

Environmental Determinants of Antimicrobial Resistance

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ABSTRACT

Antimicrobial resistance (AMR) has become a critical global health challenge, threatening the effectiveness of antibiotics, antivirals, antifungals, and antiparasitic drugs. Although clinical misuse of antibiotics in humans and animals has traditionally been highlighted as the primary driver of resistance, environmental factors play an equally significant and complex role in the emergence, persistence, and dissemination of resistant microbes and resistance genes. The environment serves as a reservoir and conduit for antimicrobial compounds and resistant organisms originating from healthcare settings, agricultural systems, industrial effluents, and community waste. This review examines the major environmental determinants of AMR—chemical contaminants, water systems, soil and agriculture, wildlife and ecosystems, and climate change. It also explores mechanisms by which environmental exposures promote resistance, including selective pressures, horizontal gene transfer, and biofilm formation. By integrating evidence from environmental science, microbiology, and public health, this article highlights emerging research frontiers and offers policy recommendations for tackling AMR within ecological contexts. A One Health approach, recognizing the interconnectedness of human, animal, and environmental health, is essential to design effective interventions that reduce the burden of antimicrobial resistance globally.

Keywords: Antimicrobial resistance, environmental determinants, antibiotic pollution, One Health, horizontal gene transfer.

INTRODUCTION

Antimicrobial resistance (AMR) occurs when microorganisms like bacteria, viruses, fungi, or parasites evolve to withstand the drugs designed to kill them or inhibit their growth [1]. This adaptive process compromises the treatment of common infectious diseases, increases the duration and severity of illness, elevates healthcare costs, and contributes significantly to global morbidity and mortality [2]. Once treatable infections such as pneumonia, urinary tract infections, tuberculosis, and bloodstream infections are becoming more difficult to manage due to diminishing antimicrobial effectiveness. While the misuse and overuse of antimicrobials in clinical medicine and animal husbandry have long been recognized as major drivers of resistance, environmental dimensions of AMR are now understood to be equally critical [3]. The environment functions as both a reservoir and a transmission pathway for antimicrobial compounds, resistant bacteria, and resistance genes. Natural ecosystems, including rivers, lakes, soils, sediments, and wetlands, interact continuously with human and animal systems [4]. Built environments such as wastewater treatment plants, hospital drainage systems, and pharmaceutical manufacturing sites further contribute to environmental contamination. These diverse settings accumulate antimicrobial residues and resistant organisms from multiple sources, creating ecological “hotspots” where selective pressures promote the survival and proliferation of resistant strains [5]. Importantly, environmental conditions do not merely store resistant organisms; they actively shape microbial evolution. Sub-inhibitory concentrations of antibiotics in water and soil can trigger stress responses in bacteria, increasing mutation rates and enhancing horizontal gene transfer [6]. In addition, environmental contaminants such as heavy metals and biocides may co-select for antibiotic resistance by maintaining shared resistance mechanisms on mobile genetic elements [7]. Climate-related factors, including temperature shifts and extreme weather events, can further influence microbial growth patterns and the geographic spread of resistant organisms. This review explores the environmental determinants of AMR by

examining how anthropogenic activities and ecological processes interact to promote resistance emergence and dissemination [8]. A comprehensive understanding of these environmental pathways is essential for designing effective mitigation strategies that extend beyond healthcare settings and incorporate environmental stewardship within a One Health framework.

2. Sources of Antimicrobials and Resistant Organisms in the Environment

2.1 Pharmaceutical Discharge

Pharmaceutical manufacturing facilities represent a significant point source of antibiotic contamination, particularly in regions where environmental regulations and monitoring systems are limited [9]. During production, waste streams containing active pharmaceutical ingredients may be discharged into nearby rivers and lakes if not adequately treated [10]. In some documented cases, antibiotic concentrations in effluents have exceeded therapeutic plasma levels found in patients, creating intense selective environments for microbial communities. Even at much lower concentrations, persistent antibiotic residues can exert chronic selective pressure. Bacteria exposed to sub-therapeutic levels may not be killed outright but can develop adaptive mechanisms such as efflux pumps, enzymatic degradation systems, or target-site modifications [11]. Over time, these resistant strains proliferate and share resistance genes with other bacteria through mobile genetic elements, amplifying environmental reservoirs of resistance.

