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# ANTIBIOTIC RESISTANCE IN AQUATIC BACTERIA: IMPLICATIONS FOR PUBLIC HEALTH AND ECOLOGICAL SYSTEMS

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**Abstract**

Antibiotic resistance in aquatic bacteria is a growing concern with significant implications for public health and ecological systems. This review article aims to provide a comprehensive overview of the current understanding of antibiotic resistance in aquatic bacteria, focusing on the sources, pathways, and consequences of resistance development and dissemination. We explore the various sources contributing to the presence of antibiotics in aquatic environments, including wastewater discharge from human and animal sources, agricultural practices, and pharmaceutical manufacturing effluents. Additionally, we discuss the pathways through which antibiotic resistance spreads in aquatic ecosystems, including horizontal gene transfer and the persistence of antibiotics in sediments and biofilms. We highlight the role of aquatic organisms as reservoirs and vectors of resistance dissemination. Furthermore, the implications of antibiotic resistance in aquatic bacteria for public health and ecological systems are examined, emphasizing the need for effective management and prevention strategies. Finally, we discuss future perspectives and research directions, including the development of alternative treatment options, rapid diagnostic tools, advanced technologies, interdisciplinary collaboration, and global cooperation. This review underscores the urgency of addressing antibiotic resistance in aquatic bacteria and provides insights to guide future research and interventions aimed at mitigating the risks associated with this global challenge.

**Keywords:** Antibiotic stewardship, Antibiotic resistance, Aquatic bacteria, Aquatic environments, Water pollution, Antibiotic usage, Resistance mechanisms

## Introduction:

Antibiotic resistance refers to the ability of bacteria or other microorganisms to resist the effects of antibiotics, rendering them ineffective in treating bacterial infections. It is a natural biological phenomenon that occurs when bacteria adapt and evolve in response to the selective pressure of antibiotics. The misuse and overuse of antibiotics have accelerated the development and spread of antibiotic resistance, posing a significant threat to public health worldwide. [1]

Statistical data on cases observed due to antibiotic resistance paints a concerning picture of its impact on public health. According to a global report, it is estimated that at least 700,000 deaths occur annually worldwide due to infections caused by antibiotic-resistant bacteria. This figure is expected to rise to millions if effective measures are not taken. In the United States alone, it is estimated that over 2.8 million antibiotic-resistant infections occur each year, resulting in more than 35,000 deaths. These infections include methicillin-resistant Staphylococcus aureus (MRSA), Clostridioides difficile (C. difficile), and multi-drug resistant strains of Escherichia coli (E. coli) and Klebsiella pneumoniae. [2]

Healthcare-associated infections (HAIs) caused by antibiotic-resistant bacteria contribute significantly to the burden of antibiotic resistance. In the European Union, it is estimated that there are approximately 3.6 million cases of HAIs each year, with a considerable proportion being caused by antibiotic-resistant bacteria.

Moreover, community-acquired infections caused by antibiotic-resistant bacteria are also on the rise. For example, urinary tract infections caused by antibiotic-resistant strains of E. coli are becoming increasingly prevalent. The burden of antibiotic-resistant infections is particularly high in vulnerable populations such as the elderly, where the mortality rates due to these infections are alarmingly high. [3]

The economic impact of antibiotic resistance is substantial as well. It is estimated that antibiotic-resistant infections cost the US healthcare system billions of dollars annually. This includes direct healthcare costs, such as hospital stays, diagnostic tests, and expensive antibiotics, as well as indirect costs associated with lost productivity and increased disability. These statistics underscore the urgent need for concerted efforts to address antibiotic resistance globally. Strengthening surveillance systems, promoting responsible antibiotic use, implementing infection prevention and control measures, and investing in research and development of new antibiotics and alternative therapies are crucial steps to combat this growing public health threat. [4] This review complies the effect of antibiotic use on environment and effect of antibiotic resistance on aquatic life. The data compiled gives an overview about the increase use of antibiotics and problems arising due increase in resistance and accumulations of these antibiotics in aquatic bacteria.

