

Monitoring the Antibiotic Resistance Development of *Escherichia coli* in the River Environment: A Systematic Review

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Abstract

One of the major challenges of the twenty-first century is antibiotic resistance in "One Health" humans, animals, and the environment, the spread of which limits treatment options for bacterial infections, increases mortality and causes economic damage. This article aims to offer a critical investigation of the development of antibiotic resistance of *E. coli* in rivers over the last 10 years. There is increasing interest in monitoring water environments, both surface water and sewage, which are major receptors, sources, and pathways of antibiotic-resistant bacteria (ARB). Additionally, they facilitate the transfer and amplification of ARB. *Escherichia coli* (*E. coli*) is a pathogen characterized by an increased level of resistance to antibiotics. A total of 3661 publications in the field of environmental, agricultural, and biological sciences were obtained from two databases (ScienceDirect and PubMed). Most publications in this field have focused on clinical isolates, which has led to a scarcity of information about natural environments, including rivers, which are important freshwater sources. Analysis 31 articles from 20 countries across five continents. The results showed that the highest resistance was against ampicillin (14/31), followed by ciprofloxacin (10/31) in the publications. Regarding antibiotic classes, the fluoroquinolone class showed a significant development in resistance. The development of multidrug resistance of *E. coli* to beta-lactam antibiotics and fluoroquinolones, such as trimethoprim/sulfamethoxazole and amoxicillin/clavulanic acid, was noted in this review. Additionally, modern resistance to azithromycin and erythromycin was explored.

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Introduction

Antibiotics are widely used to treat bacterial infections in humans, fish, and livestock, and are also added to animal feed to prevent disease and act as growth promoters. Antibiotics in surface water can come from sewage systems (such as sewer overflows, hospital waste, and wastewater treatment plants [WWTPs] effluents) and natural habitats (such as soil runoff and flow from groundwater), depending on the transport pathways, that may spread resistance to many different bacterial species through horizontal gene transfer, which explains how bacteria might acquire genetic characteristics that assist their adaption to new settings by transferring DNA outside of their direct ancestral lineages (Cheng *et al.*, 2022; Mahdi *et al.*, 2023; Sabbar *et al.*, 2023; Behling *et al.*, 2024), (Figure 1). Antibiotic resistant in wastewater streams is not successfully eliminated by the current techniques for WWTPs (Berisha *et al.*, 2024). As WWTPs are releasing more antibiotics, which leads to the emergence of microorganisms that

are resistant to them (Aladekoyi *et al.*, 2024). People's awareness of the dangers of infectious diseases has increased, leading to a rise in demand for antibiotics and random use in the medical, veterinary, and agricultural fields, leaving bacteria at risk of potentially developing antibiotic resistance. Furthermore, the introduction of an excess of antibiotics into the environment is the result of a lack of public knowledge about the danger of antibiotic contamination (Chin *et al.*, 2023; Sun *et al.*, 2024). A study conducted by experts from different institutions in five European Union countries revealed knowledge gaps that lead to the inappropriate use of antibiotics (Chalkidou *et al.*, 2023). Therefore, modifying the behavior of antibiotic providers and customers is one of the most crucial elements of reducing antibiotic resistance (Raihan *et al.*, 2024).

Concern over the environment's developing pathogenic bacterial resistance as well as its ecotoxic impacts is growing. This encompasses the ecology of the resistant bacteria as well as their resistance genes (Aziz *et al.*, 2014). Recent studies indicated that antimicrobial resistance of bacterial pathogens is a leading cause of death worldwide, with the highest mortality rate occurring in low-resource countries, according to a WHO report (WHO, 2022b). An estimated 70,000 fatalities annually are attributed to antibiotic-resistant infections, in 2050, this number is anticipated to increase quickly to almost 10 million deaths (Ansari *et al.*, 2021). Antibiotic resistance can be controlled through the "One Health" concept, as antibiotic resistance affects human and animal health and leads to significant financial and social costs as well as environmental damage (Rodríguez-Melcón *et al.*, 2024). The interdisciplinary "One Health" concept acknowledges the intimate connections between the health of human, animals, and their environmental surroundings. In order to address health issues and advance general well-being, this concept calls for coordinated efforts because it recognizes that the health of each of these elements is closely linked, that any modifications to one element may have impact on the others (Zhao *et al.*, 2024).

