Review Article

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Risk of antimicrobial and multidrug resistance on Avian Pathogenic *Escherichia coli* in public health

Ummi Rahayu[1], Freshinta J. Wibisono[2], Wiwiek Tyasningsih[3,4], Mustofa H. Effendi[4,5,6*], Budiastuti Budiastuti[7], Budiarto Budiarto[5], Dian A. Permatasari[4,5], Aswin R. Khairullah[8], Saifur Rehman[9], John Y.H. Tang[6], Riza Z. Ahmad[8], Bima P. Pratama[10], Ikechukwu B. Moses[11], Dea A.A. Kurniasih[12]

[1]Master Program of Veterinary Disease and Public Health Science, Faculty of Veterinary Medicine, Universitas Airlangga, Kampus C Mulyorejo, Jl. Dr. Ir. H. Soekarno, Surabaya, East Java, 60115, Indonesia.
[2]Faculty of Veterinary Medicine, Universitas Wijaya Kusuma Surabaya, Jl. Dukuh Kupang XXV No.54, Dukuh Kupang, Dukuh Pakis, Surabaya 60225, East Java, Indonesia.
[3]Division of Veterinary Microbiology, Faculty of Veterinary Medicine, Universitas Airlangga, Kampus C Mulyorejo, Jl. Dr. Ir. H. Soekarno, Surabaya, East Java, 60115, Indonesia.
[4]Research Group on Antimicrobial Resistance, Faculty of Veterinary Medicine, Universitas Airlangga, Kampus C Mulyorejo, Jl. Dr. Ir. H. Soekarno, Surabaya, East Java, 60115, Indonesia.
[5]Division of Veterinary Public Health, Faculty of Veterinary Medicine, Universitas Airlangga, Kampus C Mulyorejo, Jl. Dr. Ir. H. Soekarno, Surabaya, East Java, 60115, Indonesia.
[6]School of Food Industry, Faculty of Bioresources, and Food Industry, Universiti Sultan Zainal Abidin (Besut Campus), Besut 22200, Malaysia.
[7]Study Program of Pharmacy Science, Faculty of Health Science, Universitas Muhammadiyah Surabaya, Jl. Raya Sutorejo No.59, Dukuh Sutorejo, Mulyorejo, Surabaya 60113, East Java, Indonesia.
[8]Research Center for Veterinary Science, National Research and Innovation Agency (BRIN), Jl. Raya Bogor Km. 46 Cibinong, Bogor, West Java, 16911, Indonesia.
[9]Department of Pathobiology, Faculty of Veterinary and Animal Sciences, Gomal University, RV9W+GVJ, Indus HWY, Dera Ismail Khan 27000, Pakistan.
[10]Research Center for Agroindustry, National Research and Innovation Agency (BRIN), Jl. Raya Puspiptek 60, South Tangerang, West Java, 15310, Indonesia.
[11]Department of Applied Microbiology, Faculty of Science, Ebonyi State University. Abakaliki 480211, Nigeria.
[12]Research Center for Public Health and Nutrition, National Research and Innovation Agency (BRIN), Jl. Raya Bogor Km. 46 Cibinong, Bogor, West Java, 16911, Indonesia.

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*Correspondence:

Corresponding author: Mustofa H. Effendi
E-mail address: mhelmieffendi@gmail.com

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ABSTRACT

Escherichia coli is a harmful bacterium commonly found in poultry species like chickens, ducks, quails, and turkeys, which can lead to colibacillosis. This illness is caused by Avian Pathogenic *Escherichia coli* (APEC), a highly virulent strain that poses a risk of transmission through the food chain, endangering human health. Managing infections in poultry frequently involves the widespread use of antibiotics, which promotes the development of antimicrobial resistance (AMR) and multidrug resistance (MDR). The global use of antibiotics in livestock is a significant issue, with an estimated 63,000 tons used annually, expected to rise to 105,500 tons by 2030. Antibiotic residues found in poultry products, such as meat and eggs, can enter the human food supply, contributing to antibiotic resistance and diminishing the effectiveness of treatments for human infections. The transmission of APEC occurs through horizontal pathways, including direct contact between poultry via feces and the environment, and vertical transmission via eggs from infected breeders. Additionally, APEC can spread through water, feed, and environmental contamination. Antibiotic residues in poultry products can cause allergic reactions, cancer, reproductive issues, and toxicity in humans. The consequences of antimicrobial resistance include higher rates of illness, death, and healthcare costs, with the potential for further escalation.

