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Review Article

Emergence and Spread of Antimicrobial Resistance in Bacterial Food-Borne Pathogens

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Abstract

The emergence of antimicrobial resistance (AMR) in bacterial food-borne pathogens is a real concern for public health and food security worldwide. *Salmonella*, *Escherichia coli*, *Campylobacter*, *Listeria monocytogenes*, and *Shigella* pathogens are becoming resistant to antimicrobials commonly used to treat infections, reducing the effectiveness of treatment and increasing the threat of fatal disease. Risk factors associated with this crisis include excess and inappropriate use of antimicrobials in both human and veterinary medicine, extensive use in food animal production to promote growth and prevent illness, poor hygienic standards in the food production chain, and the resurgence of antimicrobial resistance genes in environmental reservoirs. Antimicrobial resistance in bacteria affecting human beings, animals, and ecosystems represents a critical One Health challenge. Its implications are severe and include greater morbidity and mortality, longer stays in hospitals, and economic burden on health care and agriculture. The fight against AMR requires the rationalized use of antibiotics, more regulation, good agricultural practices, and sustainable options, including probiotics, phytochemicals, bacteriophages, and vaccines. Priorities should be directed toward new antimicrobials, alternative treatments, and combined surveillance in the future. This review article has described the key elements of AMR in food-borne pathogens.

Keywords: Foodborne pathogens, Antimicrobial resistance, One health, Alternative therapies

Introduction

Food-borne bacterial pathogens represent a significant global public health issue because they are able to contaminate food and water, as well as cause acute illness and contribute to large-scale outbreaks [1]. They are mainly spread via poorly stored foodstuffs of animal and plant sources, undercooked, or contaminated food items, and their effects go far beyond acute morbidity to long-term effects and enormous economic burdens [2]. Some of the most important pathogens include *Salmonella* spp., *E. coli* (particularly Shiga toxin-producing strains such as O157:H7), *Campylobacter* spp., *L. monocytogenes,* and *Shigella* spp. [3]. These bacteria not only lead to gastroenteritis, systemic infection, and long-term health issues, but it is also becoming harder to handle, not only because of their ability to acquire and transmit antimicrobial resistance (AMR). The morbidity and mortality of food-borne disease are overwhelming. The World Health Organization (WHO) estimates that over 600 million individuals in the world are affected annually by food-borne diseases, with a death toll of about 420.000, and children under the age of five years are particularly vulnerable [4]. A significant part of this burden is due to bacterial pathogens, especially in low- and middle-income countries where inadequate food safety measures, lack of healthcare services/ affordable healthcare, and surveillance mechanisms contribute to this burden. These infections produce high economic costs due to the expenses of healthcare, productivity loss, and product recalls, as well as restrictive trade, which is increasing because of globalization, climate change, and international food trade [5]. Such realities point to why such a One Health approach, which connects human, animal, and environmental health, is critical.

Adding to this difficulty is the development of antimicrobial resistance in food-borne pathogens that has become one of the most significant global health threats of the 21st century [6,7]. Food-producing animals have broad use of antibiotics in treatment, prevention, and even to promote growth, which has a selective pressure on resistant strains that can easily transfer to humans through the food chain, direct contact, or environmental sources. Pathogens that cause food-borne diseases are genetically flexible and can rapidly acquire resistance genes through horizontal gene transfer and therefore exacerbate the issue [8]. Consequently, resistant pathogens, like fluoroquinolone-resistant *Campylobacter* and multidrug-resistant *Salmonella,* and extended-spectrum β-lactamase (ESBL)-producing *E. coli,* are getting harder to treat, sometimes necessitating expensive or toxic alternatives. The resultant effect is an increased burden of long-term illness, increased hospitalization, and mortality [9].

Therefore, AMR in food-borne bacterial pathogens poses a microbiological challenge, a global health and food security, and an economic crisis [10]. To solve this problem, a holistic and multi-disciplinary strategy is needed that incorporates medicine, veterinary science, agriculture, and environmental management in order to reduce resistance throughout the food chain [11]. This review thus identifies the rise and prevalence of antimicrobial resistance in food-borne bacterial pathogens, their resistance mechanisms, modes of transmission, public health consequences, and mitigation measures.