Escherichia coli is a gram-negative bacteria (Khalaf and Flayyih, 2024). *E. coli* is a type of commensal bacteria found in the intestines of humans and animals. Certain strains of *E. coli* can cause a wide range of illnesses in birds, mammals, and humans (AL-Mahfoodh *et al.*, 2021; Assafi *et al.*, 2022; Mahdi *et al.*, 2024). It also has a variety of strains that are found in soil and water. The type of *E. coli* that is most frequently detected in water is Shiga toxin-producing *E. coli* (STEC). Its presence in any water resource illustrates the organic contamination in the water and indicates that other bacteria may potentially be present (Malan and Sharma, 2022). *E. coli* was selected as an indicator in the field of "One Health" by the WHO, as it can be detected in the feces of humans, animals such as poultry, and water bodies, whether sewage water or river water in urban areas (WHO, 2020). *E. coli* is a crucial tool for assessing health risks for several reasons. As a dependable indicator of recent contamination, *E. coli* is prevalence in both human and animal waste and persists in the environment longer than many other aquatic pathogens. Because standard microbiological methods can readily identify and quantify it, it is a viable option for assessing the quality of water. Therefore, guidelines and regulatory bodies regularly consider it as a major indicator when setting and observing water quality standards. Evidence suggests that "naturalized" *E. coli*, which originates from feces and may survive wastewater treatment, also carry a variety of resistance and virulence characteristics, posing a risk to the public's health (Aklilu *et al.*, 2024; Moinet *et al.*, 2024). *E. coli* can adapt to a wide range of environmental challenges (Nowicki *et al.*, 2021; Jiao *et al.*, 2024). The remarkable genetic adaptability and even multidrug resistance (MDR) of *E. coli* allow it to survive in watery environments for months. Pathogenic *E. coli* is linked to a number of conditions, including urinary tract infections (UTIs), bloodstream (WHO, 2022b; Varandas *et al.*, 2023), enteric-diarrheal disease, septicemia, neonatal meningitis (Hamner *et al.*, 2020; Tahri *et al.*, 2021), traveler's diarrhea, hemolytic uraemic syndrome (HUS), bacillary dysentery, hemorrhagic colitis, thrombocytopenic purpura in humans, edema disease and postweaning diarrhea in pigs, colisepticaemia and hemorrhagic colitis in calves, cystitis and pyometra in dogs, coliform mastitis in cattle, and avian colibacillosis in poultry (Samanta and Bandyopadhyay, 2020). Consequently, one of the main pathogens linked to waterborne illnesses is *E. coli* (Odonkor and Mahami, 2020). This review aims to shed light on

the development of antibiotic resistance of *E. coli* in rivers that affects "One Health". Wherefore this review focused on this crucial pathogen.

