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RESEARCH ARTICLE

Trends in Biotechnology and Plant Sciences

Antibiotic-Resistant Microbes in Aquatic Environments and Agricultural Systems: Implications for Public Health

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Abstract

Resistance development against antibiotics is a major health issue faced worldwide due to overuse or misuse of antibiotics. Antibiotic-resistant bacteria (ARB) and their genes can be a warning for the general health of people when found in reservoirs of antibiotic-resistant microbes (ARMs) including aquatic environments and contaminated drinking water sources, mainly due to the contamination from agricultural runoff, wastewater discharge, and human activities. Overuse of antibiotics in the healthcare and agriculture sectors is the chief reason for antibiotic resistance. The presence of ARMs including *Staphylococcus aureus* and *Escherichia coli* in aquatic environments poses serious health hazards possibly through increased rates of morbidity and mortality. The isolation and identification of environmental bacteria from water, the assessment of water samples for antibiotic resistance, and the biochemical and molecular characterization of bacterial pollutants are all part of the fight against antimicrobial resistance (AMR). Safe drinking water access is crucial for preventing the spread of AMR and ensuring public health in both developing and developed nations. Public awareness, improved wastewater treatment, and regulatory measures are required for the mitigation of antibiotic resistance. Hence, an interdisciplinary approach that combines environmental science, healthcare, and agricultural practices is crucial to combat this public health threat and will pave the way for defining our future prospects regarding the use of antibiotics.

KEYWORDS
Antibiotic resistance, Aquatic environments, Antibiotic-resistant microbes (ARMs), Public health, Water pollution, Wastewater treatment, Agricultural runoff, environmental factors, Mitigation strategies, Public awareness.

1 | INTRODUCTION

Background on Antibiotic Resistance

Antibiotics are common agents used in modern healthcare. Antibiotics act as magic bullets against bacteria. The greatest therapeutic innovation of the 20th century is Antibiotics. Antibiotics are a class of antimicrobial substances that are active against bacteria and are used in order to cure and prevent bacterial diseases. Since their introduction, antibiotics have saved countless lives and changed medicine (Salam et al. 2023). Salvarsan, the first antibiotic, was introduced in 1910 and has had a significant impact on modern medicine therefore, increasing the average human lifespan by 23 years. The drug penicillin began the golden age of natural product antibiotic discovery in 1928 (Fig. 1). Antibiotics which kill bacteria or prevent them from multiplying, are used to treat a wide variety of bacterial infections. However, antibiotic overuse and misuse have resulted in the rise of antibiotic-resistant bacteria posing a significant public health risk (Hutchings et al. 2019). This resistance is a result of the excessive use and misuse of antibiotics which are designed to kill bacteria, viruses, fungi and parasites. Antibiotics are ineffective as bacteria develop resistance against them to withstand environmental selection pressure. The disproportionate usage of antibiotics upsurges the risk of AMR leading to serious adverse effects including higher rates of morbidity and death particularly in developing nations. An emerging problem in the healthcare industry is antibiotic resistance (Shrestha et al. 2021). Antibiotic resistance mechanisms result from genetic alterations in bacteria that lead to biochemical changes. These modifications can include the production of drug inactivating enzymes, changes to target proteins, activation of drug efflux pumps and modification of cell wall proteins to inhibit drug uptake. Resistance may arise via mutation or by acquiring new genetic material; the latter is a frequent process made possible by plasmids, which are cells in bacteria that transfer genes across cells. In animals, plants, and humans, the resistance of the microbial antibiotics can be caused by the actions of humans likewise misuse and overuse of the antibiotics. This increases the risk of severe illness, disability and death by creating infections that are difficult or impossible to cure. The complex strategy required to address antibiotic resistance includes preventing infections, guaranteeing that everyone has access to high-quality diagnosis and treatment, strategic information sharing and innovation in the form of research and development for new drugs, diagnostics and vaccines (Kakoullis et al. 2021).The increased use of antibiotics in clinical settings and other sectors of the economy, such as cattle farming, has led to bacterial resistance to these medications. Bacteria have evolved defensive mechanisms to help them survive. Furthermore, bacteria can develop acquired resistance, which is defined as resistance that results from a mutation that lessens or eliminates the effectiveness of antibiotics, or from obtaining resistance genes from other bacteria. A bacterial organism could have multiple resistance types (Pines, 2023).