Major Bacterial Food-Borne Pathogens of Concern

Bacterial pathogens are globally prevalent, frequently associated with food-borne outbreaks, and have a significant impact on food safety and public health. *Salmonella, Escherichia coli, Campylobacter, Listeria monocytogenes,* and *Shigella* are among the leading causes of food-borne illnesses worldwide, contributing to considerable morbidity, mortality, and economic losses. Their ability to contaminate a wide range of food products, persist along the food production chain, and increasingly exhibit antimicrobial resistance further underscores their public health importance *(Fig. 1)* [3].

***Salmonella* spp.** remains one of the leading causes of food-borne illnesses globally, transmitted through contaminated poultry, eggs, meat, and dairy products, as well as fresh produce [12]. Non-typhoidal *Salmonella* (NTS) typically causes gastroenteritis with diarrhea, fever, and abdominal cramps, but can also result in invasive infections in vulnerable populations. Typhoidal *Salmonella*, such as *S. Typhi* and *S. Paratyphi*, are restricted to humans and cause systemic enteric fever [13-15]. The growing concern lies in antimicrobial resistance, with NTS showing multidrug resistance to ampicillin, chloramphenicol, and TMP-SMX, alongside increasing resistance to fluoroquinolones and third-generation cephalosporins due to extended-spectrum β-lactamases (ESBLs) like *blaCTX-M*. Alarmingly, extensively drug-resistant (XDR) *S. Typhi* strains, particularly reported from Pakistan, are resistant to almost all commonly used antibiotics except azithromycin and carbapenems, complicating treatment options [16]. This makes *Salmonella* not only a significant cause of morbidity and mortality but also a priority pathogen in the fight against antimicrobial resistance.

Escherichia coli, while a normal commensal of the human gut, includes several pathogenic strains that are major food-borne threats [17,18]. Shiga toxin-producing *E. coli* (STEC), particularly O157:H7, causes hemorrhagic colitis and life-threatening hemolytic uremic syndrome (HUS), often linked to undercooked beef, unpasteurized milk, and leafy vegetables [18,19]. Enterotoxigenic *E. coli* (ETEC), enteropathogenic *E. coli* (EPEC), and enteroaggregative *E. coli* (EAEC) are important causes of travelers' and childhood diarrhea, especially in developing countries. Resistance among pathogenic *E. coli* is a rising issue, with many strains acquiring ESBL genes *(blaCTX-M)* and plasmid-mediated colistin resistance genes *(mcr-1)* that spread rapidly through the food chain, especially via poultry and meat [20]. Infections with multidrug-resistant *E. coli* are increasingly difficult to treat, and in the case of STEC, antibiotics are avoided altogether because they can trigger toxin release and worsen disease [21]. This dual challenge of virulence and resistance makes *E. coli* a significant global concern [22,23].

***Campylobacter* spp.** mainly, *C. jejuni* and *C. coli* are the most frequently reported bacterial causes of human gastroenteritis worldwide. Infection occurs through undercooked poultry, unpasteurized milk, or contaminated water, with very low infectious doses sufficient to cause disease [24]. Symptoms include fever, abdominal pain, and bloody diarrhea, with serious post-infection complications such as Guillain–Barré syndrome. Resistance in *Campylobacter* is particularly troubling: fluoroquinolone resistance, caused by mutations in the *gyrA* gene, is now widespread, limiting treatment options [25]. Tetracycline resistance via the *tet(O)* gene is also common, while macrolide resistance, though lower, is emerging. Since macrolides (e.g., azithromycin) are the preferred treatment for severe cases, the rise of resistance threatens to undermine the last reliable therapeutic option. The close link between antimicrobial use in poultry and resistance in *Campylobacter* highlights the need for strict regulation and surveillance in food production systems [25].

Listeria monocytogenes is an opportunistic food-borne pathogen of high concern due to its ability to cause listeriosis, a severe invasive infection in pregnant women, newborns, the elderly, and immunocompromised individuals [26]. Unlike many other pathogens, *Listeria* can survive and grow at refrigeration temperatures and persist in food-processing environments through biofilm formation [27]. Outbreaks are commonly linked to ready-to-eat foods, deli meats, unpasteurized cheeses, and smoked fish. Clinical manifestations include septicemia, meningitis, and adverse pregnancy outcomes such as stillbirth or neonatal sepsis [28]. Although *Listeria* remains largely susceptible to first-line antibiotics such as ampicillin combined with gentamicin, resistance has occasionally been reported to tetracyclines and macrolides through genes like *tet(M)* and *erm(B)*. Of greater concern is its resistance to disinfectants and sanitizers, which enables persistence in food-processing plants, increasing the risk of contamination and outbreaks [29]. Preventing *Listeria* infections, therefore, relies heavily on strict hygiene measures and food safety regulations rather than therapeutic interventions.