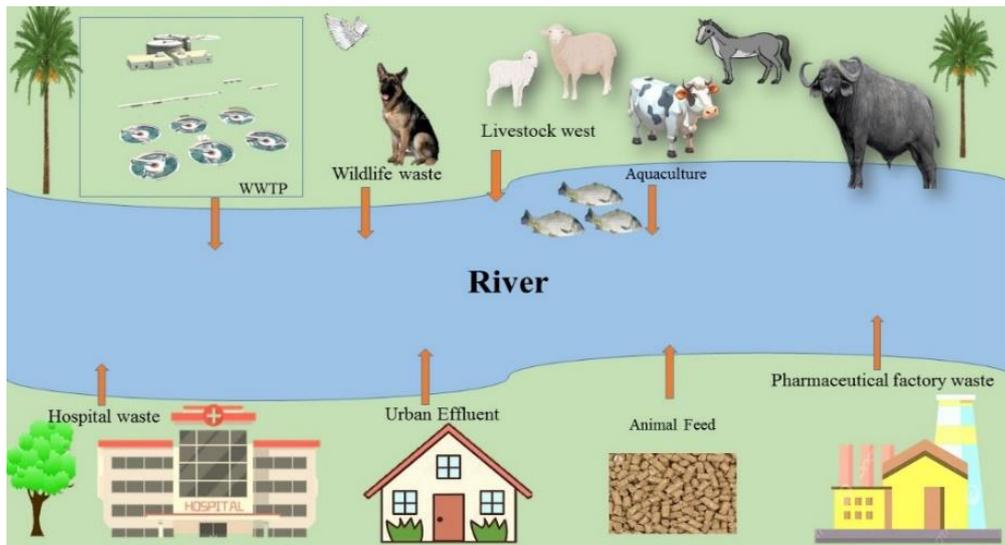


Figure 1. Sources of antibiotics pollution in rivers

Material and Methods

Screening stage and inclusion

The review was carried out using the Preferred Reporting Items for Systematic Reviews (PRISMA) methodology (Page *et al.*, 2021). The quality of the listed studies was evaluated critically using the weighted points approach. Criteria were created and given yes-or-no scores, where "not sure" equaled "no." Publications were categorized into three levels based on their quality: high quality accounts for more than 70% of the total scores allotted, intermediate quality for between 40% and 70%, and low quality for less than 40%. Inclusion and exclusion criteria were reviewed for all titles and abstracts of retrieved publications.

A publication year restriction was applied between this period to determine the development of antibiotic resistance of *E. coli* in rivers over the past decade, as well as the development in the use of molecular techniques in investigations during the selected study period.

- **Exclusion criteria**

The study excluded other types of water bodies, such as seawater, lakes, groundwater, wastewater, and drinking water, and focused on rivers only, as they are among the main sources of fresh drinking water in the world. The other restriction was to exclude articles investigating antibiotic resistance of *E. coli* in soil, air, and hospital environments, as well as on fresh foods and vegetables, and retail chicken carcasses. Other subject areas such as chemistry, biochemistry, chemical engineering, and pharmaceutical sciences were also excluded due to focus of this review on environmental, agricultural and biological aspects. There were no geographic exclusion restrictions. Duplicate articles were eliminated, and all articles found during the searches were exported to Mendeley reference management.

Results and Discussion

Phases of screening for publication inclusion

After searching the ScienceDirect and PubMed databases, the total number of articles was 3661, 3634 of which belong to ScienceDirect and 27 of which belong to PubMed. After initial screening of the titles and abstracts, 3242 articles were excluded; this means that 419 articles were read in full. The main exclusion factor was the focus on antibiotic resistance of *E. coli* in

rivers, after which 388 were excluded and 31 were focused on those who met the study criteria (Figure 2).

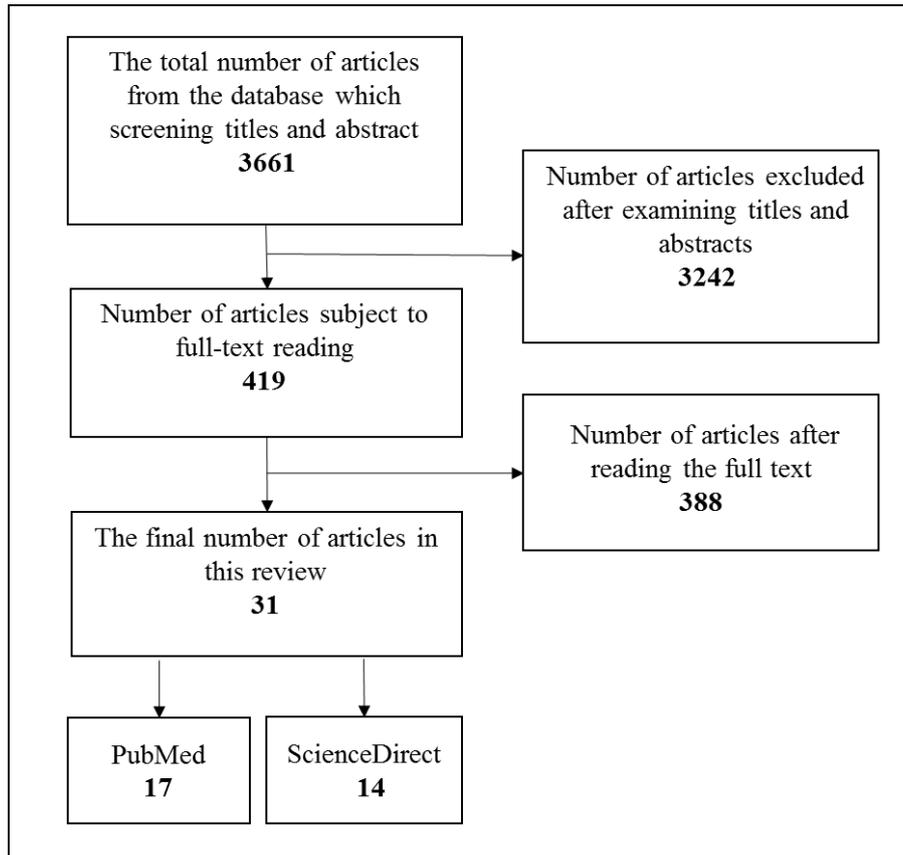


Figure 2. Flowchart showing the steps taken to exclude and include articles according to review criteria

The number of published articles on antibiotic resistance of *E. coli* in rivers conducted from 2014 to May 2024 is shown in (Figure 3).