Earthly life depends on water for human survival. Water quality is impacted by various factors including sewage, pasture runoff and farm waste, along with a lack of public awareness and education (Nvene et al. 2024). Contaminated drinking water is the ideal medium for antibiotic resistant bacteria (ARB) and environmental bacterial interaction providing a selective medium for horizontal shift of antibiotic-resistant genes (ARGs). Evaluation of water quality is crucial to forecast and reduce waterborne illnesses, especially in emerging nations' rural areas. Commensal bacteria primarily from the Enterobacteriaceae family serve as a microbiological indicator (Singh et al. 2020). Researchers examined the effects of lifestyle choices on the general health of individuals who have waterborne bacterial illnesses. The World Health Organization (WHO) reports that 485,000 people die annually worldwide as a result of contaminated drinking water (Hamad et al. 2022). Drinking water that meets medical standards is crucial for personal and national health. Domestic drinkable water sources are essential for those living in communities, especially in rural areas of underdeveloped nations with limited medically clean water supplies (Umar et al. 2022). Antimicrobial resistance is conferred by proteins and enzymes encoded by ARGs. Repeated introduction can cause pseudo persistence in aquatic habitats despite abiotic or biotic degradation (Larsson & Flach, 2022).

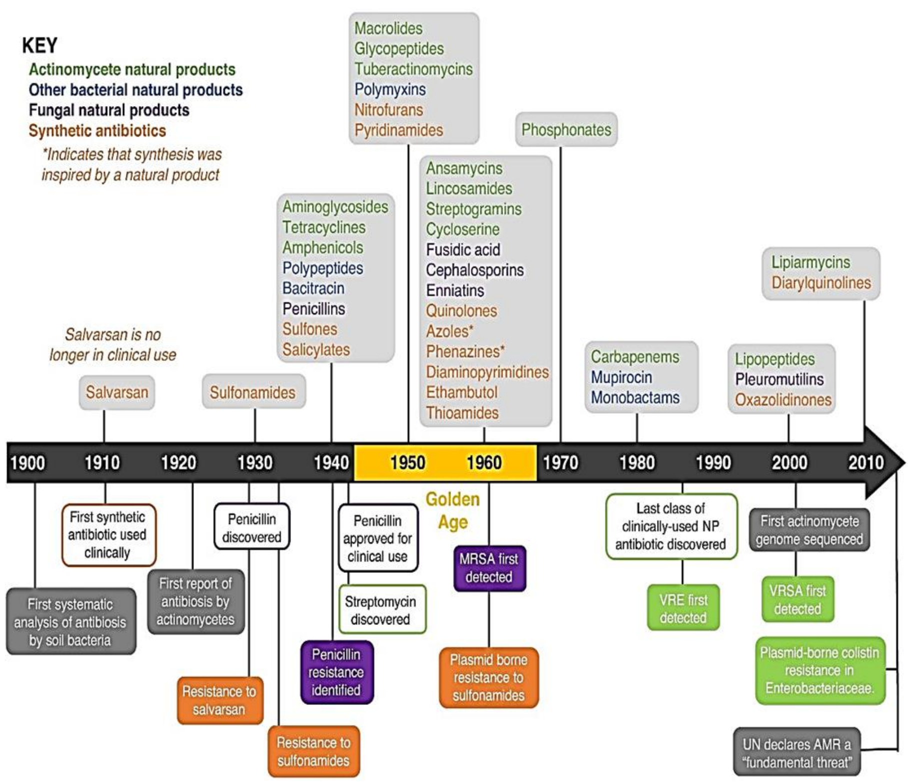

Fig. 1: Antibiotic development and the rise of resistance (Hutchings et al. 2019).

