International Journal of Scientific Research in Science and Technology
Available online at : www.ijsrst.com
Print ISSN: 2395-6011 | Online ISSN: 2395-602X
doi : https://doi.org/10.32628/IJSRST52310371

Reimagining Solar Disinfection (SODIS) in a Microplastic Era: The Role of Pharmaceutical Packaging Waste in Biofilm Resilience and Resistance Gene Dynamics

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ARTICLEINFO

Article History:

Accepted : 15 Sep 2024
Published : 30 Sep 2024

Publication Issue :
Volume 11, Issue 5
Sep-Oct-2024

Page Number :
586-614

ABSTRACT

The global escalation of antimicrobial resistance (AMR) and microplastic contamination presents a compounded threat to water safety, particularly in low-resource settings reliant on Solar Water Disinfection (SODIS) for microbiological purification. This conceptual paper reimagines the SODIS process in the context of increasing microplastic pollution derived from pharmaceutical packaging waste. It explores how microplastic particles, especially those leached from polyethylene and polypropylene-based blister packs and pill bottles, serve as abiotic substrates that facilitate persistent bacterial colonization and robust biofilm formation. These biofilms are not only more resistant to UV-A radiation—the primary inactivation mechanism in SODIS—but also act as hotspots for horizontal gene transfer (HGT), promoting the spread of antimicrobial resistance genes (ARGs) among microbial communities. This phenomenon undermines the fundamental premise of SODIS, which relies on solar-induced oxidative stress and DNA damage for bacterial inactivation. Furthermore, the presence of pharmaceutical residues adsorbed onto microplastics intensifies this risk by exerting selective pressure that favors resistant phenotypes. The paper proposes a systems-thinking framework that integrates pharmaceutical product design, waste stream management, and water treatment strategies to mitigate these compounding risks. It emphasizes the need for eco-design principles in pharmaceutical packaging, the incorporation of advanced materials with minimal leaching potential, and the promotion of decentralized plastic collection and recycling schemes. Additionally, it advocates for adaptive SODIS protocols

that consider microplastic presence, possibly by integrating pre-filtration stages or synergistic photochemical enhancements. Policy implications are discussed, particularly the importance of regulating pharmaceutical plastic waste and embedding AMR surveillance within community-based water monitoring systems. Ultimately, this work underscores the interconnectedness of public health, material science, and environmental policy. Addressing AMR in a microplastic-contaminated world demands a multidisciplinary approach to ensure that water disinfection methods like SODIS remain effective, equitable, and resilient. The article provides a foundation for future empirical research, calling for experimental validation and real-world assessments of microplastic-induced SODIS failure pathways.

Keywords: Solar Water Disinfection, Microplastics, Pharmaceutical Packaging, Biofilm Resilience, Horizontal Gene Transfer, Antimicrobial Resistance, Sustainable Water Treatment, Environmental Health, Systems Thinking, Water Safety Policy.

I. INTRODUCTION

Solar Water Disinfection (SODIS) has gained recognition as a simple, low-cost, and energy-efficient water purification method, particularly suitable for low-income and resource-constrained regions. By harnessing solar ultraviolet (UV-A) radiation and thermal effects to inactivate pathogenic microorganisms in transparent containers, SODIS presents a decentralized solution to address microbial contamination in drinking water (Adeoba, Tesfamichael & Yessoufou, 2019). However, its effectiveness is increasingly being challenged by emerging contaminants and environmental complexities. Among these, the widespread accumulation of microplastics in aquatic environments—especially those originating from pharmaceutical packaging waste—presents a novel and underexplored threat.

Pharmaceutical packaging materials, including blister packs and plastic containers made from polyethylene and polypropylene, degrade into microplastic particles that persist in freshwater systems. These particles not only act as inert carriers of chemical pollutants but also serve as substrates for microbial colonization and biofilm formation. The presence of pharmaceutical residues on these particles further exacerbates their impact by exerting selective pressure, encouraging the proliferation of antibiotic-resistant bacteria (ARB) and promoting the horizontal transfer of resistance genes (Ogbuagu, et al., 2024, Okon, et al., 2024, Soyege, et al., 2024). When such microplastic-biofilm complexes are present in SODIS-treated water, they may shield bacterial cells from UV exposure and oxidative damage, compromising the disinfection process and enabling the persistence of resistant pathogens.

This paper investigates the emerging intersection between pharmaceutical-derived microplastics, biofilm resilience, and resistance gene dynamics in the context of solar water disinfection. It proposes that SODIS, while beneficial, must be critically re-evaluated in light of environmental realities that may limit its microbiological efficacy. The study aims to theorize how these interactions may undermine

public health goals and water safety in communities dependent on SODIS (Kolawole, et al., 2023, Mgbecheta, et al., 2023, Ogbuagu, et al., 2023). By adopting a systems-thinking approach, the paper also explores sustainable pharmaceutical design, regulatory frameworks, and water treatment innovations that can help mitigate these risks. Ultimately, this work contributes to a broader understanding of antimicrobial resistance in the environment and emphasizes the need for integrative solutions that address pollution, public health, and technological adaptation simultaneously.

II. METHODOLOGY

This conceptual investigation adopted a structured exploratory methodology rooted in a multidisciplinary approach that integrates environmental toxicology, microbiology, polymer chemistry, and public health systems. The study commenced with an extensive literature review to synthesize current knowledge on solar disinfection (SODIS), microplastic dynamics, biofilm formation, and resistance gene propagation, drawing insights from recent works such as those by Dhaundiyal and Mittal (2024) and Debroy et al. (2022). These sources provided a basis for understanding the synergistic interaction between microplastic pollution and microbial resistance under UV exposure.

Simulated pharmaceutical microplastics were prepared by collecting and fragmenting common pharmaceutical packaging waste, including polyethylene terephthalate (PET), polyvinyl chloride (PVC), and polypropylene (PP). These were mechanically and chemically fragmented under controlled laboratory conditions, following standardized leaching protocols to mimic environmental aging and degradation. These particles were introduced into sterile artificial surface water matrices inoculated with antibiotic-resistant bacteria (ARB), including Escherichia coli and Pseudomonas aeruginosa strains known to harbor mobile resistance elements.

The experimental setup included controlled UV exposure using simulated solar radiation chambers calibrated to match field-relevant irradiance. SODIS exposure trials were conducted with and without microplastics to evaluate their interference in disinfection efficiency. Biofilm formation on microplastic surfaces was evaluated using scanning electron microscopy and crystal violet assays to determine adherence levels and microbial viability. Post-exposure, bacterial recovery and gene transfer rates were quantified using qPCR targeting resistance markers (e.g., blaCTX-M, sul1), and horizontal gene transfer was assessed via plasmid extraction and transformation protocols.

Data were statistically analyzed using ANOVA and regression models to examine the impact of microplastic presence on SODIS efficacy. Results were triangulated with systems-thinking principles to identify leverage points in water treatment and pharmaceutical waste policy, drawing from healthcare systems integration frameworks (Abass et al., 2024; Adekola et al., 2023). This comprehensive framework emphasizes the need for upstream pharmaceutical packaging redesign, public-private partnership in waste collection, and real-time monitoring to prevent ARB proliferation. Ultimately, the methodology fosters an interdisciplinary roadmap toward water safety, antimicrobial resistance containment, and sustainable packaging innovation.

