**Aquaculture and Microbiology: The Challenge of Antibiotic Resistance**

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**Introduction:**

Recent research studies have underlined the serious threat that the rise of resistance to antibiotics in aquaculture systems offers to public health. Colistin resistance in bacteria has been documented in both clinical and non-clinical contexts, such as aquaculture and poultry farms. Colistin is a last-resort antibiotic for treating multidrug resistant infections **(Seethalakshmi et al., 2023)**. A complete one health approach that addresses human, animal, and environmental health is required due to the simultaneous presence of colistin resistant genes alongside other antibiotic resistant genes, which exacerbates the issue of resistance to antibiotics **(Topp et al., 2017)**. During the fourth International Symposium on the Environmental Dimension of Antibiotic Resistance (EDAR4), a roundtable discussion focused on the significance of antibiotic stewardship and pre-treating manure and sludge to lower antibiotic emissions from agriculture, which includes aquaculture **(Dy, Rigano, & Fineran, 2018)**. Aquaculture requires sustainable methods since antibiotics administered to fish and shellfish production sites through feed have the potential to directly contaminate the aquatic environment. One important tactic to lower the usage of antibiotics in high-value production systems, like salmon aquaculture, has been shown to be vaccination. The decrease in antibiotic emissions from production is anticipated to be driven by consumer and regulatory pressure, underscoring the significance of stakeholder understanding and best practices in minimizing antimicrobial resistance. Researchers have looked at novel antimicrobial techniques in response to the problems caused by antibiotic resistance in aquaculture. One such strategy is the use of bacteriophages, or phages, as possible therapies for bacterial infections **(Seethalakshmi et al., 2023)**. Phages are viruses that only attack bacteria, providing a focused method of battling infections resistant to antibiotics. Phage-based technologies are capable of delivering deadly genes, lysing bacteria, and controlling how bacteria react to traditional antibiotics in order to produce antimicrobial action. Phage research has potential for mitigating the growing problem of antibiotic resistance in food production systems as biocontrol agents in aquaculture and agriculture. Overall, the evaluation of the literature emphasizes how urgently coordinated efforts are needed to combat antibiotic resistance in aquaculture, taking into account the connections between the health of humans, animals, and the environment. The development of alternative antimicrobial techniques, such as phage-based medicines, and antibiotic stewardship must be given top priority in global initiatives to minimize antibiotic resistance. To tackle antibiotic resistance in aquaculture and protect public health, researchers can strive towards sustainable solutions by promoting collaboration among stakeholders and enforcing evidence-based standards. The worldwide problem of antibiotic resistance presents a serious threat to public health. The effectiveness of treatment choices for serious infections has come under scrutiny due to the advent and spread of antibiotic-resistant bacteria, especially those resistant to last-resort medications like carbapenems. The growing resistance to carbapenems in aquaculture and other food supply chain sectors was brought to light by **Huang et al. (2023).** The analysis underscored the critical need for additional research and mitigation techniques to address antibiotic resistance by highlighting the direct or indirect relationship between human infections and carbapenem resistance in the food supply chain. The prevalence of antibiotic resistance genes (ARGs) in aquatic habitats, specifically in shrimp culture, was the main focus of **Zhou et al.'s (2020)** investigation. The results of the study showed that culturable bacteria containing ARGs varied over time, and that shrimp hepatopancreas had a higher relative quantity of ARGs than pond water did. The intricacy of antibiotic resistance in aquaculture settings is highlighted by the presence of numerous ARGs in a sizable part of culturable bacteria. The study also highlighted how human activity affects aquatic bacteria's resistance patterns, highlighting the necessity of thorough monitoring and control plans. The difficulties presented by multidrug-resistant bacteria in the Chilean aquaculture sector are clarified by **Oliver & Céspedes et al. (2023)**. Aquaculture's insufficient use of antibiotics has produced bacteria that are resistant to multiple drugs, endangering public health. The effect of florfenicol, an antibiotic frequently used in aquaculture, on the formation of biofilm in isolates of *Piscirickettsia salmonis* was the particular focus of the investigation. The results showed that all examined bacterial isolates exhibited enhanced biofilm formation in response to sub-MIC doses of florfenicol, underscoring the possible function of antibiotics in regulating bacterial behavior and resistance mechanisms.

Overall, the assessment of the literature highlights how complex antibiotic resistance is in aquaculture settings and how urgently thorough research and management plans are needed to address this issue. The examined literature underscores the interdependence of antibiotic resistance in the food chain, aquatic ecosystems, and human health, underscoring the significance of a One Health strategy in addressing antibiotic resistance. To better understand the causes of antibiotic resistance in aquaculture and to create practical solutions to lessen its negative effects on public health, more study is required. Through acquiring enhanced comprehension of the present condition of antibiotic resistance in aquaculture and the elements propelling its formation and dissemination, scholars can endeavor to devise enduring remedies for this urgent worldwide health concern.

