Agri Articles
(e-Magazine for Agricultural Articles)
Volume: 06, Issue: 01 (JAN-FEB, 2026)
Available online at http://www.agriarticles.com

Atmospheric Antibiotic Resistance Genes (ARGs): A New Route of Aquatic Contamination

*Ilakkiya S, Aruna S and Mahalakshmi S
Department of Aquatic Environment Management, Dr. M.G.R. Fisheries College and Research Institute, Ponneri, Thiruvallur-601204, India
*Corresponding Author's email: ilakkiyas12@gmail.com

Antibiotic resistance is recognized as a global health emergency. While research has traditionally focused on water and soil as reservoirs and transmission pathways for antibiotic resistance genes (ARGs), recent evidence shows that the atmosphere also serves as a significant reservoir and vector for ARGs. This article reviews current knowledge about atmospheric ARGs, their sources and transport mechanisms, deposition into aquatic systems, and the implications for environmental and human health. Airborne ARGs bind to particulate matter and can travel long distances, crossing ecological and geographical boundaries before entering water bodies through dry and wet deposition. Atmospheric transport, influenced by weather and pollution, integrates ARGs into aquatic ecosystems, potentially amplifying resistance spread through horizontal gene transfer. Understanding this emerging pathway expands the scope of antibiotic resistance research, highlighting the need for integrated monitoring frameworks, standardization of methods, and mitigation strategies bridging air and water quality management.

Keywords: Atmospheric ARGs, airborne antibiotic resistance, bioaerosols, aquatic contamination, ARG deposition, antimicrobial resistance dissemination.

Introduction

Antibiotic resistance genes (ARGs) have become pervasive environmental contaminants due to the widespread use of antibiotics in medicine, agriculture, and industry. These genes enable bacteria to withstand antibiotic exposure and can transfer between bacteria through horizontal gene transfer mechanisms. Historically, studies of ARGs have focused on soil and aquatic environments, especially wastewater influents and effluents, rivers, and marine systems. However, emerging research indicates that the atmosphere is a dynamic and underappreciated reservoir and transmission route for ARGs. ARGs can be emitted into the air through bioaerosols from wastewater treatment plants, livestock operations, urban emissions, and natural processes. Once airborne, ARGs can attach to particulate matter (PM) and be transported over short and long distances before being deposited into terrestrial and aquatic environments via dry deposition or precipitation. This article synthesizes the latest research on atmospheric ARGs and highlights their role in aquatic contamination.

Atmospheric Reservoirs of ARGs

Airborne environments contain diverse microbial communities, including bacteria carrying ARGs. Aerosolized microbes originate from numerous sources such as wastewater treatment operations, agricultural facilities, hospitals, and urban surfaces. Studies have identified ARGs in urban air across multiple cities, with notable variability in abundance and resistance classes (e.g., β-lactam, tetracycline, sulfonamide) tied to local emission sources and air quality conditions. Urban airborne ARGs often correlate with particulate matter concentrations, suggesting that PM serves as a carrier facilitating ARG persistence and transport in the atmosphere. Research focusing on atmospheric metagenomics has shown that ARGs are globally distributed in air samples, including particulate matter above remote environments and in cloud water. Clouds, for example, have been found to contain substantial numbers of ARG copies per milliliter, reflecting both aerosolization and long-range atmospheric transport potential. These findings complicate the traditional picture of ARG dissemination, indicating that air is not just a medium of bacterial transmission but also an active pathway for genetic material conferring antibiotic resistance.

Sources and Mechanisms of Airborne ARG Emission

The primary sources of ARGs in the atmosphere include:

- **Wastewater treatment plants (WWTPs)**, where aeration processes and biosolid handling generate ARG-containing bioaerosols.
- **Livestock and poultry operations**, which produce dust and airborne particulate matter enriched with resistant bacteria carrying ARGs.
- **Hospitals and urban emissions**, with airborne fine particulate matter (PM2.5) often showing higher ARG abundance near clinical settings.
- **Natural sources**, such as soil and vegetation surfaces, where wind actions can release microbial communities into the air.

ARGs attach to airborne particles, especially PM2.5 and total suspended particles (TSP), which not only facilitate their persistence in air but also influence deposition patterns onto water bodies and soil. ARGs carried on PM can travel several kilometers from their sources, depending on meteorological conditions, before deposition.

Atmospheric Transport and Deposition into Aquatic Systems

Once airborne, ARGs can be transported via several mechanisms:

- **Dry deposition**, where particles settle out of the atmosphere onto water surfaces and land.
- **Wet deposition**, where ARG-laden particles are scavenged by rain or snow and delivered to aquatic environments.

Precipitation has been shown to act as a mobile reservoir for ARGs, facilitating their transmission from the atmosphere into soil and water. This process is influenced by meteorological conditions and particulate matter concentrations. Long-range atmospheric transport has also been documented. Studies measuring ARG deposition via rain and snow at high altitude or remote locations demonstrate that ARGs can persist several kilometers above ground and travel intercontinentally within air masses before entering aquatic ecosystems.

Implications for Aquatic Contamination and Resistance Spread

The deposition of ARGs into water bodies augments the existing environmental reservoirs of antibiotic resistance. Once in aquatic environments, ARGs can:

- Integrate into microbial communities through horizontal gene transfer.
- Spread within biofilms and microbial networks in sediments and water columns.
- Enrich resistant bacterial populations even in relatively pristine waters.

Aquatic contamination by atmospheric ARGs expands the pathways through which resistance can proliferate, linking air quality to water quality and public health. This poses a concern for drinking water systems, recreational water use, aquaculture, and ecosystem health.