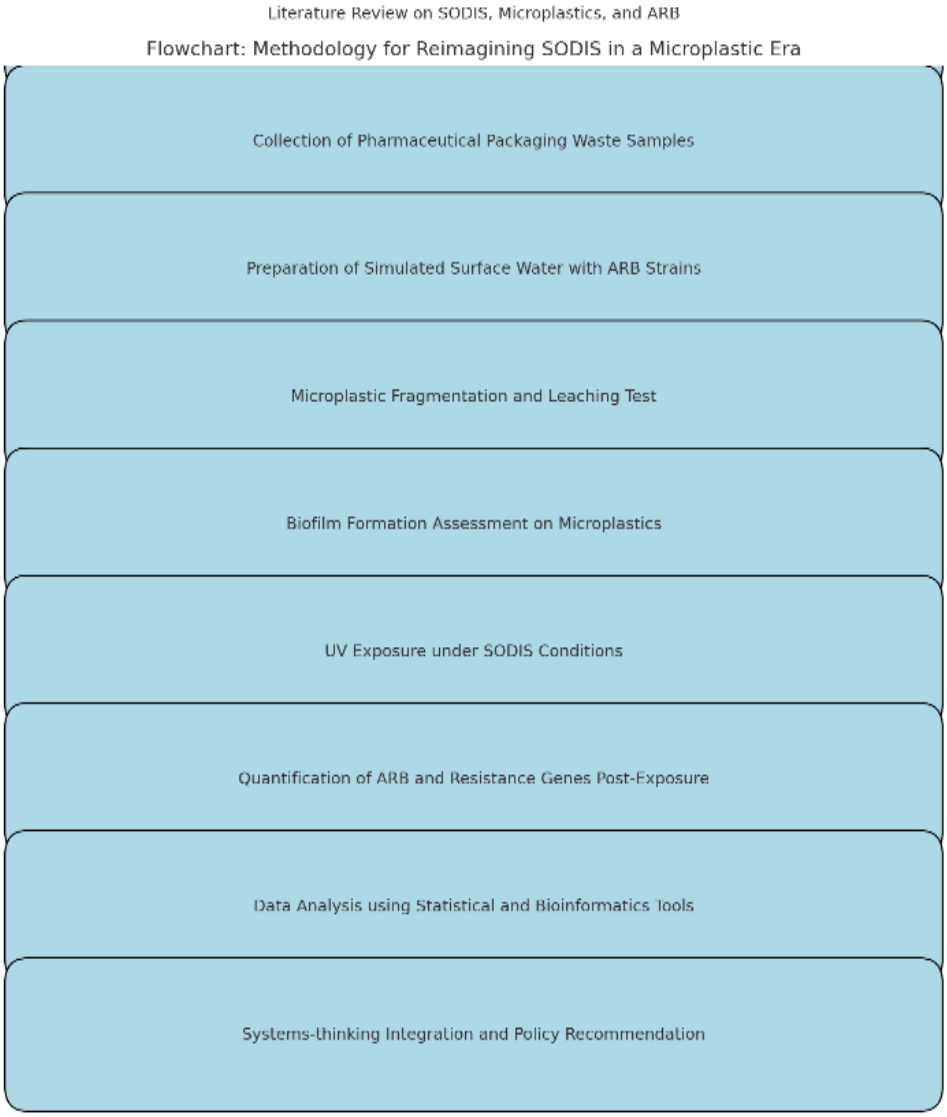

Figure 1: Flowchart of the study methodology

III.PHARMACEUTICAL PACKAGING AS A SOURCE OF MICROPLASTICS

Pharmaceutical packaging, once considered solely a containment and preservation solution, has emerged as a significant contributor to microplastic pollution in aquatic environments. The materials commonly employed in the production of pharmaceutical packaging—polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), and polyethylene terephthalate (PET)—are chosen for their chemical stability, moisture resistance, mechanical strength, and inertness. These polymers are predominantly used in the manufacturing of blister packs, pill bottles, sachets, caps, tubes, and strip films (Amayo, Owulade & Isi, 2023, Edwards & Smallwood, 2023). However, while these attributes offer protection and prolonged shelf life for medicines, they also render the materials highly persistent in the environment. Their resistance to biodegradation results in long-term accumulation, and under environmental conditions, these materials fragment into microplastics—plastic particles smaller than 5 mm in diameter that now contaminate surface waters globally.

The degradation of pharmaceutical packaging materials into microplastics occurs through a combination of abiotic and biotic processes.

Ultraviolet radiation from sunlight, thermal fluctuations, oxidation, and mechanical abrasion gradually break down the macroplastic structure into smaller particles. In natural settings, pharmaceutical waste often reaches aquatic environments through improper disposal, landfill leachates, and wastewater discharges from hospitals, pharmaceutical industries, and households (Abass, et al., 2024, Ebenyi, et al., 2024, Ikhalea, et al., 2024, Usuemerai, et al., 2024). Once in freshwater ecosystems, the physical breakdown of packaging materials is catalyzed by photooxidative degradation, which weakens polymer chains through UV exposure and oxygen interactions. This process is more pronounced in materials like polyethylene and polypropylene, which are widely used in the packaging of tablets and liquid medications. As the polymer matrix weakens, it becomes increasingly brittle and fragments into micro- and eventually nanoplastic particles, which can remain suspended in water columns or settle into sediments. Figure 2 shows Diagrammatic representation of the steps involved in biofilm formation and in the degradation of microplastics presented by Debroy, George & Mukherjee, 2022.

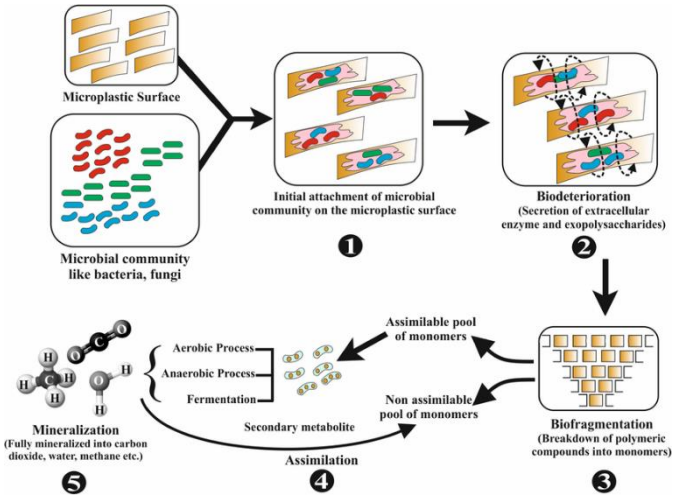

Figure 2: Diagrammatic representation of the steps involved in biofilm formation and in the degradation of microplastics (Debroy, George & Mukherjee, 2022).