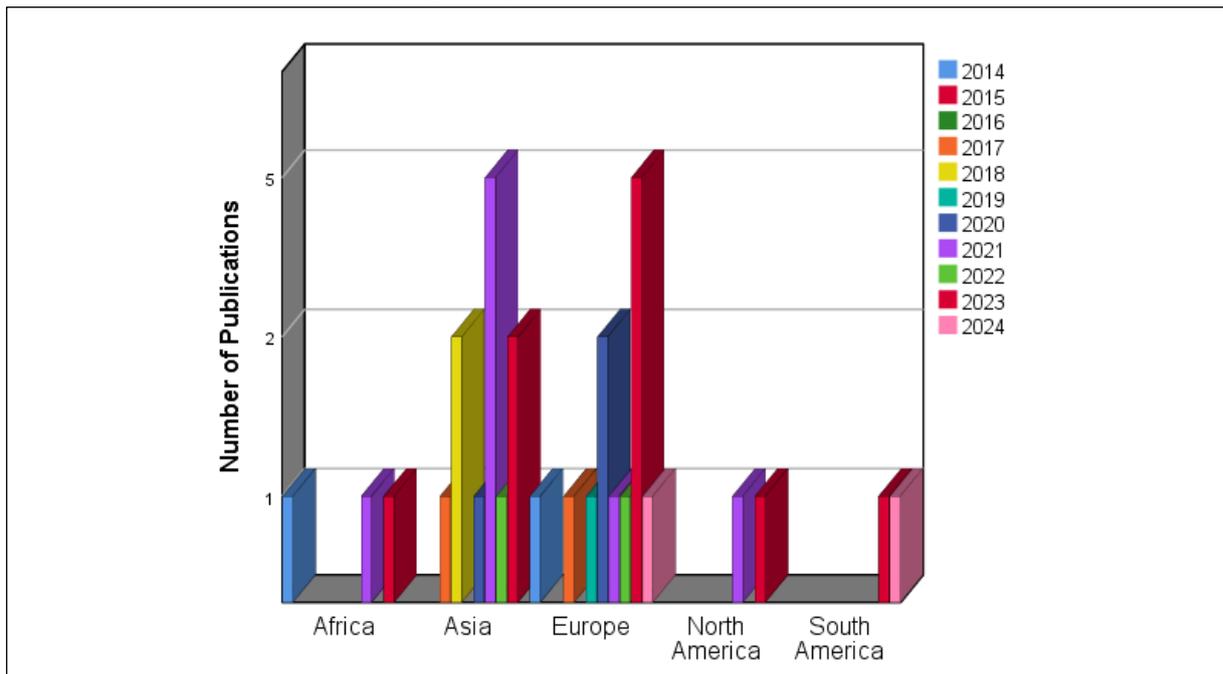


Figure 3. Number of published articles on antibiotic resistance of *E. coli* in rivers conducted on different continents from 2014 to May 2024

Features of included studies

Data extraction was performed for each of the 31 selected articles based on the number of predefined data fields. The fields used for primary data extraction were:

- (a) Country and continents of the examined samples.
- (b) Antibiotics used in the publications.
- (c) Antibiotic Classes used in the publications.
- (d) Author's name and year of publication.
- (e) The methods for identifying *E. coli* and the methods used in the detection of antibiotic resistance profile.

Screening and Exclusion Outcomes

• Geographical Distribution of Studies

The geographic distribution of included publications is shown below (Figure 4). Studies are drawn across five continents from 20 different countries across the world. As a result, the data are worldwide representative of water bodies, but they mostly come from studies conducted in Europe (n=12) and Asia (n=11). The remaining studies were found in Africa (n=4) and both North and South America (n=4). As for countries, India recorded the highest number of studies (n=5), followed by Ireland and Austria (n=3) studies. Raw data availability in ([Supplementary 1](#)).



