Comprehensive Analysis of the Impacts and Potential Risks of Disinfectant Use on the Transfer of Antibiotic Resistance Genes in Aquaculture

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Abstract

The overuse of antibiotics in intensive aquaculture has led to the continuous enrichment and dissemination of antibiotic resistance genes (ARGs) in aquatic environments, posing risks to public health. In recent years, the extensive application of disinfectants - including chlorine-based compounds, hydrogen peroxide, guanidines, and metal-based nanomaterials - and their subsequent environmental residues have raised concern. However, their impact on ARG propagation remains poorly understood. This review systematically examines the effects of typical disinfectants on horizontal gene transfer (HGT) of ARGs, changes in ARG abundance, and microbial community structure in aquaculture settings. Key findings indicate that environmentally relevant concentrations of disinfectants significantly enhance conjugative transfer frequency (by 1.30- to 10.00-fold) through oxidative stress, SOS response, and increased membrane permeability. Disinfectant exposure elevates the abundance of tetracycline, sulfonamide, and β-lactam ARGs, accompanied by enrichment of mobile genetic elements, thus enhancing ARG mobility. Moreover, disinfectants reduce microbial diversity and selectively enrich potential pathogenic host bacteria (e.g., Mycobacterium spp., Pseudomonas aeruginosa), exacerbating the risk of resistance transfer to high-risk pathogens. Collectively, disinfectant residues act synergistically with antibiotic selection pressure to drive a positive feedback loop of "selection-dispersion", turning aquaculture systems into reservoirs of multidrug resistance. Incorporation of disinfectants into environmental risk assessment frameworks and development of green alternatives that do not induce horizontal gene transfer are urgently needed.

Keywords

Aquaculture water, Antibiotic resistance genes, Microbial community structure, Horizontal gene transfer

Introduction

Since the discovery of antibiotics, their potent antimicrobial properties have established them as a cornerstone of human infection control. Concurrently, the extensive utilization of antibiotics has led to pervasive residual contamination in the environment. The widespread application of antibiotics in veterinary medicine, clinical practice, and agriculture has exerted selective pressure on bacteria, driving the emergence of antibiotic resistance genes (ARGs) through mutation, thereby conferring drug resistance. Antibiotic-resistant bacteria (ARBs) and ARGs are frequently detected in aquatic, terrestrial, and even atmospheric environments, posing latent threats to public health. The advent of ARGs has exacerbated the challenges associated with managing bacterial diseases, particularly those driven by the proliferation of multidrug-resistant pathogens. Owing to the mobility and ubiquity of aquatic ecosystems, ARG contamination in water environments is particularly pronounced. These genes can disseminate across diverse systems (e.g., oceans, groundwater, and municipal water supplies) via hydrological cycles, fostering the proliferation of drug-resistant bacteria. For human populations, the rampant emergence and dissemination of resistant bacteria, especially pathogenic strains, represent a grave menace to public health, precipitating critical healthcare concerns. Pathogens harboring ARGs, such as *Listeria*, *Aeromonas*, and *Clostridium* species, are zoonotic agents capable of inducing foodborne infections.

With the rapid expansion of the global aquaculture industry, coupled with increasing stocking densities and the pervasive use of antibiotics, the accumulation of ARBs and ARGs in aquaculture water bodies has become an escalating concern. ARGs not only undergo stable vertical transmission within bacterial populations but also disseminate horizontally across distinct bacterial taxa via horizontal gene transfer (HGT), perpetuating the spread of resistance determinants within environmental microbial communities. This process facilitates the entry of ARGs into natural ecosystems and potentially the human food chain through aquatic cycling, posing an insidious threat to public health. Therefore, in-depth investigations into the transmission mechanisms and influencing factors governing ARGs in aquaculture environments are pivotal for elucidating the dissemination dynamics of environmental resistance genes and formulating targeted pollution mitigation strategies.

Distribution and risks of ARGs in aquaculture

Against the backdrop of the continuous development of the global aquaculture industry, global aquaculture production exhibited an overall upward trend from 2008 to 2020. By 2022, global aquaculture production had reached 130.9 million tons [1]. Data released by the Food and Agriculture Organization (FAO) indicates that among the top-ranked countries in global aquaculture production in 2024, China ranked first, and together with the other 9 major producing countries, accounted for 89.8% of global aquaculture production.