Introduction

Escherichia coli is a pathogenic bacterium commonly found in poultry raised for consumption (such as quail, chicken, duck, and turkey), which causes the significant disease colibacillosis (Hidanah *et al.*, 2023; Li *et al.*, 2016). This disease is caused by Avian Pathogenic *Escherichia coli* (APEC), a highly virulent strain capable of causing severe illnesses in poultry (Ibrahim, 2019; Wibisono *et al.*, 2022). APEC's transmission through the food chain presents potential risks to human health, particularly via the consumption of contaminated poultry products (Amir *et al.*, 2017; Saraiva *et al.*, 2022).

Poultry such as chickens, turkeys, ducks, and quails are raised in large populations and are highly susceptible to bacterial infections (Abd El-Ghany, 2019). These infections can significantly affect poultry populations, leading to the widespread use of antibiotics for treatment and prevention, which contributes to the development of antibiotic resistance and the potential for harmful residues in the environment and human food supply (Nwobodo *et al.*, 2022). Pathogenic *E. coli* in consumption poultry possess numerous virulence factors that contribute to their infection and pathogenicity, allowing them to adapt and thrive (Kalule *et al.*, 2018).

The major concern with *E. coli* infections is antibiotic resistance, often manifesting as antimicrobial resistance (AMR) and multidrug resistance (MDR). The use of antibiotics in animal agriculture has led to the emergence of resistant strains of pathogenic bacteria (Xu *et al.*, 2022). Aarestrup (2012) notes that global antibiotic use in animals is nearly double that in humans. Annually, about 63.1±1.5 tons of antibiotics are used in livestock production (Van Boeckel *et al.*, 2015), with more than 80% of animals raised for food purposes receiving antibiotics. By 2030, global antibiotic use in food animals is projected to increase by 67%, reaching approximately 105,500 tons (Van Boeckel *et al.*, 2015).

Residues from antibiotics in animal products such as quail meat and eggs are higher than those in chicken eggs (8.4%) and duck eggs (2.66%), with the aminoglycoside group showing 9.15% in quail eggs (Anggita *et al.*, 2021). People who consume poultry products, such as meat, eggs, and dairy, are at risk of developing resistance to specific antimicrobials due to antibiotic residues that enter the food chain (Abreu *et al.*, 2023; Roess *et al.*, 2013). This resistance can reduce the effectiveness of antibiotics used to treat human diseases.

The widespread use of antibiotics can also result in the emergence of antibiotic-resistant bacterial strains, with the potential for resistant genes to be transferred to other pathogenic or non-pathogenic bacteria (Peterson and Kaur, 2018; Widodo *et al.*, 2022). Consistent with research by Khairullah *et al.* (2024), resistant bacteria can become pathogenic and cause negative health impacts. These resistance genes can be transferred to other bacteria, exacerbating the problem. This review aimed to assess the risks of AMR and MDR APEC in consumption poultry, focusing on dangerous virulence genes, residual contamination, and environmental health impacts.

Pathogenic *Escherichia coli* bacteria

Escherichia coli is a rod-shaped, Gram-negative bacterium that is facultatively anaerobic and belongs to the Enterobacteriaceae family. It naturally resides in the digestive tracts of both animals and humans (Santos *et al.*, 2020). While *E. coli* itself is generally harmless, certain serotypes can cause diseases, such as colibacillosis in poultry, which is caused by Avian Pathogenic *Escherichia coli* (APEC) with serogroups including O1, O2, and O78 (Kathayat *et al.*, 2021; Watts and Wigley, 2024). Some *E. coli* strains, like the EHEC O157:H7, produce shiga toxins and can lead to zoonotic diseases (Rahman *et al.*, 2020). In poultry, *E. coli* can cause a variety of infections, including yolk sac infection, omphalitis, cellulitis, swollen head syndrome, coligranuloma, and colibacillosis, which are associated with high mortality rates (Islam *et al.*, 2021).