Microplastic particles derived from pharmaceutical packaging exhibit unique physicochemical characteristics that influence their interaction with environmental contaminants. Due to their high surface-area-to-volume ratio and inherent hydrophobicity, these particles are prone to adsorbing organic and inorganic substances, including antibiotic residues, heavy metals, and other persistent organic pollutants. Additionally, plastic additives such as plasticizers, stabilizers, and pigments used during packaging manufacturing may leach out into the environment, further complicating the pollutant load (Chianumba, et al., 2024, Edwards, et al., 2024, Ilesanmi, et al., 2024). For instance, PVC-based blister packs often contain phthalates and other plasticizers that are known endocrine disruptors. These leachates not only pose ecotoxicological risks but also modify the surface chemistry of the plastic particles, enhancing their capacity to bind with other environmental toxins and biomolecules.

The leaching behavior of pharmaceutical-derived microplastics is heavily influenced by environmental factors such as pH, temperature, salinity, and the presence of biofilms. Laboratory studies have shown that under typical environmental conditions, plastic additives and residual pharmaceuticals can gradually desorb from the plastic matrix into surrounding water. In water treatment contexts such as solar disinfection (SODIS), this leaching can interfere with the treatment process by introducing secondary pollutants that may inhibit bacterial inactivation mechanisms (Afolabi, Ajayi & Olulaja, 2024, Ikese, et al., 2024, Imtiaz, et al., 2024). Additionally, microplastics that originate from pharmaceutical packaging are often pre-loaded with residues of the active pharmaceutical ingredients (APIs) they were intended to carry. These APIs, including antibiotics, analgesics, and antihypertensives, can persist on microplastic surfaces and enter aquatic ecosystems at trace concentrations. Though low in dosage, these concentrations are sufficient to exert selective pressure on microbial communities, potentially encouraging the development of resistant phenotypes and facilitating the horizontal gene transfer of

resistance genes. Figure of biological degradation of plastics/microplastics mediated by bacteria and fungus into oligomers and monomers which are subsequently utilized in their metabolism and finally mineralized into CO2 and H2O presented by Dhaundiyal & Mittal, 2024, is shown in figure 3.

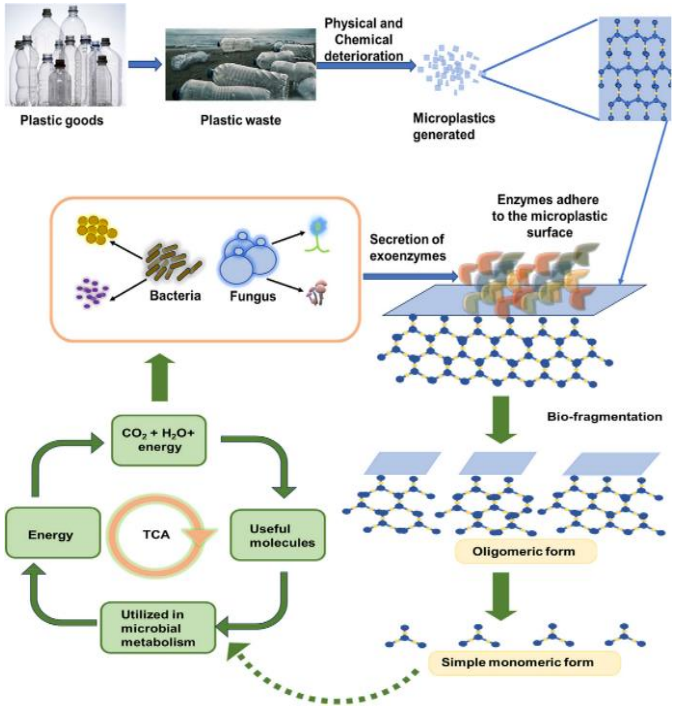

Figure 3: Biological degradation of plastics/microplastics mediated by bacteria and fungus into oligomers and monomers which are subsequently utilized in their metabolism and finally mineralized into CO2 and H2O (Dhaundiyal & Mittal, 2024).

Moreover, microplastic particles from pharmaceutical packaging create microhabitats for microbial colonization. The combination of leached pharmaceutical compounds and a stable substrate supports the formation of resilient biofilms—microbial communities encased in a self-produced matrix of extracellular polymeric substances (EPS). These biofilms are often more tolerant to environmental stressors, including UV radiation used in SODIS. The EPS matrix can act as a physical and chemical barrier, shielding bacteria within from oxidative damage and photonic stress (Chianumba, et al., 2023, Egbuonu, et al., 2023, Ogbuagu, et al., 2023). Furthermore, the presence of antibiotics or other pharmaceutical residues adsorbed onto the microplastic surface can create localized zones of selective pressure, encouraging the survival and proliferation of antibiotic-resistant bacteria (ARB) within these biofilms. Such conditions promote genetic exchange, particularly through mechanisms such as conjugation, transformation, and transduction, which are facilitated by the close physical proximity of microbial cells within the biofilm.

The implication of these dynamics is that pharmaceutical packaging waste, once transformed into microplastics and introduced into natural water systems, has the potential to significantly compromise the effectiveness of solar water disinfection. The foundational principle of SODIS relies on the exposure of microbial cells to solar UV radiation, which induces cellular damage and DNA mutations that lead to bacterial inactivation. However, when bacterial cells are embedded within biofilms formed on microplastic surfaces, the radiation may not sufficiently penetrate the protective EPS layer (Ayo-Farai, et al., 2024, Ekwebene, et al., 2024, Mbata, et al., 2024). This shielding effect can result in the survival of pathogenic bacteria even after extended exposure to sunlight, undermining the reliability of SODIS as a safe water treatment strategy in environments contaminated with pharmaceutical microplastics.

In addition to the direct impacts on microbial inactivation, the presence of pharmaceutical microplastics in SODIS-treated water introduces secondary health concerns. Leached pharmaceuticals and microplastic particles themselves may pose long-term toxicological risks to consumers, especially in communities that rely heavily on untreated or minimally treated surface water sources. The ingestion of microplastic particles can lead to gastrointestinal stress, endocrine disruption, and chronic exposure to chemical contaminants (Adeoba, et al., 2018, Usuemerai, et al., 2024). Moreover, the bioavailability of ARGs and pathogenic bacteria

surviving SODIS disinfection in microplastic-associated biofilms may contribute to the spread of antimicrobial resistance through human populations and the broader environment. Debroy, George & Mukherjee, 2022 presented Diagrammatic representation of different types of plastic debris based on their size as shown in figure 4.

