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Environmental Antimicrobial Resistance in Agricultural Water: Soil, Crops and One Health Perspectives

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ABSTRACT

Agricultural water represents an important interface connecting environmental processes, soil health, crop production, livestock systems and human health. Increasing detection of antimicrobial-resistant bacteria and resistance genes in aquatic and agricultural environments has raised concern regarding their persistence, dissemination and potential movement through food and water pathways. Irrigation with contaminated surface water may introduce resistant microorganisms into agricultural soils, where microbial communities organic matter, moisture, nutrient availability and environmental conditions can influence persistence and horizontal gene transfer. Resistant bacteria may subsequently interact with crops, farm workers, animals and downstream aquatic systems. This review examines the environmental dimensions of antimicrobial resistance in agricultural water, emphasizing soil–water interactions, crop exposure, resistance surveillance, molecular detection, agricultural practices and One Health management. Particular attention is given to β -lactamase-associated resistance and the significance of environmental investigations. Integrated monitoring, improved water quality, responsible antimicrobial use, molecular surveillance and sustainable agricultural management are essential for reducing environmental resistance dissemination.

Keywords: Antimicrobial resistance, Agricultural water, Soil health, Irrigation, β -lactamase, Crops, Environmental microbiology, One Health, Geoscience, Sustainable agriculture

1. Introduction

Agriculture depends fundamentally on interactions among soil, water, climate, microorganisms, plants and human management. Agricultural systems therefore provide an important setting for studying environmental processes that influence both productivity and public health. Soil and water science increasingly recognizes the need to understand contamination, nutrient cycling, microbial ecology and sustainable resource management as interconnected processes rather than isolated components. Current soil-science and agricultural research encompass soil chemistry, microbiology, fertility, land management, contamination, plant–soil interactions and environmental protection¹.

Antimicrobial Resistance (AMR) represents one of the emerging environmental challenges within this interconnected system. Resistant bacteria and antimicrobial-resistance genes can enter agricultural environments through wastewater, manure, biosolids, animal production, human sewage, pharmaceutical residues and contaminated surface water. Once introduced, resistance determinants may persist or circulate among environmental microbial communities^{2,3}.

Agricultural water is particularly important because rivers, canals, groundwater, treated wastewater and drainage systems can connect multiple environments. Water used for irrigation can transport microorganisms and resistance genes to agricultural soils^{4,5}. The subsequent interaction among water, soil minerals organic matter, plant roots and microorganisms may influence persistence and dissemination.

Environmental surveillance has provided evidence that clinically important resistance determinants can occur outside healthcare settings. Guma et al.⁶ reported molecular identification of two β -lactamase genes in *Klebsiella* species isolated from the Euphrates River in Iraq. Although *Klebsiella* is not specifically an agricultural pathogen, this finding illustrates the relevance of aquatic environments as reservoirs for bacteria carrying clinically important antimicrobial-resistance determinants.

The agricultural environment should therefore be viewed as part of a wider One Health network involving humans, animals, plants, water, soil and microorganisms. This perspective is particularly important because agricultural systems can simultaneously receive resistant organisms from upstream sources and provide pathways for their movement into food production.

This review examines the environmental dimensions of antimicrobial resistance in agricultural water, focusing on soil-water interactions, crop exposure, microbial persistence, β -lactamase resistance, agricultural management, molecular surveillance and One Health strategies.

2. Agricultural Water as an Environmental Interface

Agricultural water is not simply a resource for crop irrigation. It is an ecological medium containing microorganism, dissolved nutrients organic compounds, suspended particles, minerals and potentially anthropogenic contaminants.

Surface waters receiving municipal wastewater, agricultural runoff, livestock effluents and industrial discharges may contain diverse bacterial communities. During irrigation, these microorganisms can be transferred to agricultural soils and crop surfaces.

These factors influence microbial survival and the potential persistence of resistance genes.