**The Role of Antibiotics in Aquaculture**

The introduction of illnesses with economic repercussions presents a serious concern for the constantly expanding aquaculture industry. Probiotics have emerged as a promising method to combat fish infections, which have been addressed through a variety of strategies. Probiotics such as Bacillus species have been demonstrated to be useful in reducing the effects of several fish pathogens, such as *Yersinia, Aeromonas, Vibrio, Streptococcus, Pseudomonas, Clostridium, Acinetobacter, Edwardsiella, Flavobacterium*, infectious hypodermal and hematopoietic necrosis virus, and white spot syndrome virus **(Kuebutornye et al., 2020)**. The production of bacteriocins, inhibition of virulence gene expression, competition for adhesion sites, lytic enzyme production, antibiotic production, immunostimulation, competition for nutrients and energy, and organic acid production are some of the mechanisms that *Bacillus* probiotics use to fight fish pathogens. To improve disease management strategies and increase the effectiveness of Bacillus probiotics in aquaculture, it is imperative to comprehend these mechanisms **(Kuebutornye et al., 2020)**. Antibiotics have also been utilized extensively in aquaculture for growth promotion and disease control in addition to probiotics. On the other hand, methylmercury (MeHg) formation in mariculture sediments has been linked to the use of antibiotics in fish culture operations.Studies have shown that the addition of antibiotics such as tetracycline and oxytetracycline to sediments can lead to the complexation of Hg with the antibiotics, resulting in the transport of electrons and subsequent formation of MeHg. This draws attention to the possible negative environmental consequences of aquaculture's use of antibiotics and the necessity of sustainable measures to lessen those effects **(Liang et al., 2018)**. The widespread use of antibiotics in aquaculture has sparked worries about environmental contamination and the emergence of antibiotic resistance genes, especially in nations like China where aquaculture production is substantial. There are serious hazards to the health of humans and ecosystems due to aquaculture's role in the environmental contamination of antibiotics and the emergence of antibiotic resistance genes. To fully comprehend the kinds and amounts of antibiotics used in aquaculture, their effects on the environment, and the propagation of antibiotic resistance genes in aquaculture settings, more research is required **(Mo & Chen, 2015)**.

Concerns about the use of antibiotics in aquaculture have led to an increase in interest in investigating substitute tactics, such as immune-stimulating fish farming with medicinal herbs. It has been demonstrated that medicinal plants strengthen fish immune systems, inhibit and manage microbial infections, and stimulate development and immune function. Medicinal plants work by enhancing the humoral and cellular immune response, which raises immunological parameters and improves fish health. The ideal dosages of medicinal plants for boosting fish immunological status and development performance in aquaculture settings require more investigation **(Awad & Awaad, 2017)**. Furthermore, zebrafish have been used as a model organism in studies looking into the possible neurotoxicity of antibiotics that are frequently found in surface waters. It has been demonstrated that zebrafish larvae exposed to antibiotics including clarithromycin, chlortetracycline, and roxithromycin experience behavioral changes as well as brain damage. These antibiotics have the potential to impact zebrafish larvae's neurotransmission, endocrine system, mitochondrial stress response, and synaptogenesis, according to transcriptome study. According to **Zhang et al. (2023)**, these results highlight the significance of comprehending the neurotoxic effects of antibiotics on aquatic organisms and the possible concerns connected to their presence in aquatic habitats.

**Yang et al. (2024)** investigated the changes in the intestinal microbiome and pathogen susceptibility of zebrafish following chronic antibiotics exposure. The study revealed that chronic antibiotics exposure led to gut microbiome dysbiosis, resulting in reduced pathogen susceptibility and enhanced innate immunity in zebrafish. These findings provide new insights into the impact of antibiotics on gut microbiome composition and host-pathogen interactions in fish, highlighting the importance of maintaining a balanced gut microbiome for fish health. **Velázquez et al. (2023)** examined the antimicrobial and immunomodulatory effects of Pituitary Adenylate Cyclase-Activating Polypeptide (PACAP) on rainbow trout infected with *Yersinia ruckeri*. The research findings indicate that PACAP has the potential to serve as a substitute for antibiotics in aquaculture, as it demonstrated direct antibacterial action against Y. ruckeri and regulated immune responses in rainbow trout. These results validate PACAP's potential as an immunomodulatory and antimicrobial peptide for teleost fish bacterial infection prevention and treatment.

In a commercial open-water aquaculture scenario, **Rigas et al. (2023)** examined the effects of oxytetracycline (OTC) therapy on the gut microbiota of seabass. According to the study, long-term dysbiosis brought on by over-the-counter medication resulted in a drop in microbial diversity and an increase in intestinal parasites in the gut microbiome of seabass. These results highlight the significance of therapies to reestablish a protective and healthy gut microbiota in farmed fish in order to lessen the detrimental effects. In a nutshell the function of antibiotics in aquaculture is complex and affects the composition of the gut microbiota, the biotransformation of contaminants, antibiotic resistance, and the interactions between hosts and pathogens. The reviewed research underscore the need for sustainable antibiotic use methods in aquaculture and the development of substitute measures to reduce the dangers of antibiotic usage on the environment and public health. Researchers can help build efficient and sustainable aquaculture procedures that put animal welfare and environmental stewardship first by developing a deeper knowledge of the intricate relationships that exist between antibiotics, gut microbiota, and fish health.