Antibiotic resistance (AR) ranks among the top ten major hazards to public health, thus strong antibiotic and disinfectant prescriptions are required to stop its quick emergence (Wang et al. 2024). In the healthcare systems of the twenty-first century, antibiotic-resistant bacteria (ARB) constitute a major factor in treatment failure. Inappropriate use of antibiotics in human and veterinary therapy may be the first step toward the spread of AR (Fig. 1). Antibiotics pose a serious hazard to treatment since they are largely non-biodegradable and can later be found in wastewater treatment facilities as active metabolites from numerous sources such as pharmaceutical goods, hospital sewage, livestock waste and human faces (Tabrizi et al. 2022). Humans, wildlife and the environment can all spread resistant bacteria making it difficult to prevent and treat infections. Surface water contaminated with antibiotics and antibiotic resistance genes (ARGs) may have an impact on human health. This is due to the fact that incorrect metabolism and prolonged antibiotic use cause 50% to 80% of antibiotics to end up in the environment through human metabolism, cattle excretion of waste disposal. The world now faces a dilemma with antibiotic contamination. The environment pollution of antibiotics make a big contribution in the progression and spreading antibiotics resistance which highlighting the need for monitoring as well as addressing this aspect to combat antibiotic resistance effectively (Liu et al. 2021) Antibiotic resistance genes (ARGs) are favored for their binding, transmission and gene transfer due to the long-term selective pressure from antibiotics, therefore, affecting water systems and soil and are prevalent worldwide. These ARG pollution is widespread posing a health risk to humans and animals due to the overuse of antibiotics (Larsson & Flach, 2022). Drinking water contamination caused by the proliferation of pathogenic microbes can pose significant health risks to consumers. It is crucial to prevent this contamination to certify the security and quality of the drinking water. The global population is facing challenges including energy resources, public health risks, environmental pollution and clean water scarcity. Industries release massive volumes of wastewater causing environmental and public health issues. Less than 1% of water is drinkable and 2% is trapped in glaciers. About 97% of water is unfit for human consumption. The decline in groundwater levels is primarily due to depletion of surface and groundwater supplies and industrial exploitation. Modern society is now suffering from polluted water in about 40% and over 20% are freshwater scarce (Kishor et al. 2023).

Importance of Aquatic Environments

The water-based environment in which abiotic components interact with biotic components is known as an aquatic ecosystem. The environment of aquaculture is of two types: marine and freshwater. Fresh water is 3% of the present in the form of lakes and rivers on earth that are used for growing crops and drinking. The marine water is the water of the ocean which is 97%. There is one more type of water that is affected by human and industrial activities known as wastewater. To remove the contamination from wastewater, it is treated in wastewater plants (WWPs) by different treatment processes like physical, biological and chemical (Sambaza & Naicker, 2023). Untreated waste discharge and poor sanitation can contaminate water supplies with antimicrobials and can have the most effects on the environment. Antibiotics pose a serious hazard to treatment since they are largely non-biodegradable and can end up in wastewater treatment facilities (WWTPs) due to the inefficiencies of WWPs processes in their original form or as active metabolites from sources including pharmaceutical goods, hospital sewage, livestock waste and human faeces (Tabrizi et al. 2022) and may be disseminated into the environment. As such, there is a concern that these ARB and their resistance genes may cause untreatable or difficult-to-treat infections in humans and animals.

Objectives of the Review

- Estimating prevalent sources of antibiotic-resistant microbes in aquatic environments.
- Evaluating ARMS potential public threats and transmission pathways to human beings.