Pathogenic *E. coli* is classified into two main categories: Extraintestinal Pathogenic *Escherichia coli* (ExPEC) and Diarrheagenic *Escherichia coli* (DEC) (Vanstokstraeten *et al.*, 2022; Pokharel *et al.*, 2023). ExPEC includes Uropathogenic *E. coli* (UPEC), Neonatal Meningitis-Associated *E. coli* (NMEC), APEC, and Septicemic *E. coli* (SEPEC). DEC includes Enterotoxigenic *E. coli* (ETEC), Enteroinvasive *E. coli* (EIEC), Enteroaggregative *E. coli* (EAEC), Enteropathogenic *E. coli* (EPEC), Shiga Toxin-producing *E. coli* (STEC), Diffusely Adherent *E. coli* (DAEC), and Adherent-Invasive *E. coli* (AIEC). According to Lim *et al.* (2020), strains such as EPEC, ETEC, EIEC, and EHEC are known to cause foodborne illnesses.

E. coli is primarily transmitted through horizontal routes, including direct contact with infected poultry or through the respiratory tract. The bacteria can survive in feces for weeks, enabling prolonged transmission. Vertical transmission occurs through contaminated eggshells (Joseph *et al.*, 2023). Additionally, the bacteria can be spread via the digestive tract, where they can infect and multiply, leading to further transmission.

The rising threat of AMR and MDR in poultry products for human consumption

The rising incidence of Antimicrobial Resistance (AMR) and Multidrug Resistance (MDR) in poultry is a global concern, as shown in Table 1. In particular, in Indonesia, there is a widespread misuse of antibiotics by the public and farmers, who often administer antibiotics without proper veterinary supervision and fail to calculate the correct dosage (Siahaan *et al.*, 2022). According to Salam *et al.* (2023), antibiotic resistance is a major global issue and has the potential to become a leading cause of death in the next 50 years. Ahmed *et al.* (2024) report that drug-resistant microorganisms are responsible for over 1.2 million deaths annually, with the death toll projected to rise to 10 million by 2050. Furthermore, the World Bank estimates that AMR will increase healthcare costs by USD 1 trillion by 2050. *E. coli* is currently one of the main contributors to AMR, accounting for 43% of all cases (Karpov *et al.*, 2024; Murray *et al.*, 2022).

Antibiotic-resistant bacteria can lead to serious health complications, treatment failures, and even death (Mancuso *et al.*, 2021). Various incidents of AMR in poultry have been documented, including a study by Farghaly *et al.* (2017) where *E. coli* isolates exhibited resistance to amoxi-

Table 1. AMR and MDR data on *Escherichia coli* in the world.

Types of antibiotics	Country	Sample	Source
Erythromycin (98.7%) Enrofloxacin (96.1%) Tetracycline (95.2%) Doxycycline (93.9%) Lincomycin (90.0%) Streptomycin (90.0%) Ampicillin (87.8%) Sulfamethoxazole/trimethoprim (84.3%) Amoxicillin (81.7%) Cephalotin (78.7%) Florfenicol (69.6%) Amikacin (67.4%) Gentamicin (62.2%) Lomefloxacin (61.3%) Cefotaxime (52.6%)	East China	Sick chicken	(Afayibo *et al*., 2022)
Tetracycline (50%) Ciprofloxacin (46.8%)	Polandia	Wild Birds	(Nowaczek *et al*., 2021)
Tetracycline (64%) Ampicillin (55.1%) Trimetoprim (49.4%)	Qatar	Pigeons	(Alhababi *et al.*, 2020)
Trimetoprim (95.5%) Florfenicol (93.7%) Amoxicillin (93.3%) Doxycycline (92.2%) Spectinomycin (92.2%)	Yordania	Broiler chicken	(Ibrahim *et al*., 2019)
Nalidixic acid (84.8%) Ciprofloxacin (69.6%) Tetracycline (58.4%) Chloramphenicol (56.2%)	Korea	Chicken	(Kim *et al*., 2021)
Tetracycline (97.3%) Ampicillin (97.3%) Sulfamethoxazole/trimethoprim (83.7%) Sulfisoxazole (81.1%) Cefoxitin (78.4%) Streptomycin (75.7%) Gentamicin (45.9%) Nalidixic acid (45.9%)	Nigeria	Chicken	(Aworh *et al*., 2020)
Ampicillin (97.1%) Nalidixic acid (77.1%) Trimetoprim (70.5%) Streptomycin (65.7%) Sulfamethoxazole/trimethoprim (63.8%) Chloramphenicol (56.2%)	Türkiye	Chicken	(Baran *et al*., 2020)

