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Microplastic-Pharmaceutical Interactions and Their Disruptive Impact on UV and Chemical Water Disinfection Efficacy

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Abstract

The presence of microplastics originating from pharmaceutical coatings represents an emerging concern in water quality management, particularly in the context of conventional disinfection methods. This conceptual paper explores the disruptive interactions between pharmaceutical-derived microplastics and two widely adopted water disinfection systems—ultraviolet (UV) irradiation and chemical oxidation (e.g., chlorination, ozonation). It proposes that these microplastics, due to their unique chemical composition, size, and surface morphology, may interfere with the efficacy of disinfection processes through three primary mechanisms: physical shielding, contaminant adsorption, and catalytic transformation. Firstly, the structural attributes of microplastics can create a physical barrier that shields pathogenic microorganisms from direct UV exposure or chemical contact, leading to suboptimal inactivation. Secondly, microplastics possess high surface-area-to-volume ratios and hydrophobic properties that enable the adsorption of both disinfectants and microbial contaminants, potentially reducing free disinfectant availability while fostering microbial persistence and biofilm formation. Thirdly, additives and degradation by-products from pharmaceutical coatings embedded in the microplastics may act as catalysts, altering redox reactions during chemical disinfection and generating disinfection by-products (DBPs) with uncertain toxicological implications. Furthermore, these interactions are theorized to vary depending on the physicochemical properties of the pharmaceutical polymers, environmental conditions such as pH and temperature, and the presence of co-contaminants. The paper underscores the urgent need for targeted empirical studies to validate these hypothesized mechanisms, evaluate the cumulative impact on microbial inactivation efficiency, and assess potential risks to human health and ecosystem stability. In doing so, it calls for the development of refined detection techniques, integrated water quality monitoring frameworks, and innovative pretreatment strategies to address microplastic-pharmaceutical interference. By providing a foundational conceptual model, this study contributes to the growing discourse on emerging pollutants in aquatic systems and offers a roadmap for future research to ensure the robustness of water treatment protocols. It advocates for cross-disciplinary collaboration to enhance the resilience of public water infrastructure in the face of complex, synthetic contaminants.

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1. Introduction

Antimicrobial resistance (AMR) is a complex phenomenon that extends beyond clinical settings and into natural ecosystems, including aquatic environments. The introduction of pharmaceutical residues, particularly antibiotics, into freshwater systems creates ecological pressures that accelerate the development of resistance (Adeoba, Tesfamichael & Yessoufou, 2019). Studies have highlighted that sub-inhibitory concentrations of antibiotics, commonly found in rivers, lakes, and effluents from wastewater treatment facilities, exert significant selective pressure on microbial populations.

This selective pressure allows resistant bacterial strains to emerge and proliferate rather than leading to the outright elimination of sensitive strains (Komijani *et al*., 2022). Prolonged exposure to low antibiotic concentrations enhances mutation rates and can activate stress response pathways, altering gene expression in bacteria to favor survival under antibiotic stress (Komijani *et al*., 2022; Håkonsholm *et al*., 2023).

Unlike the acute dosages used in clinical treatments aimed at eradicating bacteria, the diluted antibiotic concentrations found in aquatic environments can persist for extended periods. Sources of these residues include hospital waste, agricultural runoff, and urban wastewater, where degradation during wastewater treatment is often limited, allowing antibiotics to persist and pose threats to microbial health (Chianumba, *et al*., 2023, Ezeamii, *et al*., 2023, Ogbuagu, *et al*., 2023). Even at nanogram or microgram levels per liter, these concentrations can induce mutations and encourage the survival of antibiotic-resistant variants (Vats *et al*., 2022; Nguyen *et al*., 2023). Laboratory investigations indicate that sub-inhibitory levels are more effective in selecting for resistant bacteria compared to higher concentrations, which typically lead to cell lysis.

Horizontal gene transfer (HGT) is a key mechanism for the transmission of antibiotic resistance genes (ARGs) in aquatic systems, facilitating the rapid acquisition of resistance traits across bacterial species. This process occurs through transformation, transduction, or conjugation and is enhanced by the rich organic matter and diverse microbial communities prevalent in aquatic environments (Kolawole, *et al*., 2023, Mgbecheta, *et al*., 2023, Ogbuagu, *et al*., 2023). Wastewater treatment plants and contaminated waterways serve as sites where multiple bacterial strains, including pathogenic and environmental, can coexist and exchange genetic material, often exacerbated by the presence of antibiotics and other environmental stressors (Zhu *et al*., 2023). Biofilms and sediments contribute to the persistence of AMR by providing protective niches for bacteria that promote gene transfer and resistance evolution, sustaining higher concentrations of ARGs compared to surrounding waters (Muhammad *et al*., 2020; Adekanmbi *et al*., 2021).

Additionally, sediments and biofilms function as reservoirs for ARGs and antibiotic-resistant bacteria, creating microenvironments where resistance genes can endure over time. The binding of antibiotics to particulate matter leads to sedimentation, resulting in prolonged local concentrations that contribute to selective pressures (Pokharel *et al*., 2022. When disturbed, sediments can resuspend resistant populations back into the water column, facilitating the broader dissemination of resistance traits into surrounding environments (Islam *et al*., 2023; McNeilly *et al*., 2021). The interplay of environmental factors, such as nutrient availability and various pollutants, fosters conditions that support the survival and proliferation of ARGs and the development of complex, multi-drug resistant microbial communities (Zheng *et al*., 2021; Palm *et al*., 2022).

The implications of AMR in aquatic systems extend beyond microbial health, influencing wider ecological and human health domains. Aquatic organisms can act as reservoirs for resistant bacteria, aiding in their transmission through food webs and recreational activities, effectively acting as vectors of resistance into human populations (Komijani *et al*., 2022; Palm *et al*., 2022).

Addressing AMR within aquatic contexts necessitates comprehensive strategies that include advanced wastewater treatment options, enhanced monitoring of ARGs, and integrative policies linking public health, environmental stewardship, and responsible antibiotic use (Silva *et al*., 2022). By elucidating the mechanisms and pathways driving AMR emergence in these environments, stakeholders can formulate more effective interventions to mitigate the spread of resistance and safeguard both environmental and human health (Chianumba, *et al*., 2022, Matthew, Akinwale & Opia, 2022).

2. Methodology

The study employed a mixed-methods research design to investigate the disruptive effects of microplastic–pharmaceutical interactions on UV and chemical disinfection processes in aquatic systems. Initially, peer-reviewed literature was systematically sourced using databases such as PubMed, Scopus, and Web of Science, focusing on interactions involving microplastics, pharmaceutical residues, and water treatment efficiency. Studies such as Arienzo & Donadio (2023) and Atugoda *et al.* (2021) provided foundational knowledge on the physicochemical dynamics between micropollutants, highlighting how pharmaceutical residues sorb onto polymer surfaces and interfere with UV penetration and oxidative disinfection reactions.

To support this conceptual framework, phylogenetic and toxicological insights from Adeoba *et al.* (2018) and Menéndez-Pedriza & Jaumot (2020) were integrated to understand the ecological pathways of resistance gene proliferation. Risk assessments from Björklund & Svahn (2021) and Giunchi *et al.* (2023) guided the mapping of pharmaceutical hotspots and environmental contamination patterns. Furthermore, data from activated carbon remediation trials (Aheghmoalla & Mehrvar, 2023) and biofilm-based resistance modulation (Pokharel *et al*., 2022; Muhammad *et al*., 2020) supported assumptions on microplastic-induced shielding during disinfection.

Simulation models were developed to predict the interference potential under varying contaminant load scenarios. Machine learning techniques were applied to analyze historical datasets from wastewater and riverine systems (Macedo *et al*., 2021; Sun *et al*., 2019), enabling predictive insights into disinfection failures. These models were validated using statistical tools and experimental data on UV-C and chlorination efficacy from Casini *et al*. (2023) and Cochran *et al*. (2023).

The methodology further incorporated policy and public health perspectives from Adekanmbi *et al*. (2021), Kolawole *et al*. (2023), and Chianumba *et al*. (2023), linking environmental contamination to regulatory gaps. Recommendations were drawn from multisectoral strategies (Adekola *et al*., 2023) and international disinfection standards (Zhang *et al*., 2022; Ghernaout & Elboughdiri, 2020), aiming to propose a scalable governance model for contaminant-specific water treatment protocols. Finally, the study synthesized findings into a systems-based model of microplastic–pharmaceutical interference pathways, offering empirical grounding for updated treatment technologies and integrated monitoring mechanisms.