Sources and Types of Antibiotic-Resistant Microbes in Aquatic Environments

Sources of Contamination

Water is an essential habitat for bacteria, which helps them spread throughout many environmental niches. Human exposure to antibiotic-resistant bacteria (ARB) and antibiotic-resistant genes (ARGs) poses extra health hazards. The acquisition and spread of antibiotic resistance can occur in aquatic environments. Antibiotic-resistant and multidrug-resistant microorganisms arise from the usage of these antibiotics in agriculture, livestock, and human medicine (Vaz-Moreira et al. 2014). The intensively farmed soils and their constituent microbial communities are frequently exposed to anthropogenically induced stressors, such as agricultural chemicals and pollutants (Kelbrick et al. 2023). Livestock manure typically contains antibiotic resistance genes (ARGs), which are difficult to eradicate using standard treatment techniques. The escalation of resistant clinical infections may be attributed to exposure to these ARGs, which includes bacterial ingestion and inhalation. Water samples from urban river flows in Curitiba, Brazil, were tested for the presence of associated resistant bacteria and antibiotics. A technique for measuring antibiotics was created by combining mass spectrometry and liquid chromatography to identify antibiotic-resistant coliforms. All of the water samples contained antibiotics, ranging in concentration from 0.13 to 4.63μgL−1. It was discovered that Enterococcus spp. showed resistance to ciprofloxacin and norfloxacin, whereas *Escherichia coli* was resistant to ciprofloxacin, doxycycline, sulfamethoxazole and amoxicillin. There is a growing chance that ARB will infiltrate the environment through wastewater discharge and residue recycling (He et al. 2020). In China, by conducting an experimental study on different water bodies, it was witnessed that the type of antibiotics found in a particular water body was related to the nearby available industries, the pharmaceutical company's antibiotic disposal mode, and the listed area's antibiotic type which is used in the livestock industry (Okeke et al. 2022) (Fig. 2).

Types of Antibiotic-Resistant Microbes

The pre-existing genome of the bacterium and the uptaking of foreign DNA can cause mutation which can be a main reason for rising antibiotics resistance. In the Aqua environment, the continual accumulation of antibiotics has led to the rise of antimicrobial-resistant genes in the atmosphere (Sánchez-Baena et al. 2021). Human exposure to antibiotic-resistant bacteria (ARB) and antibiotic-resistant genes (ARGs) poses extra health hazards. Gram-negative bacteria of the family Enterobacteriaceae with resistance to antibiotics are commonly reported in drinking water and in natural water systems. Azithromycin, found in fresh water and wastewater, is a promising alternative medication against antibiotic-resistant *Escherichia coli* that is a common reason of gastrointestinal tract and urinary infectious disorders. It effectively treats common diarrheagenic bacteria like *E. coli*, *Shigella* spp., *Salmonella* spp., *Campylobacter* spp. and unlike other macrolides.A sufficient supply of safe drinking water is crucial for health protection (Tabrizi et al. 2022). High levels of antibiotic resistance were found in Pakistan throughout the past ten years, especially in pathogens like *Salmonella* spp. and *E. coli* (Bilal et al. 2021).

Mechanisms of Resistance and Dissemination

Mechanisms of Antibiotic Resistance

Complex microbial communities such as biofilm are formed when the aquatic microorganisms accumulate and exchange their genetic material. In such situations, the genetic material is transferred to another microbe in two ways: (1) horizontal transmission through channels (like transduction, and transformation) and (2) vertical transmission to the next generation (Okeke et al. 2022) (Fig. 3).