2.2 Wastewater Treatment Plants (WWTPs)

Municipal, hospital, and industrial wastewater streams converge in wastewater treatment plants (WWTPs), making them critical nodes in the environmental AMR network [12]. Wastewater contains unmetabolized antibiotics excreted by humans and animals, disinfectants, heavy metals, and high densities of diverse microorganisms. Although conventional treatment processes such as sedimentation, biological digestion, and chlorination reduce microbial loads, they are not specifically designed to eliminate antimicrobial residues or resistance genes [13]. As a result, treated effluents may still contain resistant bacteria and mobile genetic elements such as plasmids and integrons. The high microbial density and nutrient availability within WWTPs create favorable conditions for horizontal gene transfer, particularly within biofilms that form on treatment infrastructure. Once released into receiving water bodies, these organisms and genes can persist and disseminate downstream, contributing to broader environmental contamination.

2.3 Agricultural Runoff

Agricultural practices are a major contributor to environmental AMR. Antibiotics administered to livestock for therapeutic, prophylactic, or growth-promotion purposes are often incompletely metabolized, with substantial fractions excreted in urine and feces [14]. Manure containing active antibiotic residues and resistant bacteria is commonly applied to farmland as fertilizer. Rainfall events and irrigation can mobilize these contaminants, transporting them into surrounding soils, groundwater, and surface waters. Within soil ecosystems, antibiotic residues alter microbial community composition, favoring resistant organisms and increasing the abundance of resistance genes [15]. These genes may be transferred to pathogenic bacteria through horizontal gene exchange mechanisms. Furthermore, crops grown in contaminated soils or irrigated with polluted water may become vehicles for the transmission of resistant bacteria into the human food chain.

2.4 Aquaculture and Fish Farming

Aquaculture systems, particularly intensive fish and shrimp farming operations, frequently rely on antibiotics to prevent and control disease outbreaks in densely stocked environments [16]. Unlike terrestrial livestock systems, antibiotics used in aquaculture are often applied directly into water, facilitating immediate environmental dispersion [17]. Uneaten medicated feed and fish excreta introduce antibiotic residues and resistant bacteria into surrounding aquatic ecosystems. Sediments beneath fish farms can accumulate high concentrations of antimicrobial compounds, creating persistent selection zones for resistance. Aquatic bacteria exposed to these pressures may develop resistance traits that are transferable to human pathogens [18]. Additionally, water currents can transport resistant organisms beyond farm boundaries, extending the ecological footprint of aquaculture-related contamination. Consequently, aquaculture represents an important but sometimes underrecognized contributor to the global environmental burden of antimicrobial resistance.

3. Environmental Mechanisms that Promote Resistance

3.1 Selective Pressure in Ecological Systems

Selective pressure occurs when antimicrobial compounds in the environment kill or inhibit susceptible microbes, allowing resistant organisms to survive and multiply [19]. Even sub-inhibitory antibiotic concentrations can trigger bacterial stress responses that increase mutation rates and promote resistance emergence. Moreover, residual antimicrobial agents may persist in sediments for long periods, creating chronic selection environments.

3.2 Horizontal Gene Transfer (HGT)

A central mechanism driving AMR spread is horizontal gene transfer (HGT), the movement of genetic material between microorganisms independent of reproduction [20]. In natural environments, HGT occurs via transformation (uptake of free DNA), transduction (viral-mediated), and conjugation (direct cell-to-cell contact)

[21]. Environmental conditions such as biofilm formation (dense microbial communities attached to surfaces) enhance HGT rates. Biofilms in rivers, wastewater systems, and soil provide stable habitats where resistance genes can circulate among diverse bacterial species.