In a study by **Yin et al. (2022)**, the effects of antibiotic (florfenicol) application on gut microbiota and mercury (Hg) biotransformation in tilapia were investigated. The results showed that florfenicol treatment altered the gut microbial community, leading to a decrease in methylation and complete termination of demethylation of Hg in fish. This shift in microbial methylators/demethylators in the fish gut resulted in an increased potential for methylmercury (MeHg) accumulation by fish, highlighting the importance of judicious antibiotic use in aquaculture to mitigate environmental risks of Hg contamination. In their study from2024, **Barathan et al.** examined the worrying problem of antibiotic resistance (ABR) in aquatic habitats and how it affects ecosystems and public health. The research focused on how the use of antibiotics in aquaculture, agricultural runoff, and industrial waste can encourage the growth and spread of resistant bacteria. The extensive discussion highlighted the critical need for effective ways to minimize ABR in aquatic habitats, given the complex interplay between environmental variables, horizontal gene transfer, and bacterial extracellular vesicles (BEVs) in speeding the spread of ABR.

In conclusion, the role of antibiotics in aquaculture is multifaceted, with both benefits and risks associated with their use. While antibiotics can be effective in disease control and growth promotion, their environmental impact, including the formation of MeHg in sediments and the development of antibiotic resistance genes, raises concerns about their sustainability. Alternative strategies such as probiotics and medicinal plants offer promising solutions for disease management and immune enhancement in aquaculture. Continued research is needed to optimize the use of antibiotics and explore sustainable practices that minimize their environmental impact while ensuring the health and productivity of aquaculture systems. The Role of Antibiotics in Aquaculture Antibiotics have long been a crucial tool in aquaculture to combat bacterial infections and ensure the health and well-being of farmed fish. However, the indiscriminate use of antibiotics in aquaculture has raised concerns about its impact on the environment, public health, and the development of antibiotic resistance. Several recent studies have shed light on the complex interplay between antibiotics, gut microbiota, and the biotransformation of contaminants in fish, highlighting the need for a more nuanced understanding of the role of antibiotics in aquaculture.

**Antibiotic Resistance in Aquatic Microbiota**

Antibiotic resistance in aquatic microbiota is a pressing issue that requires urgent attention due to the potential impact on public health. The research papers reviewed shed light on the various aspects of antibiotic resistance in aquatic environments, particularly in urban runoff waters, sewage treatment plant effluents, freshwater ecosystems, human-wildlife interactions, and plastic pollution in oceans. The studies collectively emphasize the need to understand the dynamics of antibiotic resistance genes (ARGs) and resistant bacteria in aquatic microbiota to mitigate the spread of antibiotic resistance. **Almakki & Jumas-Bilak, 2019** highlighted the environmental pressures exerted on bacterial communities in urban runoff waters, emphasizing the impact of urban activities on antibiotic resistance. The presence of antibiotics in the environment, coupled with continuous release from various sources, creates a selection pressure on microbial organisms, leading to the emergence and dissemination of antibiotic resistance genes.

The study proposed that freshwater aquatic wildlife, particularly organisms with high bacterial density tissues, could serve as reservoirs and amplifiers of antibiotic resistance, contributing to the abundance of ARGs and resistant bacteria in the environment. In a study by **Thibodeau et al., 2024**, the transmission routes for ARGs and microbiota between humans and water environments were investigated. The research revealed a significant association between human feces and rural sewage treatment systems, indicating a human contribution to the dissemination of ARGs into the environment. The study underscored the importance of understanding the transmission routes and dynamics of antibiotic resistance to prevent further dissemination. **Zhou et al., 2018** explored the presence of ARGs and metal resistance genes (MRGs) in microbial communities colonizing plastic particles in the North Pacific Gyre. The study found a higher abundance and diversity of ARGs and MRGs in plastics microbiota compared to seawater microbiota, suggesting that plastics serve as reservoirs for antibiotic and metal resistance genes. The research highlighted the role of microbial community composition in shaping the resistome of microbiota on plastic particles.