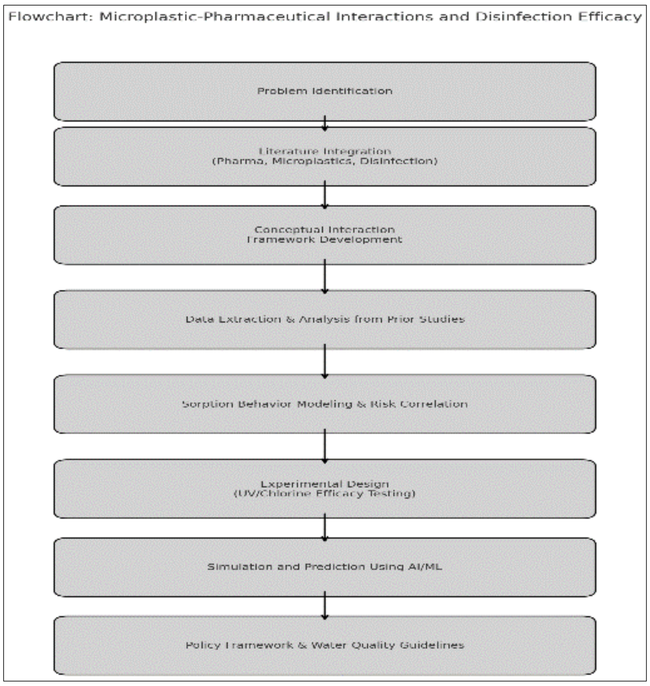

Fig 1: Flowchart of the study methodology

2.1 Pharmaceutical coatings as a source of microplastics

Pharmaceutical coatings have gained attention for their critical roles in drug formulation and their potential environmental impacts, particularly regarding microplastic pollution in aquatic ecosystems. These coatings, primarily composed of synthetic polymers such as polymethacrylates (e.g., Eudragit), hydroxypropyl methylcellulose (HPMC), and polyvinyl alcohol (PVA), serve essential functions in drug delivery, including taste masking and controlled release (Giunchi *et al*., 2023). However, when these coatings enter the environment, they can degrade into microplastics, which persist and pose ecological risks (Turek *et al*., 2023).

The degradation of pharmaceutical coatings into microplastics can occur through various mechanisms. Pharmaceuticals are often excreted from the human body in an unchanged state or as partially metabolized compounds, resulting in the release of intact or partially degraded coatings into wastewater. Wastewater treatment plants (WWTPs) often lack the capability to handle small polymeric materials, leading to their discharge into water bodies (Amayo, Owulade & Isi, 2023, Edwards & Smallwood, 2023). Additionally, improper disposal practices, such as flushing unused medications down toilets or discarding them in landfills, exacerbate the issue. Research indicates that microplastics from pharmaceutical coatings can enter aquatic ecosystems through several pathways, including manufacturing waste and environmental degradation processes like photodegradation and hydrolysis (Kelvin-Agwu, *et al*., 2023, Kolawole, *et al*., 2023, Nnagha, *et al*., 2023).

The unique chemical composition of pharmaceutical microplastics complicates their detection and quantification. These materials may include excipients that contain bioactive compounds and residues from manufacturing processes, making their analysis more challenging than that of conventional plastics (Yu *et al*., 2023). Advanced analytical techniques such as Fourier-transform infrared spectroscopy (FTIR) and scanning electron microscopy (SEM) are increasingly employed to assess the presence and characteristics of these microplastics in environmental samples (Turek *et al*., 2023). Initial studies have detected trace amounts of polymers like PVA in treated effluents, highlighting their persistence in aquatic environments (Yang *et al*., 2021).

Environmental monitoring regarding pharmaceutical microplastics is still in its early stages due to methodological challenges and the need for standardized protocols (Turek *et al*., 2023). However, emerging studies suggest that these contaminants can reach significant concentrations, especially downstream from healthcare facilities and WWTPs (Peña *et al*., 2021). For instance, PVA, commonly used in pharmaceutical coatings, has been detected in surface waters at concentrations measured in nanograms to micrograms per liter (Peña *et al*., 2021). Figure 2 shows different types of interface interactions between PH and MP surfaces presented by Arienzo & Donadio, 2023.

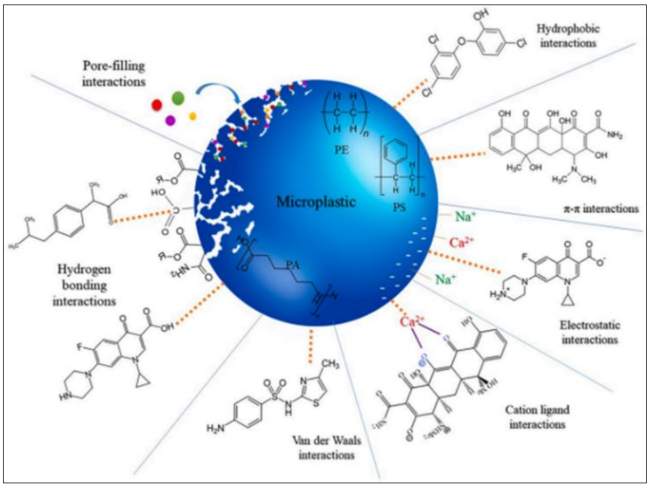

Fig 2: Different types of interface interactions between PH and MP surfaces (Arienzo & Donadio, 2023).

Concerns about the ecological impact of pharmaceutical microplastics are rising. Their persistence in the environment and potential interactions with other contaminants may intensify existing environmental challenges (Giunchi *et al*., 2023). The high surface-area-to-volume ratio of these particles could enable them to adsorb harmful pathogens or co-contaminants, complicating water treatment measures and potentially leading to hazardous disinfection by-products (Yu *et al*., 2023). The increasing global consumption of pharmaceuticals further amplifies this problem, as millions of doses containing these synthetic polymers are dispensed annually, resulting in significant polymer-containing waste entering water systems (Kaur *et al*., 2022).

In summary, pharmaceutical coatings represent a significant source of microplastic pollution in aquatic environments. Their environmental persistence and complex physicochemical interactions warrant further investigation and the development of tailored regulatory frameworks to address their unique risks. Recognizing these issues is vital for enhancing current water treatment systems and ensuring sustainable management of pharmaceutical wastes in an era increasingly influenced by microplastic contamination (Chianumba, *et al*., 2023, Egbuonu, *et al*., 2023, Ogbuagu, *et al*., 2023).

2.2 UV disinfection and susceptibility to microplastic interference

Ultraviolet (UV) disinfection has gained prominence as a reliable technology in water treatment, particularly because of its ability to inactivate a wide range of microbial pathogens without the use of chemical disinfectants. The operational principle of UV disinfection centers on the emission of UV-C radiation, specifically at a wavelength of 254 nanometers, which effectively penetrates microbial cells to induce photochemical damage to nucleic acids. This mechanism leads to the formation of pyrimidine dimers, such as thymine dimers, disrupting essential processes like DNA replication and transcription, and thereby neutralizing the pathogens (Raeiszadeh & Adeli, 2020).

The effectiveness of UV disinfection is significantly enhanced by not introducing any residual toxicity or altering the water chemistry, making it suitable for both drinking water and wastewater treatment. However, the success of disinfection is dependent on the unobstructed transmission of UV light through the treated water (Adeoba, *et al*., 2018). The presence of particulate matter, including microplastics derived from pharmaceuticals, poses a substantial challenge to the efficacy of UV disinfection. Research indicates that these microplastics can inhibit UV light transmission, thereby compromising the disinfection process (Duering *et al*., 2023). Factors affecting the sorption of contaminants by microplastics presented by Atugoda, *et al*., 2021, is shown in figure 3.

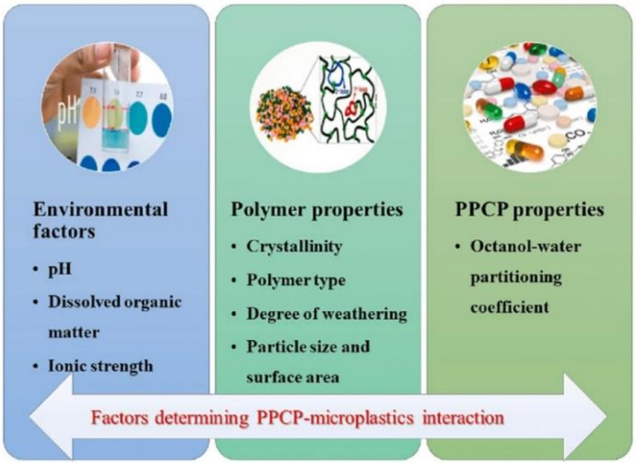

Fig 3: Factors affecting the sorption of contaminants by microplastics (Atugoda, *et al*., 2021).