## Sources and pathways of antibiotic resistance in aquatic environment

One significant source is the discharge of untreated or inadequately treated wastewater from various human and animal sources. Hospitals, households, agricultural operations, and aquaculture facilities release wastewater containing antibiotics, metabolites, and resistant bacteria, which enter water bodies through sewage outfalls or runoff. The use of antibiotics in livestock and aquaculture practices, such as growth promotion or disease prevention, also introduces antibiotics into aquatic environments. Additionally, pharmaceutical manufacturing effluents can be a notable source, as they often contain high concentrations of antibiotics. These sources collectively introduce a diverse array of antibiotics and resistance genes into aquatic environments. [5]

Once antibiotics are released into water bodies, they can follow various pathways that promote the spread of antibiotic resistance. Horizontal gene transfer plays a significant role in facilitating the transfer of resistance genes between bacteria. Mobile genetic elements, such as plasmids and integrons, allow for the rapid dissemination of resistance traits, enabling susceptible bacteria to acquire resistance and exacerbating the prevalence of antibiotic resistance in aquatic environments. Moreover, antibiotics can persist in sediments and biofilms, providing suitable niches for the survival and proliferation of antibiotic-resistant bacteria. [6] These bacteria can later be released back into the water column, further contributing to the overall pool of resistant strains. Aquatic organisms, including fish and other aquatic animals, can act as reservoirs of antibiotic-resistant bacteria and serve as potential vectors for the spread of resistance within the aquatic ecosystem.

Understanding the sources and pathways of antibiotic resistance in aquatic environments is crucial for developing effective strategies to mitigate its impact. Monitoring and managing wastewater discharges, implementing proper treatment technologies, and promoting responsible antibiotic use in agriculture and aquaculture are essential steps towards reducing antibiotic pollution in water bodies. [7] Additionally, promoting awareness among healthcare providers, researchers, policymakers, and the general public about the ecological consequences and public health implications of antibiotic resistance in aquatic bacteria is vital for fostering a multidisciplinary approach to address this growing concern. [8]

**Factors contributing to the selection and dissemination of antibiotic resistance**

Several factors contribute to the selection and dissemination of antibiotic resistance in aquatic ecosystems, leading to the proliferation and spread of resistant bacteria and resistance genes. One key factor is the continuous and widespread use of antibiotics in human and veterinary medicine. The release of antibiotics into aquatic environments through wastewater discharge and agricultural runoff creates selective pressure, favoring the survival and proliferation of resistant bacteria. [9] Antibiotics exert a strong selective force by inhibiting susceptible bacteria while allowing resistant strains to thrive and multiply. Additionally, the improper disposal of expired or unused antibiotics can directly introduce high concentrations of these drugs into water bodies, further promoting the development and dissemination of resistance.

The horizontal transfer of resistance genes among bacteria also plays a crucial role in the spread of antibiotic resistance in aquatic ecosystems. Mobile genetic elements, such as plasmids and integrons, facilitate the transfer of resistance genes between different bacterial species. This genetic exchange occurs through mechanisms like conjugation, transformation, and transduction. [10] Consequently, even non-resistant bacteria can acquire resistance genes from their surroundings, contributing to the overall pool of resistant strains. The presence of diverse bacterial populations in aquatic environments provides ample opportunities for genetic exchange and the dissemination of resistance traits. [11]

Environmental factors can also impact the selection and dissemination of antibiotic resistance in aquatic ecosystems. Factors such as temperature, pH, nutrient availability, and oxygen levels can influence bacterial growth rates and the dynamics of resistance gene transfer. Moreover, the persistence of antibiotics in water bodies, sediments, and biofilms creates reservoirs for resistant bacteria. These bacterial reservoirs can serve as a constant source of resistance genes and contribute to the spread of antibiotic resistance over time. [12]

The interconnectedness of aquatic ecosystems, including rivers, lakes, and oceans, further facilitates the dissemination of antibiotic resistance. Resistant bacteria and resistance genes can be transported through water currents, migratory organisms, or human activities, extending the reach of antibiotic resistance beyond local environments. This highlights the need for a holistic and global approach to address the challenge of antibiotic resistance in aquatic ecosystems. To effectively combat antibiotic resistance in aquatic environments, it is crucial to implement strategies such as proper wastewater treatment, responsible antibiotic use in human and veterinary medicine, and the promotion of eco-friendly agricultural practices. Additionally, monitoring and surveillance programs can help assess the prevalence and distribution of antibiotic resistance in aquatic ecosystems, informing targeted interventions and mitigation strategies. [13]

## Effect of Antibiotics on aquatic environment

The increasing use of antibiotics has profound effects on the environment, leading to various environmental challenges. One major consequence is the contamination of water bodies. Antibiotics, their metabolites, and antibiotic-resistant bacteria can enter water sources through different routes. Improper disposal of unused antibiotics, inadequate wastewater treatment, and runoff from agricultural fields where antibiotics are used in animal farming contribute to this contamination. Antibiotic-contaminated water bodies can disrupt ecosystems, harm aquatic organisms, and promote the development and spread of antibiotic resistance in the environment. [14]