Figure 4: An interactive map that allows clicking on dots to show the number of research per country on antibiotic resistance of *E. coli* in rivers: India (5, red); Austria, Ireland (3, blue); Tanzania, Taiwan, USA (2, green); Bangladesh, Belgium, Borneo, Brazil, Croatia, Egypt, Greece, Italy, Japan, Lebanon, Peru, Portugal, UK, and South Africa (1, yellow), ([Supplementary 2](#))

• Antibiotic Resistance Patterns

The investigations included used (n=68) antibiotics, ciprofloxacin was the most frequently used antibiotic as it was tested in (n=29) investigations, while both tetracycline and trimethoprim/sulfamethoxazole had a frequency of (n=24) followed by the rest of the antibiotics shown in (Table 1).

• Classes of Antibiotics Used

As for the classes of antibiotics, cephalosporins ranked highest, followed by aminoglycosides and penicillins (Figure 5). The author's names for the included articles according to the chronological hierarchy of the year of publication are shown in (Table 2).

• **Methods for Identifying *E. coli* and Antibiotic Resistance**

The culture plating test method was the most common used in diagnosing *E. coli* with Biochemical assay or PCR, while the Disk Diffusion Method was the most common method in testing for antibiotic sensitivity (Table 2).

Table 1. Antibiotics used in the ScienceDirect and PudMed publications from 10 years (2014- May 2024)

Antibiotic	No.	Antibiotic (Continued)	No.	Antibiotic (Continued)	No.
Ciprofloxacin	29	Aztreonam	6	Doxycycline	2
Tetracycline	24	Cefuroxime	6	Gentamycin	2
Trimethoprim/ Sulfamethoxazole	24	Amoxicillin	5	Ofloxacin	2
Ampicillin	23	Colistin	5	Penicillin	2
Gentamicin	23	Ertapenem	5	Sulfamethiazole	2
Cefotaxime	21	Piperacillin	5	Sulfamethoxazole	2
Chloramphenicol	21	Fosfomycin	4	Ampicillin/Sulbactam	1
Ceftazidime	16	Tobramycin	4	Carbenicillin	1
Imipenem	15	Trimethoprim	4	Cefaclor	1
Meropenem	15	Azithromycin	3	Cefixime	1
Amikacin	13	Cefazolin	3	Cefotaxim/Clavulanic Acid	1
Nalidixic Acid	13	Cefpodoxime	3	Doripenem	1
Amoxicillin/ Clavulanic Acid	13	Clindamycin	3	Gatifloxacin	1
Cefepime	11	Erythromycin	3	Linezolid	1
Ceftriaxone	11	Moxifloxacin	3	Methicillin	1
Cefoxitin	9	Levofloxacin	3	Metronidazole	1
Kanamycin	8	Vancomycin	3	Neomycin	1
Nitrofurantoin	8	Cefalexin	2	Netillin	1
Piperacillin/ Tazobactam	8	Cefoperazone	2	Netilmicin	1
Streptomycin	8	Cephalothin	2	Oxacillin	1
Norfloxacin	7	Cephalexin	2	Rifampicin	1
Tigecycline	7	Ceftazidime/ Clavulanic Acid	2	Sulfadiazine	1

- (No.): number of articles that used the antibiotic.

Table 2. Methods of identification of *E. coli* and profile of antibiotics used in the ScienceDirect and PudMed publications from 10 years (2014- May 2024)

Method	Refernceses
Quantitative Real-Time PCR (qPCR) for the 16S rRNA Gene	(Amos <i>et al.</i> , 2014)
Membrane Filter Method, Biochemical assay, PCR, Disk Diffusion Method (Kirby–Bauer Method)	(Nontongana <i>et al.</i> , 2014)
Culture plating test, Disk Diffusion Method	
Colilert™ Method, Disk Diffusion Method, rep-PCR	(Azzam <i>et al.</i> , 2017)
Culture plating test, PCR, Disk Diffusion Method	(Zarfel <i>et al.</i> , 2017)
Culture plating test, Disk Diffusion Method	(Dhawde <i>et al.</i> , 2018)
qPCR, Disk Diffusion Method	(Diwan <i>et al.</i> , 2018)
Culture plating test, PCR, Disk Diffusion Method	(González-Plaza <i>et al.</i> , 2019)