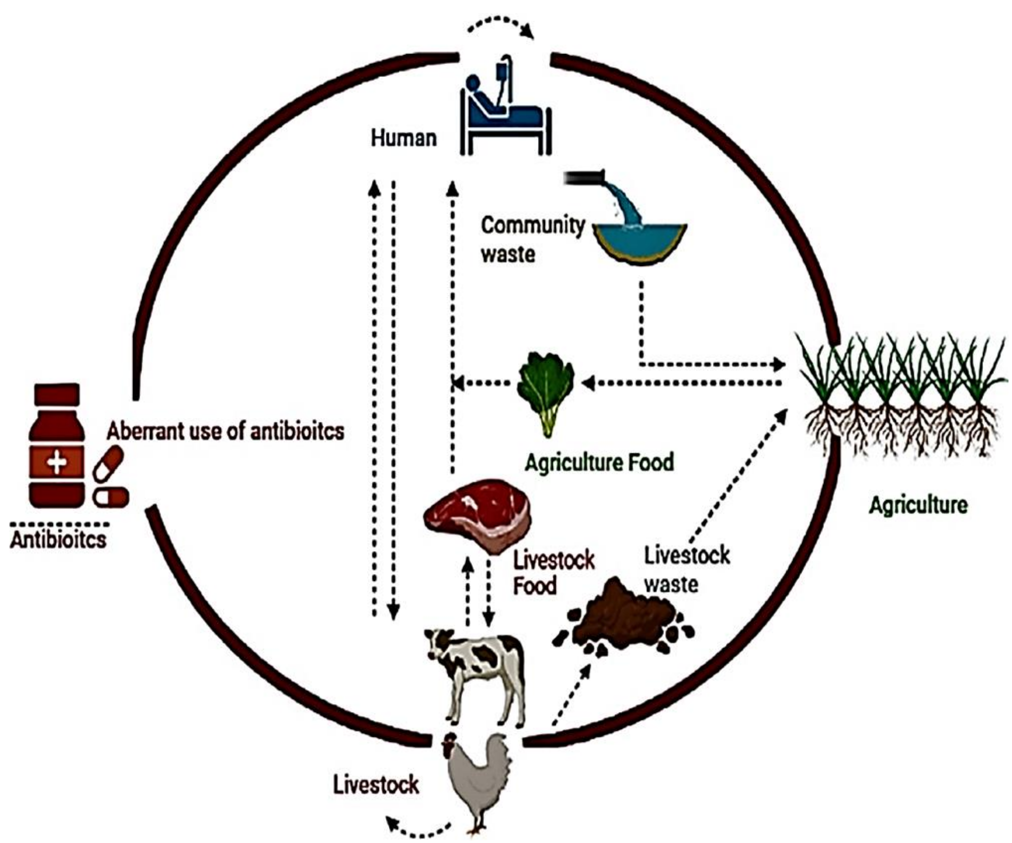

Fig. 2: One Health drivers associated with antibiotic resistance (Lajqi Berisha et al. 2024).

The three main causes of resistance are genetic mutations in microbes which occur when one species picks up resistance from another, natural resistance in some types of bacteria which existed even before antibiotics were discovered and selection pressure from antibiotic use which gives mutated strains a competitive advantage. The capability of bacteria, to survive the effects of antibiotics that it was once sensitive to (Adedeji, 2016). During the transfer of genetic materials, there is a possible risk of mutations leading to the development of novel ARGs that can induce ARBs and cause widespread bacterial resistance. Due to the complex nature of the microbes, it is very difficult to eliminate their complex communities (Endale et al. 2023), (Larsson & Flach, 2022).

Environmental Factors Influencing Resistance

Wastewater is rich with potential electron acceptors, sources of Carbon and many nutrients which make it a favorable habitat for bacteria and their growth. The recorded data indicates that the irrigation water imports less ARG as compared to the fertilizers that bring more ARG in the crops. The organic and chemical fertilizers, including chicken manure, urea, $(NH_4)_2HPO_4$, and $K_2(SO_4)$, enhance ARGs' frequency and diversity. In saline soils, the reduction of ARGs can indicate the increase in the depth of soil, growth in MGEs and ARGs quality and low electric conductivity (Kaviani Rad et al. 2022). Water is one of the many habitats where metal- and antibiotic-resistant bacteria are common, and their genetic diversity and resistance to antibiotics are growing. Bacteria have evolved to be resistant to metals even in pure water environments. This has resulted in the selection of antibiotic-resistant strains of bacteria that have the potential to spread resistance to human illnesses. Multiple drug resistance and heavy metal toxicity in drinking water are serious health risks.