With the substantial growth in demand for aquatic products, intensive aquaculture models have become the primary approach in modern aquaculture. To prevent and treat various fish diseases, large quantities of antibiotics are commonly used in aquaculture. The excessive use of antibiotics in aquaculture has led to antibiotic residue pollution in aquaculture water bodies and accelerated the development of antibiotic resistance in farmed fish and the aquaculture environment [2].

Meanwhile, residual antibiotics gradually accumulate in water and sediments, exerting persistent antibiotic selection pressure on local bacterial communities. Bacteria acquire ARGs through random chromosomal mutations, develop drug resistance, and transmit ARGs to bacteria in the environment, thereby increasing the levels of antibiotic resistance in aquaculture production environments and their surroundings [3]. Studies have shown that the proliferation of ARB containing ARGs in the environment will increase the migration, transformation, and dissemination of ARGs among environmental microorganisms, ultimately leading to the environment becoming a natural reservoir for various ARGs [4].

In aquaculture practice, a wide range of antibiotics are used, covering multiple drug categories, such as β-lactams, chloramphenicols, macrolides, and tetracyclines, totaling more than twenty types, while the main antibiotic resistance genes detected in aquaculture water are tetracycline, macrolide, quinolone, and sulfonamide resistance genes [5-7]. A recent study using metagenomic sequencing and other omics methods found the widespread presence of tetracycline, sulfonamide, and macrolide-lincosamide-streptogramin resistance genes in aquaculture wastewater [8].

Particularly in China, multi-species intensive pond aquaculture is one of the important aquaculture methods to increase aquatic product yield and economic benefits. This aquaculture model carries the risk of generating and transmitting ARGs [9]. In recent years, ARGs have been detected in aquaculture environments across various regions, as shown in Table 1 [10-13].

Table 1. Detection of antibiotic resistance genes in aquaculture.

Location	Antibiotic resistance genes	References
Estuarine Aquaculture Area of Hangzhou Bay	*sul1*, *sul2*, *tetA*, *tetB*, *tetC*, *tetM*, *qnrS*, *floR*	[10]
Recirculating Mariculture System in Yantai	*tetB*, *tetG*, *tetX*, *sul1*, *sul2*, *qnrA*, *qnrB*, *qnrS*, *ermF*	[11]
Pond Aquaculture Around Honghu Lake, Hubei Province	*qnrB*, *tetX*, *sul1*, *tetB*, *sul2*, *floR*, *cat1*, *tetG*, *qnrS*, *cmlA*, *ermF*, *qnrA*, *ermT*	[12]
Mariculture System in Qionghai, Hainan Province	*sul1*, *sul2*, *tetB*, *tetC*, *tetG*, *cmlA*, *ereA*, *floR*	[13]

In the environment, ARGs exhibit persistence, mobility, and transmissibility. Notably, the spread of ARGs from non-pathogenic bacteria to pathogens may pose greater ecotoxicological effects and environmental health risks than antibiotics themselves [14]. The environmental dissemination of ARGs is jointly influenced by natural factors and human activities. Anthropogenic activity areas such as aquaculture, wastewater treatment, and livestock and poultry farming, as well as natural environments such as water sources, plants, and animals, may all participate in their transmission process, thereby posing potential risks to ecosystems and human and animal health [15]. Furthermore, studies have found that a large number of fish pathogens carrying ARGs (such as *Listeria*, *Aeromonas*, and *Clostridium*) are zoonotic pathogens that may cause foodborne infections [16]. It is estimated that by 2050, the increase in antibiotic resistance is projected to cause 10 million deaths annually and result in global costs of up to US$100 trillion [17].

Transmission mechanisms of ARGs

Bacteria acquire antibiotic resistance through two primary mechanisms: spontaneous gene mutations that generate ARGs, and horizontal gene transfer (HGT) that enables the acquisition of ARGs from external sources. The former is primarily propagated to progeny via vertical gene transfer (VGT), whereas the latter possesses greater potential for rapid ARG dissemination, facilitating transfer between distinct bacterial strains and even across different species [18]. Drug-resistant bacteria can acquire exogenous ARGs through HGT, evolving into multidrug-resistant strains with resistance to multiple antibiotics. HGT refers to the transfer of genetic material between conspecific or heterologous organisms, encompassing conjugation, transformation, and transduction.

(1) Conjugation involves the direct contact between donor and recipient bacteria, followed by the transfer of mobile genetic elements (typically plasmids or transposons) from the donor to the recipient via a conjugation bridge. Plasmids carrying ARGs can be transmitted to other strains, even to bacterial populations belonging to different genera [19].