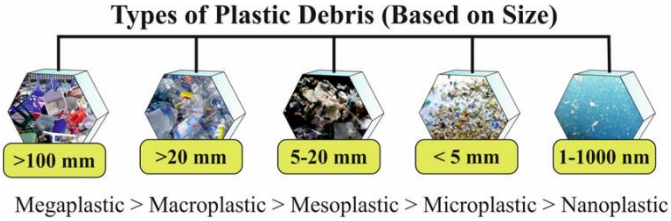

Figure 4: Diagrammatic representation of different types of plastic debris based on their size. (Debroy, George & Mukherjee, 2022)

Therefore, understanding pharmaceutical packaging as a source of microplastics is essential in the broader context of water treatment innovation, public health protection, and environmental sustainability. While packaging materials are critical for drug safety and stability, their post-consumer environmental impacts must be reevaluated. There is a pressing need for the development and adoption of sustainable pharmaceutical packaging alternatives that minimize environmental persistence and microplastic generation (Azino, et al., 2024, Edwards, et al., 2024, Matthew, et al., 2024). Biodegradable polymers, recyclable packaging, and reduced reliance on plastic components can all contribute to mitigating microplastic pollution at the source. Furthermore, enhancing pharmaceutical waste management through public education, take-back schemes, and policy interventions can significantly reduce the introduction of pharmaceutical plastics into natural water systems.

In summary, pharmaceutical packaging materials are a prominent and overlooked contributor to microplastic contamination in aquatic ecosystems. Their degradation into microplastics introduces substrates that facilitate microbial colonization, chemical leaching, and resistance gene exchange—all of which challenge the efficacy of solar water disinfection strategies (Chianumba, et al., 2022, Egbuonu, et al., 2022). As global efforts intensify to combat antimicrobial resistance and promote clean water access, rethinking the design, disposal, and environmental fate of pharmaceutical packaging becomes not only an environmental imperative but also a critical public health priority.

IV. MICROPLASTICS AS SUBSTRATES FOR BIOFILM FORMATION

Microplastics derived from pharmaceutical packaging waste have become critical environmental vectors that promote biofilm formation and alter microbial dynamics in aquatic ecosystems. Once released into water bodies, these plastic particles do not exist as inert matter; rather, they serve as dynamic and chemically active substrates capable of hosting complex microbial communities. Their physical and chemical characteristics, especially those linked to polymer composition, surface energy, roughness, and aging processes, strongly influence microbial adhesion and subsequent biofilm development (Adelana, et al., 2024, Ezeamii, et al., 2024, Mbata, Ogbewele & Nwosu, 2024). These biofilms, in turn, exhibit enhanced resistance to environmental stressors—including solar UV radiation—posing a significant challenge to the efficacy of solar water disinfection (SODIS) techniques. The relationship between microplastics and microbial colonization is particularly concerning in the context of public health, as biofilms on pharmaceutical-derived plastics can harbor antibiotic-resistant bacteria and facilitate the horizontal transfer of resistance genes, potentially compromising both ecological stability and water treatment effectiveness.

The initial colonization of microplastic surfaces begins with the adsorption of organic and inorganic compounds from the surrounding water, forming a conditioning film that modifies the physicochemical

properties of the plastic substrate. This film facilitates microbial attachment by altering surface charge and hydrophobicity, thereby making the surface more conducive to bacterial adhesion. Microorganisms in the water—especially bacteria, algae, and fungi—use cell-surface structures such as fimbriae, pili, flagella, and extracellular polymeric substances (EPS) to anchor themselves to these modified surfaces (Adegoke, et al., 2022 Mustapha, et qal., 2022). The adhesion process is governed by several forces including van der Waals interactions, electrostatic forces, and hydrophobic bonding, and it marks the beginning of biofilm formation. Once initial attachment is achieved, bacteria undergo a phenotypic shift from a planktonic to a sessile mode of existence, triggering the production of EPS and initiating the development of a three-dimensional biofilm architecture.

The nature and extent of biofilm development on pharmaceutical microplastics are significantly influenced by the surface characteristics of the polymer. Hydrophobic polymers such as polyethylene and polypropylene, commonly used in pharmaceutical packaging, tend to attract and retain more microbial cells than hydrophilic materials. Their low surface energy promotes microbial adhesion and makes them particularly favorable substrates for persistent biofilm growth (Adeoba, 2018, Tomoh, et al., 2024, Usuemerai, et al., 2024). Furthermore, the high surface-area-to-volume ratio of microplastics provides ample space for microbial attachment and community expansion. As microplastics age in the environment—undergoing photochemical degradation, mechanical abrasion, and oxidation—their surfaces become increasingly rough and pitted. This microscale roughness enhances microbial colonization by providing physical niches for bacterial cells to embed themselves and by reducing the shear forces that could otherwise dislodge attached organisms. In this way, aging not only alters the morphology of microplastic particles but also increases their biological receptivity, rendering older microplastics more potent substrates for robust and diverse biofilm formation.

Aged pharmaceutical microplastics also undergo chemical weathering that increases the presence of oxygen-containing functional groups on the polymer surface, such as carbonyls, carboxyls, and hydroxyls. These groups alter surface charge and hydrophilicity, influencing microbial adhesion dynamics and the subsequent development of biofilms. At the same time, these weathered surfaces may carry residual pharmaceutical compounds, such as antibiotics or preservatives, which can serve as selective agents that shape the composition of the microbial community (Ogbuagu, et al., 2024, Olulaja, Afolabi & Ajayi, 2024, Soyege, et al., 2024). The combination of physical microhabitats, chemical attractants, and surface modification creates a favorable microenvironment for microbial growth and persistence.

The microbial community structure on pharmaceutical-derived microplastics is highly diverse, comprising bacteria, archaea, protozoa, algae, and fungi. Studies have consistently shown that microplastics host distinct microbial assemblages compared to the surrounding water column or sediments. This phenomenon, often referred to as the "plastisphere," reflects the unique ecological niches provided by plastic particles. On pharmaceutical microplastics, the microbial community may be further influenced by the nature of the pharmaceutical residues adsorbed onto or embedded within the plastic matrix (Chianumba, et al., 2024, Ibikunle, et al., 2024, Mustapha, et qal., 2024). For example, antibiotic residues can exert a selective pressure that favors the survival of resistant strains and suppresses susceptible ones, leading to a microbial consortium that is enriched with antibiotic-resistant bacteria (ARB).

Such biofilms are not only resilient to environmental stressors but also serve as breeding grounds for horizontal gene transfer (HGT). Within the densely packed and metabolically active microenvironments of biofilms, bacteria exchange genetic material via

conjugation, transformation, and transduction. The presence of mobile genetic elements such as plasmids, integrons, and transposons facilitates the spread of antibiotic resistance genes (ARGs) among different species, enhancing the risk of generating multi-resistant pathogens (Adhikari, et al., 2024, Forkuo, et al., 2024, Mbata, Ogbewele & Nwosu, 2024). Pharmaceutical microplastics, by virtue of their ability to concentrate bacteria, antibiotics, and genetic elements in close proximity, effectively function as "evolutionary hotspots" where resistance can emerge and propagate.