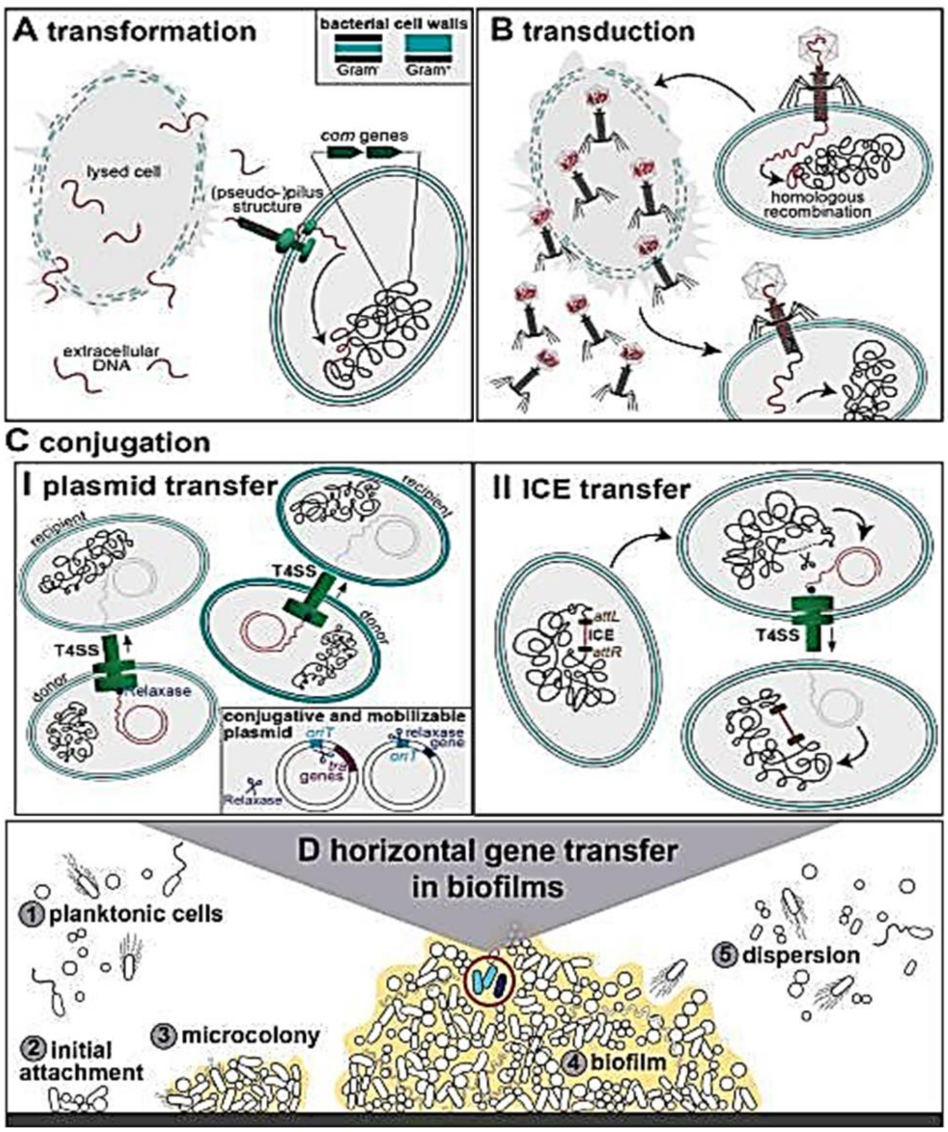

Fig. 3: Horizontal gene transfer in polymicrobial biofilms. (A) Transformation, (B) Transduction and (C) Conjugation. Transferred, transduced or conjugative DNA is shown in red, host DNA in black. (D) Stages of polymicrobial biofilm formation from (1,2) initial attachment of planktonic cells, (3) microcolony formation to (5) dispersion of cells from a (4) mature biofilm. The light blue cells (4) show a conjugation event, the dark blue cell transformation or transduction. (Michaelis & Grohmann, 2023).