Soil is especially important because it contains one of the most diverse microbial communities on Earth. The introduction of resistant bacteria into soil does not necessarily mean that resistance will persist indefinitely. Some introduced organisms may decline rapidly because of competition or unfavorable environmental conditions. Others may become temporarily established or exchange genetic material with indigenous microorganisms.

The interaction between agricultural water and soil therefore represents a dynamic environmental process rather than a simple contamination event.

3. Environmental Sources of Antimicrobial Resistance

AMR can enter agricultural environments through several pathways.

3.1. Wastewater

Municipal and hospital wastewater can contain antimicrobial-resistant bacteria and resistance genes. If wastewater receives inadequate treatment before environmental discharge or agricultural reuse, resistant microorganisms may enter surface waters and irrigation networks.

3.2. Livestock and poultry production

Veterinary antimicrobial use can select for resistant microorganisms in animal gastrointestinal systems. Manure application to agricultural land can subsequently introduce bacteria and resistance genes into soil.

3.3. Agricultural runoff

Rainfall and irrigation can transport bacteria and genetic material from animal facilities, manure-amended fields and contaminated soils into drainage channels and rivers.

3.4. Aquatic environments

Rivers and canals can integrate contamination from multiple upstream sources. The Euphrates River investigation reported by Guma et al. demonstrates how environmental water can be investigated for clinically important β -lactamase genes⁶.

3.5. Human activities

Population growth, inadequate sanitation, wastewater discharge, informal settlements and poor waste management can increase microbial loading in water resources.

These sources frequently overlap. A river receiving wastewater may subsequently be used for irrigation, creating a direct environmental connection between human activity, water quality, soil, crops and food systems.

4. β -Lactamase Genes and Environmental Resistance

β -lactam antibiotics are among the most widely used antimicrobial classes in human and veterinary medicine. Resistance can arise through several mechanisms, including enzymatic degradation of β -lactam compounds.

β -lactamases hydrolyze the β -lactam ring of susceptible antibiotics, reducing their antimicrobial activity. Genes encoding these enzymes may occur on chromosomes or mobile genetic elements such as plasmids, transposons and integrons.

Environmental bacteria can provide reservoirs in which resistance genes persist and potentially move between microbial populations. Horizontal gene transfer can occur through mechanisms including conjugation, transformation and transduction.

The environmental detection of resistance genes therefore has significance beyond the individual bacterial species in which they are identified.

Guma et al.⁶ investigated β -lactamase-associated genes in

Klebsiella species recovered from the Euphrates River in Iraq. Their study is particularly relevant to geoscience and agriculture because river systems can function as interfaces connecting environmental microbiology with agricultural water resources.

The presence of resistance genes in environmental water should not automatically be interpreted as evidence of human infection. Instead, it indicates that the environmental compartment may contribute to the maintenance or movement of resistance determinants (Table 1).

Table 1: Major environmental pathways contributing to antimicrobial resistance in agricultural systems.

Environmental Source	Main Pathway	Potential Agricultural Consequence	Monitoring Priority
Municipal wastewater	Discharge into rivers/canals	Resistant bacteria enter irrigation water	High
Hospital wastewater	Wastewater discharge	High antimicrobial-resistance burden	High
Livestock manure	Land application	Introduction of resistant bacteria and genes into soil	High
Poultry litter	Agricultural amendment	Soil and groundwater contamination	High
Agricultural runoff	Transport during rainfall/irrigation	Movement into surface waters	Moderate-high
Contaminated rivers	Irrigation	Direct crop and soil exposure	High
Biosolids	Soil amendment	Introduction of microbial contaminants	Moderate-high
Septic systems	Groundwater contamination	Potential irrigation-water contamination	Moderate
Industrial discharge	Surface-water contamination	Chemical and microbial stress	Site-dependent

5. Soil as a Reservoir and Filter

Soil occupies a central position in agricultural geoscience because it receives materials transported by water, air organisms and human activities. Its physical and chemical properties influence microbial survival and contaminant mobility.

Clay minerals and organic matter can adsorb microorganisms and extracellular DNA. Such interactions may influence the persistence and mobility of resistance determinants.