The use of antibiotics also disrupts microbial communities in the environment. Even at low concentrations, antibiotics can selectively kill susceptible bacteria, including beneficial ones that play crucial roles in nutrient cycling, soil fertility, and overall ecosystem functioning. This disruption can have cascading effects on the health and stability of ecosystems, affecting plant growth, decomposition processes, and the interactions between organisms. [15] Furthermore, the release of antibiotics into the environment creates selective pressure for the development and dissemination of antibiotic-resistant bacteria. In aquatic environments, soil, and agricultural settings, the presence of antibiotics provides favorable conditions for the survival and proliferation of antibiotic-resistant bacteria. These resistant bacteria can enter human and animal populations through direct contact or consumption of contaminated water or food, contributing to the overall burden of antibiotic resistance. [16]

Antibiotics also pose ecotoxicity risks and can have direct toxic effects on non-target organisms. Certain antibiotics have been found to disrupt the growth and development of aquatic organisms, such as fish and amphibians, leading to population declines and ecological imbalances. The widespread use of antibiotics in agricultural practices can also affect beneficial soil microorganisms and beneficial insects, impacting overall biodiversity and ecosystem functioning. Moreover, the release of antibiotics into the environment contributes to the presence of antibiotic resistance genes. [17] These genes can persist in environmental reservoirs, such as soil and water, and can be transferred between different bacteria, including harmless or naturally occurring species. This genetic transfer fuels the spread of antibiotic resistance, potentially impacting the effectiveness of antibiotics in medical and veterinary settings. [18]

To mitigate the environmental impact of increased antibiotic use, it is crucial to promote responsible antibiotic use practices. This includes proper disposal of unused medications, adherence to appropriate dosing and treatment guidelines, and a shift towards sustainable agricultural practices that minimize the use of antibiotics. Improving wastewater treatment processes to effectively remove antibiotics from wastewater is also essential. Additionally, supporting research and development of eco-friendly alternatives to antibiotics, such as phage therapy and probiotics, can help reduce the environmental footprint of antibiotic use while ensuring effective disease management. [19]

## Problems due to antibiotic resistance in aquatic bacteria

Antibiotic resistance in aquatic bacteria has been a major problem arising with due increase in use of antibiotics. Addressing antibiotic resistance in aquatic bacteria requires a holistic approach that includes responsible antibiotic use in healthcare and agriculture, improved wastewater treatment to minimize antibiotic release, surveillance of resistance in aquatic environments, and public education on the importance of prudent antibiotic use. [20] Some of the problem that arises due to antibiotic resistance as shown in **figure 1** been explained below.

Reduced Treatment Efficacy: Antibiotic resistance in aquatic bacteria can diminish the effectiveness of antibiotics used to treat infections in both humans and animals. This can lead to increased treatment failure rates and difficulties in managing bacterial diseases.

Spread of Resistance Genes: Aquatic bacteria with antibiotic resistance genes can transfer these genes to other bacteria through horizontal gene transfer. This can contribute to the spread of resistance within the aquatic environment and potentially to other settings, such as clinical settings, exacerbating the global issue of antibiotic resistance.

Persistence of Resistant Strains: Antibiotic-resistant bacteria in aquatic environments can persist over time due to the continuous exposure to antibiotics present in the water. These resistant strains can dominate the microbial community, making it challenging to control and eliminate them from the ecosystem.

Environmental Dissemination: Antibiotic-resistant bacteria released into aquatic environments can spread beyond the water body. This dissemination can occur through wastewater discharges, agricultural runoff, or contaminated aquatic organisms, leading to the contamination of other water sources and potential exposure to humans and animals.

Impact on Aquatic Ecosystems: Antibiotic resistance in aquatic bacteria can disrupt the balance of microbial communities in aquatic ecosystems. This disruption can affect nutrient cycling, ecological processes, and the overall biodiversity and functioning of the ecosystem.

Potential Zoonotic Infections: Antibiotic-resistant bacteria in aquatic environments can pose a risk to human health through zoonotic infections. Humans can be exposed to resistant bacteria through recreational activities in contaminated water or consumption of contaminated seafood, leading to difficult-to-treat infections.

Transfer to Land-based Systems: Antibiotic-resistant bacteria in aquatic environments can spread to terrestrial ecosystems through the water cycle or via contaminated water sources used for irrigation or drinking water. This can further contribute to the dissemination of resistance genes and the potential for human exposure.