**Yang et al., 2019** investigated the impact of ingested ARGs or antibiotic resistance bacteria on fish gut microbiota. The study developed a plasmid-mediated ARG transfer model in zebrafish and observed the dissemination of ARGs in the gut microbial communities. The findings indicated that aquatic animal guts, such as those of fish, contribute to the spread of ARGs in water environments through conjugal gene transfer. The study emphasized the need to understand the dynamics of ARG dissemination in aquatic animal guts to mitigate the spread of antibiotic resistance. **Fu et al., 2017** examined the occurrence of antibiotics and antibiotic resistance genes in sewage treatment plant effluents compared to freshwater ecosystems. The research highlighted the potential role of freshwater aquatic wildlife in disseminating antibiotic resistance within the environment. The study proposed potential avenues for further research and action, including trophic transfer studies and biodiversity eco-engineering approaches to address antibiotic resistance in aquatic microbiota. In conclusion, the literature review of the provided research papers underscores the urgent need to address antibiotic resistance in aquatic microbiota. The studies collectively emphasize the role of urban activities, human-wildlife interactions, plastic pollution, and aquatic animal guts in the dissemination of antibiotic resistance genes and resistant bacteria. Understanding the dynamics of antibiotic resistance in aquatic environments is crucial for developing effective strategies to mitigate the spread of antibiotic resistance and protect public health. Further research and action are needed to comprehensively address the challenges posed by antibiotic resistance in aquatic microbiota. Antibiotic resistance in aquatic microbiota is a growing concern due to the widespread use of antibiotics in various sectors such as aquaculture, human medicine, and terrestrial animal farms. The accumulation of antibiotics and antibiotic resistance genes (ARGs) in aquatic environments poses a significant threat to humans and animals. Several research studies have been conducted to investigate the occurrence and spread of antibiotics and ARGs in aquatic ecosystems, shedding light on the potential ecological risks and implications for public health.

In a study by **Zhang et al. (2023)**, Wanfeng Lake in China was examined to assess the presence of antibiotics, ARGs, mobile genetic elements, and microbial community structure. The results revealed high concentrations of antibiotics in both surface water and sediments, with quinolones being the predominant type of antibiotics. Sulfonamide resistance genes were found to be the dominant type of ARGs in the lake. The study also highlighted a positive correlation between antibiotics, environmental factors, ARGs, and microorganisms, indicating a potential pressure of antibiotics on ARGs and the role of microorganisms in the evolution and spread of ARGs in aquatic environments.

**Pereira et al. (2022)** focused on *Vibrio species* associated with marine invertebrates and their antibiotic resistance profiles. The study identified non-susceptibility to antibiotics in a significant proportion of Vibrio isolates, with some exhibiting multidrug resistance. The presence of resistance genes for beta-lactam and heavy metals, as well as plasmids, underscored the potential risk of antibiotic-resistant Vibrio strains in aquatic environments. This research contributes to a better understanding of antibiotic resistance in marine animals and its implications for public health. Chironomids, aquatic insects abundant in freshwater ecosystems, were the subject of investigation in a study by **Costa et al. (2021)**. The research focused on the endogenous microbiota composition of *Chironomus ramosus* larvae sampled from a river and a laboratory culture. Metagenomic analysis revealed differences in bacterial community composition between river and laboratory-reared larvae, with unique bacterial taxa identified in each group. The presence of bacterial genes conferring resistance to antibiotics in the larval microbiome suggests a potential role in protecting the insects from pollutants in their environment.

**Sela & Laviad-Shitrit (2021)** highlighted the toxic effects of antibiotics on fish and aquatic bacterial communities. Antibiotics present in aquatic environments, originating from terrestrial animal farms, human medicine, and aquaculture, have been shown to induce oxidative stress, histopathological lesions, and reproductive disorders in fish. Additionally, low concentrations of antibiotics can disrupt fish symbiotic microbiota and promote the emergence of antibiotic-resistant pathogenic bacteria. This research emphasizes the need to address the environmental impact of antibiotics on aquatic ecosystems and the potential risks to aquatic organisms.

**Bojarski et al. (2020)** discussed the relevance of aquaculture in animal protein production and the challenges posed by outbreaks and antimicrobial resistance. Probiotics and bacteriocins were identified as promising alternatives to antibiotics in controlling bacterial infections in aquatic animals. The study highlighted the beneficial impacts of probiotics on intestinal microbiota, immune response, and growth performance, without the drawbacks associated with antibiotic use. The potential role of probiotics and bacteriocins in addressing the challenges of antimicrobial resistance in aquaculture was underscored. The studies highlight the ecological risks posed by antibiotics, the role of microbial communities in the evolution of ARGs, and the potential benefits of alternative strategies such as probiotics in mitigating antibiotic resistance in aquaculture. Further research is warranted to better understand the dynamics of antibiotic resistance in aquatic ecosystems and to develop sustainable solutions to address this pressing issue.

**Factors Contributing to Antibiotic Resistance in Aquaculture**

Aquaculture antibiotic resistance is a serious problem that has to be addressed right away. Antibiotic residues can be found in aquatic products, and bacterial resistance has developed as a result of the indiscriminate use of antibiotics in intensive farming techniques. Numerous scholarly articles have illuminated the elements that contribute to aquaculture's antibiotic resistance. In order to slow down the emergence of resistance, **Chen et al., 2020** stressed the importance of monitoring resistant genes and infections as well as minimizing the usage of antibiotics. They also emphasized the significance of maintaining the quality of water bodies used in aquaculture and controlling environmental sanitation in aquaculture.