3.3 Co-selection by Heavy Metals and Biocides

Environmental pollutants such as heavy metals (e.g., mercury, copper, zinc) and biocides (chlorine, triclosan) can co-select for antimicrobial resistance [22]. Bacteria often possess resistance mechanisms that confer simultaneous tolerance to both antibiotics and other stressors. For example, metal resistance genes may be located on the same plasmid as antibiotic resistance genes, enabling co-selection when heavy metals are present [23]. Thus, environments contaminated with industrial pollutants inadvertently support persistence of resistant determinants.

4. Environmental Hotspots for Antimicrobial Resistance

4.1 Aquatic Ecosystems

Rivers, lakes, estuaries, and coastal waters are among the most significant environmental reservoirs of AMR. Surface waters receive inputs from WWTP effluents, agricultural runoff, and untreated sewage. Studies have detected resistant bacteria and resistance genes in water systems far from urban centers, underscoring the broad dispersal potential [24]. Water bodies also facilitate transport of resistant organisms to drinking water sources and recreational areas.

4.2 Soils and Sediments

Soils, especially those treated with manure or biosolids, accumulate antibiotics and resistant microbes [25]. Soil bacteria constitute one of the largest reservoirs of natural antibiotic resistance genes, many of which predate clinical antibiotic use. However, anthropogenic inputs amplify the presence of clinically relevant resistance genes that can transfer to human pathogens via HGT [26]. Sediments in rivers and coastal regions serve as sinks for both antimicrobial compounds and resistant bacteria.

4.3 Urban and Industrial Environments

Infrastructure associated with dense human populations like sewers, landfills, and industrial discharge sites concentrates chemicals and microbes [27]. In urban wastewater systems, untreated or partially treated sewage creates high microbial densities and frequent antibiotic exposures, further facilitating resistance development [28]. Industrial effluents containing pharmaceutical residues pose similar threats.

5. Strategies to Address Environmental AMR

Addressing antimicrobial resistance (AMR) in the environment requires coordinated, multisectoral action that integrates environmental protection with public health and agricultural reform [29]. Because environmental reservoirs act as both sources and transmission pathways for resistant organisms, interventions must reduce contamination at origin while limiting downstream dissemination.

5.1 Regulating Agricultural Use

Agricultural stewardship is critical in reducing environmental antibiotic burdens. Phasing out Non-therapeutic Antibiotic Use: Eliminating antibiotics as growth promoters and restricting prophylactic use in livestock and aquaculture reduces unnecessary environmental exposure [30].

Promoting Alternative Practices: Improved animal nutrition, vaccination programs, enhanced biosecurity, and better housing conditions can prevent disease without reliance on routine antimicrobial use [31].

Managing Manure: Composting, anaerobic digestion, and other manure treatment methods reduce viable resistant bacteria and degrade antibiotic residues before field application [32].

5.2 Environmental Surveillance Programs

Systematic environmental monitoring of antibiotic residues and resistance genes in water, soil, and sediments is essential [33]. Surveillance systems support trend analysis, identify emerging hotspots, and inform risk assessment and policy adjustments [34].

5.3 Research and Innovation

Continued research into microbial ecology, resistance gene mobility, and environmental selection thresholds is needed [35]. Emerging tools such as metagenomics, biosensors for rapid detection, and predictive ecological modeling can enhance understanding and guide targeted interventions [36].

5.4 One Health Policies

A One Health framework integrates human, animal, and environmental health sectors. Coordinated governance across ministries of health, agriculture, environment, and water resources ensures harmonized policies, shared data systems, and sustainable strategies to mitigate environmental drivers of AMR [37].

CONCLUSION

Antimicrobial resistance is not solely a clinical or agricultural problem; it is deeply embedded in environmental contexts shaped by human activity, ecological processes, and global change. Environmental determinants such as antibiotic pollution, wastewater effluents, agricultural runoff, heavy metals, and climate factors create conditions that select for resistance and facilitate its spread across ecosystems and populations. Addressing AMR therefore requires a holistic strategy that integrates environmental science with public health, veterinary medicine, and

policy frameworks. Strengthening waste management, regulating antimicrobial use, expanding surveillance, and embracing One Health principles are essential steps toward mitigating resistance emergence and safeguarding the effectiveness of life-saving drugs for future generations.

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