Method	Refernceses
Membrane Filter Method, qPCR, Disk Diffusion Method	(Hanna <i>et al.</i> , 2020)
Biochemical assay, Disk Diffusion Method	(Pantanella <i>et al.</i> , 2020)
Culture plating test, PCR, Disk Diffusion Method	(Ali <i>et al.</i> , 2021)
Culture plating test, Real Time PCR	(Dagher <i>et al.</i> , 2021)
Culture plating test, Biochemical assay, Disk Diffusion Method	(Hooban <i>et al.</i> , 2021)
Culture plating test, Biochemical assay, Disk Diffusion Method	(Kimera <i>et al.</i> , 2021)
Membrane Filter Method, Disc Diffusion Method	(Lihan <i>et al.</i> , 2021)
Culture plating test, Biochemical assay, Broth Dilution Method	(Mukherjee <i>et al.</i> , 2021)
Culture plating test, PCR, Broth Dilution Method	(Nishimura <i>et al.</i> , 2021)
Biochemical assay, Double Disk Method, Synergy Test (DDST)	(Teng <i>et al.</i> , 2021)
Culture plating test, Real Time PCR.	(Asaduzzaman <i>et al.</i> , 2022)
Membrane Filter Method, PCR, Disk Diffusion Method	(Hooban <i>et al.</i> , 2022)
Culture plating test, Disk Diffusion Method	(Chen <i>et al.</i> , 2023)
Colilert® method from IDEXX, Sensititre ARIS 2X	(Crettels <i>et al.</i> , 2023)
Membrane Filter Method, Indole Biochemical, PCR, Disk Diffusion Method	(Daly <i>et al.</i> , 2023)
Most Probable Number (MPN), Gram technique, Disk Diffusion Method	(Dioli <i>et al.</i> , 2023)
Culture plating test, Indole Biochemical, PCR, Disk Diffusion Method	(Gomes <i>et al.</i> , 2023)
Culture plating test, PCR, Pulsed-Field Gel Electrophoresis (PFGE), Disk Diffusion Method	(LaMontagne <i>et al.</i> , 2023)
Biochemical assay, PCR, Disk Diffusion Method	(Palmeira <i>et al.</i> , 2023)
16S rRNA Gene, Disk Diffusion Method	(Ripanda <i>et al.</i> , 2023)
Culture plating test, PCR, Disk Diffusion Method	(D. Singh <i>et al.</i> , 2023)
Culture plating test, Disk Diffusion Method	(Skof <i>et al.</i> , 2024)
MPN, Disk Diffusion Method	(Ferro <i>et al.</i> , 2024)

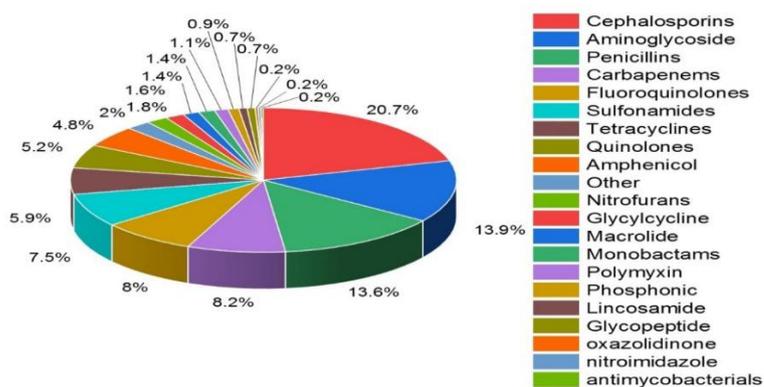


Figure 5. Antibiotic Classes used in the ScienceDirect and PudMed publications from 10 years (2014- May 2024)

Rivers and other natural water resources are important resources that have a big impact on the economy, agricultural production, and public health. Disease outbreaks caused by contaminated water have a high rate of morbidity and mortality, particularly in children and other individuals at risk (Lin *et al.*, 2022). This review of the literature was conducted to examine the body of research

on the topic of antibiotic-resistant *E. coli* in rivers and the role that the natural aquatic environment plays in harboring and transferring these bacteria. Antibiotic resistance complicates the treatment of infectious diseases, lengthens the course of therapy, increases financial costs, and heightens fatality rates. Therefore, resistant infections pose a significant threat to the health of humans, animals, and the environment (Türkyılmaz and Darcan, 2024).