cillin + clavulinic acid (71.4%), ciprofloxacin (57.1%), tetracycline (71.4%), trimethoprim-sulfamethoxazole (100%), chloramphenicol (85.7%), nalidixic acid (57.1%), and streptomycin (71.4%). Ranabhat *et al*. (2024) also reported AMR to gentamicin (90.2%) and tetracycline (67.2%). Hasan *et al*. (2024) found antimicrobial resistance to ampicillin (86%), ciprofloxacin (86%), and trimethoprim-sulfamethoxazole (73%).

Patel *et al*. (2024) found AMR to fluoroquinolone antibiotics, including enrofloxacin (72.46%), levofloxacin (69.56%), and ciprofloxacin (66.66%), followed by amoxyclav (63.77%) and tetracycline (59.42%). Khong *et al*. (2023) reported that *E. coli* isolates showed the greatest resistance to cephalothin (54.4%), tetracycline (27.9%), and streptomycin (29.4%). Salam *et al*. (2024) also reported varying levels of resistance in *E. coli* isolates, with the highest resistance found to amoxicillin-sulbactam (82%), followed by streptomycin (76%), cefotaxime and trimethoprim/sulfamethoxazole (73%), tetracycline and ciprofloxacin (68%), chloramphenicol (66%), cefaclor (65%), and cefixime (62%).

MDR refers to bacteria that have become resistant to multiple types of antibiotics with different mechanisms of action. The term MDR applies to bacteria that are resistant to three or more different classes of antibiotics, rendering them more dangerous than before (Effendi *et al*., 2021).

E. coli, as a commensal bacterium that has become multidrug-resistant, presents a significant health risk (Pradika *et al*., 2019). This is due to *E. coli*'s ability to transfer resistance genes to other pathogenic bacteria within the digestive tract (Wibisono *et al*., 2022). Putri *et al*. (2023) identified several risk factors for multidrug resistance in *E. coli*, including the type of farm, type of feed, veterinary support, chlorine levels in water, antibiotic programs, and references for antibiotic administration. The consequences of AMR and MDR include increased treatment costs, higher fatality, morbidity, and mortality rates associated with infectious diseases.

Transmission pattern of the *Escherichia coli* pathogen

Various transmission routes for *E. coli* pathogens from animals to humans, such as those carried by migratory birds, play a significant role in the spread of various human and animal pathogens, including bacteria, viruses, fungi, and parasites (Mihaela and Marina, 2014). Pathogenic bacteria can be transmitted to humans and animals through poultry or birds via contaminated water, particularly if the water is used for household or agricultural purposes (Islam *et al*., 2021). The aquatic environment serves as a dynamic medium capable of transmitting pathogens over long distances (Chen *et al*., 2020; Bombaywala *et al*., 2021), due to the extensive movement of organisms, which creates a complex disease transmission network (Khairullah *et al*., 2022).

Hernández-Vásquez *et al*. (2022) highlight water pollution as a major environmental issue affecting people's quality of life worldwide, with around two billion people still consuming water contaminated with harmful microorganisms. Sabar *et al*. (2022) indicate that water consumed by the public often contains human and animal feces, with *E. coli* acting as a key indicator of fecal contamination, potentially causing gastrointestinal infections. This contamination results from the consumption of water tainted by human and animal waste, often from unclean water sources. According to research by Swelum *et al*. (2021), *E. coli* can spread through direct contact with birds or other poultry, as well as through the respiratory tract, with bacteria capable of surviving in feces for several weeks. Vertical transmission can also occur, as when eggshells contaminated with feces carry pathogenic *E. coli*.