(2) Natural transformation occurs when bacteria directly uptake free deoxyribonucleic acid (DNA) from the environment and acquire corresponding genetic traits. For transformation to occur, the cell membrane must undergo changes in permeability, i.e., the membrane must enter a receptive state [20].

(3) Transduction involves the transfer of DNA from donor cells to recipient cells via phage infection, resulting in genetic alterations in the recipient cells. The recipient bacteria acquire the donor DNA fragment carried by the phage vector and obtains the corresponding genetic traits [21].

Application of disinfectants in aquaculture

Disinfectants play a crucial role in aquaculture by eliminating pathogenic microorganisms in the environment, interrupting disease transmission pathways, and in some cases, removing organic waste and mitigating malodors [22]. Common disinfectant categories include nanoscale heavy metals, quaternary ammonium compounds, peroxides, guanidines, organic halogens, and alcohols. These agents exert potent antimicrobial and bactericidal effects through mechanisms such as enhancing bacterial membrane permeability, interfering with enzymatic systems, and inducing protein coagulation and denaturation [23]. Ozone (O_3), a strong oxidant with broad-spectrum antimicrobial activity, has been widely utilized in water treatment to reduce microbial loads, oxidize organic compounds, and control odors. In Pacific white shrimp culture systems, ozone application has been shown to achieve stable ammonia removal rates ranging from 5-50 mg/h [24]. Hydrogen peroxide (H_2O_2) is commonly employed as a biocide in recirculating aquaculture systems (RAS) to control microbial pathogen populations, prevent fish diseases, and remove organic carbon and odor-causing compounds. Studies have demonstrated that H_2O_2 treatment at a concentration of 0.15 μL/L effectively reduces dissolved organic carbon (DOC) and odor compounds, primarily geosmin and 2-methylisoborneol, in recirculating water systems [25]. Additionally, H_2O_2 has been utilized to enhance dissolved oxygen (DO) levels, maintain water quality, improve production performance, and eliminate pathogenic bacteria through accelerated nutrient decomposition [26].

Nanoscale heavy metal disinfectants are widely utilized in aquaculture due to their broad-spectrum activity, but their persistent nature leads to environmental accumulation and potential ecological risks. Nanomaterials have found extensive applications in aquaculture due to their unique physicochemical properties, including high surface area, excellent drug loading capacity, and adsorption capabilities [27]. These applications span multiple domains, including feed nutrition enhancement, disease management, water quality regulation, and environmental remediation, with promising results demonstrated in empirical studies. Nanoparticles exhibit significant potential in inhibiting microbial growth, offering novel strategies for fish disease management. For instance, silver nanoparticles (Ag NPs) have been shown to significantly reduce the viability of fish pathogens such as Aeromonas hydrophila [28]. Furthermore, numerous studies have documented the efficacy of nanoparticles (e.g., silver, copper, and zinc), titanium dioxide, graphene, and carbon nanotubes in controlling microbial infections in aquaculture systems [29]. Combinations of graphene oxide nanoparticles (GO NPs) and CuO NPs (GO-CuO-NPs) at a concentration of 3 mg/mL exhibit potent activity against Escherichia coli and Salmonella typhimurium [30]. Biologically derived selenium nanoparticles (Se NPs) at a concentration of 75 μg/mL demonstrate strong antibiofilm activity against Aeromonas hydrophila and Vibrio harveyi [31].

In addition to antimicrobial applications, nanomaterials are increasingly being utilized to enhance feed nutrition and promote aquatic organism growth. Research has demonstrated the efficacy of Se NPs in red sea bream diets, with supplementation levels of 1-2 mg Se NPs per kilogram of feed shown to improve fish growth rates and survival rates [32]. Another study reported significant improvements in growth performance and modulation of beneficial gut microbiota in zebrafish fed diets supplemented with Se NPs [33]. Iron oxide nanoparticles have also been shown to promote fish growth and enhance immune function, offering dual benefits for health management and environmental remediation [34].

Effects of disinfectants on the HGT of ARGs

Disinfectants, particularly commonly used types such as chlorine-based compounds, alcohols, quaternary ammonium salts, and H_2O_2, have been widely employed in hospitals, the food industry, and public health settings. However, most non-biodegradable disinfectants are discharged into wastewater treatment plants and receiving water bodies, leading to environmental accumulation of these chemicals [35]. Studies have demonstrated that chloramine and free chlorine can enhance the natural transformation efficiency of ARGs in *Acinetobacter baylyi* ADP1 (*A. Baylyi* ADP1) bacteria through oxidative stress pathways mediated by reactive oxygen species (ROS), with increases of over 10.00-fold compared to control groups [36].