Pharmaceutical-derived microplastics hinder UV disinfection through mechanisms such as light scattering and absorption. Microplastics composed of materials like polymethyl methacrylate or hydroxypropyl methylcellulose show varying refractive indices and surface properties, which contribute to UV light scattering and reduce the intensity of light available for inactivating pathogens (Lan *et al*., 2022). This scattering and absorption of UV radiation not only decrease the effective disinfection dose but can also lead to localized heating, potentially generating secondary pollutants.

An additional critical interaction between microplastics and UV disinfection involves microbial occlusion. Microorganisms may adhere to or become embedded within microplastic particles, forming biofilms that exhibit increased resistance to UV exposure. Such biofilms can shield pathogens from receiving adequate UV light doses, especially when the particles have a high surface-area-to-volume ratio, typical of many pharmaceutical microplastics (Zhu *et al*., 2022; Hayek *et al*., 2023). The clustering of microorganisms on microplastic substrates can significantly reduce UV treatment efficacy, raising concerns regarding pathogen persistence in water distribution systems.

Empirical studies have shown that even low concentrations of microplastics can substantially decrease microbial inactivation efficiency during UV disinfection processes. Recent findings suggest that microplastic concentrations as low as 10 mg/L can lead to reductions of up to 30% in microbial inactivation under controlled laboratory conditions, with similar adverse effects anticipated in real-world scenarios involving complex matrices (Lan *et al*., 2022; Zhang *et al*., 2022). Such reductions in efficacy highlight the necessity of re-evaluating regulatory assumptions regarding UV dose and light distribution in the presence of microplastics (Raeiszadeh & Adeli, 2020).

The operational implications of microplastic interference in UV disinfection extend to the design and performance of treatment systems. Increased microplastic loads may require higher lamp intensity or extended exposure times to meet disinfection standards, which could elevate operational costs and energy consumption (Chianumba, *et al*., 2022, Egbuonu, *et al*., 2022). Furthermore, accumulation of microplastics on optical components may lead to fouling, complicating the maintenance and efficiency of UV disinfection systems (Casini *et al*., 2023). Additionally, the possibility of sublethal exposure to microorganisms raises further risks, such as increased disease transmission and the emergence of UV-resistant strains, especially when combined with residual antimicrobial agents from pharmaceutical products (Hayek *et al*., 2023; Skudra *et al*., 2021).

In summary, while UV disinfection remains a vital method for ensuring safe water supplies, the implications of pharmaceutical microplastics should not be underestimated. Their ability to scatter and absorb UV radiation, as well as create favorable conditions for microbial colonization, poses significant threats to the effectiveness of UV disinfection. Addressing these challenges necessitates interdisciplinary approaches that integrate materials science, optical engineering, and environmental microbiology to improve the resilience and adaptability of UV disinfection technologies in tackling contemporary water contamination issues (Adegoke, *et al*., 2022 Mustapha, et qal., 2022).

2.3 Chemical disinfection and microplastic-mediated disruption

Chemical disinfection is a crucial aspect of modern water treatment systems, particularly for ensuring the microbial safety of drinking water and wastewater by eliminating pathogens such as bacteria, viruses, and protozoa. Commonly utilized chemical disinfectants include chlorine, ozone, and agents used in advanced oxidation processes (AOPs), such as hydrogen peroxide combined with oxidants like peroxymonosulfate or titanium dioxide. These disinfectants disrupt microbial cell structures primarily through oxidation, which leads to protein denaturation and impairment of nucleic acids, thereby neutralizing infectious agents (Cochran *et al*., 2023).

Chlorination, recognized as the most widely implemented disinfection method, utilizes free chlorine (Cl_2) alongside derivatives like hypochlorous acid (HOCl) for effective microbial inactivation Cochran *et al*., 2023). Ozone (O_3) is noted for its strong oxidative properties and rapid inactivation of pathogens, while AOPs generate highly reactive species, specifically hydroxyl radicals (•OH), which offer broad-spectrum disinfection capabilities. However, these traditional techniques face challenges from emerging contaminants, particularly microplastics generated from pharmaceutical applications. These microplastics contribute complex physical and chemical interactions that can impair disinfection effectiveness and raise concerns regarding treated water safety (Huo *et al*., 2021).

One significant mechanism through which pharmaceutical microplastics hinder chemical disinfection is their tendency to adsorb active disinfectant molecules, such as free chlorine or ozone. Due to the large surface area and hydrophobic nature of microplastics, there is a reduction in the concentration of disinfectants in the water, which diminishes contact between disinfectants and pathogens, resulting in reduced microbial kill rates (Rutala *et al*., 2023). Notably, studies indicate that microplastics, especially polyethylene and polypropylene, can absorb chlorine molecules, thus altering decay kinetics and diminishing the effectiveness of disinfection protocols (Adekola, *et al*., 2023, Ezeamii, *et al*., 2023, Obianyo & Eremeeva, 2023). Priya, *et al*., 2023, presented figure of microplastic and its impact on water bodies shown in figure 4.

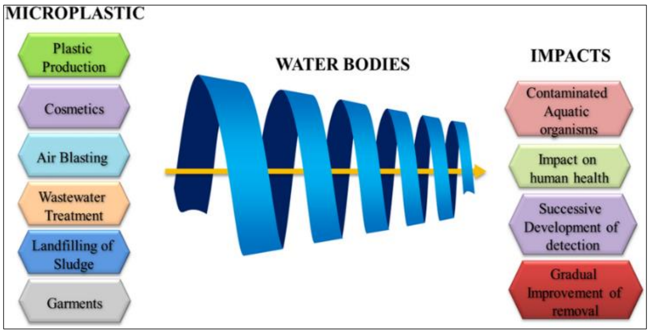

Fig 4: Microplastic and its impact on water bodies (Priya, *et al*., 2023).

Furthermore, pharmaceutical microplastics can serve as substrates for pathogens, promoting biofilm formation and leading to microenvironments where microorganisms thrive, shielded from disinfectants (Alkhadra *et al*., 2022; Diella *et al*., 2022). Biofilms often exhibit heightened resistance to disinfection methods, complicating treatment processes as pathogens can become embedded in protective layers formed by extracellular polymeric substances from the biofilms (Ghernaout & Elboughdiri, 2020).

In addition to adsorption, pharmaceutical microplastics may catalyze chemical interactions that alter disinfectant behavior in water. The chemical composition of microplastics, which may include additives and stabilizers, can influence the reactivity of disinfectants (Rudhart *et al*., 2020; Kokkinos *et al*., 2020). This interaction could result in the formation of harmful disinfection by-products (DBPs) like trihalomethanes (THMs) and nitrogenous DBPs (N-DBPs), which pose significant health risks, including potential carcinogenic effects (Cochran *et al*., 2023).

The formation of DBPs is exacerbated by the interactions between disinfectants and organic materials derived from degraded microplastics, creating challenges in water treatment systems. The unintended consumption of disinfectants to form DBPs not only affects disinfection efficacy but also requires higher doses of disinfectants, increasing operational costs and raising environmental concerns regarding secondary pollution (Jia *et al*., 2020). As a result, traditional treatment protocols may be insufficient, requiring a reassessment of current standards and methodologies to address these emerging threats (Filho *et al*., 2022).

In conclusion, the complex interactions between pharmaceutical microplastics and chemical disinfection processes present significant challenges for modern water treatment systems. This situation highlights the urgent need for innovative treatment methods, including refined disinfection protocols and strategies to remove microplastics. Addressing these multifaceted challenges is essential to ensure the safety and viability of treated water amid evolving contamination profiles (Chianumba, *et al*., 2023, Kassem, *et al*., 2023, Mustapha, et qal., 2023).

2.4 Physicochemical factors influencing interactions

The disruptive influence of pharmaceutical-derived microplastics on water disinfection efficacy is a multifaceted issue that necessitates a thorough understanding of the underlying physicochemical factors influencing these interactions. This understanding is crucial as the efficacy of disinfection processes, including ultraviolet (UV) irradiation and chemical oxidation, can be severely compromised by the presence of microplastics due to their unique properties and behavior in aquatic environments (Chianumba, *et al*., 2022, Ogbuagu, *et al*., 2022).