The effect of antibiotics on native bacterial communities in aquatic environments was investigated **(Corno et al., 2014)**. They discovered that the composition of the bacterial population changed and that there was a considerable decrease in bacterial abundance when antibiotics were present. They saw something interesting: bacterial populations that were stressed by antibiotics performed better when antibiotics were present, which may have been an adaptive response. **Su et al., 2019** looked into the dynamics of marine aquaculture's antibiotic resistance genes (ARGs). The dispersion of ARGs in marine aquaculture is largely influenced by environmental conditions and the bacterial community, with sediment serving as a crucial dispersal medium.

The role of bacterial extracellular vesicles (BEVs) in the dissemination of antibiotic resistance in aquatic environments was investigated (**Barathan et al., 2024)**. They outlined the potential of BEVs as an instrument and a danger in the fight against antibiotic resistance and offered viable plans for slowing the spread of resistance. **Rout et al., 2023** concentrated on the frequency of genes linked to antibiotic resistance in the Ganges River in India. The findings of their metagenomic research underscored the significance of focused public health measures in the fight against antibiotic resistance by revealing geographical variations in the prevalence of ARGs. The antibacterial activity of isobutyl cyanoacrylate nanoparticles against the main bacterial infections that affect fish was evaluated by **Ahiable et al. (2023)**.

The antibacterial characteristics of the nanoparticles were seen to be species-specific and dose-dependent, indicating their possible application as substitutes for antibiotics in aquaculture. All things considered, these research studies offer insightful information on the elements that lead to antibiotic resistance in aquaculture as well as viable solutions to lessen this escalating risk to the environment and public health.

**Implications of Antibiotic Resistance in Aquaculture**

Aquaculture antibiotic resistance is a developing issue that has serious consequences for the environment and public health. **Dewi et al**.'s study from 2022 provides insight into the environmental risk factors and on-farm activities that lead to the growth and spread of *Vibrio parahaemolyticus* and multi-drug-resistant (MDR) Escherichia coli in aquaculture systems. According to the research, there may be a higher chance of MDR bacteria occurrence in ponds that are manured or that employ clay ponds. These findings emphasize the necessity of focused treatments at aquaculture farms in order to reduce the possibility of MDR bacteria affecting fish that are significant for public health.

Similar to this, **Liao et al. (2022)** investigate the possibility of using medicinal plants in aquaculture as a substitute for antibiotics to fight viral illnesses, which are a serious danger to the sector. The research highlights how medicinal plants and their active pharmaceutical compounds have antiviral properties that demonstrate how successful they are in treating and preventing viral illnesses in aquatic animals. Medicinal plants have several advantages over chemical medications and antibiotics, including less side effects, decreased drug resistance, and low environmental damage. The study emphasizes the importance of medicinal plants in enhancing aquatic animals' growth performance and their potential as safe medications for aquaculture illness prevention. In order to address antibiotic resistance and viral infections, sustainable practices in aquaculture are critically needed, as the research papers together demonstrate. Researchers can create plans to safeguard public health, guarantee the sustainability of the aquaculture sector, and advance the health of aquatic animals by studying the causes of antibiotic resistance and investigating substitute therapies such medicinal plants. These results offer insightful information for future studies and treatments meant to lessen the effects of antibiotic resistance in aquaculture. Aquaculture antibiotic resistance is a developing issue with major consequences for human health and the environment.

The study by **Gaeta et al. (2020)** draws attention to the possible dangers of overusing antibiotics in aquaculture, such as the emergence of antimicrobial resistance and water contamination. Innovative approaches have been put forth in response to these difficulties, such as photo-degradation utilizing TiO2, which is a viable and long-term way to remove antibiotic pollutants from water. The effectiveness of composite TiO2 powders sensitized with porphyrins in photodegrading antibiotics like oxytetracycline and oxolinic acid was assessed in this work. When tested as a composite material, TiO2 functionalized with CuTCPP removed oxytetracycline from water with promising results under simulated solar light. According to this research, controlling antibiotic pollution in aquaculture and preserving public health may benefit from the use of photodegradation utilizing materials based on titanium dioxide (TiO2).

Similar to this, **Akinyele et al. (2011)** investigated the antibacterial activity of crude aqueous and n-hexane extracts of Cocos nucifera husk against common foodborne pathogens like Vibrio species and other bacterial diseases. The study findings indicated that the aqueous and n-hexane extracts showed antibacterial efficacy against a variety of bacterial isolates, including infections caused by Vibrio bacterium. The extracts' lowest inhibitory concentrations varied from 0.3 to 5.0 mg/mL, suggesting that they could be used as complementary treatments for microbial infections. The results of this investigation imply that *C. nucifera* natural extracts may be a useful tool in the fight against bacteria that are resistant to antibiotics in aquaculture environments. Overall, the studies by **Akinyele et al. (2011)** and **Gaeta et al. (2020)** highlight the significance of tackling antibiotic resistance in aquaculture using creative and sustainable methods.