Guanidine-based disinfectants are extensively utilized due to their broad-spectrum antimicrobial efficacy and safety. Research has shown that exposure to 0.1-1.0 mg/L polyhexamethylene biguanide hydrochloride and polyhexamethylene guanidine hydrochloride increases the conjugative transfer frequency of the RP4-7 plasmid from Escherichia coliDH5α to Escherichia coliEC600 by 1.3-2.50-fold and 1.10-3.90-fold, respectively. These disinfectants also induce reactive oxygen species production, trigger the SOS response, enhance membrane permeability, upregulate global regulatory genes and DNA transfer/replication processes, and promote energy metabolism. Additionally, treatment with chloramine, free chlorine, and H_2O_2 at concentrations of 0.1-1.0, 0.1-1.0, and 0.2-3.0 mg/L, respectively, has been found to increase the conjugative transfer frequency of the pCM184-Cm plasmid from *Escherichia coli* S17-1 to *Escherichia coli* K-12 by 1.9-7.50-fold, 3.40-6.40-fold, and 1.40-5.40-fold, respectively. Intergeneric conjugative transfer to *Salmonella typhimurium* has also been enhanced by 1.40-2.30-fold [37].

The widespread application of nanomaterials in aquaculture, industry, agriculture, and other fields has led to significant residual contamination in the environment. Amid the challenge of widespread antibiotic resistance, nanomaterials are rapidly gaining attention due to their unique antimicrobial properties, such as those exhibited by CuO NPs, ZnO NPs, Ag NPs, and TiO_2 NPs [38]. Nanomaterials can inhibit bacterial growth and reproduction by disrupting cell membrane structures, blocking metabolic processes, and directly damaging bacterial DNA, among other mechanisms. However, they can also induce adaptive changes in bacteria or facilitate the acquisition of antibiotic resistance through HGT pathways [39]. Studies have reported that metal nanomaterials such as CuO NPs and Ag NPs can promote the HGT of ARGs [40,41]. Exposure to 5 μmol/L CuO NPs increases the interspecies conjugative transfer frequency of the RP4 plasmid by 2.00-fold, and extending the treatment duration from 8 to 24 hours further enhances this transfer frequency by 4.00-fold. This effect may be attributed to the global SOS response induced by DNA damage and the increased cell membrane permeability caused by CuO NPs. In conclusion, as environmental residues of disinfectants increase, greater attention should be paid to the risk of resistance gene dissemination.

Effects of disinfectants on ARGs in the environment

The extensive use of disinfectants has led to their widespread persistence in the environment, which has been shown to exert direct impacts on environmental ARGs. Multiple disinfectants have been demonstrated to influence ARG dissemination [42]. Notably, no significant changes were observed following 21 days of exposure to 10.0 and 100.0 mg/L ZnO NPs, whereas the abundances of sul1, sul2, and aadA1 in landfill leachate increased dramatically within 7 days under 500.0 mg/L ZnO NP stress [43]. Additionally, the abundance of ARGs in tap water increased by 6.4 to 109.20-fold after chlorination treatment, with six transposase-encoding genes detected. Studies have found that the abundance of tetracycline resistance genes in activated sludge exposed to 10 μg/L polystyrene (PS) NPs was 1.09 times higher than in the control group, and PS NPs were shown to significantly increase the relative abundance of sulfonamide resistance genes (*sul1*) by 2.28-3.25-fold in sludge [44,45]. Low-dose chlorine has been found to significantly increase the abundance and transcriptional activity of ARGs, particularly promoting the enrichment of β-lactam, multidrug, and tetracycline resistance genes, while activating ARG-carrying hosts and enhancing plasmid-mediated HGT [46]. Various types of disinfectants have been investigated in studies, with many reported to alter the abundance of ARGs in the environment, most commonly promoting their enrichment and posing significant health threats.