***Shigella* spp.** Highest infectivity is seen with *Shigella* spp. *(S. sonnei* and *S. flexneri)* which can cause disease after a few organisms within the body. They easily spread via contaminated foods and drinks and via person-to-person contact, and so are especially prevalent in places with poor sanitation [30]. Shigellosis clinically manifests as dysentery with fever, cramping abdominal pains, and bloody diarrhea. Treatment can be very much required in order to reduce the morbidity and avert the spread; however, resistance is quick to develop. Ciprofloxacin, TMP-SMX, and azithromycin-resistant strains are now widespread, and in recent years, extensively drug-resistant (XDR) S. sonnei has been reported across the world, providing few effective oral treatment options [31]. This tendency presents a significant public health problem because *Shigella* epidemics can spread rapidly, and the emergence of resistant bacteria adds further limitations to treatment choices in both communal and medical institutions. These major bacterial foodborne pathogens are shown in *Fig. 1*.

Emerging Food-Borne Bacterial Pathogens

Emerging food-borne bacterial pathogens are also of concern. *Vibrio parahaemolyticus* and *V. vulnificus*, which are linked with the consumption of seafood, are of increasing concern because they are spreading as a consequence of climate change [32]. *Yersinia enterocolitica*, which is mainly spread by pork, has been found to cause outbreaks regionally, and the bacteria are resistance to fluoroquinolones and cephalosporins [33]. *Cronobacter sakazakii* is a pathogen that is present in powdered infant formula and is a specific hazard to neonates, resulting in meningitis and septicemia with high mortality rates [34]. They are less frequent, but mention of these causative organisms illustrates how dynamic food-borne diseases are and how new hazards are being detected, commonly in conjunction with frontline antibiotic resistance. These emerging food-borne bacterial pathogens are explained in the following section:

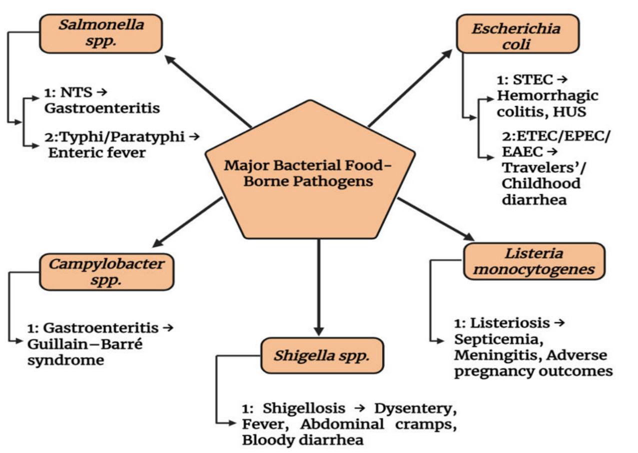

Fig 1. Major bacterial food-borne pathogens of concern

Vibrio parahaemolyticus: *V. parahaemolyticus* is a naturally occurring halophilic, Gram-negative bacterium in estuarine and marine habitats is *Vibrio parahaemolyticus*. One of the most common causes of gastroenteritis linked to seafood is eating raw or undercooked shellfish, including clams, crabs, and oysters [35]. The thermostable direct hemolysin (TDH) and TDH-related hemolysin (TRH) toxins of *V. parahaemolyticus* are primarily responsible for its pathogenicity; they damage intestinal epithelial cells and cause fever, cramping in the abdomen, watery diarrhea, and nausea. Infection rates in temperate places have increased because of the expansion of their ecological niche brought on by climate change, particularly ocean warming [36].

Vibrio vulnificus: Another halophilic marine bacterium linked to serious wound and foodborne illnesses is *Vibrio vulnificus*. It can infect shellfish, especially oysters, and is prevalent in warm coastal waters. Ingestion or contact with tainted seawater through exposed wounds can result in infection [37]. Known for its high death rate, *V. vulnificus* frequently causes necrotizing fasciitis and septicemia, particularly in people with diabetes, liver illness, or immunocompromised conditions. The production of cytolysins, metalloproteases, and capsular polysaccharides that aid in tissue destruction and immune evasion is linked to the organism's virulence [38]. Because of the growing worldwide seafood trade and rising sea surface temperatures, its increasing prevalence is becoming a significant problem.