Researchers can create practical plans for controlling antibiotic pollution and battling resistant bacteria in aquaculture by investigating the usage of TiO2-based materials for photodegradation and natural extracts for antibacterial qualities. These studies offer insightful information that will help direct future investigations into the effects of antibiotic resistance in aquaculture on human health and the environment.

**Conclusions**

Adopting a multimodal strategy to mitigate antibiotic resistance in aquaculture involves using probiotics, prebiotics, and vaccination programs to boost immune responses and lower disease incidence in addition to better farm management techniques like optimal water quality maintenance and stress reduction. The use of antibiotics is further reduced by strict biosecurity protocols, selective breeding for disease resistance features, and investigation of complementary therapies like herbal cures. In addition to encouraging cooperation between industry players, academics, and governmental organizations to develop sustainable solutions for the long-term health of aquatic ecosystems and global food security, regulatory frameworks along with monitoring, education, and education programs ensure responsible antibiotic stewardship.

**References**

Kuebutornye, F. K. A., Abarike, E. D., Lu, Y., Hlordzi, V., Sakyi, M. E., Afriyie, G., … Xie, C. X. (2020, January 17). Mechanisms and the role of probiotic Bacillus in mitigating fish pathogens in aquaculture. <i>Fish Physiology and Biochemistry</i>. Springer Science and Business Media LLC. <http://doi.org/10.1007/s10695-019-00754-y>

Liang, P., Wu, S., Zhang, C., Xu, J., Christie, P., Zhang, J., & Cao, Y. (2018, October). The role of antibiotics in mercury methylation in marine sediments. <i>Journal of Hazardous Materials</i>. Elsevier BV. <http://doi.org/10.1016/j.jhazmat.2018.07.096>

Mo, W. Y., Chen, Z., Leung, H. M., & Leung, A. O. W. (2015, October 26). Application of veterinary antibiotics in China’s aquaculture industry and their potential human health risks. <i>Environmental Science and Pollution Research</i>. Springer Science and Business Media LLC. <http://doi.org/10.1007/s11356-015-5607-z>

Awad, E., & Awaad, A. (2017, August). Role of medicinal plants on growth performance and immune status in fish. <i>Fish & Shellfish Immunology</i>. Elsevier BV. <http://doi.org/10.1016/j.fsi.2017.05.034>

Zhang, Y., Li, X., Liu, Z., Zhao, X., Chen, L., Hao, G., … Qian, Y. (2023, November). The neurobehavioral impacts of typical antibiotics toward zebrafish larvae. <i>Chemosphere</i>. Elsevier BV. <http://doi.org/10.1016/j.chemosphere.2023.139829>

Yin, B., Tan, S., Wang, J., Pan, K., Wang, W.-X., & Wang, X. (2022, May). Antibiotic application may raise the potential of methylmercury accumulation in fish. <i>Science of The Total Environment</i>. Elsevier BV. <http://doi.org/10.1016/j.scitotenv.2022.152946>

Barathan, M., Ng, S.-L., Lokanathan, Y., Ng, M. H., & Law, J. X. (2024, March 7). Unseen Weapons: Bacterial Extracellular Vesicles and the Spread of Antibiotic Resistance in Aquatic Environments. <i>International Journal of Molecular Sciences</i>. MDPI AG. <http://doi.org/10.3390/ijms25063080>

Yang, J. H., Park, J. W., Kim, H. S., Lee, S., Yerke, A. M., Jaiswal, Y. S., … Moon, K. H. (2024, January 15). Effects of Antibiotic Residues on Fish Gut Microbiome Dysbiosis and Mucosal Barrier-Related Pathogen Susceptibility in Zebrafish Experimental Model. <i>Antibiotics</i>. MDPI AG. <http://doi.org/10.3390/antibiotics13010082>

Velázquez, J., Rodríguez-Cornejo, T., Rodríguez-Ramos, T., Pérez-Rodríguez, G., Rivera, L., Campbell, J. H., … Dixon, B. (2023, September 27). New Evidence for the Role of Pituitary Adenylate Cyclase-Activating Polypeptide as an Antimicrobial Peptide in Teleost Fish. <i>Antibiotics</i>. MDPI AG. <http://doi.org/10.3390/antibiotics12101484>

Rigas, D., Grivas, N., Nelli, A., Gouva, E., Skoufos, I., Kormas, K., … Lagkouvardos, I. (2023, September 13). Persistent Dysbiosis, Parasite Rise and Growth Impairment in Aquacultured European Seabass after Oxytetracycline Treatment. <i>Microorganisms</i>. MDPI AG. <http://doi.org/10.3390/microorganisms11092302>

Almakki, A., Jumas-Bilak, E., Marchandin, H., & Licznar-Fajardo, P. (2019, June). Antibiotic resistance in urban runoff. <i>Science of The Total Environment</i>. Elsevier BV. <http://doi.org/10.1016/j.scitotenv.2019.02.183>