Increased Healthcare Burden: The emergence and spread of antibiotic resistance in aquatic bacteria can place a significant burden on healthcare systems. Treating infections caused by antibiotic-resistant bacteria requires more extensive and costly interventions, including the use of alternative, often more expensive, antibiotics or combination therapies.

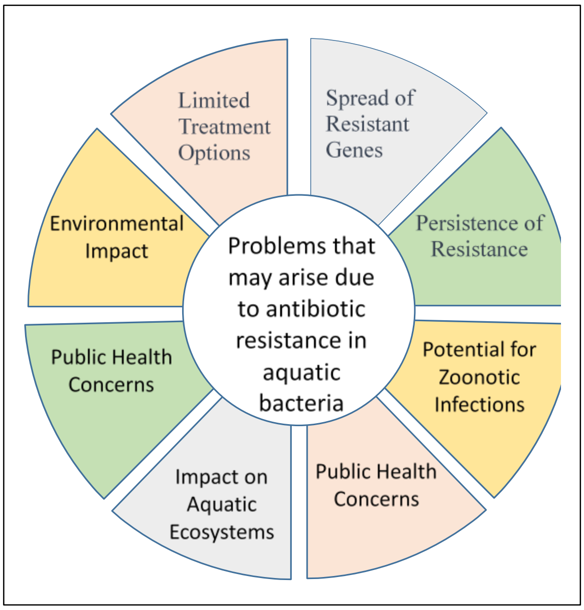


**Fig 1:** Problems arising due to antibiotic resistance in aquatic bacteria

### Impact of antibiotic resistance in aquatic bacteria on public health

Antibiotic resistance in aquatic bacteria has emerged as a significant concern with farreaching implications for public health, as supported by various research and review studies. These studies have shed light on the profound impact of antibiotic resistance in aquatic environments, such as lakes, rivers, and oceans, on the transmission of resistant bacteria to humans. [2]

Research has highlighted that the widespread use of antibiotics in agriculture, human medicine, and veterinary practices has led to the release of significant amounts of antibiotics and resistant bacteria into aquatic ecosystems. These resistant bacteria can originate from sewage discharges, agricultural runoff, or the disposal of unused medications. Once in the water, these bacteria can multiply and exchange genetic material, thereby increasing the pool of antibiotic resistance genes. [21]

Studies have further demonstrated that antibiotic-resistant bacteria in aquatic environments can directly pose a threat to public health through recreational activities, such as swimming and water sports. Individuals coming into contact with contaminated water can acquire these resistant bacteria, leading to infections that are difficult to treat with conventional antibiotics. This can result in prolonged illness, increased healthcare costs, and higher mortality rates. [4]

Additionally, research has shown that aquatic environments can serve as reservoirs of antibiotic resistance genes, which can be transferred to pathogenic bacteria that infect humans. This horizontal gene transfer can occur through various mechanisms, including direct contact between bacteria, uptake of genetic material by bacteria, or the exchange of plasmids. As a result, antibiotic resistance can spread rapidly, undermining the effectiveness of antibiotics in treating common infections. [22]

Furthermore, there is a potential for antibiotic-resistant bacteria in aquatic environments to enter the food chain, leading to the consumption of contaminated seafood and other aquatic products. This can introduce resistant bacteria into the human gut, increasing the risk of colonization and subsequent transmission to other individuals. This interplay between aquatic bacteria and public health poses a significant challenge in the fight against infectious diseases. [23]

The transmission of resistant bacteria through water, direct contact, and the food chain has the potential to cause treatment failures, increased morbidity and mortality, and a rise in healthcare costs. Urgent action is needed to address this issue by implementing comprehensive strategies, including improved surveillance, responsible antibiotic use, and advanced wastewater treatment methods to minimize the release of antibiotics and resistant bacteria into aquatic environments. [8]

**Monitoring and surveillance of antibiotic resistance in aquatic environments**

Monitoring and surveillance of antibiotic resistance in aquatic environments are critical components in addressing the growing concern of antibiotic resistance. Several approaches have been employed to track and understand the prevalence and dynamics of antibiotic resistance in these ecosystems.