The articles that were considered have publication dates ranging from 2014 to May 2024; the fact that only 31 publications out of 3661 met the study criteria indicates the scarcity of studies on antibiotic resistance of *E. coli* in rivers due to the focus on clinical isolates only along many years, and to a much lesser extent on wastewater in non-clinical settings (Gholizadeh *et al.*, 2023). The lack of publications in 2020 is due to the lockdown measures that accompanied the COVID-19 pandemic, which caused disruptions in sample collection and made it impossible to use laboratories to conduct tests in health facilities (WHO, 2022b; Dioli *et al.*, 2023; Ferro *et al.*, 2024). A rise in publishing about antibiotic resistance of *E. coli* in rivers occurring after 2020 (22/31; 71%), the abrupt rise in publications that have been seen in recent years is in line with the scientific community's growing interest in learning more about how antibiotic resistance spreads in natural environments (Stanton *et al.*, 2022). In particular, the WHO Member States' Global Action Plan on Antimicrobial Resistance focused on tracking the β -lactamase production *E. coli* (ESBL-Ec) across the three sectors-human, animal, and environmental-to achieve a multisector "One Health" strategy to control this problem, as any health threat to one sector will impact the others (WHO, 2021).

According to author affiliation data, research study sites were typically situated in areas that were convenient and close to the researchers' location. Therefore, the location of the researchers doing this kind of research is probably the reason for the unequal geographic distribution of study locations, as the interested researchers are unevenly distributed, resulting in a different geographic distribution of the countries in which the publications was published (Stanton *et al.*, 2022). The lack of studies may be due to a lack of resources. For example, in South America there is a correlation between the increase in the country's total income and the number of studies conducted (Domínguez *et al.*, 2021). The small number of studies in Africa is due to the economic situation, low funding for research, and research centers. This is consistent with a study (Sartorius *et al.*, 2024) that shows, according to publications covering exposure to resistant bacterial agents that are available in Scopus, PubMed, Web of Science, and MEDLINE, relatively few studies in the WHO African Region quantify the impact that is associated with antimicrobial resistance.

Publications showed that the highest resistance was against ampicillin (14/31), followed by ciprofloxacin (10/31), and tetracycline (9/31), which indicates a steady increase in resistance to these commonly used antibiotics. Ampicillin is a semisynthetic antibiotic that is a member of the aminopenicillin group. It is used as a valuable agent in the treatment of some bacterial infections, such as *E. coli*, in which *E. coli* resistance, which is the most commonly reported (Peechakara *et al.*, 2023). The results of this review were consistent with the results of the WHO in Europe. It showed that clinical *E. coli* resistance to aminopenicillin was 54.6% (WHO, 2022a), indicating a simultaneous increase in the rate of clinical and environmental *E. coli* resistance. Ciprofloxacin is a widely used medication that has been found in a variety of environmental matrices, including soil, groundwater, and surface waterways. The high resistance to ciprofloxacin is a result of its high presence in water, which is estimated at 50-80%. This is because ciprofloxacin is frequently utilized in aquaculture to treat and prevent infections caused by bacteria in aquatic animals. In addition, this chemical could reach the environment through a variety of pathways, such as leachate from landfills, agricultural runoff, and wastewater discharges (Alhaideri *et al.*, 2021; Grčić *et al.*, 2023; Munzhelele *et al.*, 2024; Sassa-deepaeng *et al.*, 2024). Residues of ciprofloxacin in wastewater released into the environment activate bacterial resistance to antibiotics (Nwabuife *et al.*, 2022).

Regarding the classes of antibiotics, the fluoroquinolones class showed a noticeable development in resistance, especially since 2020. Fluoroquinolones are antimicrobial medications that are

frequently used to treat human infections caused by *E. coli* or other bacteria that are Gram-negative. Because fluoroquinolones are widely used for multiple clinical indications in veterinary medicine, bacterial resistance to these agents has developed over time (Egwu *et al.*, 2024). Most human health concerns revolve around the use of fluoroquinolones (such as enrofloxacin) in food animals. In certain nations, these antibiotics have been discontinued or not allowed for use in food animals. Due to the rise of fluoroquinolone-resistant bacteria, enrofloxacin was removed from usage in the chicken industry in 2005, and the use of fluoroquinolones in food animals is prohibited in the United States (Davies and Singer, 2020). In the European Union, some studies have shown that more than 60% of isolates are resistant to fluoroquinolones, while others have shown resistance rates as high as 90% in some countries. Although antibiotics have been outlawed as growth promoters in animal production, this class of antibiotic remains commonly utilized in the European Union, suggesting a high level of persisting resistance. According to the European Food Safety Committee, high levels of resistance have a significant impact on the treatment of human campylobacteriosis, to the point that the antibiotic is no longer advised for its use (Roth *et al.*, 2019; Wallace *et al.*, 2021).