Bortolaia *et al*. (2010) explain that horizontal transmission occurs when infected poultry spread bacteria to healthy individuals through body fluids, aerosols, feathers, and contaminated droppings. In poultry farms for consumption, *E. coli* can be transmitted vertically to offspring. Vertically transmitted APEC (Avian Pathogenic *E. coli*) can increase mortality rates in chicks within the first week of life due to horizontal transmission in hatcheries and farms. Infected eggs from the reproductive tracts of poultry can spread APEC to embryos during incubation. Additionally, uninfected poultry can become exposed to the bacteria through contact with infected birds via feathers and droppings. These interactions serve as primary channels for the spread of APEC infection.

Arsène *et al*. (2022) note that interactions between humans and animals, both direct and indirect, can facilitate the transfer of antibiotic residues. Direct interactions occur when antibiotics used in animals or plants result in residues that enter the food supply after slaughter or harvest. Indirectly, antibiotic residues accumulate in water and soil through manure or human waste, which can then contaminate food, particularly vegetables, through watering or contact with animal waste.

Khairullah *et al*. (2024) identify the fecal-oral route as a primary mechanism for APEC transmission in poultry, where bacteria excreted through the feces of infected birds contaminate the environment, feed, and water sources. Chickens can ingest APEC through contaminated feed or water, or via direct contact with infected feces. Transmission can also occur through the respiratory tract or retrogradely through the vaginal/cloacal route. Research on colibacillosis cases shows that the fecal-oral and respiratory routes are the most common means of transmission. Additionally, there is evidence of vertical transmission of APEC from infected mother birds to their chicks via eggs, which can lead to increased mortality during the first week of life, as well as horizontal transmission in hatcheries.

Fathima *et al*. (2022) report high levels of antimicrobial resistance in chicks at hatching, which may stem from the gut microbiota of the birds (via vertical transmission) or from the hatchery environment. Horizontal transmission of bacteria occurs within and between groups of chickens, spreading widely from farms to the surrounding environment (Dame-Korevaar *et al*., 2019; Osman *et al*., 2018).

Avian Pathogenic *Escherichia coli* (APEC) in commercial poultry

APEC can act as either a primary or secondary pathogen in various poultry species, including broiler chickens, laying hens, turkeys, and ducks (Collingwood *et al*., 2014; Hu *et al*., 2022). This infection is syndromic and leads to colibacillosis, with *E. coli* as the causative agent. One method to determine the pathogenic potential of APEC strains is serotyping, which categorizes *E. coli* based on somatic (O), capsular (K), and flagellar (H) antigens. Certain O serotypes are particularly associated with *E. coli* pathogenicity (Hu *et al*., 2022). Common serotypes linked to colibacillosis include O1:K1, O2:K1, O5, O8, O35, O150, and O78:K80 (Cordoni *et al*., 2016).

E. coli is classified into eight p*hyl*ogenetic groups, namely *E. coli* sensu stricto (A, B1, B2, C, D, E, F) and *E. coli* cryptic clade I. The majority of *E. coli* strains that infect humans (ExPEC) belong to groups B2 and D, while APEC is generally found in groups C, F, B1, and B2 (Jeong *et al*., 2021). APEC enters the chicken's body via the oral or nasal tract, where it initially explores the mucosa of the digestive and reproductive tracts without immediately causing disease. However, APEC can invade the mucosal layer and spread to extra-intestinal organs such as the heart, liver, lungs, spleen, kidneys, and reproductive organs. This infection causes colibacillosis, which is characterized by high morbidity and mortality rates, production losses, and potential transmission to humans via food (Kathayat *et al*., 2021; Sarowska *et al*., 2019).

A significant and contagious disease caused by APEC infection in quail is septicemic colibacillosis (Matin *et al*., 2017). While *E. coli* is normally part of the intestinal flora, certain strains are pathogenic and can lead to diseases that have substantial economic impacts (Hassan *et al*., 2021). In 2011, *E. coli* infections caused losses estimated at $500 billion globally (Kawecki *et al*., 2012). Pathogenic *E. coli* can lead to peritonitis, pericarditis, airsacculitis, osteomyelitis, cellulitis, synovitis, salpingitis, yolk sac infection, and coliosticemia associated with APEC (Guabiraba and Schouler, 2015; Kunert-Filho *et al*., 2015; Crémet *et al*., 2015).