One approach involves the collection and analysis of water and sediment samples from various aquatic sites. These samples are tested for the presence of antibiotic-resistant bacteria and the abundance of antibiotic resistance genes. Culturing techniques, such as selective media, are used to isolate and identify resistant strains, while molecular methods, such as polymerase chain reaction (PCR), are employed to detect and quantify resistance genes. This allows researchers to assess the diversity and levels of antibiotic resistance in aquatic environments over time. [24]

Additionally, surveillance efforts often involve the monitoring of specific resistance mechanisms, such as extendedspectrum beta-lactamases (ESBLs) or carbapenemases, which confer resistance to crucial antibiotics. By targeting these specific markers, researchers can track the emergence and spread of resistant bacteria with high clinical relevance. This information can guide the development of effective treatment strategies and inform public health interventions. [25]

Another important approach is the surveillance of antibiotic use in agriculture, aquaculture, and human medicine. By monitoring the quantities and types of antibiotics used in these sectors, researchers can better understand the potential sources and drivers of antibiotic resistance in aquatic environments. [26] This information can inform policy decisions, promote responsible antibiotic use, and guide efforts to minimize the release of antibiotics into water bodies.

Furthermore, the integration of genomic and metagenomic sequencing technologies has revolutionized the surveillance of antibiotic resistance in aquatic ecosystems. Whole-genome sequencing of resistant bacteria allows for in-depth characterization of their genetic makeup, including the identification of resistance genes and their associated mobile genetic elements. Metagenomic analysis provides a broader picture of the resistome in the environment by sequencing DNA directly from environmental samples, enabling the detection of resistance genes even in unculturable bacteria. These approaches enable researchers to track the spread and evolution of antibiotic resistance in real-time, providing valuable insights into the dynamics of resistance dissemination. [27]

These comprehensive strategies facilitate the understanding of the prevalence, diversity, and mechanisms of antibiotic resistance in aquatic bacteria. By gathering this knowledge, scientists and policymakers can develop evidence-based interventions to mitigate the spread of antibiotic resistance, preserve the effectiveness of antibiotics, and safeguard public health.

## Strategies for Combating Antibiotic Resistance

Several research and review articles have provided valuable insights into the measures contributing to the prevention of antibiotic resistance dissemination. These measures are crucial to combat the increasing threat of antibiotic resistance and preserve the effectiveness of antibiotics.

Responsible Antibiotic Use: Multiple studies emphasize the importance of responsible antibiotic use as a key measure to prevent the dissemination of antibiotic resistance. Research highlights the need for appropriate prescribing practices, including accurate diagnosis, proper dosage, and duration of treatment.[28] Additionally, patient education on the importance of completing the full course of antibiotics and avoiding the sharing or self-medication of antibiotics is essential in preventing the development of antibiotic resistance. [29]

Infection Prevention and Control: Effective infection prevention and control measures play a vital role in minimizing the spread of antibiotic-resistant bacteria. Research demonstrates the significance of implementing rigorous hygiene practices, such as hand hygiene, proper sanitation, and effective sterilization, to prevent healthcare-associated infections and the subsequent emergence of antibiotic resistance. [30] Similar infection control measures are also crucial in veterinary settings and agriculture to minimize the transmission of resistant bacteria. [31]

Surveillance and Monitoring: Comprehensive surveillance and monitoring systems are critical in tracking the prevalence and trends of antibiotic resistance. Surveillance efforts should extend to community settings, agriculture, and the environment to obtain a holistic understanding of antibiotic resistance dissemination.

Antibiotic Stewardship Programs: Implementing antibiotic stewardship programs is crucial for optimizing antibiotic use and minimizing the development of resistance. Multiple studies have demonstrated the effectiveness of stewardship interventions in reducing inappropriate antibiotic prescribing and overall antibiotic consumption. These programs involve multidisciplinary teams, education initiatives, guidelines development, and continuous monitoring to ensure responsible antibiotic use across healthcare, veterinary, and agricultural sectors. [32]

Public Awareness and Education: Raising public awareness about antibiotic resistance is essential in promoting responsible behaviour and preventing the dissemination of resistance. Research highlights the positive impact of public education campaigns on improving knowledge, attitudes, and behaviours towards antibiotic use. Educating the public about the consequences of antibiotic resistance, the importance of completing prescribed courses, and the role of individuals in preventing its spread can significantly contribute to mitigating resistance dissemination. [33]

International Collaboration: Collaboration at national and international levels is crucial in addressing antibiotic resistance on a global scale. Research by Tacconelli et al. emphasizes the need for international cooperation in surveillance data sharing, harmonization of policies and guidelines, and research collaboration to tackle the challenges of antibiotic resistance. Joint efforts can promote knowledge exchange, foster best practices, and facilitate the development of global strategies to prevent the dissemination of antibiotic resistance. [34]