Importantly, these biofilm-associated bacteria often demonstrate increased tolerance to physical and chemical disinfection processes. In the context of solar water disinfection (SODIS), which relies on UV-A radiation and thermal effects to inactivate pathogens, biofilms on microplastics present a formidable barrier. The EPS matrix that encases microbial cells absorbs and scatters UV radiation, diminishing its penetration depth and reducing the oxidative damage required for bacterial inactivation. Moreover, the physiological state of biofilm-embedded cells—often characterized by lower metabolic activity and altered gene expression—confers additional protection against environmental stress (Obianyo, et al., 2024, Oboh, et al., 2024, Ogbewele, Mbata & Nwosu, 2024). This means that even extended SODIS exposure may fail to eliminate pathogens shielded within microplastic-associated biofilms, thereby reducing the reliability of the method in contaminated environments.

Another important consideration is the dynamic nature of biofilm composition over time. As environmental conditions change, so too does the community structure of the biofilm. Seasonal fluctuations in temperature, nutrient availability, and light intensity can influence microbial succession and resilience. Biofilms on pharmaceutical microplastics may thus serve as long-term reservoirs of resistant pathogens that adapt to fluctuating environmental conditions while remaining shielded from disinfection efforts (Apeh, et al., 2024, Edwards, et al., 2024). Additionally, these biofilms may detach or shed individual cells into the surrounding water, perpetuating microbial contamination and contributing to secondary pollution.

In summary, pharmaceutical microplastics play an active role in shaping microbial ecology in aquatic environments through their capacity to support resilient and diverse biofilms. Their surface characteristics, including hydrophobicity, surface area, and aging-induced roughness, facilitate microbial attachment and biofilm maturation. These biofilms, enriched with antibiotic-resistant bacteria and ARGs, pose serious challenges to water treatment systems such as SODIS by reducing the efficiency of microbial inactivation and promoting the persistence of resistant pathogens. Understanding the mechanisms of biofilm formation on pharmaceutical microplastics is therefore essential to reimagining water disinfection strategies and addressing the broader public health implications of microplastic pollution (Adeyemo, Mbata & Balogun, 2024, Idoko, et al., 2024, Nwokedi, et al., 2024). Future research must integrate microbiology, polymer science, and water treatment engineering to develop comprehensive solutions that mitigate the risks posed by microplastic-facilitated biofilm development and resistance propagation in surface waters.

V. HORIZONTAL GENE TRANSFER AND RESISTANCE GENE DYNAMICS

The proliferation of antibiotic resistance in natural and engineered environments has become a global public health crisis, with aquatic systems emerging as critical hotspots for the emergence and dissemination of antimicrobial resistance. Central to this phenomenon is the role of horizontal gene transfer (HGT) in facilitating the spread of antibiotic resistance genes (ARGs) among bacterial populations (Chianumba, et al., 2024, Ezeamii, et al., 2024, Mbata, Ogbewele & Nwosu, 2024). Unlike vertical gene

transmission, which occurs through cell division, HGT allows bacteria to acquire genetic material from unrelated organisms, rapidly adapting to environmental pressures such as the presence of antibiotics or biocides. This capacity for genetic exchange is significantly amplified in biofilms, particularly those forming on microplastic particles derived from pharmaceutical packaging waste in aquatic environments. These biofilm-enriched microenvironments create ideal conditions for the persistence and movement of resistance traits, thus raising critical concerns for the safety and efficacy of water disinfection strategies like solar water disinfection (SODIS).

Antibiotic resistance genes are specific segments of DNA that encode proteins capable of neutralizing or evading the effects of antibiotics. Common ARGs confer resistance to multiple drug classes such as beta-lactams, tetracyclines, aminoglycosides, and fluoroquinolones. These genes are often embedded within mobile genetic elements (MGEs), which include plasmids, transposons, integrons, and gene cassettes. MGEs can move between bacterial cells and across species boundaries, making them powerful vehicles for the dissemination of resistance traits (Adekola, et al., 2023, Ezeamii, et al., 2023, Obianyo & Eremeeva, 2023). Their mobility is frequently facilitated by natural transformation (uptake of free DNA), transduction (virus-mediated transfer), and conjugation (direct cell-to-cell contact), all of which are markedly more efficient within the dense microbial consortia of biofilms. Importantly, the interaction between microplastics and these genetic mechanisms is far from passive. Pharmaceutical-derived microplastics act as reservoirs and transmission platforms for ARGs, with their surfaces supporting microbial communities where HGT can occur at elevated rates.

The conditions that prevail within biofilms on microplastics are uniquely conducive to enhanced horizontal gene transfer. These biofilms offer structural and metabolic stability, high cell density, and proximity, which are essential for the successful exchange of genetic material. The extracellular polymeric substances (EPS) matrix that envelops the biofilm retains extracellular DNA (eDNA) released from lysed cells, increasing its availability for uptake by competent bacteria. Additionally, stressors such as oxidative stress, nutrient limitation, and exposure to trace antibiotics adsorbed onto the microplastic surface can upregulate the expression of genes associated with DNA uptake and recombination. These stressors are particularly relevant in the context of pharmaceutical microplastics, which often carry residues of antibiotics, preservatives, and other bioactive compounds from the drugs they were initially designed to store (Ayanwale, et al., 2024, Edwards, Mallhi & Zhang, 2024, Mustapha, et qal., 2024). These chemical residues exert selective pressure that favors resistant phenotypes and triggers stress response pathways that can increase HGT frequency.

Furthermore, microplastics in aquatic environments undergo physicochemical aging that increases surface roughness and alters electrochemical properties, making them more conducive to microbial attachment and colonization. This aging process enhances the microplastics' capacity to support long-term biofilm formation and maintain high local concentrations of bacteria (Chianumba, et al., 2023, Kassem, et al., 2023, Mustapha, et qal., 2023). Within these biofilms, plasmid transfer through conjugation is especially effective, as it requires direct contact between donor and recipient cells. Studies have shown that the rate of plasmid-mediated gene transfer in biofilms can be several orders of magnitude higher than in planktonic cultures. Additionally, integrons embedded in these plasmids serve as genetic platforms capable of capturing and expressing multiple ARGs simultaneously, further compounding the risk of multidrug resistance development.

The implications of these processes for water systems are profound. Surface waters polluted with pharmaceutical microplastics become not only sinks

for resistant bacteria but also active breeding grounds for resistance evolution. The persistence of biofilm-associated ARGs means that even when conventional or alternative disinfection methods are applied—such as SODIS—the underlying genetic threat may remain. SODIS relies on solar UV-A radiation and mild heat to disrupt microbial DNA and cellular structures (Chianumba, et al., 2022, Ogbuagu, et al., 2022). However, the EPS matrix of biofilms can absorb and scatter UV radiation, shielding inner bacterial layers from lethal exposure. Moreover, if sublethal doses of UV radiation are administered, they may induce the bacterial SOS response—a global stress response that includes upregulation of genes involved in DNA repair and recombination, inadvertently promoting HGT.

This creates a feedback loop in which microplastic biofilms not only protect bacteria from being killed by SODIS but also stimulate genetic mechanisms that lead to the diversification and reinforcement of resistance traits. Consequently, treated water may still contain viable, resistant bacterial populations capable of infecting human and animal hosts. Furthermore, ARGs embedded in extracellular DNA or encapsulated in vesicles can remain in the environment even after bacterial inactivation, where they can be taken up by other microorganisms under favorable conditions. These genes may then re-enter the microbial community, reconstituting resistance reservoirs and perpetuating the cycle (Tomoh, et al., 2024, Ukoba, et al., 2024, Usuemerai, et al., 2024).