Colibacillosis is a fatal disease that poses a significant threat to the poultry industry (Kabir, 2010). According to Hegazy *et al*. (2017), APEC causes severe diseases in consumed poultry such as quail, chickens, ducks, and turkeys. In quail, APEC infection can lead to hepatitis and pericarditis in birds aged 21 days and coligranulomatosis in quail aged 8-12 months (Ito *et al*., 1990). Infected chickens show symptoms of watery diarrhea, anorexia, weakness, weight loss, and death (Kika *et al*., 2023; Matin *et al*., 2017). Ducks infected with colibacillosis often exhibit congested lungs and minor bleeding in the heart and air sacs (Stordeur *et al*., 2004).

Escherichia coli survival enhancer gene

Colibacillosis is a disease caused by pathogenic *E. coli*. The pathogenic potential of *E. coli* is enhanced by the presence of virulence factors, which are regulated by specific gene codes (De Carli *et al*., 2015). APEC-induced colibacillosis is associated with various genes, each contributing to the pathogenicity of *E. coli* and enabling it to infect poultry (Joseph *et al*., 2023). According to Rezatofighi *et al*. (2021), avian *E. coli* can serve as a potential reservoir for ExPEC strains in humans, making it a potential zoonotic threat.

The virulence genes of APEC include *fim*C, *pap*C, *tsh*, *mat*, *irp*2, *fyu*A, *hyl*F, *iuc*D, *iro*N, *iss*, *Cva/cvi*, *neu*C, *omp*A, *vat*, *ibe*A, and *ibe*B (Al-Kandari and Woodward, 2019; Ievy *et al*., 2020; Newman *et al*., 2021; Sgariglia *et al*., 2019). As stated by Croxen and Finlay (2010), *E. coli* can become pathogenic with just a few key genes through a mix-and-match mechanism, which enables the bacteria to cause serious diseases.

APEC strains produce various virulence factors that aid in host tissue colonization, such as adhesins (encoded by *pap*C and *tsh*), iron uptake systems (*iut*A, *irp*2, *sit*, and *iro*N), serum resistance factors (*iss*, *omp*T, and *kps*II), toxins (*vat*), and other factors (cvi/cva and etsB) (Kathayat *et al*., 2021; Paixao *et al*., 2016). The virulence of APEC strains, including *omp*T, *iut*A, *iss*, *pap*-C, *cva/cvi*, and *tsh*, is commonly found in pathogenic *E. coli* strains from poultry (Subedi *et al*., 2018). Furthermore, Kendek *et al*. (2024) reported that 60% of *E. coli* isolates possess the *hly*F gene, which is associated with colisepticaemia in poultry.

Escherichia coli virulence gene mechanism

The *fim*C gene is involved in the mechanism of adherence and colonization of epithelial cells (Islam *et al*., 2021). Schwan (2011) noted that the *fim*C gene is linked to pyelonephritis. The *pap*C gene encodes pilin, which assists *E. coli* in adhering to the surface of epithelial cells in the urinary tract and other organs, facilitating colonization and infection (Choudhary and Madhwal, 2020; Mohamed *et al*., 2014).

The *iss* gene is a virulence factor that enhances bacterial survival. The *iss* gene (Increased Serum Survival) has been found in the intestines of quail (Rodriguez-Siek *et al*., 2005). This virulence gene is pathogenic and has zoonotic potential. The *iss* gene plays a critical role in the virulence of *E. coli* (Dissanayake *et al*., 2014; Paixao *et al*., 2016). In a study by Badouei *et al*. (2016), *iss* was found in 90.3% of septicemic quail isolates and 64.3% of fecal isolates. Similarly, Kafshdouzan *et al*. (2013) found the *iss* gene in 68.2% of APEC isolates and in 24.5% of fecal isolates. According to Khusnan and Prihtiyantoro (2020), *iss* was present in 61.9% of *E. coli* isolates from quail.