Yersinia enterocolitica: A chronic concern with chilled goods, especially milk, pig products, and ready-to-eat items, is *Yersinia enterocolitica*, a psychrotrophic, Gram-negative bacterium that can survive and grow at refrigeration temperatures [39]. It results in yersiniosis, which can mimic appendicitis and is characterized by fever, enterocolitis, and mesenteric lymphadenitis. A plasmid-encoded type III secretion system (T3SS) and outer membrane proteins that promote adhesion, invasion, and resistance to host immune systems are examples of virulence factors [40]. The organism is a major concern for food sectors that use lengthy cold chains because of its capacity to survive at low temperatures and withstand cold storage.

Cronobacter sakazakii: An opportunistic bacterium primarily associated with powdered infant formula, *Cronobacter sakazakii* (previously known as *Enterobacter sakazakii),* poses a significant risk to newborns and babies [41]. This Gram-negative bacterium can cause serious infections like necrotizing enterocolitis, sepsis, and newborn meningitis. Its survival in dry food matrices and resistance to desiccation help explain why it persists in production settings. To increase its survival during processing and storage, *C. sakazakii* creates biofilms and has stress tolerance mechanisms [42]. Its importance to public health is highlighted by the severity of infection consequences, even if its prevalence is minimal.

Mechanisms of Antimicrobial Resistance in Food-Borne Pathogens

There are now a variety of mechanisms through which food-borne bacterial pathogens overcome the effects of antimicrobial agents, and this makes their treatment and control measures complicated [43,44]. These are drug inactivation via enzymes, efflux pumps, and decreasing permeability, target change or shielding, and horizontal gene transfer *(Fig. 2)* [18]. Importantly, the relative contribution of these mechanisms varies among major food-borne pathogens and explains the distinct resistance patterns observed in organisms such as *Salmonella, Campylobacter, Escherichia coli,* and *Shigella*. Cumulatively, these mechanisms of adaptation not only contribute to bacterial survival on exposure to antimicrobial stress but also promote the distribution and perpetuation of resistance throughout ecosystems [45].

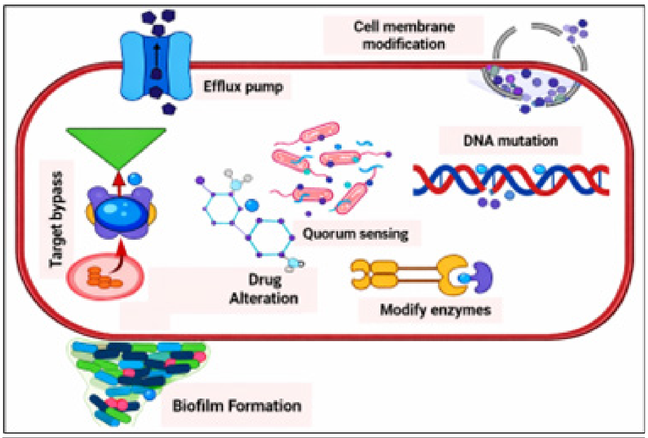

Fig 2. Phenotypic mechanism of antibiotic resistance in foodborne bacterial pathogens

Enzymatic Inactivation of Drugs

The enzymatic alteration or deactivation of antimicrobial compounds is one of the most common AMR mechanisms of food-borne pathogens. Numerous bacteria will make enzymes, e.g., β-lactamases that cleave the β-lactam ring in penicillin and cephalosporins, making them inactive. Extended-spectrum beta-lactamases (ESBLs) are the most common cause of β-lactam resistance in *E. coli* and *Salmonella* spp.[46], and are particularly relevant to the emergence of multidrug-resistant and extensively drug-resistant *(XDR) S. Typhi,* where ESBLs and carbapenemases severely limit therapeutic options. ESBLs cause resistance to large numbers of β-lactams (including third-generation cephalosporins). On the same note, carbapenemases destroy carbapenems, which are called antibiotics of last resort. Aminoglycoside-modifying enzymes (AMEs) physically alter aminoglycosides by adding phosphate, acetate, or adenosine groups, hence reducing their affinity to the ribosomal sites [47]. These enzymatic alterations highly limit the treatment measures and the rise of multidrug resistance in food-borne bacteria.