By implementing these measures, as supported by various research and review articles, we can significantly contribute to preventing the dissemination of antibiotic resistance. These efforts require the active involvement of healthcare professionals, policymakers, researchers, and the general public to ensure responsible antibiotic use, effective infection prevention and control, surveillance, stewardship, public education, and international collaboration. [35]

**Future perspectives and research directions**

The management and prevention of antibiotic resistance are critical challenges that require continuous research and innovative strategies. Looking towards the future, several promising perspectives and research directions have emerged to address this global issue. One important focus is the development of novel antibiotics and alternative treatment options. Researchers are exploring new sources, such as natural compounds, bacteriophages, and antimicrobial peptides, as potential alternatives to traditional antibiotics. Additionally, the repurposing of existing drugs and combination therapies that target multiple mechanisms of bacterial resistance are being investigated.

Another promising area of research is the development of rapid diagnostic tools and point-of-care tests. Timely and accurate identification of bacterial infections and determination of their antibiotic susceptibility profiles can enable targeted and effective treatment, reducing the unnecessary use of broad-spectrum antibiotics. Molecular techniques, such as whole-genome sequencing and metagenomics, hold great promise in this regard.

Furthermore, the application of advanced technologies, such as artificial intelligence, machine learning, and big data analytics, has the potential to revolutionize the field of antibiotic resistance management. These technologies can aid in predicting antibiotic resistance patterns, optimizing treatment regimens, and identifying new targets for drug development. Additionally, they can support surveillance systems by analyzing large-scale data sets to monitor the spread of resistance and identify emerging hotspots.

Interdisciplinary collaboration and a One Health approach are crucial for effectively managing antibiotic resistance. Strengthening cooperation between human and veterinary medicine, agriculture, environmental sciences, and policy-making can foster a comprehensive understanding of the issue and facilitate the development of holistic strategies. Education and awareness programs targeting healthcare professionals, patients, and the general public are also important in promoting responsible antibiotic use and infection prevention.

Finally, global efforts to combat antibiotic resistance require strong policy frameworks and international cooperation. Encouraging the implementation of antimicrobial stewardship programs, promoting regulatory measures, and supporting research funding are essential steps. Additionally, fostering partnerships between academia, industry, and public health organizations can expedite the translation of research findings into practical solutions.

The future of managing and preventing antibiotic resistance lies in the development of new therapies, rapid diagnostics, advanced technologies, interdisciplinary collaboration, and global cooperation. By embracing these research directions and working collectively, it is possible to overcome the challenges posed by antibiotic resistance and safeguard the effectiveness of antibiotics for future generations.

## Conclusion

The review reveals a complex and concerning issue that poses risks to both public health and ecological systems. The presence of antibiotic-resistant bacteria and resistance genes in aquatic environments highlights the need for effective management and prevention strategies. This review has explored various aspects, including the sources and pathways of antibiotic resistance, factors contributing to its selection and dissemination, and the implications for public health and ecological systems.

Looking ahead, future research and perspectives hold promise in tackling antibiotic resistance in aquatic bacteria. The development of alternative treatment options, such as novel antibiotics, phage therapy, and antimicrobial peptides, shows potential for combating resistant strains. Rapid diagnostic tools and point-of-care tests are essential for timely and accurate identification of infections, enabling targeted and appropriate antibiotic use. Advanced technologies, including artificial intelligence and big data analytics, offer opportunities for predicting resistance patterns and optimizing treatment strategies.

Interdisciplinary collaboration and a One Health approach are vital for effectively managing antibiotic resistance. Strengthening partnerships between human and veterinary medicine, agriculture, and environmental sciences will contribute to a comprehensive understanding of the issue. Education and awareness programs are crucial for promoting responsible antibiotic use and infection prevention practices among healthcare professionals, patients, and the general public.

To drive progress, future research should focus on developing comprehensive surveillance systems to monitor the prevalence and spread of antibiotic resistance in aquatic environments. The exploration of innovative strategies, such as the use of nanotechnology, targeted drug delivery systems, and gene-editing techniques, will contribute to the development of effective interventions. Furthermore, policy frameworks, regulatory measures, and global cooperation are necessary to ensure the implementation of antimicrobial stewardship programs and the translation of research findings into practical solutions.

In conclusion, the review highlights the urgent need to address antibiotic resistance in aquatic bacteria. By adopting a multi-faceted approach that encompasses research, education, policy, and collaboration, we can strive to mitigate the risks posed by antibiotic resistance, safeguard public health, and preserve the delicate balance of ecological systems for future generations.

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