Effects of disinfectants on environmental microbial communities

Microbial communities are closely associated with ARGs, as bacteria within these communities can harbor ARGs, indicating that the diversity and structure of microbial communities directly influence the dissemination of ARGs. Selective pressures resulting from residual disinfectants in the environment can impact environmental microbial communities. Studies have demonstrated that treatment with Al_2O_3 NPs, CuO NPs, and ZnO NPs reduces bacterial community diversity and affects the abundance of mobile genetic elements (MGEs), thereby altering host bacterial populations and influencing ARG dissemination [47]. Additionally, recent research has shown that treatment with non-spherical polyethylene nanoparticles (PE NPs) further simultaneously increases the abundance and diversity of ARGs in rhizosphere soil, with a shift in the primary bacterial hosts of ARGs toward higher-risk potential pathogenic taxa, particularly *Pseudomonas aeruginosa* [48]. Disinfectants also alter environmental microbial community structure; studies have found that chlorine and chloramine treatment reduce microbial community diversity and restructure microbial communities, enriching certain bacterial taxa such as Mycobacterium and Sphingomonas, and increasing the proportion of primary host bacteria for ARGs and MGEs, thereby enhancing ARG abundance [49]. The combined use of nanomaterials and disinfectants also modifies microbial community structure. A study showed that the composite disinfectant HPS, consisting of H_2O_2 and Ag NPs, influences the intestinal microbial community of shrimp and the microbial community in rearing water. HPS use reduces Vibrio populations and total bacterial counts in rearing water, with Vibrio and Pseudomonas aeruginosa becoming the dominant bacterial groups in water samples [50]. In conclusion, disinfectants may alter the structure of environmental microbial communities, thereby changing the host bacteria of ARGs and influencing ARG dissemination. Furthermore, the acquisition of antibiotic resistance by more pathogenic bacteria poses significant human health risks.

Conclusion

In summary, this study systematically reveals the overlooked role of disinfectant residues in facilitating the dissemination of ARGs within aquaculture environments. The key findings are threefold. First, disinfectants, including chloramine, free chlorine, hydrogen peroxide, guanidine-based compounds, and metal-based nanoparticles, at environmentally relevant concentrations significantly enhance HGT of ARGs via mechanisms involving oxidative stress, SOS response, and increased membrane permeability. Second, sublethal disinfectant exposure consistently elevates the absolute or relative abundance of diverse ARGs (e.g., tetracycline, sulfonamide, and β-lactam resistance genes) and MGEs, indicating that disinfectants not only co-select for resistance but also promote ARG mobility. Third, disinfectant-induced shifts in microbial community structure - marked by reduced diversity and enrichment of specific taxa (e.g., Mycobacterium, Pseudomonas aeruginosa) - redirect ARG hosts toward potentially pathogenic bacteria, thereby amplifying public health risks.

Collectively, these findings challenge the conventional view that disinfectants solely mitigate microbial contamination. Instead, disinfectant residues, especially from intensive aquaculture practices, may create a "selection-dispersion" feedback loop when combined with antibiotic pressure, turning aquaculture systems into reservoirs of multidrug resistance. Given the potential entry of such resistance into natural ecosystems and the human food chain, we advocate for integrating disinfectant residues into environmental risk assessment frameworks for antimicrobial resistance (AMR). Future efforts should prioritize developing degradable, low-residue disinfectants that do not induce HGT, alongside establishing surveillance systems that jointly monitor antibiotics, disinfectants, ARGs, and microbial community dynamics in aquaculture.

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Conflicts of Interest

The author declares no conflict of interest.

References

[1] Adenaya, A., Berger, M., Brinkhoff, T., Ribas-Ribas, M., Wurl, O. (2023) Usage of antibiotics in aquaculture and the impact on coastal waters. *Marine Pollution Bulletin*, 188, 114645.

[2] Okeke, E. S., Chukwudozie, K. I., Nyaruaba, R., Ita, R. E., Oladipo, A., Ejeromedoghene, O., Atakpa, E. O., Agu, C. V., Okoye, C. O. (2022) Antibiotic resistance in aquaculture and aquatic organisms: a review of current nanotechnology applications for sustainable management. *Environmental Science and Pollution Research*, 29(46), 69241-69274.

[3] Petchiappan, A., Chatterji, D. (2017) Antibiotic resistance: current perspectives. *ACS Omega*, 2(10), 7400-7409.

[4] Vass, M., Abramova, A., Bengtsson-Palme, J. (2026) Antimicrobial resistance dissemination via horizontal gene transfer is constrained in stratified waters. *Communications Biology*, 9, 435

[5] Bondad-Reantaso, M. G., MacKinnon, B., Karunasagar, I., Fridman, S., Alday-Sanz, V., Brun, E., Le Groumellec, M., Li, A., Surachetpong, W., Karunasagar, I., Hao, B., Dall'Occo, A., Urbani, R., Caputo, A. (2023) Review of alternatives to antibiotic use in aquaculture. *Reviews in Aquaculture*, 15(4), 1421-1451.