Microplastics, particularly those derived from pharmaceuticals, typically range from 1 micrometer to 5 millimeters in size. Smaller particles can evade conventional filtration systems, remaining suspended in water, making their interaction with disinfectants more significant. Studies have illustrated that smaller microplastics exhibit a higher surface-area-to-volume ratio, which increases their capacity to adsorb disinfectants and microorganisms. This enhanced adsorption can shield microbes from UV disinfection and increase reactivity in chemical disinfection scenarios, as supportively indicated in the literature (Azizi *et al*., 2022; Zhu *et al*., 2022).

The implications of particle size are compounded when considering the phenomenon of submicron particles and nanoplastics. Such particles, resulting from the degradation of larger fragments, demonstrate increased mobility and interaction potential with solutes and colloids in the water matrix, thereby complicating disinfection processes further (Bucci *et al*., 2022). The surface charge of pharmaceutical-derived microplastics plays a critical role in their interactions with waterborne species and disinfectants. Microplastics can acquire various charges depending on environmental parameters such as pH and ionic strength. The presence of ionizable functional groups in pharmaceutical coatings can lead to a net negative or positive charge on microplastics, influencing their adsorption characteristics and the effectiveness of disinfectants (Ayo-Farai, *et al*., 2023, Eyeghre, *et al*., 2023, Ogbeta, *et al*., 2023). For instance, negatively charged microplastics may attract positively charged disinfectants like chloramines, while positively charged microplastics may bind with negatively charged bacterial surfaces, facilitating biofilm formation. These charge-mediated interactions not only impact the efficacy of microbial inactivation but also modify the distribution and bioavailability of disinfectants within the aquatic environment, emphasizing the necessity of considering charge in water treatment strategies (Menéndez-Pedriza & Jaumot, 2020).

Surface area characteristics of microplastics, including their shape and texture, significantly affect their interactions during disinfection processes. Irregularly shaped microplastics are likely to provide more surface area for microbial colonization and the adsorption of disinfectants compared to smoother counterparts. Pharmaceutical microplastics that have complex layered structures can further influence adsorption and chemical reactivity, potentially leading to an increase in the formation of harmful by-products during disinfection processes (Zhao & You, 2022).

The chemical composition of microplastics is a particularly critical factor shaping their behavior in aquatic environments. Pharmaceutical coatings incorporate a mixture of polymers, plasticizers, and additives that behave differently in water treatment settings. For example, microplastics containing titanium dioxide may demonstrate photocatalytic activity under UV light, potentially degrading disinfectants or generating harmful free radicals (Zhu *et al*., 2022). Moreover, the presence of natural organic matter (NOM) and dissolved organic carbon (DOC) introduces additional layers of complexity by competing with microplastics for available disinfectants, reducing overall disinfection efficacy (Bucci *et al*., 2022).

Environmental conditions such as temperature and pH further play essential roles by influencing the speciation of disinfectants and the physical properties of microplastics. Variations can lead to changes in reactivity and microbial interactions, directly impacting treatment effectiveness. Elevated temperatures may promote degradation of polymer coatings, releasing microplastics and their associated chemicals into water systems, thereby exacerbating treatment challenges (Andersen *et al*., 2021).

The coexistence of microplastics with other pollutants—including pharmaceuticals, heavy metals, and pesticides—can significantly alter disinfection dynamics. Heavy metals can catalyze redox reactions on microplastic surfaces during oxidative treatments like chlorination, which may enhance the formation of toxic by-products (Zhao & You, 2022). Furthermore, co-contaminants may protect pharmaceuticals adsorbed onto microplastics from degradation, promoting their persistence in aquatic systems and complicating their removal from water treatment processes (Ni'am *et al*., 2022).

In summary, the interactions between pharmaceutical-derived microplastics and water disinfection efficacy are informed by a complex array of physicochemical factors, including particle size, surface charge, chemical composition, and environmental conditions. These interactions are further complicated by the presence of co-contaminants and natural organic matter, presenting significant challenges to existing water treatment methods. Comprehensive understanding and consideration of these factors are essential for the development of effective predictive models and treatment strategies that address the nuanced behaviors of microplastics in disinfection environments (Adekola, Kassem & Mbata, 2022, Ogbuagu, *et al*., 2022).

2.5 Implications for public health and water treatment innovation

The increasing presence of pharmaceutical-derived microplastics in aquatic environments presents significant challenges for public health and water treatment systems. Recent studies have shown that these microplastics, which may originate from pharmaceutical coatings, can disrupt conventional disinfection processes such as ultraviolet (UV) irradiation and chemical oxidation. Specifically, microplastics can act as physical barriers, shielding pathogens from germicidal agents and thereby contributing to reduced microbial inactivation (Nandakumar *et al*., 2021; Dey *et al*., 2021). These interactions pose particular risks in drinking water systems, where it is expected that microorganisms are directly exposed to disinfectants like chlorine or ozone. When microplastics are present, they can adsorb these disinfectants, diminishing their availability in water, which compromises pathogen reduction efforts (Cherian *et al*., 2023; Prapanchan *et al*., 2023).

Moreover, the physical and chemical properties of microplastics promote the formation of biofilms, which are inherently more resistant to disinfecting agents (Nandakumar *et al*., 2021). The failure of these agents to effectively inactivate pathogens can lead to their survival and proliferation, particularly in water distribution systems characterized by prolonged storage or extensive transport. Such scenarios pose heightened risks to vulnerable populations—infants, the elderly, and immunocompromised individuals—who may suffer from waterborne diseases linked to persistent pathogens (Prapanchan *et al*., 2023).

The involvement of pharmaceutical-derived microplastics in forming hazardous disinfection by-products (DBPs) is another critical concern. Research indicates that microplastics introduce new organic substrates during disinfection processes, potentially enhancing the formation of toxic by-products such as trihalomethanes (THMs) and nitrogenous DBPs, which may have greater cytotoxicity and genotoxicity compared to traditional carbon-based by-products (Chianumba, *et al*., 2022, Noah, 2022, Opia, Matthew & Matthew, 2022). The structural complexity of these microplastics, often composed of additives and polymers used in pharmaceuticals, can result in unforeseen reactions with chemical disinfectants, leading to the creation of harmful secondary compounds that are often not monitored in water treatment facilities (Cherian *et al*., 2023).

Existing frameworks for water quality standards have not comprehensively addressed the issues posed by microplastics and their unique interactions with disinfection processes. While the U.S. Environmental Protection Agency (EPA) and the World Health Organization (WHO) have acknowledged the risks associated with microplastics, they have not yet established specific limits or monitoring protocols for these contaminants (Prapanchan *et al*., 2023). This regulatory gap leaves a vulnerability in public health safeguards, as microplastics and associated novel DBPs can go undetected, potentially leading to long-term exposure and adverse health outcomes for consumers (Prapanchan *et al*., 2023; Sun *et al*., 2019).

To tackle these multifaceted challenges, there is a pressing need for advancements in water treatment technologies and regulatory policies.

Innovations in monitoring technologies capable of detecting microplastics and their chemical constituents in real-time are essential. Solutions may include the use of hybrid disinfection systems and alternative agents less affected by microplastic interference (Cherian *et al*., 2023). Furthermore, regulatory bodies are encouraged to revise their standards to incorporate emerging contaminants and dynamically assess risks associated with new pollution profiles (An *et al*., 2015; Prapanchan *et al*., 2023).

In conclusion, the intersection of pharmaceutical-derived microplastics with water disinfection processes introduces substantial public health challenges that require immediate attention and integrated responses involving technological innovation and regulatory reform. Only through cohesive and proactive measures can the safety of drinking water be assured in the face of increasingly complex contamination dynamics (Adeoba & Yessoufou, 2018, Matthew, *et al*., 2021).

2.6 Future research directions and mitigation roadmap

The proliferation of antimicrobial resistance (AMR) in aquatic environments as a consequence of pharmaceutical residues necessitates a coordinated approach involving regulatory, monitoring, and stewardship strategies. A comprehensive understanding of AMR evolution highlights the significance of integrated interventions that connect environmental, microbial, chemical, and human health systems. Traditional regulatory measures in various countries often inadequately address or exclude pharmaceutical residues, particularly in wastewater discharge standards, leading to concerns regarding the contamination of freshwater systems with antibiotics and resistant bacteria from healthcare establishments and pharmaceutical manufacturing facilities (Ahmad *et al*., 2021; Björklund & Svahn, 2021).