Soil moisture is another important factor. Microbial activity generally changes considerably with water availability. Wet conditions can facilitate microbial interactions, while drying may reduce the survival of some organisms.

Soil pH can influence bacterial growth and antibiotic persistence. Temperature, redox conditions, nutrient availability and salinity can similarly alter microbial community composition.

Consequently, the risk associated with agricultural AMR cannot be evaluated using water concentration alone. Soil characteristics must also be considered.

This is consistent with modern soil-science approaches emphasizing soil chemistry, physics, microbiology, fertility, environmental quality and land management as interconnected research areas.

6. Crop Exposure and Plant-Microbe Interactions

Crops can interact with microorganisms present in irrigation water and soil. Leaf surfaces, roots, rhizospheres and harvested plant tissues represent distinct microbial habitats.

Root-associated microbial communities are particularly important. The rhizosphere contains root exudates that provide nutrients and signaling compounds to microorganisms. These conditions can support microbial growth and alter microbial community structure.

Irrigation water contaminated with resistant bacteria may deposit microorganisms directly onto plant surfaces. However,

detection on a crop does not necessarily indicate internal colonization or successful transfer into edible tissues.

The probability of exposure depends on crop type, irrigation technique, water quality, environmental conditions and time between irrigation and harvest.

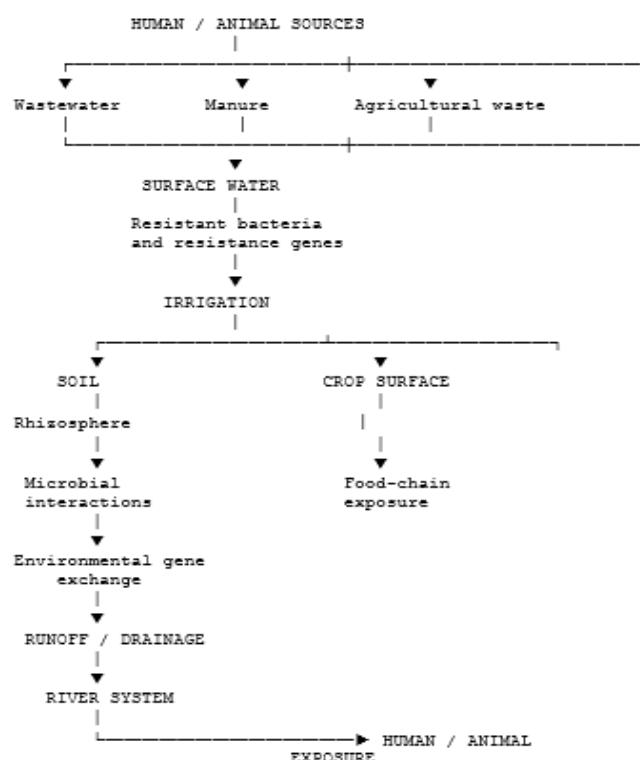


Figure 1: Conceptual pathway of antimicrobial-resistance dissemination through agricultural systems.

The diagram represents a conceptual One Health pathway rather than a quantitative estimate of transmission probability.

7. Agricultural Practices Influencing AMR

Agricultural management can influence environmental

resistance through water use, manure management, fertilizer selection, antibiotic application, crop rotation and soil conservation.

Excessive antimicrobial use in livestock production can increase selection pressure. Manure management is therefore important because untreated manure may contain resistant bacteria and resistance genes.

Composting can modify microbial communities and may reduce some microbial hazards, although treatment effectiveness depends on temperature, duration, moisture and management conditions⁷.

Irrigation method can also influence exposure. Drip irrigation can reduce direct contact between irrigation water and edible plant surfaces compared with overhead irrigation, although the overall environmental risk depends on crop type and production system.

Integrated agricultural management should therefore include both productivity and environmental quality.

8. Antimicrobial Resistance and Agricultural Geoscience

Geoscience contributes to AMR research by providing tools for understanding the movement of contaminants and microorganisms through soil, groundwater, surface water, sediments and agricultural landscapes^{8,9}.