Efflux Pumps and Reduced Permeability

Efflux systems and changes in membrane permeability are another primary defense strategy employed by food-borne pathogens. Efflux pumps are membrane-bound proteins that actively transport antimicrobials to the extracellular space, reducing the drug concentrations to below efficacious levels [48]. For example, the efflux pump AcrAB-TolC in *E. coli* and *Salmonella* confers resistance to several classes of pharmaceutical antibiotics, including fluoroquinolones, tetracyclines, and chloramphenicol [49]. The CmeABC efflux pump is very important in *Campylobacter* spp. in resistance to macrolides and fluoroquinolones. Meanwhile, decreased expression or structural modulation of outer membrane porins reduces antibiotic uptake [50]. Collectively, these mechanisms promote multidrug resistance and enable the bacteria to persist even against a varied collection of antimicrobial substances.

Target Modification and Protection

The mechanism of action of an antimicrobial agent is usually its binding to a particular target in bacteria, and mutation or variation of that target may cause resistance [45]. *Campylobacter* and *Salmonella* have point mutations in their gyrA gene that change the DNA gyrase, resulting in fluoroquinolone resistance [18]. Similarly, mutation in the ribosomal RNA or ribosomal proteins may lead to macrolide, tetracycline, and aminoglycoside resistance *(Fig. 2)* [51]. The other example is for *Streptococcus pneumoniae,* in which mutations in penicillin-binding proteins decrease β-lactam binding affinity (this again is rarer in the prototypical food-borne pathogen). Bacteria will also employ protective proteins, including *tet(M)*, that protect the ribosomal targets against tetracycline. Such alterations help bacteria to grow and survive beyond antimicrobials [52].

Horizontal Gene Transfer

Horizontal gene transfer (HGT) is a key driver in the spread of AMR in food-borne pathogens, contributing to the rapid uptake of resistance determinants that build up in other bacteria. β-lactam, aminoglycoside, and sulfonamide resistance genes can be found on plasmids, which transfer between bacteria easily in a cross-species and cross-genus manner since they are extrachromosomal elements of DNA [53]. Transposons are mobile pieces of genetic material that incorporate resistance genes into the DNA of chromosomes or plasmids and enable their transmission. Integrons encode multidrug resistance and integrate gene cassettes encoding resistance determinants [8]. As another example, integrons in the *Shigella* and *Salmonella* are often carry resistance genes to sulfonamides, aminoglycosides, and trimethoprim [54]. In *Salmonella* and *Shigella,* integrons frequently harbor resistance genes against sulfonamides, aminoglycosides, and trimethoprim, contributing to the emergence of multidrug-resistant and XDR lineages. Environments within the food chain, livestock production systems, and environmental reservoirs facilitate horizontal gene transfer (HGT), serving as reservoirs for the emergence and dissemination of novel multidrug-resistant food-borne pathogens that can be transmitted between animals and humans [53].

Drivers of AMR Emergence in Food-Borne Bacteria

The emergence of antimicrobial resistance (AMR) of food-borne pathogens is not a random process, but its rapid development is a direct consequence of the selective pressures and interdependent activities in human health, agriculture, food production, and the environment *(Table 1)* [55]. Mounting evidence points to several important drivers that promote the existence and proliferation of resistant bacteria throughout the continuum of the farm-to-fork. This has been a significant global public health hazard [56].

Overuse and Misuse of Antibiotics in Human Medicine

Inappropriate prescription of antibiotics in medical care among human beings is one of the major contributors to AMR in human health. Such are the use of antibiotics to treat viral diseases, over-the-counter self-medication, inadequate treatment with antibiotics, and excessive use of broad-spectrum agents, which exert potent selective pressure on resistance [57]. These selective conditions, such as food-borne pathogens like *Salmonella* and *Shigella,* can cause recurrent infections in humans, leading to repeated exposure to antibiotics, thereby letting the resistant strains multiply. Also, multidrug-resistant strains of enteric pathogens acquired in the hospital setting may be the cause of hospital-acquired infections whose transmission into the community could be accomplished by host carriers and through contaminated sewage streams [58].

Antibiotic Use in Food Animals

One of the most significant causes of food-borne bacterial resistance is the extensive use of antimicrobials in the food production of livestock. Antibiotics are often administered not only for treatment (therapy) but also for disease prevention (prophylaxis) and growth promotion. Continuous low-dose exposure creates an ideal environment for the selection of resistant bacteria in the gut flora of animals [59]. These resistant pathogens, such as *E. coli, Salmonella,* and *Campylobacter,* can then contaminate meat, milk, eggs, and other animal-derived foods [60]. For instance, the widespread use of tetracyclines and fluoroquinolones in poultry and cattle farming has been strongly linked to resistance in *Campylobacter* and *E. coli*. Moreover, resistant strains can spread to farm workers and surrounding communities, creating a One Health problem that connects animal, human, and environmental health *(Table 1)* [61].