Methods for Identifying Resistant Microbes

Antibiotic usage is a hand-out factor which leads to the growing threat of antimicrobial resistance (AMR) in public health worldwide. Next-generation sequencing (NGS), microbiological culturing, and quantitative PCR (qPCR) are techniques that offer information about water quality and many other aquatic environments. Using qPCR in combination with an integron detection primer (intl1), the antibiotic resistance genes (ARGs): blaCTX-M-15, blaCTX-M-32, ampC, blaTEM, sul1, tetM, mcr-1 and many more, ARMs and ARGs could be detected in aquatic settings including the detection of antibiotic-resistant Escherichia coli. The wastewater treatment method could dramatically lower the abundance of ARGs and ARBs (Buriánková et al. 2021).

Public Health Implications

Human Exposure Routes

Untreated waste discharge and poor sanitation can contaminate water supplies with antimicrobials and can have the most effects on the environment. The ARM can be exposed to humans by direct contact (like swimming, and drinking) and indirect contact (like Livestock and Crops consumption). The drugs including ARPs and ARGs can end up in untreated drinking water sources due to human and livestock waste, wastewater treatment plants, hospital sewage, and agricultural operations (Larsson & Flach, 2022), (Niang et al. 2023).

Health Risks Associated with Resistant Microbes

ARBs are quite common in river systems, lakes, and dams, where they might cause epidemic illnesses due to Enterobacteriaceae, MRSA, and VRE, which produce extended-spectrum β-lactamases. Antibiotic resistance endures in freshwater bodies contaminated with high antibiotic concentrations, despite dilution and natural degradation. For those who depend on freshwater resources for drinking, agriculture irrigation, and fish-eating, the findings are alarming (Nnadozie & Odume, 2019). Human health is also in danger when the residues of antibiotics affect human health by entering into their bodies through contaminated agricultural products and unclean water. This can result in developing diseases like disorder of microflora in the natural intestinal, cancer and many allergic reactions (Ahmad et al.2024), (Serwecińska, 2020) (Fig. 4).

Vulnerable Populations

ARMs have a higher impact on population groups like infants, children, elders, patients, immunocompromised individuals, and chronic disease patients due to their low immunity. The people related to agriculture and living in industrial areas are also at risk due the exposure to antibiotics or the untreated wastewater of the industries.