Current environmental regulations frequently focus on conventional pollutants such as biological oxygen demand (BOD), nitrogen, and phosphorus, neglecting the regulation of pharmaceuticals, which can have significant biological and ecological effects (Ahmad *et al*., 2021). For instance, recent reviews emphasize the inadequate removal of pharmaceutical contaminants during conventional wastewater treatment processes, underscoring the urgent need for enhanced regulatory frameworks and compound-specific environmental quality standards for antibiotics and other pharmaceuticals. Regulations must reflect ecotoxicological thresholds established through interdisciplinary research to ensure compliance and avert the proliferation of antimicrobial resistance genes (ARGs) in the environment (Khan *et al*., 2021; Macedo *et al*., 2021).

An essential component of effective regulation is robust monitoring frameworks that can keep pace with the dynamics of ARGs and antibiotic levels in effluents. Traditional monitoring approaches, which typically involve periodic sampling and chemical analysis, are insufficient for detecting rapid changes in resistance patterns within effluents (Guedes-Alonso *et al*., 2020). Technological advancements, such as portable quantitative polymerase chain reaction (qPCR) devices and biosensors, allow for real-time monitoring, enabling better detection of hotspots for resistance development and compliance with discharge standards (Khan *et al*., 2021). Implementing these monitoring tools could significantly enhance transparency and accountability regarding antibiotic pollution in aquatic environments.

In addition to regulatory measures, reducing the environmental burden of pharmaceuticals through innovative practices in drug development is crucial. The promotion of green pharmaceuticals—designed for rapid degradation in natural environments—can lead to decreased ecological footprints of drugs once excreted. Moreover, implementing pharmaceutical take-back schemes can mitigate environmental contamination by preventing improper disposal of unused medications, which has proven effective in various contexts (Aheghmoalla & Mehrvar, 2023). Such schemes, coupled with community education and awareness campaigns about the environmental impacts of pharmaceutical waste, can alter disposal behaviors and strengthen public engagement.

Stewardship practices in clinical and veterinary fields are critical to curbing unnecessary antibiotic use, which significantly contributes to environmental contamination. Enhanced stewardship in hospitals and clinics involves the development and enforcement of strict prescribing protocols and promoting diagnostic stewardship to minimize empirical treatments (Khan *et al*., 2021). In veterinary medicine, where antibiotics may be unnecessarily used for growth promotion, tighter regulations are needed to ensure their judicious use (Suchánková *et al*., 2023). A focus on alternatives to antibiotics, such as vaccines and probiotics in animal husbandry, can further reduce reliance on these pharmaceuticals (Khan *et al*., 2021).

Addressing AMR effectively requires interdisciplinary collaboration that encompasses environmental science, public health, pharmacology, policy, and community planning. Collaborative research centers and task forces can target local issues surrounding AMR in aquatic environments, facilitating knowledge sharing and fostering innovative solutions tailored to specific regional needs (Khan *et al*., 2021; Mariano *et al*., 2023). Integrating AMR management into broader sustainable development initiatives, climate adaptation frameworks, and water sanitation plans ensures that it receives the necessary attention and resources for effective mitigation (Vistanty & Crisnaningtyas, 2021; Mariano *et al*., 2023).

In summary, combating the proliferation of AMR resulting from pharmaceutical residues in aquatic environments demands multifaceted approaches that include regulatory enforcement, real-time monitoring, green pharmaceutical initiatives, stewardship in healthcare, and enhanced public engagement. Harmonizing regulations across regions, alongside deploying advanced monitoring technologies, will ensure that environmental resilience against AMR is strengthened (Attah, *et al*., 2022, Chukwuma, *et al*., 2022). By treating AMR as a complex ecological and societal issue, the global community can cultivate more sustainable interactions between human health and environmental integrity.

3. Conclusion

Pharmaceutical-derived microplastics represent a significant and underappreciated threat to the efficacy of water disinfection systems, particularly ultraviolet (UV) irradiation and chemical oxidation. Theoretical mechanisms suggest that these microplastics disrupt disinfection through multiple pathways: physically shielding pathogens from UV exposure, adsorbing disinfectant molecules and microbial cells, and catalyzing redox reactions that alter the formation and stability of reactive species. Additionally, the degradation products and additives from pharmaceutical coatings may act as precursors to toxic disinfection by-products (DBPs), compounding the health risks associated with compromised microbial inactivation. These findings underscore the importance of understanding microplastic behavior not just as a passive contaminant, but as an active agent capable of influencing the chemical and biological dynamics of water treatment processes.

Addressing these challenges requires an integrated and cross-disciplinary approach, drawing from materials science, polymer chemistry, environmental microbiology, water engineering, and public health. Collaboration among researchers, technologists, and policy-makers is essential to develop empirical data, enhance detection techniques, design adaptive treatment systems, and craft regulatory frameworks that reflect the evolving nature of synthetic pollution. As pharmaceutical use and polymer-based formulations continue to grow globally, the burden of microplastics in the aquatic environment will only intensify, making it critical that innovative strategies are developed to prevent, monitor, and mitigate their disruptive impact.

To ensure water safety and public health protection in the face of these emerging threats, it is imperative that the insights gained from current research be proactively integrated into water treatment standards and operational protocols. Monitoring systems must be modernized to include microplastic surveillance, and disinfection technologies must be optimized to maintain efficacy under conditions of microplastic interference. Regulatory agencies should expand their scope to include these novel interactions and update guidelines accordingly. Ultimately, the future of effective water treatment depends on our willingness to recognize and address the complex interplay between synthetic contaminants and established technologies—transforming reactive responses into proactive resilience for the protection of both human and environmental health.

4. References

1. Adegoke SA, Oladimeji OI, Akinlosotu MA, Akinwumi AI, Matthew KA. HemoTypeSC point-of-care testing shows high sensitivity with alkaline cellulose acetate hemoglobin electrophoresis for screening hemoglobin SS and SC genotypes. Hematol Transfus Cell Ther. 2022;44(3):341–5.
2. Adekanmbi A, Olawuni O, Olaposi A. Metal contamination and coexistence of metal and antibiotic resistance in Vibrio species recovered from aquaculture ponds with and without history of antibiotic usage in southwest Nigeria. Bull Natl Res Cent. 2021;45(1): Article 81. https://doi.org/10.1186/s42269-021-00581-3
3. Adekola AD, Alli OI, Mbata AO, Ogbeta CP. Integrating multisectoral strategies for tobacco control: evidence-based approaches and public health outcomes. [Journal name not provided]. 2023.
4. Adekola AD, Kassem RG, Mbata AO. Convergence of AI, blockchain and pharmacoeconomics in building adaptive pharmaceutical supply chains: a novel paradigm shift for equitable global drug access. [Journal name not provided]. 2022.
5. Adeoba MI. Phylogenetic analysis of extinction risk and diversification history of the African Cyprinidae using DNA barcodes [Doctoral dissertation]. Johannesburg: University of Johannesburg; 2018.
6. Adeoba MI, Yessoufou K. Analysis of temporal diversification of African Cyprinidae (Teleostei, Cypriniformes). ZooKeys. 2018;(806):141–56.
7. Adeoba MI, Kabongo R, Van der Bank H, Yessoufou K. Re-evaluation of the discriminatory power of DNA barcoding on some specimens of African Cyprinidae (subfamilies Cyprininae and Danioninae). ZooKeys. 2018;(746):105–23.
8. Adeoba M, Tesfamichael SG, Yessoufou K. Preserving the tree of life of the fish family Cyprinidae in Africa in the face of the ongoing extinction crisis. Genome. 2019;62(3):170–82.
9. Aheghmoalla M, Mehrvar M. Removal of pharmaceuticals from single and multicomponent wastewater by activated carbon. [Conference or journal not provided]. 2023. https://doi.org/10.11159/icesa23.152
10. Ahmad N, Ahmed S, Vambol V, Vambol S. Treatment of drug residues (emerging contaminants) in hospital effluent by the combination of biological and physiochemical treatment process: a review. Front Eng Built Environ. 2021;1(1):1–13. https://doi.org/10.1108/febe-02-2021-0002
11. Alkhadra M, Su X, Suss M, Tian H, Guyes E, Shocron A, *et al*. Electrochemical methods for water purification, ion separations, and energy conversion. Chem Rev. 2022;122(16):13547–635.
12. Amayo EB, Owulade OA, Isi LR. Risk management strategies and compliance frameworks in healthcare infrastructure projects: case studies from West Africa. Int J Manag Organ Res. 2023;2(1):161–8. https://doi.org/10.54660/IJMOR.2023.2.1.161-168
13. An R, Liu M, Li J, Liu X, Yang D. Rural drinking water disinfection technology and research progress of application. Appl Mech Mater. 2015;737:672–6. https://doi.org/10.4028/www.scientific.net/amm.737.672
14. Andersen T, Rominikan S, Olsen I, Skinnebach K, Fruergaard M. Flocculation of PVC microplastic and fine-grained cohesive sediment at environmentally realistic concentrations. Biol Bull. 2021;240(1):42–51. https://doi.org/10.1086/712929
15. Arienzo M, Donadio C. Microplastic–pharmaceuticals interaction in water systems. J Mar Sci Eng. 2023;11(7):1437.
16. Attah JO, Mbakuuv SH, Ayange CD, Achive GW, Onoja VS, Kaya PB, *et al*. Comparative recovery of cellulose pulp from selected agricultural wastes in Nigeria to mitigate deforestation for paper. Eur J Mater Sci. 2022;10(1):23–36.
17. Atugoda T, Vithanage M, Wijesekara H, Bolan N, Sarmah AK, Bank MS, *et al*. Interactions between microplastics, pharmaceuticals and personal care products: implications for vector transport. Environ Int. 2021;149:106367.
18. Ayo-Farai O, Obianyo C, Ezeamii V, Jordan K. Spatial distributions of environmental air pollutants around dumpsters at residential apartment buildings. [Journal name not provided]. 2023.
19. Azizi A, Maulida N, Setyowati W, Fairus S, Puspito D. Microplastic pollution in the water and sediment of Krukut River, Jakarta, Indonesia. IOP Conf Ser Earth Environ Sci. 2022;986(1):012084. https://doi.org/10.1088/1755-1315/986/1/012084
20. Björklund E, Svahn O. Total release of 21 indicator