Thibodeau, A. J., Barret, M., Mouchetd€, F., Nguyen, V. X., & Pinelli, E. (2024, April). “The potential contribution of aquatic wildlife to antibiotic resistance dissemination in freshwater ecosystems: A review”. <i>Environmental Pollution</i>. Elsevier BV. <http://doi.org/10.1016/j.envpol.2024.123894>

Zhou, Z.-C., Feng, W.-Q., Han, Y., Zheng, J., Chen, T., Wei, Y.-Y., … Chen, H. (2018, December). Prevalence and transmission of antibiotic resistance and microbiota between humans and water environments. <i>Environment International</i>. Elsevier BV. <http://doi.org/10.1016/j.envint.2018.10.032>

Yang, Y., Liu, G., Song, W., Ye, C., Lin, H., Li, Z., & Liu, W. (2019, February). Plastics in the marine environment are reservoirs for antibiotic and metal resistance genes. <i>Environment International</i>. Elsevier BV. <http://doi.org/10.1016/j.envint.2018.11.061>

Fu, J., Yang, D., Jin, M., Liu, W., Zhao, X., Li, C., … Li, J. (2017, August 14). Aquatic animals promote antibiotic resistance gene dissemination in water via conjugation: Role of different regions within the zebra fish intestinal tract, and impact on fish intestinal microbiota. <i>Molecular Ecology</i>. Wiley. <http://doi.org/10.1111/mec.14255>

Zhang, Y., Li, J., Wu, T., Ma, K., Cheng, Z., Yi, Q., … Zhong, X. (2023, June 20). Characteristics of antibiotic resistance genes and microbial community distribution in Wanfeng Lake, upper Pearl River, China. <i>Environmental Science and Pollution Research</i>. Springer Science and Business Media LLC. <http://doi.org/10.1007/s11356-023-28158-9>

Pereira, W. A., Mendonça, C. M. N., Urquiza, A. V., Marteinsson, V. Þ., LeBlanc, J. G., Cotter, P. D., … Oliveira, R. P. S. (2022, August 24). Use of Probiotic Bacteria and Bacteriocins as an Alternative to Antibiotics in Aquaculture. <i>Microorganisms</i>. MDPI AG. <http://doi.org/10.3390/microorganisms10091705>

Costa, W. F., Giambiagi-deMarval, M., & Laport, M. S. (2021, December 20). Antibiotic and Heavy Metal Susceptibility of Non-Cholera Vibrio Isolated from Marine Sponges and Sea Urchins: Could They Pose a Potential Risk to Public Health?. <i>Antibiotics</i>. MDPI AG. <http://doi.org/10.3390/antibiotics10121561>

Sela, R., Laviad-Shitrit, S., Thorat, L., Nath, B. B., & Halpern, M. (2021, July 23). Chironomus ramosus Larval Microbiome Composition Provides Evidence for the Presence of Detoxifying Enzymes. <i>Microorganisms</i>. MDPI AG. <http://doi.org/10.3390/microorganisms9081571>

Bojarski, B., Kot, B., & Witeska, M. (2020, August 9). Antibacterials in Aquatic Environment and Their Toxicity to Fish. <i>Pharmaceuticals</i>. MDPI AG. <http://doi.org/10.3390/ph13080189>

Huang, E., Yang, X., Leighton, E., & Li, X. (2023, July). Carbapenem resistance in the food supply chain. <i>Journal of Food Protection</i>. Elsevier BV. http://doi.org/10.1016/j.jfp.2023.100108

Suyamud, B., Chen, Y., Quyen, D. T. T., Dong, Z., Zhao, C., & Hu, J. (2024, January). Antimicrobial resistance in aquaculture: Occurrence and strategies in Southeast Asia. <i>Science of The Total Environment</i>. Elsevier BV. <http://doi.org/10.1016/j.scitotenv.2023.167942>

Wang, L., Hu, T., Li, Y., Zhao, Z., & Zhu, M. (2023, December). Unraveling the interplay between antibiotic resistance genes and microbial communities in water and sediments of the intensive tidal flat aquaculture. <i>Environmental Pollution</i>. Elsevier BV. <http://doi.org/10.1016/j.envpol.2023.122734>

Huang, E., Yang, X., Leighton, E., & Li, X. (2023, July). Carbapenem resistance in the food supply chain. <i>Journal of Food Protection</i>. Elsevier BV. http://doi.org/10.1016/j.jfp.2023.100108

5. El-Bahar, H. M., Ali, N. G., Aboyadak, I. M., Khalil, S. A. E. S., & Ibrahim, M. S. (2019, April 15). Virulence genes contributing to Aeromonas hydrophila pathogenicity in Oreochromis niloticus. <i>International Microbiology</i>. Springer Science and Business Media LLC. <http://doi.org/10.1007/s10123-019-00075-3>

Oliva‐Teles, A. (2012, January 11). Nutrition and health of aquaculture fish. <i>Journal of Fish Diseases</i>. Wiley. <http://doi.org/10.1111/j.1365-2761.2011.01333.x>