[6] Liu, X., Wang, H., Zhao, H. (2020) Propagation of antibiotic resistance genes in an industrial recirculating aquaculture system located at northern China. *Environmental Pollution*, 261, 114155.

[7] Yuan, X., Lv, Z., Zhang, Z., Han, Y., Liu, Z., Zhang, H. (2023) A review of antibiotics, antibiotic resistant bacteria, and resistance genes in aquaculture: occurrence, contamination, and transmission. *Toxics*, 11(5), 420.

[8] He, Y., Yuan, Q., Mathieu, J., Stadler, L., Senehi, N., Sun, R., Alvarez, P. J. (2020) Antibiotic resistance genes from livestock waste: occurrence, dissemination, and treatment. *NPJ Clean Water*, 3(1), 4.

[9] Huang, L., Xu, Y. B., Xu, J. X., Ling, J. Y., Chen, J. L., Zhou, J. L., Zheng, L., Du, Q. P. (2017) Antibiotic resistance genes (ARGs) in duck and fish production ponds with integrated or non-integrated mode. *Chemosphere*, 168, 1107-1114.

[10] Yuan, J., Ni, M., Liu, M., Zheng, Y., Gu, Z. (2019) Occurrence of antibiotics and antibiotic resistance genes in a typical estuary aquaculture region of Hangzhou Bay, China. *Marine Pollution Bulletin*, 138, 376-384.

[11] Wang, J. H., Lu, J., Wu, J., Zhang, Y., Zhang, C. (2019) Proliferation of antibiotic resistance genes in coastal recirculating mariculture system. *Environmental Pollution*, 248, 462-470.

[12] Wang, Q., Mao, C., Lei, L., Yan, B., Yuan, J., Guo, Y., Li, T., Xiong, X., Cao, X., Han, J., Ke, Y., Zhou, B. (2022) Antibiotic resistance genes and their links with bacteria and environmental factors in three predominant freshwater aquaculture modes. *Ecotoxicology and Environmental Safety*, 241,

113832.

[13] He, L. X., He, L. Y., Gao, F. Z., Wu, D. L., Ye, P., Cheng, Y. X., Chen, Z. Y., Hu, L. X., Liu, Y. S., Chen, J., Ying, G. G. (2022) Antibiotics, antibiotic resistance genes and microbial community in grouper mariculture. *Science of the Total Environment*, 808, 152042.

[14] Zhao, W., Wang, B., Yu, G. (2018) Antibiotic resistance genes in China: occurrence, risk, and correlation among different parameters. *Environmental Science and Pollution Research*, 25(22), 21467-21482.

[15] Pan, Y., Gao, S. H., Dai, Z., Li, T., Gao, R., Xie, J., Wang, A. (2026) Multidrug-resistant and various high-risk ARGs in wastewater effluent exhibit nonnegligible AMR risks. *Water Research*, 125616.

[16] Fu, S., Wang, Q., Wang, R., Zhang, Y., Lan, R., He, F., Yang, Q. (2022) Horizontal transfer of antibiotic resistance genes within the bacterial communities in aquacultural environment. *Science of the Total Environment*, 820, 153286.

[17] Darby, E. M., Trampari, E., Siasat, P., Gaya, M. S., Alav, I., Webber, M. A., Blair, J. M. (2023) Molecular mechanisms of antibiotic resistance revisited. *Nature Reviews Microbiology*, 21(5), 280-295.

[18] Andam, C. P., Fournier, G. P., Gogarten, J. P. (2011) Multilevel populations and the evolution of antibiotic resistance through horizontal gene transfer. *FEMS Microbiology Reviews*, 35(5), 756-767.

[19] Soucy, S. M., Huang, J., Gogarten, J. P. (2015) Horizontal gene transfer: building the web of life. *Nature Reviews Genetics*, 16(8), 472-482.

[20] Johnston, C., Martin, B., Fichant, G., Polard, P., Claverys, J. P. (2014) Bacterial transformation: distribution, shared mechanisms and divergent control. *Nature Reviews Microbiology*, 12(3), 181-196.

[21] Zhang, J., He, X., Shen, S., Shi, M., Zhou, Q., Liu, J., Wang, M., Sun, Y. (2021) Effects of the newly isolated T4-like phage on transmission of plasmid-borne antibiotic resistance genes via generalized transduction. *Viruses*, 13(10), 2070.

[22] Zhu, Z., Gross, A., Brown, P. B., Luo, G. (2025) Disinfection by-products in aquaculture: sources, impacts, removal and future research. *Reviews in Aquaculture*, 17(3), e70035.