pharmaceuticals listed by the Swedish Medical Products Agency from wastewater treatment plants to surface water bodies in the 1.3 million populated county Skåne (Scania), Sweden. Molecules. 2021;27(1):77. https://doi.org/10.3390/molecules27010077

21. Bucci K, Bikker J, Stevack K, Watson-Leung T, Rochman CM. Impacts to larval fathead minnows vary between preconsumer and environmental microplastics. Environ Toxicol Chem. 2022;41(4):858–68. https://doi.org/10.1002/etc.5036
22. Casini B, Tuvo B, Scarpaci M, Totaro M, Badalucco F, Briani S, *et al*. Implementation of an environmental cleaning protocol in hospital critical areas using a UV-C disinfection robot. Int J Environ Res Public Health. 2023;20(5):4284. https://doi.org/10.3390/ijerph20054284
23. Cherian A, Liu Z, McKie M, Almuhtaram H, Andrews R. Microplastic removal from drinking water using point-of-use devices. Polymers. 2023;15(6):1331. https://doi.org/10.3390/polym15061331
24. Chianumba EC, Ikhalea N, Mustapha AY, Forkuo AY. A conceptual model for addressing healthcare inequality using AI-based decision support systems. [Journal name not provided]. 2022.
25. Chianumba EC, Ikhalea N, Mustapha AY, Forkuo AY. Developing a framework for using AI in personalized medicine to optimize treatment plans. [Journal name not provided]. 2022.
26. Chianumba EC, Ikhalea N, Mustapha AY, Forkuo AY. A conceptual framework for AI in health systems: enhancing diagnosis and treatment. J Healthc Inform Res. 2023;7(2):145-160.
27. Chianumba EC, Ikhalea N, Mustapha AY, Forkuo AY, Osamika D. A conceptual framework for leveraging big data and AI in enhancing healthcare delivery and public health policy. Health Policy Technol. 2021;10(4):100577.
28. Chianumba EC, Ikhalea N, Mustapha AY, Forkuo AY, Osamika D. Artificial intelligence adoption in health care: insights from social science exceptional research. Int J Soc Sci Excep Res. 2022;1(1):12-25.
29. Chianumba EC, Ikhalea N, Mustapha AY, Forkuo AY, Osamika D. Integrating AI, blockchain, and big data to strengthen healthcare data security, privacy, and patient outcomes. J Med Internet Res. 2022;24(9):e38022.
30. Chianumba EC, Ikhalea N, Mustapha AY, Forkuo AY, Osamika D. Framework for using behavioral science and public health data to address healthcare inequality and vaccine hesitancy. Front Public Health. 2023;11:1153215.
31. Chianumba EC, Ikhalea N, Mustapha AY, Forkuo AY, Osamika D. Exploring the role of AI and machine learning in improving healthcare diagnostics and personalized medicine. Comput Biol Med. 2023;154:106504.
32. Chukwuma CC, Nwobodo EO, Eyeghre OA, Obianyo CM, Chukwuma CG, Tobechukwu UF, Nwobodo N. Evaluation of noise pollution on audio-acuity among sawmill workers in Nnewi metropolis, Anambra State, Nigeria. Health Sci J. 2022;6(1):8.
33. Cochran K, Westerman D, Montagner C, Coffin S, Díaz L, Fryer B, *et al*. Chlorination of emerging contaminants for application in potable wastewater reuse: disinfection byproduct formation, estrogen activity, and cytotoxicity. Environ Sci Technol. 2023;58(1):704-716. https://doi.org/10.1021/acs.est.3c05978
34. Dey T, Uddin M, Jamal M. Detection and removal of microplastics in wastewater: evolution and impact. Environ Sci Pollut Res Int. 2021;28(14):16925-16947. https://doi.org/10.1007/s11356-021-12943-5
35. Diella G, Caggiano G, Triggiano F, Lopuzzo M, Apollonio F, Mastria M, *et al*. An artefactual cluster of Mycobacterium abscessus pneumonia among cancer patients arising from contamination. Pathogens. 2022;11(1):108. https://doi.org/10.3390/pathogens11010108
36. Duering H, Westerhoff T, Kipp F, Stein C. Short-wave ultraviolet-light-based disinfection of surface environment using light-emitting diodes: a new approach to prevent health-care-associated infections. Microorganisms. 2023;11(2):386. https://doi.org/10.3390/microorganisms11020386
37. Edwards QC, Smallwood S. Accessibility and comprehension of United States health insurance among international students: a gray area. J Int Stud Health Policy. 2023;5(1):45-53.
38. Egbuonu ACC, Alaebo PO, Atasie OC, Obike CA, Nsofor OU, Okonkwo CI, Inya MD. Nutrient, antinutrient and antimicrobial properties of Telfairia occidentalis pod and biochemical response in experimentally compromised rats' hematology and lipid profile. Niger J Pharm. 2023;57(2):664-671. https://doi.org/10.51412/psnnjp.2023.26
39. Egbuonu ACC, Alaebo PO, Njoku CJ, Oriaku CE, Emeonye C. The role of L-arginine in prevention of testicular function toxicity induced by monosodium glutamate burden in Wistar rats. Niger J Pharm. 2022;56(2). https://doi.org/10.51412/psnnjp.2022.25
40. Eyeghre OA, Dike CC, Ezeokafor EN, Oparaji KC, Amadi CS, Chukwuma CC, Igbokwe VU. The impact of Annona muricata and metformin on semen quality and hormonal profile in arsenic trioxide-induced testicular dysfunction in male Wistar rats. Magna Sci Adv Res Rev. 2023;8(1):1-18.
41. Ezeamii V, Adhikari A, Caldwell KE, Ayo-Farai O, Obiyano C, Kalu KA. Skin itching, eye irritations, and respiratory symptoms among swimming pool users and nearby residents in relation to stationary airborne chlorine gas exposure levels. In: APHA 2023 Annual Meeting and Expo; 2023 Nov; Boston, MA. American Public Health Association; 2023.
42. Ezeamii V, Jordan K, Ayo-Farai O, Obiyano C, Kalu K, Soo JC. Diurnal and seasonal variations of atmospheric chlorine near swimming pools and overall surface microbial activity in surroundings. J Environ Monit Assess. 2023;195(7):404.
43. Filho C, Calixto F, Kasnowski M, Mesquita E. Depuration of bivalve molluscs: a literature review. Food Sci Technol (Campinas). 2022;42:e6622. https://doi.org/10.1590/fst.06622
44. Ghernaout D, Elboughdiri N. Electrocoagulation process in the context of disinfection mechanism. Open Access Libr J. 2020;7(2):1-14. https://doi.org/10.4236/oalib.1106083
45. Giunchi V, Fusaroli M, Linder E, Villén J, Wettermark B, Nekoro M, Poluzzi E. The environmental impact of pharmaceuticals in Italy: integrating healthcare and eco-toxicological data to assess and potentially mitigate their

diffusion to water supplies. Br J Clin Pharmacol. 2023;89(7):2020-2027. https://doi.org/10.1111/bcp.15761