The development of *E. coli* resistance to multidrug has also been observed in this review. Antibiotics beta-lactams and fluoroquinolones, such as trimethoprim/sulfamethoxazole and amoxicillin/clavulanic acid, are a major concern. Multidrug-resistant organisms are a concern due to rising antimicrobial resistance, their potential impact on patient safety, and their effects on surveillance systems (Abalkhail *et al.*, 2022). If not effectively controlled, the alarmingly high prevalence of multidrug-resistant *E. coli* might have fatal consequences for the public's health as well as treatment failures and possibly even mortality (Egwu *et al.*, 2023).

Azithromycin and erythromycin belong to the macrolides class of antibiotics, which are characterized by a large ring lactone structure, which has an effective effect in treating enteric bacterial infections, including *E. coli* (Ajenifuja and Oni, 2022). However, this review recorded the modern resistance of *E. coli* to these two antibiotics since 2019, which is a great concern.

The widespread use of traditional cultural methods is due to their ease of implementation, low cost, and good standard of interpretation. The use of molecular techniques has increased in modern research, although the use of molecular detection methods is often limited to detecting pathogenic bacteria in clinical settings, which constitutes a knowledge gap regarding bacterial resistance in natural surface waters (Yamin *et al.*, 2023).

- **Development of Antibiotic Resistance of *E. coli*: Environmental Factors**

An important factor in the emergence and spread of clinically relevant antibiotic resistance genes (ARGs) is the natural aquatic environment. The possibility that the aquatic environment serves as a reservoir for the accumulation of ARGs in places suffering from anthropogenic pollution (Hooban *et al.*, 2020). One of the reasons for the increase in bacterial resistance in rivers is the decrease in minimum flows, which leads to a decrease in the volume of dilution and thus higher concentrations downstream from discharge points such as wastewater treatment plants. In addition, sewer overflow and sediment resuspension during heavy rainfall events can enhance the release of antibiotics and ARB into the aquatic space. These factors, coupled with the expected sharp variation in river flows, will increase the risk of ARB and antibiotic contamination (Haenni *et al.*, 2022). Environmental factors also play an important role in the spread of antibiotic resistance of bacteria in humans, plants, animals, and the environment due to the interaction between environmental changes and the native microbial population (Zhao *et al.*, 2024). For example, global warming has not only increased average temperatures but has also intensified environmental stresses caused by antibiotics, thus accelerating the spread of antibiotic resistance in aquatic systems (Magnano San Lio *et al.*, 2023). According to a cross-sectional study done in 30 European nations, resistant *E. coli* is strongly linked to the warming season's temperature shift (Kaba *et al.*, 2020). High temperatures

accelerate the spread of resistant bacteria to antibiotics and endanger human health, through increasing host populations, triggering heat shock reactions, and encouraging horizontal gene transfer (Burnham, 2021). Temperature affects variables including pH, CO₂, and salinity, which in turn affect how antibiotic resistance spreads. For instance, high temperatures can raise salinity and decrease pH, which changes sensitive bacteria's are to antibiotics and encourages horizontal gene transfer, increasing the risk of resistant bacteria to antibiotics (Grilo *et al.*, 2021).

Conclusions

The resistance of *E. coli* to antibiotics in rivers has increased alarmingly over time, and even with modern antibiotics that still show some effectiveness, resistance is beginning to emerge. Therefore, more efforts to monitor rivers and more research on antibacterial treatments should be done to diminish and eventually eradicate antibiotic resistance, which is a huge global issue. Scientific cooperation should also be strengthened to establish a global response to antibiotic resistance. These results can be used to serve the health of humans, animals and the environment. Recommendations: (a) Conduct surveillance for *E. coli* resistance in rivers. (b) Use unified and standardized methods for sensitivity tests to facilitate comparison between research results. (c) Using molecular detection methods alongside traditional methods. (d) Tracing the source of resistant *E. coli* in rivers, whether human or animal. (e) Leveraging artificial intelligence (AI) to analyze big data on antibiotic resistance, develop predictive models to assess water quality trends, and improve monitoring strategies for rapid decision-making, making it a priceless resource for public health authorities.

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Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Funding Declaration

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Author Contribution

All authors designed the study. The first and second authors analyzed the data. The first author wrote the original draft, with input and review from the second and third authors.

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