Barathan, M., Ng, S.-L., Lokanathan, Y., Ng, M. H., & Law, J. X. (2024, March 7). Unseen Weapons: Bacterial Extracellular Vesicles and the Spread of Antibiotic Resistance in Aquatic Environments. <i>International Journal of Molecular Sciences</i>. MDPI AG. <http://doi.org/10.3390/ijms25063080>

Rout, A. K., Tripathy, P. S., Dixit, S., Behera, D. U., Behera, B., Das, B. K., & Behera, B. K. (2023, December 14). Unveiling the Microbiome Landscape: A Metagenomic Study of Bacterial Diversity, Antibiotic Resistance, and Virulence Factors in the Sediments of the River Ganga, India. <i>Antibiotics</i>. MDPI AG. <http://doi.org/10.3390/antibiotics12121735>

Ahiable, M. G., Matsunaga, K., Hokin, M., Iida, K., Befu, F., & Oshima, S.-I. (2023, November 28). In Vitro Efficacy of Isobutyl Cyanoacrylate Nanoparticles against Fish Bacterial Pathogens and Selection Preference by Rainbow Trout (Oncorhynchus mykiss). <i>Microorganisms</i>. MDPI AG. <http://doi.org/10.3390/microorganisms11122877>

Salgueiro, V., Reis, L., Ferreira, E., Botelho, M. J., Manageiro, V., & Caniça, M. (2021, September 20). Assessing the Bacterial Community Composition of Bivalve Mollusks Collected in Aquaculture Farms and Respective Susceptibility to Antibiotics. <i>Antibiotics</i>. MDPI AG. <http://doi.org/10.3390/antibiotics10091135>

Oliva‐Teles, A. (2012, January 11). Nutrition and health of aquaculture fish. <i>Journal of Fish Diseases</i>. Wiley. <http://doi.org/10.1111/j.1365-2761.2011.01333.x>

Barathan, M., Ng, S.-L., Lokanathan, Y., Ng, M. H., & Law, J. X. (2024, March 7). Unseen Weapons: Bacterial Extracellular Vesicles and the Spread of Antibiotic Resistance in Aquatic Environments. <i>International Journal of Molecular Sciences</i>. MDPI AG. <http://doi.org/10.3390/ijms25063080>

Rout, A. K., Tripathy, P. S., Dixit, S., Behera, D. U., Behera, B., Das, B. K., & Behera, B. K. (2023, December 14). Unveiling the Microbiome Landscape: A Metagenomic Study of Bacterial Diversity, Antibiotic Resistance, and Virulence Factors in the Sediments of the River Ganga, India. <i>Antibiotics</i>. MDPI AG. <http://doi.org/10.3390/antibiotics12121735>

Ahiable, M. G., Matsunaga, K., Hokin, M., Iida, K., Befu, F., & Oshima, S.-I. (2023, November 28). In Vitro Efficacy of Isobutyl Cyanoacrylate Nanoparticles against Fish Bacterial Pathogens and Selection Preference by Rainbow Trout (Oncorhynchus mykiss). <i>Microorganisms</i>. MDPI AG. <http://doi.org/10.3390/microorganisms11122877>

Salgueiro, V., Reis, L., Ferreira, E., Botelho, M. J., Manageiro, V., & Caniça, M. (2021, September 20). Assessing the Bacterial Community Composition of Bivalve Mollusks Collected in Aquaculture Farms and Respective Susceptibility to Antibiotics. <i>Antibiotics</i>. MDPI AG. <http://doi.org/10.3390/antibiotics10091135>

Dewi, R. R., Hassan, L., Daud, H. M., Matori, M. F., Zakaria, Z., Ahmad, N. I., … Jajere, S. M. (2022, July 27). On-Farm Practices Associated with Multi-Drug-Resistant Escherichia coli and Vibrio parahaemolyticus Derived from Cultured Fish. <i>Microorganisms</i>. MDPI AG. <http://doi.org/10.3390/microorganisms10081520>

 Liao, W., Huang, L., Han, S., Hu, D., Xu, Y., Liu, M., … Li, P. (2022, June 13). Review of Medicinal Plants and Active Pharmaceutical Ingredients against Aquatic Pathogenic Viruses. <i>Viruses</i>. MDPI AG. <http://doi.org/10.3390/v14061281>

Gaeta, M., Sanfilippo, G., Fraix, A., Sortino, G., Barcellona, M., Oliveri Conti, G., … D’Urso, A. (2020, May 27). Photodegradation of Antibiotics by Noncovalent Porphyrin-Functionalized TiO2 in Water for the Bacterial Antibiotic Resistance Risk Management. <i>International Journal of Molecular Sciences</i>. MDPI AG. <http://doi.org/10.3390/ijms21113775>

Akinyele, T. A., Okoh, O. O., Akinpelu, D. A., & Okoh, A. I. (2011, March 3). In-Vitro Antibacterial Properties of Crude Aqueous and n-Hexane Extracts of the Husk of Cocos nucifera. <i>Molecules</i>. MDPI AG. <http://doi.org/10.3390/molecules16032135>