Monitoring and Methodological Challenges

Studying atmospheric ARGs presents unique challenges. Low biomass and highly variable distribution of airborne microbes complicate sampling and quantification. A range of methodologies, including high-throughput quantitative PCR and metagenomic sequencing, are used to detect ARGs in air samples, but the lack of standardized protocols makes cross-study comparison difficult. Robust monitoring frameworks are needed to understand ARG dynamics in the atmosphere and their deposition into aquatic systems. Integrating airborne ARG monitoring with traditional water quality surveillance can help identify hotspots and temporal trends in environmental antibiotic resistance.

Mitigation and Policy Considerations

Addressing atmospheric routes of ARG dissemination requires coordinated strategies that cut across environmental media:

- **Emission reduction at sources**, such as improving control of bioaerosols at WWTPs and agricultural sites.
- **Air quality management policies** that include ARGs and antibiotic resistance potential in risk assessments.
- **Holistic frameworks** that integrate air, water, and land stewardship under One Health initiatives.

Standardizing detection methods and strengthening regulatory standards can improve surveillance and guide mitigation actions.

Conclusion

Atmospheric ARGs represent an emerging pathway of antibiotic resistance dissemination that connects air quality with aquatic ecosystem contamination. ARGs can attach to airborne particulates, travel across landscapes, and deposit into water bodies through dry and wet processes. These mechanisms extend the environmental reach of antibiotic resistance, compounding existing challenges in antimicrobial resistance management. Addressing this requires integrated monitoring, improved source controls, and collaborative policy frameworks that consider air-to-water transmission pathways of ARGs.

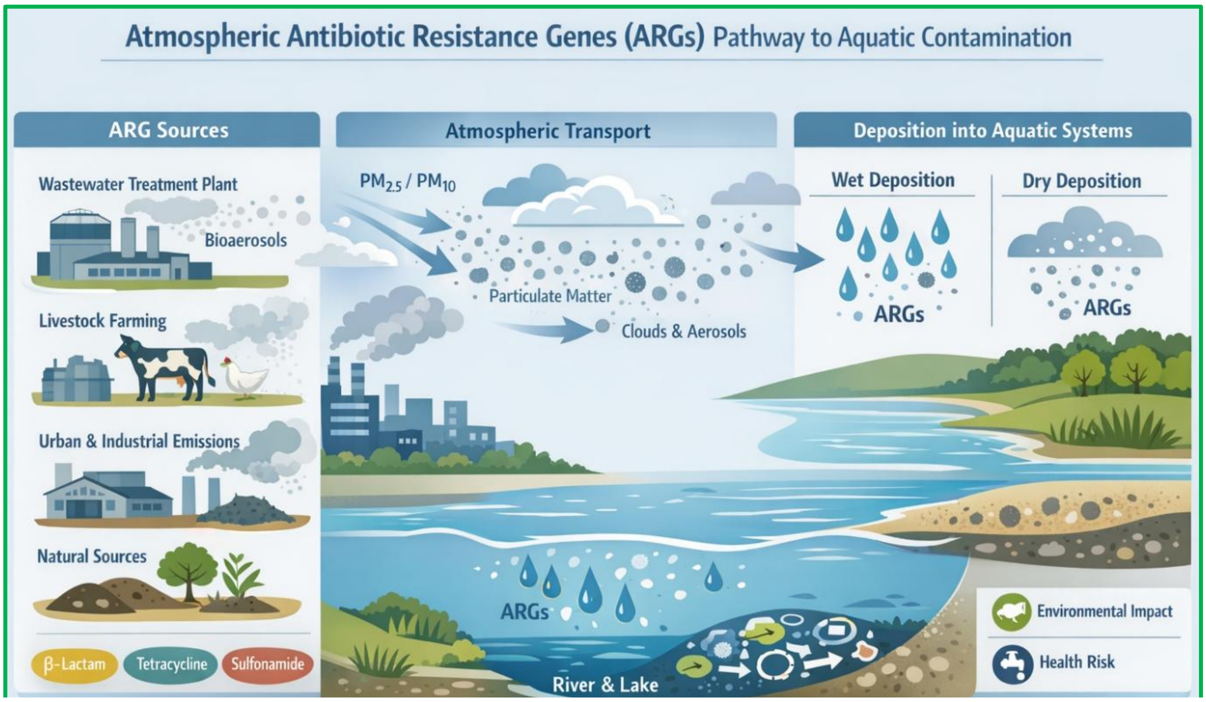

Figure 1. Schematic representation of atmospheric antibiotic resistance genes (ARGs) as an emerging route of contamination into aquatic systems. ARGs originate from anthropogenic and natural sources, are transported via particulate matter and bioaerosols, and are deposited into water bodies through wet and dry deposition, where they may integrate into microbial communities and spread resistance.

References

1. Ben, Y., et al. (2022). Critical review of antibiotic resistance genes in the atmosphere. *Environmental Science: Processes & Impacts*, *24*, 870–883.
2. Li, et al. (2025). Key contribution and risk of airborne antibiotic resistance. *Environmental Science & Technology*, *59*, 10788–10798.
3. Rossi, F., et al. (2023). Quantification of antibiotic resistance genes in clouds at a mountain site. *Science of The Total Environment*, *865*, 161264.

4. Wang, et al. (2023). Atmospheric antibiotic resistome driven by air pollutants. *Science of The Total Environment*, *902*, 165942.
5. Zhang, et al. (2022). Global dispersal and potential sources of antibiotic resistance genes in atmospheric remote depositions. *Environment International*, *160*, 107077.
6. Zhang, et al. (2018). Global survey of antibiotic resistance genes in air. *Environmental Science & Technology*.