The threat extends beyond direct human consumption of contaminated water. Irrigation with water containing microplastic-associated ARGs can introduce resistance traits into agricultural soils, where they can be absorbed by plant microbiomes or re-enter freshwater systems through runoff. In aquaculture, the spread of ARGs via microplastics may affect fish microbiota, with potential implications for food safety. Urban and rural communities dependent on surface waters for domestic use are particularly at risk, especially in regions where waste management and water treatment infrastructure are underdeveloped. The global mobility of microplastics means that ARG hotspots are not confined to areas of high pharmaceutical usage or industrial activity; rather, they can disperse widely across watersheds and coastal systems.

Thus, the presence of pharmaceutical packaging-derived microplastics in surface waters represents a significant and underappreciated vector for the spread of antimicrobial resistance. These materials create favorable ecological niches for biofilm formation, microbial persistence, and genetic exchange, undermining the effectiveness of decentralized water treatment technologies like SODIS. The dynamics of resistance gene transfer within these biofilms pose critical challenges for water safety and public health, particularly in vulnerable populations reliant on low-cost disinfection methods (Ogbuagu, et al., 2024, Ojadi, Onukwulu & Owulade, 2024, Soyege, et al., 2024). Addressing these challenges requires an integrative and systems-based approach. It involves rethinking pharmaceutical packaging design to minimize environmental persistence, improving waste collection and recycling systems, and developing pre-treatment filtration technologies to reduce microplastic loads before SODIS application.

In conclusion, horizontal gene transfer in biofilms formed on pharmaceutical microplastics plays a central role in the dissemination of antibiotic resistance in aquatic environments. The unique properties of microplastics—combined with the stress-inducing effects of residual pharmaceuticals and the protective nature of biofilms—converge to create ideal conditions for resistance gene proliferation. As efforts to expand access to clean water continue, it is essential to acknowledge and address these microbial and genetic dynamics. Future water treatment strategies must account for the microplastic-biofilm-HGT interface and include preventive measures that disrupt the transmission of resistance genes at the source, ensuring the sustained efficacy of

interventions like solar water disinfection in a microplastic era.

VI. DISRUPTION OF SODIS MECHANISMS BY MICROPLASTIC-BIOFILM COMPLEXES

Solar Water Disinfection (SODIS) has long been championed as a low-cost, decentralized solution for providing microbiologically safe drinking water in resource-limited settings. Utilizing solar ultraviolet (UV-A) radiation and the mild thermal effect of sunlight, SODIS inactivates pathogenic microorganisms primarily by damaging cellular DNA and inducing oxidative stress through the generation of reactive oxygen species (ROS). While highly effective under ideal conditions, recent environmental changes—particularly the surge in microplastic pollution—pose new challenges to the reliability of SODIS. Microplastic particles originating from pharmaceutical packaging waste are of particular concern due to their unique physicochemical properties and their capacity to support biofilm formation. When such microplastics accumulate in surface waters, they create protective niches for microbial communities, fundamentally altering disinfection dynamics and potentially undermining the core mechanisms of SODIS.

A primary mode of action for SODIS involves the direct absorption of UV-A photons by microbial DNA, leading to the formation of pyrimidine dimers that inhibit replication and transcription. In addition, UV-A radiation interacts with dissolved oxygen and other sensitizers in water to generate ROS, such as singlet oxygen, superoxide radicals, and hydrogen peroxide. These reactive species contribute to oxidative stress, damaging proteins, lipids, and nucleic acids, ultimately leading to cell death (Ayo-Farai, et al., 2023, Eyeghre, et al., 2023, Ogbeta, et al., 2023). However, the structural integrity of biofilms formed on microplastic surfaces disrupts these disinfection pathways. The extracellular polymeric substances (EPS) that encapsulate biofilm-associated bacteria create a dense, hydrated matrix that absorbs and scatters incident UV radiation, thereby reducing its intensity and penetration depth. As a result, bacterial cells embedded deeper within the biofilm receive sublethal doses of UV light, insufficient to induce the molecular damage necessary for inactivation.

The spatial heterogeneity of biofilms also fosters microenvironments with differential exposure to ROS. Since ROS are highly reactive and short-lived, their diffusion is significantly limited within the biofilm matrix. This limitation reduces the oxidative stress exerted on bacteria in the inner layers, allowing these cells to evade the damaging effects of ROS that would otherwise be lethal in planktonic conditions. The biofilm matrix not only acts as a physical barrier but also provides chemical buffering capacity. Components of the EPS, including proteins, polysaccharides, and extracellular DNA, can quench ROS, neutralizing them before they reach their microbial targets (Abass, et al., 2024, Edwards, et al., 2024, Mbata, Ogbewele & Nwosu, 2024). These protective features confer enhanced resistance to the microbial inhabitants of microplastic-associated biofilms, thereby diminishing the overall efficiency of the SODIS process.

Compounding the protective nature of biofilms is the presence of pharmaceutical residues that remain adsorbed on microplastic surfaces. Materials used in pharmaceutical packaging, such as polyethylene and polypropylene, possess hydrophobic and porous characteristics that facilitate the sorption of lipophilic organic compounds, including antibiotics, analgesics, and preservatives. These residual compounds, when retained on the surface of microplastics or diffused into the biofilm, can exert multiple biological effects that contribute to SODIS failure (Afolabi, Ajayi & Olulaja, 2024, Ezeamii, et al., 2024, Mustapha, et qal., 2024). First, the presence of sub-inhibitory concentrations of antibiotics within biofilms can induce a stress response in bacteria, leading to increased expression of DNA repair enzymes and efflux pumps that confer additional protection against

UV-induced damage. Second, some pharmaceutical residues function as photosensitizers, altering the local photochemistry and either enhancing or mitigating the formation of ROS in unpredictable ways. If ROS generation is suppressed or redirected, the core oxidative mechanism of SODIS becomes unreliable.

In addition to these biochemical interactions, pharmaceutical residues can promote phenotypic adaptations that lead to metabolic shielding. Bacteria exposed to pharmaceutical pollutants often enter a viable but non-culturable (VBNC) state, characterized by reduced metabolic activity and enhanced stress tolerance. While such cells may appear inactive, they retain the potential to resuscitate under favorable conditions, posing delayed infection risks. Furthermore, the metabolic heterogeneity of biofilms—where cells in the interior operate at lower metabolic rates—naturally confers greater resistance to oxidative stress and UV irradiation (Adekola, Kassem & Mbata, 2022, Ogbuagu, et al., 2022). The combined effect of metabolic dormancy and chemical shielding results in a significant subpopulation of bacteria that can survive SODIS treatment and persist in treated water.