Transmission Pathways of AMR Food-Borne Pathogens

Farm-to-Fork Continuum: The farm-to-fork continuum describes the journey of food from primary production to consumption, and at every stage, resistant bacteria can enter or proliferate. On farms, resistant pathogens originating from livestock or contaminated feed can contaminate meat, milk, or eggs [78]. In aquaculture and produce farming, resistant bacteria from fertilizers, and irrigation water may persist on seafood, fruits, and vegetables. Once these foods enter the processing chain, opportunities for amplification and cross-contamination increase, making the entire continuum a major route for AMR dissemination [79].

Food Processing and Handling Practices: In slaughter-houses, dairies, and food processing plants, lapses in hygiene and sanitation allow resistant pathogens to contaminate products. For example, improper separation of clean and contaminated carcasses during meat processing may spread resistant *Salmonella* [80]. Similarly, inadequate pasteurization or unsanitary handling of milk and dairy products can allow resistant *L. monocytogenes* or *E. coli* strains to persist. Resistant bacteria can also survive in biofilms that form on food-contact surfaces, making eradication difficult and contributing to long-term contamination [81].

Table 1. *Drivers of antimicrobial resistance in food-borne bacteria*

Driver of AMR	Key Practices/ Source	Examples of Commonly Used Antibiotics	Major Pathogens Involved	Mechanism of Resistance Spread	Public Health Implications	References
Antibiotic Use in Food Animals (Therapy)	Treatment of sick animals with antibiotics	Penicillins, tetracyclines, fluoroquinolones	*E. coli, Salmonella, Campylobacter*	Selection pressure enriches resistant strains in gut flora	Infections in humans become harder to treat	[62]
Antibiotic Use in Food Animals (Prophylaxis)	Preventive use in herds/flocks	Sulfonamides, macrolides	*E. coli, Salmonella*	Maintains background resistance even without active infection	Reduces drug effectiveness in clinical medicine	[62]
Antibiotic Use in Food Animals (Growth Promotion)	Low-dose continuous feed additives	Tetracyclines, streptomycin	*Enterococcus* spp., *E. coli*	Promotes selection of multidrug-resistant gut bacteria	Transmission to humans via meat, eggs, milk	[63]
Poultry Farming	Antibiotics in broiler & layer systems	Fluoroquinolones, tetracyclines	*Campylobacter jejuni, E. coli*	Resistant pathogens contaminate meat/ eggs	Foodborne outbreaks with drug-resistant strains	[64, 65]
Cattle & Dairy Farming	Antibiotics for mastitis, growth	β-lactams, tetracyclines	*Salmonella* spp., *L. monocytogenes*	Resistant bacteria in milk & meat	Milk-borne resistant infections	[66]
Aquaculture	Antibiotics in fish/ shrimp farms	Oxytetracycline, sulfonamides	*Vibrio* spp., *Aeromonas* spp.	Resistance genes spread via water	Marine resistome expansion	[67]
Slaughterhouse Contamination	Cross-contamination during slaughter	N/A	*Salmonella, Campylobacter*	Spread from gut contents to carcasses	Multidrug-resistant pathogens enter food chain	[68]
Dairy Processing	Post-pasteurization contamination	N/A	*L. monocytogenes*	Survival and recontamination in dairy products	Risk of outbreaks via cheese/milk	[69]
Produce Contamination	Irrigation with contaminated water	N/A	*E. coli O157:H7, Salmonella*	Resistant strains spread from manure/ water	Fresh produce as AMR carriers	[70]
Food Handlers	Poor hygiene in food processing	N/A	*Shigella* spp., *E. coli*	Transfer via human contact	Foodborne outbreaks in retail/household settings	[71, 72]
Global Food Trade	Export/import of contaminated foods	N/A	*Salmonella, Campylobacter*	Rapid transboundary movement	Globalization of resistant pathogens	[73]
Environmental Release (Manure Use)	Animal manure as fertilizer	Residual antibiotics, resistant bacteria	*E. coli, Salmonella*	Resistance genes move to soil microbes & crops	Human exposure via raw produce	[74]
Environmental Release (Wastewater)	Hospital/industrial effluents	Multiple antibiotic residues	Environmental bacteria & pathogens	Horizontal gene transfer in water bodies	Creates "hotspots" of AMR	[75]
Soil Resistome	Long-term accumulation of resistance genes	N/A	*Pseudomonas, Enterobacteriaceae*	Natural gene exchange via plasmids, transposons	Source of novel AMR traits	[76]
Aquatic Ecosystems	Runoff from farms, aquaculture	Tetracyclines, quinolones	*Vibrio, Aeromonas, Enterococcus*	Resistance genes persist in sediments & rivers	Zoonotic spillover to humans and wildlife	[77]