The *tsh* gene in avian APEC is associated with virulence and infection, often located on virulence plasmids related to ColV. The *tsh* gene influences the ability of *E. coli* to cause disease and plays a key role in the early stages of respiratory infections, helping the bacteria adapt and infect host cells more effectively (Dozois *et al*., 2000). The *pap*C gene (P fimbriae assembly protein C) helps bacteria attach to host cell surfaces in the respiratory, digestive, and urinary tracts (Mansoor and Salman, 2023; Mellata *et al*., 2003).

The *Vat* gene, encoding vacuolating autotransporter toxin, secretes *Vat*, heat-stable enterotoxin 1 (AstA), and Colicin V (ColV), encoded by *vat*, astA, and cvaA/B (Mortezaei *et al*., 2013; Huja *et al*., 2014). The *vat* gene allows the toxin to enter the bloodstream and damage blood vessels throughout the body (Soon-Gu *et al*., 2008). Sharif *et al*. (2018) reported that the *vat* gene was present in 40% of APEC cases in poultry.

The *hly*F gene expressed by *hly*F-producing *E. coli* induces autophagy in eukaryotic cells. This phenotype is associated with increased production of outer membrane vesicles (OMVs) by *hly*F-expressing bacteria. The *hly*F protein has a predicted catalytic domain of the short-chain dehydrogenase/reductase superfamily, suggesting its role in promoting OMV production. Increased OMV production is linked to toxin release. The *hly*F gene is expressed during extraintestinal infections and contributes to the virulence of extraintestinal pathogenic *E. coli* in poultry, causing colibacillosis (Murase *et al*., 2016; Thomrongsuwannakij *et al*., 2020).

The *iro*N gene is commonly found in APEC strains, as it encodes siderophores like aerobactin, salmokelin, and yersiniabactin, which help absorb iron, promoting bacterial growth and development. The *iro*N gene's ability to access iron in blood serum is crucial, as *E. coli* can trigger sepsis and infect iron-deficient organs (Su *et al*., 2016; Kathayat *et al*., 2021).

Impact of residual antibiotics on humans and the environment

The poultry industry relies heavily on the use of various antibiotics, which has led to the emergence and spread of antimicrobial resistance (AMR) and multidrug resistance (MDR) in birds and poultry intended for consumption. This situation is worsened by the ability of bacteria to transfer genetic material that contains resistance traits. Such transfers can occur both vertically through genetic mutations, as well as horizontally via mechanisms like conjugation, transduction, and transformation, enabling the spread of resistance between bacteria (Yanestria *et al*., 2022).

The consumption of poultry meat contaminated with resistant bacteria can lead to infections in humans that are harder to treat, increasing the risk of severe complications. Nhung *et al*. (2017) pointed out that the rising incidence of colibacillosis in poultry has led to an increased use of antibiotics for both treatment and prevention, which, unfortunately, has contributed to the growing issue of multidrug resistance (MDR).

Bacanlı and Başaran (2019) noted that antibiotic residues in poultry products can trigger and accelerate the development of bacterial resistance. These residues not only increase the risk of transmitting antibiotic-resistant bacteria to humans but can also cause allergic reactions, such as penicillin allergies, and lead to more serious health problems. For example, residues of substances like sulfamethazine, oxytetracycline, and furazolidone have been linked to cancer, while gentamicin can lead to nephropathy and anap*hyl*actic shock. Additionally, chloramphenicol residues can cause bone marrow toxicity, mutagenic effects, and reproductive disorders in humans.

Research by Beyene (2016) highlighted that antibiotic residues can have severe hidden risks, such as being covalently bound to various intracellular components like glycogen, glutathione (GSH), DNA, RNA, proteins, and phospholipids, contributing to long-term health risks. Chloramphenicol residues have been specifically reported to potentially cause cancer (Shahid *et al*., 2021). Other compounds, such as nitrofurans, nitroimidazoles, and quinoxalines, are known to interact with or bind to various intracellular molecules, posing additional health threats. Tetracycline residues have been associated with several health issues, including developmental impairments in fetuses, digestive disturbances, pro-inflammatory effects, cytotoxicity, and immune system disorders (Haque *et al*., 2023).

