR [181].

9. Conclusion and perspectives

The presence of antibiotic residues in poultry food products poses significant public health risks, including allergic reactions, toxicity, and, most critically, the promotion of antimicrobial resistance (AMR). The misuse and overuse of antibiotics in poultry farming contribute to the emergence of resistant bacteria, which can be transmitted to humans through the consumption of contaminated meat. AMR presents a major global challenge, as it diminishes the effectiveness of life-saving antibiotics in treating infections. Additionally, prolonged exposure to antibiotic residues may disrupt the gut microbiota, leading to broader health concerns such as metabolic disorders or compromised immune responses. Addressing these risks requires multifaceted solutions, including stricter regulations to control antibiotic usage, improved farming practices, and the promotion of alternatives such as probiotics, vaccines, and natural supplements. Public awareness campaigns are also crucial to educate consumers about the dangers of antibiotic residues and the importance of supporting sustainable farming practices.

To mitigate the impact of antibiotic residues on public health, a comprehensive and coordinated response is necessary. This includes enforcing stringent regulations on antibiotic usage in poultry farming, promoting alternatives to antibiotics, and advancing consumer education about the risks associated with contaminated food products. Future research must prioritize the development of sensitive detection methods for antibiotic residues, the exploration of safer alternatives for disease management in poultry, and a deeper understanding of the long-term effects of low-level antibiotic exposure on human health. Through collaborative efforts across regulatory, scientific, and agricultural sectors, it is possible to reduce the risks posed by antibiotic residues and safeguard both human and animal health.

CRediT authorship contribution statement

Sylvester Chibueze Izah: Writing – review & editing, Writing – original draft, Project administration, Methodology, Data curation, Conceptualization. **Akmaral Nurmahanova:** Writing – review & editing, Writing – original draft, Supervision, Investigation, Formal analysis. **Matthew Chidozie Ogwu:** Writing – review & editing, Validation, Formal analysis. **Zhexenbek Toktarbay:** Writing – review & editing, Formal analysis, Data curation. **Zoya Umirbayeva:** Writing – review & editing, Validation, Formal analysis. **Kurmanbay Ussen:** Writing – review & editing, Validation, Formal analysis, Data curation. **Laura Koibasova:** Writing – review & editing, Validation, Formal analysis. **Saltanat Nazarbekova:** Writing – review & editing, Validation, Formal analysis. **Bekzat Tynybekov:** Writing – review & editing, Validation, Project administration, Investigation. **Zhanhu Guo:** Writing – review & editing, Supervision, Project administration.

Consent to participate

Not applicable.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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