[23] Zhu, S., Yang, B., Jia, Y., Yu, F., Wang, Z., Liu, Y. (2023) Comprehensive analysis of disinfectants on the horizontal transfer of antibiotic resistance genes. *Journal of Hazardous Materials*, 453, 131428.

[24] Aguilar-Alarcón, P., Zherebker, A., Rubekina, A., Shirshin, E., Simonsen, M. A., Kolarevic, J., Lazado, J., Nikolaev, E. N., Asimakopoulos, A. G., Mikkelsen, Ø. (2022) Impact of ozone treatment on dissolved organic matter in land-based recirculating aquaculture systems studied by Fourier transform ion cyclotron resonance mass spectrometry. *Science of The Total Environment*, 843, 157009.

[25] Pettersson, S. J., Lindholm-Lehto, P. C., Pulkkinen, J. T., Kiuru, T., Vielma, J. (2022) Effect of ozone and hydrogen peroxide on off-flavor compounds and water quality in a recirculating aquaculture system. *Aquacultural Engineering*, 98, 102277.

[26] Bögner, D., Bögner, M., Schmachtl, F., Bill, N., Halfer, J., Slater, M. J. (2021) Hydrogen peroxide oxygenation and disinfection capacity in recirculating aquaculture systems. *Aquacultural Engineering*, 92, 102140.

[27] Fajardo, C., Martinez-Rodriguez, G., Blasco, J., Mancera, J. M., Thomas, B., De Donato, M. (2022) Nanotechnology in aquaculture: applications, perspectives and regulatory challenges. *Aquaculture and Fisheries*, 7(2), 185-200.

[28] Kakakhel, M. A., Zaheer Ud Din, S., Wang, W. (2022) Evaluation of the antibacterial influence of silver nanoparticles against fish pathogenic bacterial isolates and their toxicity against common carp fish. *Microscopy Research and Technique*, 85(4), 1282-1288.

[29] Wang, M., Li, S., Chen, Z., Zhu, J., Hao, W., Jia, G., Chen, W., Zheng, Y., Qu, W., Liu, Y. (2021) Safety assessment of nanoparticles in food: current status and prospective. *Nano Today*, 39, 101169.

[30] Rajapaksha, P., Cheeseman, S., Hombsch, S., Murdoch, B. J., Gangadoo, S., Blanch, E. W., Truong, Y., Cozzolino, D., McConville, C. F., Crawford, R. J., Truong, V. K., Elbourne, A., Chapman, J. (2019) Antibacterial properties of graphene oxide-copper oxide nanoparticle nanocomposites. *ACS Applied Bio Materials*, 2(12),

5687-5696.

[31] Abid, N., Khan, A. M., Shujait, S., Chaudhary, K., Ikram, M., Imran, M., Haider, J., Khan, M., Khan, Q., Maqbool, M. (2022) Synthesis of nanomaterials using various top-down and bottom-up approaches, influencing factors, advantages, and disadvantages: a review. *Advances in Colloid and Interface Science*, 300, 102597.

[32] Dawood, M. A., Koshio, S., Zaineldin, A. I., Van Doan, H., Moustafa, E. M., Abdel-Daim, M. M., Esteban, M. A., Hassaan, M. S. (2019) Dietary supplementation of selenium nanoparticles modulated systemic and mucosal immune status and stress resistance of red sea bream (Pagrus major). *Fish Physiology and Biochemistry*, 45(1), 219-230.

[33] Anwar, Z., Ye, C., Wang, M., Zeng, S., Gao, M., Guo, S., Kakakhel, M. A., Hu, B., Zhao, G., Hong, Y. (2024) Effects of dietary selenium on growth performance, antioxidant status, and gut microbial diversity of zebrafish (Danio rerio). *Aquaculture Reports*, 37, 102276.

[34] Nwanna, L. C., Ikuesan, B. B. (2025) Aloe vera leaf (Aloe barbadensis) iron-oxide nanoparticles improved growth performance, immune response and survival of African sharptooth catfish (Clarias gariepinus) challenged with Aeromonas hydrophilia. *Journal of Applied Aquaculture*, 37(2), 208-225.

[35] Hu, Z., Yang, L., Liu, Z., Han, J., Zhao, Y., Jin, Y., Sheng, Y., Zhu, L., Hu, B. (2023) Excessive disinfection aggravated the environmental prevalence of antimicrobial resistance during COVID-19 pandemic. *Science of the Total Environment*, 882, 163598.