Cross-Contamination in Retail and Household Settings: During handling and preparation of food products in markets or at home, cross-contamination is a major hazard factor. Raw meat may transfer resistant bacteria to fresh vegetables or ready-to-eat foodstuffs by using a common cutting board, a knife, or a storage vessel [82]. Hygienic cooking or refrigeration is also relevant in terms of bacterial survival and transmission [83]. Even low-level resistant strains can infect people, in case they colonize especially children, older people, or people with compromised immunity.

International Trade and Travel: Globalization also boosts the movement of resistant pathogens across borders. Seafood, fresh produce, and meat trade may bring foreign bacterial species whose resistant nature was not a common phenomenon [84]. Similarly, international travel exposes individuals to resistant strains present in food or water, which can then spread upon their return home. This unregulated and swift movement facilitates the internationalization of AMR transmission, and it explains the need to work more internationally to combine surveillance systems [85].

Public Health Implications of AMR in Food-Borne Pathogens

The existence of antimicrobial resistance (AMR) in foodborne pathogens poses a significant threat to the population, whose impacts extend beyond personal infection, affecting healthcare systems, food safety, and global economies [18,86,87]. Antibiotic resistance in pathogens not only complicates treatment outcomes but also increases the risk of transmission of pathogens with serious consequences to society [60].

Increased Morbidity and Mortality

Diseases resulting from antimicrobial-resistant food-borne pathogens are often associated with increased morbidity and mortality, as opposed to those affected by susceptible pathogens [65,88]. Antibiotic-resistant *Salmonella, E. coli,* and *L. monocytogenes* infections frequently lead to long-term illnesses, increased complications, and increased incidences of hospitalizations. There is a disproportionately increased risk in the vulnerable group, e.g. those are children, the elderly, and the immunocompromised, with some of the infections developing into life-threatening ailments, e.g., septicemia or meningitis [89].

Limited Treatment Options

The limitation of effective treatment options is one of the most relevant immediate effects of AMR. The first-line antibiotics have included fluoroquinolones and third-generation cephalosporins, to which there has been increased resistance in food-borne pathogens. In some cases, pathogens exhibit multi-drug resistance (MDR), rendering conventional therapies ineffective and forcing reliance on last-resort antibiotics such as carbapenems or colistin [90]. This not only complicates treatment regimens but also increases the risk of adverse side effects and treatment failure.

Economic Burden on Healthcare and the Food Industry

The economic implications of resistant food-borne pathogens are twofold:

Healthcare Systems: Resistant infections increase the length of hospital stays, diagnostic costs, and treatment expenses, straining already burdened healthcare systems. The need for more expensive or prolonged therapies further amplifies costs [91].

Food Industry: Outbreaks of resistant pathogens can lead to mass recalls, trade restrictions, reputational damage, and loss of consumer trust. Also, the cost of the operations is greatly increasing due to regulatory interventions, testing requirements, and stricter biosecurity measures. Taken together, AMR exerts an economic dual burden on the food production industry and on public health [92].

Zoonotic and Pandemic Potential: Food-borne pathogens are zoonotic in nature and are transmitted between animals and humans either through food, direct contact, or via environmental contamination. With the introduction of resistance characteristics, the threats grow exponentially, since these pathogens can evolve far and wide both in species and geographical distributions [87]. Globalization of food trade and human movements can lead to localized outbreaks becoming a worldwide menace. The development of pandemic-potential strains, e.g., multidrug-resistant *Salmonella* or *E. coli,* shows the ability of AMR food-borne pathogens to cross borders and become global crises, particularly in those environments with low surveillance and limited healthcare resources [93].

Strategies to Mitigate AMR in Food-Borne Pathogens

The alarming rise of antimicrobial resistance (AMR) in food-borne pathogens requires multifaceted mitigation strategies that combine human, animal, and environmental health interventions under a One Health approach [94]. Preventing the spread of resistant strains and reducing antibiotic dependence are essential to safeguarding public health, food security, and global economies (*Table 2*) [95,96].