Spatial variability is particularly important. A resistance determinant detected in one river location may not be uniformly distributed throughout the watershed. Concentrations can change with hydrology, wastewater inputs, rainfall, sediment movement and seasonal agricultural activity.

Geospatial mapping can identify potential contamination hotspots. Remote sensing cannot directly identify bacterial resistance genes under ordinary agricultural monitoring conditions, but satellite and geospatial information can characterize land use, irrigation networks, water bodies, crop distributions and environmental conditions that influence exposure¹⁰.

Agro-geoinformatics increasingly integrates spatial information with agricultural sustainability, environmental research, natural-resource conservation, land management, climate change and agricultural decision-making.

Combining geospatial data with microbiological sampling can therefore strengthen environmental AMR surveillance.

9. Molecular Surveillance

Culture-based microbiology remains important because it provides viable isolates for antimicrobial susceptibility testing. However, molecular methods can detect resistance determinants that may be difficult to identify through conventional culture.

Polymerase Chain Reaction (PCR) can target specific resistance genes. Quantitative PCR can estimate relative or absolute abundance under appropriate experimental conditions. Metagenomic sequencing can provide broader information concerning microbial communities and resistance genes.

Whole-genome sequencing can additionally characterize bacterial lineages, plasmids, virulence determinants and resistance-associated mutations.

The molecular study of β -lactamase genes in *Klebsiella* from the Euphrates River⁶ provides an example of how targeted molecular surveillance can identify environmental resistance determinants.

10. Agricultural Water Quality and Food Safety

Water quality is a major determinant of agricultural sustainability and food safety. Water containing fecal indicators, pathogenic bacteria, resistant organisms or chemical contaminants can introduce multiple risks.

Water-quality assessment should therefore include conventional physicochemical parameters alongside microbiological indicators where risk warrants¹¹.

Microbiological analysis may include fecal indicators, bacterial pathogens, antimicrobial susceptibility patterns and selected resistance genes.

This integrated approach is more informative than testing a single bacterial indicator because environmental AMR is influenced by multiple factors.

11. Nanotechnology and Agricultural Environmental Monitoring

Nanotechnology has potential applications in agricultural environmental monitoring, including nanosensors, biosensors, antimicrobial surfaces and analytical platforms.

Nanotechnology-based systems have also been investigated in drug-delivery and tissue-engineering applications. Shallal et al.¹² reviewed nanotechnology-based drug-delivery approaches for bone tissue engineering. Although that work is biomedical rather than agricultural, the underlying concept of controlled nanoscale interactions has relevance to environmental sensor development.

However, nanotechnology can also introduce environmental concerns. Shallal and Owaid discussed hazards and challenges associated with nanotechnology in agriculture¹³. Nanomaterials entering soil or water may interact with microorganisms, plants, minerals and organic matter.

Consequently, the application of nanotechnology to AMR surveillance should incorporate environmental fate, toxicity, persistence and ecotoxicological assessment.

12. Immunological and Environmental Biomarkers

Environmental contamination can affect organisms through complex pathways. Biomarkers may provide information about physiological responses to environmental stressors, although they require careful interpretation.

Shallal reported changes in inflammatory markers and biochemical parameters associated with smoking in males¹¹. Although smoking is unrelated to agricultural AMR, this work illustrates the broader importance of biomarker interpretation when evaluating environmental or lifestyle exposures.

Similarly, Shallal's work on immunomodulatory pathways in renal failure demonstrates the complexity of inflammatory signaling and biomarker relationships¹⁴. These concepts may inform environmental health studies where agricultural workers, livestock or wildlife are exposed to multiple environmental stressors.

Biomarker studies should therefore incorporate appropriate controls and avoid attributing nonspecific inflammatory changes to a single environmental exposure without supporting evidence.

13. One Health Framework

The One Health concept provides an appropriate framework for agricultural AMR because resistant microorganisms can circulate between humans, animals, plants, soil, water and food systems.