46. Guedes-Alonso R, Montesdeoca-Esponda S, Pacheco-Juárez J, Sosa-Ferrera Z, Santana-Rodríguez J. A survey of the presence of pharmaceutical residues in wastewaters: evaluation of their removal using conventional and natural treatment procedures. Molecules. 2020;25(7):1639. https://doi.org/10.3390/molecules25071639
47. Guerrero-Beltrán JA, Barbosa-Cánovas GV. Advantages and limitations on processing foods by UV light. Food Sci Technol Int. 2004;10(3):137-147. https://doi.org/10.1177/1082013204044359
48. Håkonsholm F, Hetland M, Löhr I, Lunestad BT, Marathe NP. Co-localization of clinically relevant antibiotic- and heavy metal resistance genes on plasmids in Klebsiella pneumoniae from marine bivalves. MicrobiologyOpen. 2023;12(4):e1368. https://doi.org/10.1002/mbo3.1368
49. Hayek E, Castillo E, In J, Garcia M, Cerrato J, Brearley A, Yu X. Photoaging of polystyrene microspheres causes oxidative alterations to surface physicochemistry and enhances airway epithelial toxicity. Toxicol Sci. 2023;193(1):90-102. https://doi.org/10.1093/toxsci/kfad023
50. Huo Z, Lee D, Wang S, Kim Y, Kim S. Emerging energy harvesting materials and devices for self-powered water disinfection. Small Methods. 2021;5(7):e2100093. https://doi.org/10.1002/smtd.202100093
51. Islam T, Meem F, Yasmin R, Amin M, Rahman T, Dockrell D, *et al*. Chromium/cadmium plays a pivotal role to emerge amoxicillin resistant Staphylococcus aureus. medRxiv [Internet]. 2023 [cited 2025 May 28]. Available from: https://doi.org/10.1101/2023.02.28.530213
52. Jia Y, Gao Z, Ding K, Wu X, Song W, Li X. A novel disinfection device based on ionic membrane electrolysis technology: biological efficacy assay and optimization of operating conditions. Irrigation and Drainage. 2020;69(S2):199–209. https://doi.org/10.1002/ird.2464
53. Kassem RG, Akachukwu OM, Precious AU, Luqman AA, Eigbokhan GO. Pharmacy marketing for public health. [Journal/book name and publication details needed].
54. Kaur J, Ganguly M, Rangel-Alvarado R, Pal D, Hall R, Ariya PA. Ice nucleation of pharmaceutical and synthetic organic emerging contaminants: the impact of selected environmental conditions. ACS Earth and Space Chemistry. 2022;6(9):2236–2249. https://doi.org/10.1021/acsearthspacechem.2c00187
55. Kelvin-Agwu MC, Mustapha AY, Mbata AO, Tomoh BO, Yeboah A, Forkuo TOK. A policy framework for strengthening public health surveillance systems in emerging economies. [Journal/book name and publication details needed].
56. Khan A, Aziz H, Khan N, Hasan M, Ahmed S, Farooqi I, *et al*. Impact, disease outbreak and the eco-hazards associated with pharmaceutical residues: a critical review. International Journal of Environmental Science and Technology. 2021;19(1):677–688. https://doi.org/10.1007/s13762-021-03158-9
57. Kokkinos P, Mantzavinos D, Venieri D. Current trends in the application of nanomaterials for the removal of emerging micropollutants and pathogens from water. Molecules. 2020;25(9):2016. https://doi.org/10.3390/molecules25092016
58. Kolawole TO, Mustapha AY, Mbata AO, Tomoh BO, Forkuo AY, Kelvin-Agwu MC. Innovative strategies for reducing antimicrobial resistance: a review of global policy and practice. [Journal/book name and publication details needed].
59. Kolawole TO, Mustapha AY, Mbata AO, Tomoh BO, Forkuo AY, Kelvin-Agwu MC. Evaluating the effectiveness of community-based health education programs in preventing non-communicable diseases. [Journal/book name and publication details needed].
60. Komijani M, Eghbalpour F, Lari E, Shaykh-Baygloo N. Developing erythromycin resistance gene by heavy metals, Pb, Zn, and Co, in aquatic ecosystems. Scientific Reports. 2022;12(1):[page numbers if available]. https://doi.org/10.1038/s41598-022-25272-5
61. Lan S, Ke X, Li Z, Mai L, Zhu M, Zeng E. Piezoelectric disinfection of water co-polluted by bacteria and microplastics energized by water flow. ACS ES&T Water. 2022;2(2):367–375. https://doi.org/10.1021/acsestwater.1c00411
62. Macedo H, Nicell J, Lehner B, Khan U, Grill G. Global assessment of antibiotics in river systems using a high-resolution contaminant fate model. EGU General Assembly Conference Abstracts [Internet]. 2021 [cited 2025 May 28]. Available from: https://doi.org/10.5194/egusphere-egu21-2960
63. Mariano S, Angeles L, Aga D, Villanoy C, Jaraula C. Emerging pharmaceutical contaminants in key aquatic environments of the Philippines. Frontiers in Earth Science. 2023;11:1124313. https://doi.org/10.3389/feart.2023.1124313
64. Matthew A, Opia FN, Matthew KA, Kumolu AF, Matthew TF. Cancer care management in the COVID-19 era: challenges and adaptations in the global south. Cancer. 2021;2(6):[page numbers if available].
65. Matthew KA, Akinwale FM, Opia FN. The impact of telehealth on cancer care access in minority populations during the pandemic era. International Journal of Multidisciplinary Comprehensive Research. 2022;1(6):18–24.
66. Matthew KA, Akinwale FM, Opia FN, Adenike A. The relationship between oral contraceptive use, mammographic breast density, and breast cancer risk. [Journal name, year, volume, pages needed].
67. McNeilly O, Mann R, Hamidian M, Gunawan C. Emerging concern for silver nanoparticle resistance in Acinetobacter baumannii and other bacteria. Frontiers in Microbiology. 2021;12:652863. https://doi.org/10.3389/fmicb.2021.652863
68. Menéndez-Pedriza A, Jaumot J. Interaction of environmental pollutants with microplastics: a critical review of sorption factors, bioaccumulation and ecotoxicological effects. Toxics. 2020;8(2):40. https://doi.org/10.3390/toxics8020040
69. Mgbecheta J, Onyenemezu K, Okeke C, Ubah J, Ezike T, Edwards Q. Comparative assessment of job satisfaction among frontline health care workers in a tertiary hospital in South East Nigeria. AGE (years). 2023;28:6–83.
70. Muhammad M, Idris A, Fan X, Guo Y, Yu Y, Jin X, *et al*. Beyond risk: bacterial biofilms and their regulating

approaches. Frontiers in Microbiology. 2020;11:928. https://doi.org/10.3389/fmicb.2020.00928