Future Directions

Tackling the growing problem of antimicrobial resistance (AMR) in food-borne pathogens requires practical, innovative, and globally coordinated solutions. With resistant strains of *Salmonella*, *E. coli*, and *Campylobacter* becoming more common, the search for safe and effective alternatives to conventional antibiotics is more important than ever. Promising options include bacteriophages that specifically attack resistant bacteria, antimicrobial peptides produced by natural immune defenses, nanotechnology-based drug delivery systems designed to reduce toxicity while improving precision, and the use of probiotics and plant-derived compounds to strengthen host immunity and block pathogen colonization. Vaccination in food animals, such as poultry, against *Salmonella*, also offers a way to lower infection rates and reduce the need for antibiotics. At the same time, modern tools like genomics, proteomics, and metagenomics can speed up the discovery

Table 2. *Strategies to mitigate AMR in food-borne pathogens under One Health*

Strategy	Specific Action	Target Sector	Expected Impact	Examples/ Tools	References
Rational Antibiotic Use	Prescribe only when clinically indicated	Human Medicine	Reduce unnecessary exposure to antimicrobials	Prescription guidelines	[97]
	Correct dosing and full treatment adherence	Human Medicine	Minimize resistance selection	Clinical stewardship programs	[97]
	Avoid self-medication	Human Medicine	Prevent misuse and resistance	Public health education	[98]
Veterinary Stewardship	Use only under veterinary supervision	Veterinary Medicine	Ensure responsible use	Prescription-only model	[99]
	Ban use for growth promotion	Veterinary Medicine	Reduce selective pressure	EU/WHO bans, alternative feed strategies	[99]
	Limit prophylactic use	Veterinary Medicine	Prevent resistance buildup	Targeted metaphylaxis	[99]
Good Agricultural Practices	Improve farm biosecurity and sanitation	Agriculture	Reduce pathogen circulation	Hygiene protocols	[100]
Food Safety Practices	Prevent cross-contamination	Food Chain	Limit spread of resistant bacteria	HACCP implementation	[101]
Food Handling	Proper cooking and storage	Consumers	Inactivate resistant bacteria	Food safety campaigns	[102]
Alternatives to Antibiotics	Phytochemicals and essential oils	Veterinary/ Agriculture	Suppress resistant pathogens	Plant-based feed additives	[103,104]
	Probiotics and prebiotics	Veterinary/ Agriculture	Enhance gut health and immunity	*Lactobacillus*, inulin	[103,105,106]
	Vaccines against pathogens	Veterinary	Reduce infection incidence	*Salmonella* vaccines in poultry	[103]
Policy & Regulation	Enforce restrictions on antibiotic sales	Governance	Minimize OTC misuse	Prescription-only policies	[107]
	Establish integrated surveillance networks	One Health (Human–Animal–Environment)	Early detection of resistance	WHO-GLASS, OIE-WAHIS	[107]
Global Cooperation	Harmonize regulations and outbreak response	International	Prevent cross-border AMR threats	Tripartite collaboration (WHO–FAO–OIE)	[108]

of resistance genes, new therapeutic targets, and early outbreak signals. The One Health approach is central, recognizing that resistance spreads across humans, animals, and the environment, and highlighting the need for strong surveillance in farms, hospitals, food production systems, and even wastewater. Success will depend on collaboration between researchers, veterinarians, farmers, policymakers, and global organizations, with special attention to low- and middle-income countries where resources are limited. Sustainable, fair, and coordinated efforts will be key to protecting both food safety and public health.

Conclusion

A major health concern across the globe is antimicrobial resistance among food-borne pathogens, e.g., *Salmonella*, *E. coli, Campylobacter, L. monocytogenes,* and *Shigella*. This crisis is spurred by the misuse of antibiotics in humans and animals, their use in large amounts in food production, poor hygiene practices, and environmental reservoirs of resistance genes. The effects are far-reaching, including sickness and death, extended hospital stays, a reduction in costs incurred in health care, and lost profits in the economy. AMR, as a classical example of One Health, connects the health of humans, animals, and the environment. It should be handled by more responsible usage of antibiotics, tighter actions, and safer food processing and farming. Other potential options, like probiotics, bacteriophages, vaccines, and phytochemicals, are promising as additional ways to mitigate the use of antibiotics. Consequently, the COVID-19 pandemic has exacerbated the spread of AMR, which requires immediate international cooperation and interdisciplinary action.

With antimicrobial protection, we are securing the future of effective treatment, robust food systems, and population health.

Declarations

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