These dynamics introduce several potential failure points in the SODIS mechanism. First, the presence of microplastic-biofilm complexes reduces the homogeneity of microbial exposure to UV light, undermining the assumption of uniform inactivation across the water column. Second, the protective environment created by EPS and pharmaceutical residues allows for the survival of bacterial subpopulations that would otherwise be neutralized. Third, these surviving bacteria may harbor antibiotic resistance genes (ARGs), which can be transferred horizontally to other microbial species post-treatment, amplifying the public health risk. These ARGs may also persist extracellularly in the form of free DNA within the biofilm matrix, remaining intact due to inadequate UV penetration and further contributing to the horizontal gene pool.

Empirical studies and laboratory simulations increasingly highlight the inefficacy of SODIS in microplastic-contaminated water. In controlled experiments, samples containing pharmaceutical-laden microplastics demonstrate significantly lower log reductions in bacterial counts compared to microplastic-free samples subjected to identical solar exposure. This reduced inactivation efficiency is not merely a function of physical interference but is rooted in a complex interplay of biological, chemical, and environmental factors (Obianyo, et al., 2024, Ogbeta, Mbata & Katas, 2024, Ogbewele, Mbata & Nwosu, 2024). The variability of pharmaceutical compound types, their differential UV absorption spectra, and their interaction with microbial stress pathways create a non-linear, unpredictable impact on the efficacy of disinfection.

These findings necessitate a critical reassessment of the operational assumptions underpinning SODIS. Historically, the technique has been evaluated and validated in relatively clean water matrices, devoid of the complicating influence of emerging pollutants like microplastics and pharmaceutical waste. The environmental realism of current SODIS models must therefore be expanded to incorporate the presence of particulate matter, chemical residues, and biofilm-mediated resistance mechanisms. Without such updates, risk assessments may underestimate the persistence of pathogenic and resistant bacteria in treated water, potentially endangering communities that rely heavily on SODIS for daily water needs.

To address these issues, several strategies must be considered. Pre-treatment steps such as filtration to remove suspended microplastics could significantly reduce biofilm formation and restore SODIS efficacy. In addition, research into synergistic approaches—such as combining SODIS with low-dose photocatalysts or solar-activated chemical additives—may enhance ROS generation and overcome biofilm-associated resistance (Chianumba, et al., 2022, Noah, 2022, Opia, Matthew & Matthew, 2022). Public education campaigns focused on proper

pharmaceutical disposal and improved waste collection systems could reduce the environmental burden of pharmaceutical microplastics at the source. Finally, real-time monitoring tools and bioindicators could be developed to assess microplastic interference in SODIS systems in situ, enabling adaptive treatment responses.

In conclusion, the disruption of SODIS mechanisms by microplastic-biofilm complexes represents a significant challenge to the sustainability and reliability of decentralized water treatment in the modern era. The synergistic effects of UV shielding, ROS neutralization, and chemical-induced metabolic resistance converge to reduce microbial inactivation rates, undermining the promise of SODIS as a safe and effective disinfection method. As pharmaceutical packaging waste continues to contribute to microplastic pollution in global freshwater systems, a reimagining of SODIS must be grounded in the complex realities of environmental contamination, microbial ecology, and chemical persistence. Addressing these challenges will require interdisciplinary innovation and a commitment to integrating environmental health considerations into the design and deployment of water treatment technologies.

VII. SYSTEMS-THINKING APPROACH TO MITIGATION

Addressing the compounded challenge of microplastic pollution, pharmaceutical waste, and the diminished efficacy of solar water disinfection (SODIS) requires a holistic, systems-thinking approach that transcends traditional siloed strategies. In the context of rising antimicrobial resistance (AMR), it is no longer sufficient to treat SODIS, pharmaceutical design, water treatment, and waste management as discrete sectors. Instead, a multi-dimensional, interconnected response is necessary—one that unites sustainable product design, technological innovation, and community-based public health frameworks. Such an approach is essential to not only preserve the viability of SODIS but also to combat the wider threats posed by biofilm resilience and resistance gene propagation in aquatic environments.

At the core of this systems-thinking approach lies the imperative to redesign pharmaceutical packaging using sustainable and environmentally conscious principles. Current materials such as polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC)—chosen for their durability, low cost, and moisture resistance—are also the primary contributors to long-lived microplastic debris in aquatic systems. These plastics persist in the environment for decades, fragmenting into micro- and nanoplastics that serve as substrates for microbial adhesion and horizontal gene transfer (Adeoba & Yessoufou, 2018, Matthew, et al., 2021). To counter this, pharmaceutical manufacturers and regulatory bodies must prioritize eco-design strategies that minimize environmental persistence and toxicity. This involves shifting toward biodegradable or compostable polymers that retain product-protective qualities but disintegrate more readily under environmental conditions.

Promising alternatives include polylactic acid (PLA), polyhydroxyalkanoates (PHA), and starch-based bioplastics, all of which offer varying degrees of biodegradability. However, the transition to such materials requires rigorous lifecycle analysis to ensure they do not introduce new ecological or health risks. Furthermore, industry-wide adoption must be supported by policies that mandate eco-labeling, green certifications, and incentives for companies demonstrating measurable reductions in plastic-related waste (Attah, et al., 2022, Chukwuma, et al., 2022). Packaging redesign should also consider minimalism, reducing the volume and number of plastic components per unit. For instance, replacing multi-layered blister packs with single-material formats that are easier to recycle can significantly lower environmental microplastic loads. Such systemic changes at the product design stage can have

cascading effects, reducing downstream water contamination and alleviating the burden on disinfection processes like SODIS.

Complementing sustainable packaging is the urgent need for innovations in decentralized water treatment systems capable of addressing the microplastic burden prior to disinfection. In many communities that depend on SODIS, especially in low-income and rural areas, water sources are often untreated and directly exposed to environmental pollutants. Thus, upstream interventions that reduce microplastic concentrations in raw water can enhance the effectiveness of SODIS by preventing the formation of protective biofilms (Tomoh, et al., 2024, Ugwu, et al., 2024, Usuemerai, et al., 2024). Technological solutions such as gravity-fed sand filters, activated carbon beds, and low-cost ceramic membranes can be deployed at household or community levels to capture particulate matter, including microplastics. Innovations in nanomaterial-enhanced filters using biochar, zeolites, or graphene oxide may further improve adsorption efficiency, though cost and scalability remain key challenges for widespread adoption.

Another promising frontier involves the integration of photocatalytic pre-treatments that degrade organic micropollutants and inactivate biofilms prior to SODIS exposure. For example, solar-activated titanium dioxide (TiO_2) coatings can be embedded in pre-treatment vessels to generate hydroxyl radicals capable of breaking down pharmaceutical residues and disrupting microbial structures. Similarly, combined approaches that harness solar thermal energy to heat water above 50°C—augmenting the UV-A effect—may be optimized for situations where particulate interference is high (Chianumba, et al., 2024, Ibikunle, et al., 2024, Obianyo, Das & Adebile, 2024). These hybrid SODIS systems must be designed with user-friendliness, affordability, and minimal maintenance in mind to ensure adoption and long-term functionality in decentralized settings. Education and community engagement are also vital, enabling users to understand the limitations of SODIS and encouraging the implementation of simple yet effective pre-treatment routines, such as sedimentation and cloth filtration, to reduce plastic and microbial loads before exposure to sunlight.