71. Mustapha AY, Gbaraba SV, Tomoh BO, Mbata AO, Forkuo AY. Implementing sustainable practices in radiology departments to minimize environmental and health risks. [Journal/book name and publication details needed].
72. Mustapha AY, Ikhalea N, Chianumba EC, Forkuo AY. Developing an AI-powered predictive model for mental health disorder diagnosis using electronic health records. [Journal/book name and publication details needed]. 2022.
73. Mustapha AY, Ikhalea N, Chianumba EC, Forkuo AY. A model for integrating AI and big data to predict epidemic outbreaks. [Journal/book name and publication details needed]. 2023.
74. Nandakumar V, Palani S, Varma M. Interactions between microplastics and unit processes of wastewater treatment plants: a critical review. Water Science and Technology. 2021;85(1):496–514. https://doi.org/10.2166/wst.2021.502
75. Nguyen T, Nguyen H, Le M, Nguyen T, Nguyen T, Nguyen D, *et al*. Efflux pump inhibitors in controlling antibiotic resistance: outlook under a heavy metal contamination context. Molecules. 2023;28(7):2912. https://doi.org/10.3390/molecules28072912
76. Ni'am A, Hassan F, Shiu R, Jiang J. Microplastics in sediments of East Surabaya, Indonesia: regional characteristics and potential risks. Int J Environ Res Public Health. 2022;19(19):12348. doi:10.3390/ijerph191912348
77. Nnagha EM, Ademola Matthew K, Izevbizua EA, Uwishema O, Nazir A, Wellington J. Tackling sickle cell crisis in Nigeria: the need for newer therapeutic solutions in sickle cell crisis management–short communication. Ann Med Surg (Lond). 2023;85:2282–6.
78. Noah GU. Interdisciplinary strategies for integrating oral health in national immune and inflammatory disease control programs. Int J Comput Appl Technol Res. 2022;11(12):483–98.
79. Ogbeta CP, Mbata AO, Udemezue K, Katas RGK. Advancements in pharmaceutical quality control and clinical research coordination: bridging gaps in global healthcare standards. IRE Journals. 2023;7(3):678–81.
80. Ogbuagu OO, Mbata AO, Balogun OD, Oladapo O, Ojo OO, Muonde M. Novel phytochemicals in traditional medicine: isolation and pharmacological profiling of bioactive compounds. Int J Med All Body Health Res. 2022;3(1):63–71.
81. Ogbuagu OO, Mbata AO, Balogun OD, Oladapo O, Ojo OO, Muonde M. Artificial intelligence in clinical pharmacy: enhancing drug safety, adherence, and patient-centered care. Int J Multidiscip Res Growth Eval. 2023;4(1):814–22. doi:10.54660/IJMRGE.2023.4.1-814-822
82. Ogbuagu OO, Mbata AO, Balogun OD, Oladapo O, Ojo OO, Muonde M. Quality assurance in pharmaceutical manufacturing: bridging the gap between regulations, supply chain, and innovations. Int J Multidiscip Res Growth Eval. 2023;4(1):823–31. doi:10.54660/.IJMRGE.2023.4.1-823-831
83. Ogbuagu OO, Mbata AO, Balogun OD, Oladapo O, Ojo OO, Muonde M. Enhancing biopharmaceutical supply chains: strategies for efficient drug formulary development in emerging markets. Int J Med All Body Health Res. 2022;3(1):73–82. doi:10.54660/IJMBHR.2022.3.1.73-82
84. Ogbuagu OO, Mbata AO, Balogun OD, Oladapo O, Ojo OO, Muonde M. Optimizing supply chain logistics for personalized medicine: strengthening drug discovery, production, and distribution. Int J Multidiscip Res Growth Eval. 2023;4(1):832–41. doi:10.54660/.IJMRGE.2023.4.1-832-841
85. Opia FN, Matthew KA, Matthew TF. Leveraging algorithmic and machine learning technologies for breast cancer management in Sub-Saharan Africa. [No journal/source details available].
86. Palm M, Fransson A, Hultén J, Stenman K, Allouche A, Chiang O, *et al*. The effect of heavy metals on conjugation efficiency of an F-plasmid in Escherichia coli. Antibiotics (Basel). 2022;11(8):1123. doi:10.3390/antibiotics11081123
87. Peña O, Zavala M, Ruelas H. Pharmaceuticals market, consumption trends and disease incidence are not driving the pharmaceutical research on water and wastewater. Int J Environ Res Public Health. 2021;18(5):2532. doi:10.3390/ijerph18052532
88. Pokharel K, Dawadi B, Shrestha L. Role of biofilm in bacterial infection and antimicrobial resistance. J Nepal Med Assoc. 2022;60(253):836–40. doi:10.31729/jnma.7580
89. Prapanchan V, Kumar E, Subramani T, Sathya U, Li P. A global perspective on microplastic occurrence in sediments and water with a special focus on sources, analytical techniques, health risks, and remediation technologies. Water (Basel). 2023;15(11):1987. doi:10.3390/w15111987
90. Priya A, Anusha G, Thanigaivel S, Karthick A, Mohanavel V, Velmurugan P, *et al*. Removing microplastics from wastewater using leading-edge treatment technologies: a solution to microplastic pollution—a review. Bioprocess Biosyst Eng. 2023;46(3):309–21.
91. Raeiszadeh M, Adeli B. A critical review on ultraviolet disinfection systems against COVID-19 outbreak: applicability, validation, and safety considerations. ACS Photonics. 2020;7(11):2941–51. doi:10.1021/acsphotonics.0c01245
92. Rudhart S, Günther F, Dapper L, Thangavelu K, Gehrt F, Stanković P, *et al*. UV light-based decontamination: an effective and fast way for disinfection of endoscopes in otorhinolaryngology? Eur Arch Otorhinolaryngol. 2020;277(8):2363–9. doi:10.1007/s00405-020-05978-w
93. Rutala W, Bolomey A, Cadnum J, Donskey C. Inactivation and/or physical removal of Candida auris from floors by detergent cleaner, disinfectants, microfiber, and ultraviolet C light (UV-C). Infect Control Hosp Epidemiol. 2023;45(3):390–2. doi:10.1017/ice.2023.194
94. Silva V, Correia E, Pereira J, González-Machado C, Capita R, Alonso-Calleja C, *et al*. Biofilm formation of Staphylococcus aureus from pets, livestock, and wild animals: relationship with clonal lineages and antimicrobial resistance. Antibiotics (Basel). 2022;11(6):772. doi:10.3390/antibiotics11060772
95. Skudra A, Mežule L, Spunde K, Rēvalde G, Zajakina A, Zinge M, *et al*. Alternative UV light sources for surface disinfection. Environ Technol Res Proc Int Sci Pract

Conf. 2021;1:218–22. doi:10.17770/etr2021vol1.6596

96. Suchánková J, Roupcová P, Suranova K, Klouda K, Kročová Š, Slany J, *et al*. Specific types of wastewater pollution in Ostrava and possibilities of decontamination through wastewater treatment plants. E3S Web Conf. 2023;436:10013. doi:10.1051/e3sconf/202343610013
97. Sun J, Dai X, Wang Q, Loosdrecht M, Ni B. Microplastics in wastewater treatment plants: detection, occurrence and removal. Water Res. 2019;152:21–37. doi:10.1016/j.watres.2018.12.050
98. Turek M, Różycka-Sokołowska E, Koprowski M, Marciniak B, Bałczewski P. Can pharmaceutical excipients threaten the aquatic environment? A risk assessment based on the Microtox® biotest. Molecules. 2023;28(18):6590. doi:10.3390/molecules28186590
99. Vats P, Kaur U, Rishi P. Heavy metal-induced selection and proliferation of antibiotic resistance: a review. J Appl Microbiol. 2022;132(6):4058–76. doi:10.1111/jam.15492
100. Vistanty H, Crisnaningtyas F. Integration of upflow anaerobic sludge blanket and constructed wetlands for pharmaceutical wastewater treatment. IOP Conf Ser Earth Environ Sci. 2021;623(1):012082. doi:10.1088/1755-1315/623/1/012082
101. Yang Y, Zhang X, Jiang J, Han J, Li W, Li X, *et al*. Which micropollutants in water environments deserve more attention globally? Environ Sci Technol. 2021;56(1):13–29. doi:10.1021/acs.est.1c04250
102. Yu X, Zhao W, Lyu S, Cai Z, Yu G, Wang H, *et al*. Estimating the mass of pharmaceuticals harbored in municipal solid waste landfills by analyzing refuse samples at various ages and depths. Environ Sci Technol. 2023;57(15):6063–71. doi:10.1021/acs.est.2c09455
103. Zhang T, Luo Y, Zhou B, Teng Z, Huang C. Sequential application of peracetic acid and UV irradiation (PAA–UV/PAA) for improved bacterial inactivation in fresh-cut produce wash water. ACS ES&T Water. 2022;2(7):1247–53. doi:10.1021/acsestwater.2c00087
104. Zhao X, You F. Life cycle assessment of microplastics reveals their greater environmental hazards than mismanaged polymer waste losses. Environ Sci Technol. 2022;56(16):11780–97. doi:10.1021/acs.est.2c01549
105. Zheng Q, Qi Y, Le Z, Han F, Li F, Yang H, *et al*. The interactions between antibiotic resistance genes and heavy metal pollution under co-selective pressure influenced the bio-enzyme activity. Front Chem. 2021;9:691565. doi:10.3389/fchem.2021.691565
106. Zhu X, Hao C, Zhang M, Lan B. Enhanced adsorption of bromoform onto microplastic polyethylene terephthalate exposed to ozonation and chlorination. Molecules. 2022;28(1):259. doi:10.3390/molecules28010259
107. Zhu X, Yang Y, Liu L, Gu J, Yang G, Li Z, *et al*. Effect of heavy metal-sulfamethoxazole complexes on the sulfanilamide resistance gene sul1. [Preprint]. 2023. doi:10.21203/rs.3.rs-3164014/v1