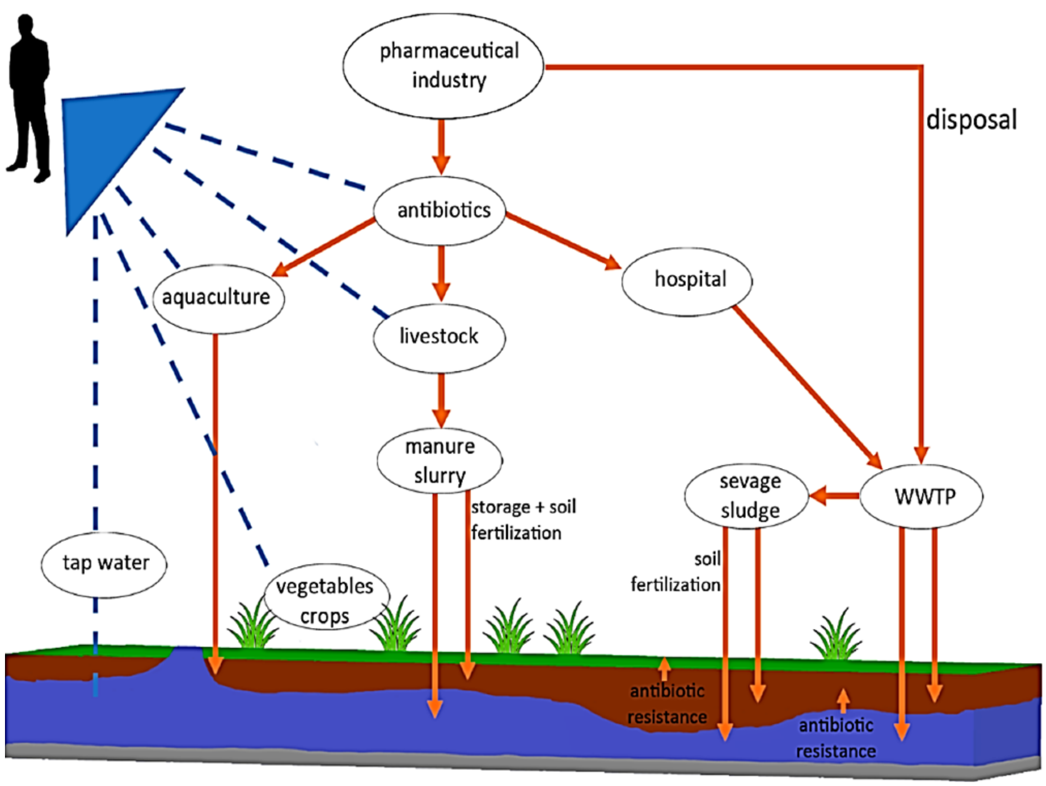

Fig. 4: Antibiotic residues released in the surroundings while antimicrobials and antibiotic-resistant bacteria are exposed to humans (Serwecińska, 2020).

Case Studies: Notable Outbreaks

Over a five-year (2017–2022) study in multi hospitals, a study conducted to investigate the resistance of Gram-negative *Pseudomonas aeruginosa* and *Acinetobacter baumannii* antibiotics.The information proved useful in identifying variations in the hospital-acquired antibiotics' susceptibility and in suggesting novel treatment approaches, especially for empirical treatment of serious illnesses.Antibiotic use peaked between 2020 and 2022, most likely as a result of the COVID-19 pandemic and an increase in the number of hospitalized patients who needed severe care. On the other hand, the number of multi-resistant *A. baumannii* strains has been rising over time, probably due to the growing use of broad-spectrum antibiotics, specifically carbapenems, third-generation cephalosporins, and inhibitory penicillins. This highlights the need to combat bacterial drug resistance by employing stronger and more irrational drugs (Mączyńska et al. 2023).

Future Directions

There is a big need to make further investigations into the ARM impact on the ecology of the microbes and their genetic adaptations. Investigating the new treatment strategies, surveillance and long-term monitoring.To manage and detect the ARM technologies including AI, IoT, CRISPR, nanotechnology and biosensors are used for collecting and monitoring the data. Reduce the misuse of antibiotics in clinical and industrial sectors by making some policies for social welfare and public awareness. To track the use of antibiotics and play a significant role to elongate the life span of antibiotics by doing public campaigns so the public can make use of antibiotics wisely.

Conclusion

The rise of antibiotic-resistant microbes (ARMs) in aquatic environments is alarming global health issues in many developing and un-developing countries. Water is the main component of human health so the aquatic environment has a great importance on the life present on Earth. Human life is disturbed due to the ARMs in environments by both direct and indirect exposure which puts different groups of people like children, infants and elderly at higher risk of various health threats. ARMs and their genes come from many sources including agricultural settings, antibiotics, pollutants, and public wastage. Many techniques are used to overcome this scenario but more efforts are required to tackle root causes of this issue. The contamination of resistant microbes can damage human health and can cause chronic diseases. It is vital to encourage interdisciplinary collaboration among researchers, public health officials and policymakers to combat antibiotic resistance. Doing campaigns and conducting public seminars for awareness in common people for their welfare can lead to overcoming this global health hazard.

Conflict of Interest

All authors have declared that there is no conflict of interest regarding the publication of this article.

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