[36] Zhang, S., Wang, Y., Lu, J., Yu, Z., Song, H., Bond, P. L., Guo, J. (2021) Chlorine disinfection facilitates natural transformation through ROS-mediated oxidative stress. *The ISME Journal*, 15(10), 2969-2985.

[37] Zhang, Y., Gu, A. Z., He, M., Li, D., Chen, J. (2017) Subinhibitory concentrations of disinfectants promote the horizontal transfer of multidrug resistance genes within and across genera. *Environmental Science & Technology*, 51(1), 570-580.

[38] Wu, G., Guo, W., Fan, N., Jin, R. (2025) A critical review of antibiotic resistance genes transmission driven by non-antibiotic pollutants: roles and molecular mechanisms. *Frontiers of Environmental Science & Engineering*, 19(9), 123.

[39] Jin, C., Cao, J., Zhang, K., Zhang, X., Cao, Z., Zou, W. (2023) Promotion effects and mechanisms of molybdenum disulfide on the propagation of antibiotic resistance genes in soil. *Ecotoxicology and Environmental Safety*, 256, 114913.

[40] Zhang, S., Wang, Y., Song, H., Lu, J., Yuan, Z., Guo, J. (2019) Copper nanoparticles and copper ions promote horizontal transfer of plasmid-mediated multi-antibiotic resistance genes across bacterial genera. *Environment International*, 129, 478-487.

[41] Lu, J., Wang, Y., Jin, M., Yuan, Z., Bond, P., Guo, J. (2020) Both silver ions and silver nanoparticles facilitate the horizontal transfer of plasmid-mediated antibiotic resistance genes. *Water Research*, 169, 115229.

[42] Wang, X., Li, J., Pan, X. (2024) How micro-/nano-plastics influence the horizontal transfer of antibiotic resistance genes-a review. *Science of the Total Environment*, 944, 173881.

[43] Shi, J., Su, Y., Zhang, Z., Wei, H., Xie, B. (2019) How do zinc oxide and zero valent iron nanoparticles impact the occurrence of antibiotic resistance genes in landfill leachate? *Environmental Science: Nano*, 6(7), 2141-2151.

[44] Zhou, C. S., Wu, J. W., Liu, B. F., Ma, W. L., Yang, S. S., Cao, G. L. (2022) (Micro) nanoplastics promote the risk of antibiotic resistance gene propagation in biological phosphorus removal system. *Journal of Hazardous Materials*, 431, 128547.

[45] Azizi, S. M. M., Haffiez, N., Zakaria, B. S., Dhar, B. R. (2022) Thermal hydrolysis of sludge counteracts polystyrene nanoplastics-induced stress during anaerobic digestion. *ACS Es&T Engineering*, 2(7), 1306-1315.

[46] Meng, Q., Wang, J., Li, K., Zhang, Y., Hu, Z., Wang, F., Pan, F., Fu, J., Dang, C. (2025) Low-dose chlorine disinfection poses a greater potential risk of antibiotic resistance genes (ARGs) and their pathogenic hosts. *Water Research*, 124895.

[47] Zhang, Y., Xu, R., Xiang, Y., Lu, Y., Jia, M., Huang,

J., Xu, Z., Cao, J., Xiong, W., Yang, Z. (2021) Addition of nanoparticles increases the abundance of mobile genetic elements and changes microbial community in the sludge anaerobic digestion system. *Journal of Hazardous Materials*, 405, 124206.

[48] Liu, B., Wang, S., Ren, J., Zhang, Z., Ma, J., Li, T., Zhou, Q., Sun, J. (2025) Impacts of non-spherical polyethylene nanoplastics on microbial communities and antibiotic resistance genes in the rhizosphere of pea (Pisum sativum L.): an integrated metagenomic and metabolomic analysis. *Journal of Hazardous Materials*, 140425.

[49] Ke, Y., Sun, W., Chen, Z., Zhu, Y., Chen, X., Yan, S., Li, Y., Xie, S. (2024) Effects of disinfectant type and dosage on biofilm's activity, viability, microbiome and antibiotic resistome in bench-scale drinking water distribution systems. *Water Research*, 249, 120958.

[50] Hou, D., Lin, Z., Zhou, J., Xue, Y., Sun, C. (2023) Germicidal effect of hydrogen peroxide nano-silver ion composite disinfectant and its effect on the microbial community of shrimp intestine and rearing water. *Frontiers in Marine Science*, 10, 1189013.