These conditions make the treatment of disease-causing bacteria increasingly difficult and pose a significant threat to both animal and human health (Effendi *et al*., 2022). Resistant bacteria can be transmitted from poultry to humans through the food chain, jeopardizing public health (Bennani *et al*., 2020). Furthermore, waste from livestock containing antibiotics and resistant pathogens can contaminate soil and water sources, negatively impacting ecosystems (Iwu *et al*., 2020). The rise of resistant pathogens diminishes the effectiveness of existing antibiotics, making the treatment of infections more challenging and dangerous.

Comprehensive approaches to prevent and control APEC in poultry production

Maintaining clean poultry enclosures is a crucial first step in preventing APEC infections in poultry. According to research by Joseph *et al*. (2023), biosecurity plays a key role in the prevention and control of APEC in poultry farms. Proper sanitation helps minimize the buildup of harmful microorganisms, such as *E. coli*, within the cages and surrounding areas. The use of effective disinfectants to clean equipment, cages, and other poultry facilities is essential for preventing cross-contamination. Additionally, proper management of poultry waste and droppings is vital to prevent the spread of pathogens to the surrounding environment, including feed and water sources. Poulsen *et al*. (2017) emphasized the importance of routine disinfection in farm areas, hatcheries, and poultry maintenance rooms (brooders). The application of an all-in-all-out system can further limit the spread of infection. Moreover, eggs that fall onto the floor should be discarded or prevented from becoming contaminated by promptly collecting or cleaning them.

Proper ventilation in poultry houses helps reduce humidity and improves air circulation, which can lower the infection rates of pathogenic bacteria, including APEC. High humidity can facilitate the spread of airborne bacteria, worsening contamination in the house. As such, maintaining a good ventilation system and proper temperature control is critical for maintaining poultry health (Khairullah *et al*., 2024).

Contaminated feed and water can serve as major transmission routes for APEC in poultry. Ensuring that these sources remain free from bacterial contamination is essential (Fancher *et al*., 2020). Feed should be stored in a clean, dry environment to prevent contamination, while the quality of drinking water should be regularly monitored. Providing nutritious feed also strengthens poultry immunity against APEC infections (Kathayat *et al*., 2021).

Vaccination is an effective method to reduce infection rates and enhance poultry immunity. Several vaccines specifically developed for APEC can be administered to reduce bacterial virulence and boost the immune response. Timely and appropriate vaccination is essential for preventing outbreaks of APEC-related diseases (Ghunaim *et al*., 2014).

The use of antibiotics in poultry must be managed carefully and in line with medical guidelines to prevent the development of antibiotic resistance. Misuse or overuse of antibiotics can exacerbate AMR issues, potentially making APEC infections more difficult to treat in the future (Ranabhat *et al*., 2024). Therefore, strict antibiotic use control policies are essential to minimize the risk of antibiotic-resistant bacteria.

Regular monitoring of poultry health is crucial for the early detection of APEC infections. A comprehensive health screening program, including laboratory testing of samples from suspected infected birds, is vital for early identification and timely treatment (Christensen *et al*., 2021). Early detection can help contain the spread of infection and prevent greater economic losses. Healing (2009) noted that regular monitoring and surveillance are key to controlling primary disease agents.

To control APEC transmission in poultry, both horizontal (between individuals in the flock) and vertical (from parent to offspring) transmission routes must be managed (Joseph *et al*., 2023). Implementing healthy flock management practices, such as isolating infected and healthy birds, can reduce transmission risk. Additionally, controlling infection in parent birds and using vaccines for parent stock can help prevent vertical transmission (Conan *et al*., 2012).

Conclusion

AMR and MDR in APEC found in poultry intended for consumption present a significant threat. The presence of virulence genes in these pathogens enhances their ability to cause severe infections. Antibiotic residues in poultry products, along with the growing resistance of bacteria to multiple antibiotics, represent a major issue that not only affects animal health but also has the potential to transfer to humans through the food chain. The spread of antibiotic-resistant APEC poses a serious risk, as these resistant bacteria can be released into the environment through livestock waste, contaminating soil and water. This increases the likelihood of antibiotic-resistant infections in humans and contributes to the global AMR and MDR crisis. Strict regulation of antibiotic use in poultry farming is crucial, along with enhanced prevention and control measures to mitigate the negative effects on both public health and the environment.

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Conflict of interest

The authors have declared no conflict of interest.

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