The major advantage of such integration is the ability to

identify relationships between environmental reservoirs and clinically important resistance¹⁵.

For example, if a resistance gene is detected in agricultural water, soil, animal samples and clinical isolates, genomic and epidemiological analysis may help determine whether these findings represent related transmission pathways or independent occurrences.

Such interpretation requires carefully designed sampling rather than assuming that detection in different compartments establishes direct transmission (Table 2).

14. Environmental Management Strategies

Table 2: Integrated strategies for controlling antimicrobial-resistance dissemination in agricultural landscapes.

Intervention	Environmental target	Expected benefit	Key implementation consideration
Irrigation-water monitoring	Rivers, canals, wells	Early identification of contamination	Seasonal sampling
Wastewater treatment	Municipal/hospital effluent	Reduce microbial and resistance burden	Treatment efficiency
Manure management	Agricultural soil	Reduce introduction of resistant organisms	Composting and controlled application
Antimicrobial stewardship	Livestock systems	Reduce selection pressure	Veterinary oversight
Drip irrigation	Crop exposure	Reduce direct contact with contaminated water	Appropriate crop and soil design
Soil monitoring	Agricultural fields	Identify persistent contamination	Spatially representative sampling
Molecular surveillance	Resistance genes	Detect emerging resistance	Validated assays
Whole-genome sequencing	Resistant isolates	Track lineages and transmission	Laboratory capacity
GIS mapping	Agricultural landscapes	Identify spatial hotspots	Accurate georeferenced data
Farmer education	Farm-level practices	Improve prevention	Local extension programs

15. Climate, Hydrology and Future Agricultural Risk

Climate variability can modify environmental AMR pathways. Rainfall events can mobilize contaminants from agricultural fields into rivers, while drought can increase reliance on lower-quality irrigation sources.

Flooding may redistribute contaminated sediments and microorganisms across agricultural landscapes. Conversely, prolonged dry periods can concentrate contaminants in limited water resources.

Hydrological modeling can therefore complement microbiological surveillance. Agricultural geoscience approaches that combine rainfall, drainage, groundwater, soil characteristics, land use and water-quality measurements may provide better estimates of environmental exposure.

Climate-smart agricultural planning should incorporate water-quality risks alongside conventional considerations such as yield, water availability, soil fertility and drought tolerance.

16. Research Gaps

Several research gaps remain.

First, standardized environmental AMR sampling protocols are required. Differences in sample collection, DNA extraction, culture methods and reporting can make studies difficult to compare.

Second, more research is needed to distinguish viable resistant bacteria from extracellular resistance DNA. Detection of a resistance gene does not necessarily demonstrate that a viable pathogen is present.

Third, quantitative risk assessment should evaluate the probability of human or animal exposure rather than relying solely on detection frequency.

Fourth, more longitudinal research is needed to determine whether resistant organisms persist in agricultural soils after contaminated irrigation ceases.

Fifth, genomic studies should investigate plasmid-mediated resistance and horizontal gene transfer in agricultural microbial communities.

Finally, research should integrate geoscience, agronomy, microbiology, environmental chemistry, molecular biology and public health.

17. Conclusion

Antimicrobial resistance in agricultural water represents an important intersection between geoscience, soil science, environmental microbiology and sustainable agriculture. Rivers, irrigation systems, wastewater, manure, soil and crops can form interconnected pathways through which resistant microorganisms and resistance genes move across environmental compartments. β -lactamase investigations in aquatic environments demonstrate the value of molecular surveillance for identifying resistance determinants beyond clinical settings. Sustainable management requires improved irrigation-water quality, responsible antimicrobial use, manure management, soil monitoring, molecular surveillance and geospatial assessment. A One Health approach can integrate environmental, agricultural, veterinary and human-health information to clarify resistance pathways and guide prevention. Future research should prioritize standardized sampling, quantitative risk assessment, genomic surveillance, hydrological modeling and environmentally responsible agricultural practices to reduce resistance dissemination while maintaining productive food systems.

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