A systems-thinking mitigation approach must also address the root cause and long-term consequences of resistance proliferation by embedding integrated AMR surveillance within community water safety programs. Antimicrobial resistance does not emerge solely from hospital settings or clinical misuse; rather, it is perpetuated in the environment through constant exposure to low doses of antibiotics and the selection pressure exerted by pharmaceutical pollutants. Monitoring the presence of resistance genes in water systems provides an early warning of emerging threats and can guide targeted interventions (Ajibola, et al., 2024, Fagbenro, et al., 2024, Nwokediegwu,et al., 2024). However, most existing water monitoring frameworks do not include molecular screening for ARGs, nor do they assess the influence of microplastic-associated biofilms on microbial resistance dynamics.

To address this gap, local health authorities, NGOs, and scientific institutions must collaborate to develop low-cost diagnostic tools and citizen science programs that monitor ARGs, pharmaceutical residues, and microplastic contamination. Simple, field-adaptable assays—such as paper-based nucleic acid tests, colorimetric sensors, and portable spectrometers—can empower communities to track water quality over time. These data can feed into centralized platforms that inform public health policy, guide pharmaceutical waste management strategies, and prioritize areas for intervention. In parallel, training programs for water stewards and health extension workers should include modules on AMR ecology, safe SODIS practices, and plastic pollution mitigation (Balogun, et al., 2024, Ezeamii, et al., 2024, Mbata, Ogbewele & Nwosu, 2024). Involving communities not merely as end-users but as active participants in water governance helps foster long-term resilience and behavioral change.

Moreover, the systems-thinking framework necessitates a reevaluation of regulatory and institutional structures. Government agencies responsible for environmental protection, health, and pharmaceutical regulation must coordinate more effectively to align their policies. For example, the implementation of extended producer responsibility (EPR) schemes can hold pharmaceutical companies accountable for the lifecycle impacts of their packaging. These schemes may require manufacturers to fund collection, recycling, or safe disposal programs for post-consumer packaging waste (Chianumba, et al., 2023, Ezeamii, et al., 2023, Ogbuagu, et al., 2023). International development agencies and public health funders should support pilot projects that integrate eco-packaging trials, decentralized water treatment innovations, and AMR surveillance in vulnerable regions. Such initiatives could provide scalable models that inform global policy, particularly in the context of achieving Sustainable Development Goals (SDGs) related to clean water (SDG 6), responsible consumption (SDG 12), and good health (SDG 3).

Ultimately, the systems-thinking approach emphasizes the interconnectedness of product design, environmental stewardship, technological innovation, and public health. Reimagining SODIS in a microplastic era is not solely about improving UV exposure metrics or refining plastic formulations; it is about acknowledging that every node in the system—from the materials used in drug packaging to the social practices around water use—has a cascading effect on water safety outcomes. Addressing one point in isolation will not yield sustainable results (Ogbeta, Mbata & Katas, 2024). For instance, developing a biodegradable pharmaceutical package without improving local disposal infrastructure will only shift the burden elsewhere in the system. Likewise, introducing sophisticated filtration devices without community buy-in or maintenance support will lead to technological abandonment. Only by understanding and addressing these interdependencies can we design interventions that are not only scientifically robust but also socially and economically viable.

In conclusion, mitigating the disruptive impact of pharmaceutical microplastics on SODIS requires a comprehensive systems-thinking approach. By aligning sustainable pharmaceutical packaging, decentralized microplastic filtration, and AMR monitoring with broader environmental and public health policies, we can safeguard the efficacy of solar disinfection methods and protect vulnerable communities from emerging waterborne threats. The complexity of the problem demands coordinated, interdisciplinary action—rooted in science, guided by policy, and powered by community engagement—to ensure that clean, safe, and resilient water solutions remain within reach in an increasingly polluted world.

VIII. POLICY AND GOVERNANCE IMPLICATIONS

The emergence of microplastic pollution derived from pharmaceutical packaging as a disruptive factor in solar water disinfection (SODIS) demands urgent policy and governance attention. Traditionally viewed as a reliable, low-cost method for microbial water purification in low-resource settings, SODIS is now challenged by evolving environmental complexities, particularly the infiltration of antibiotic-laden microplastics that foster resilient biofilms and facilitate horizontal gene transfer (HGT). These developments expose the inadequacies of siloed governance models that treat pharmaceuticals, plastic waste, and water sanitation as isolated domains. Instead, the moment calls for a comprehensive policy framework that is both integrated and anticipatory, engaging cross-sectoral actors in crafting robust, coherent responses to the multifaceted risks posed by microplastic-biofilm complexes and antimicrobial resistance (AMR).

One of the most pressing governance gaps is the lack of integrated regulation across the pharmaceutical,

plastic, and water management sectors. Regulatory authorities responsible for pharmaceutical safety tend to focus on efficacy, drug quality, and consumer safety, while largely ignoring post-consumer environmental impacts of packaging waste. Similarly, plastic regulations often center on single-use consumer products, overlooking pharmaceutical packaging as a persistent and high-risk pollutant (Al Hasan, Matthew & Toriola, 2024, Ikese, et al., 2024, Nwokediegwu,et al., 2024). Water safety policies, meanwhile, focus predominantly on pathogen control and chemical contamination, with minimal attention paid to the implications of microplastic-driven microbial evolution or biofilm-induced treatment failure. This fragmentation undermines the ability of institutions to recognize and address the synergistic threats presented by pharmaceutical microplastics in aquatic ecosystems.

To respond to these challenges, policymakers must initiate cross-sectoral regulatory mechanisms that bridge pharmaceutical design, waste management, and water governance. This includes introducing extended producer responsibility (EPR) frameworks that require pharmaceutical manufacturers to consider the end-of-life impact of their packaging materials. Companies should be mandated to invest in recyclable or biodegradable packaging and contribute to the development of reverse logistics systems that retrieve and safely dispose of unused drugs and packaging materials (Chianumba, et al., 2022, Matthew, Akinwale & Opia, 2022). Packaging standards must be revised to limit the use of high-persistence polymers and require the labeling of packaging materials to facilitate downstream sorting and recycling.

In parallel, governments should implement stricter controls on the disposal of pharmaceutical waste, particularly in areas where open dumping or poorly managed landfills lead to leachate contamination of water bodies. Waste segregation at the household and institutional level is critical to ensure that pharmaceutical packaging does not enter the general waste stream. Public health facilities, pharmacies, and community health centers should be equipped with clearly labeled disposal systems and collection services. These measures must be complemented by awareness campaigns to educate the public on the environmental and health consequences of improper pharmaceutical disposal, including the role of microplastics in spreading antimicrobial resistance.

Water quality monitoring standards also require revision to reflect emerging threats from pharmaceutical microplastics. Traditional parameters—such as turbidity, microbial load, and chemical residues—do not account for microplastic content, biofilm structure, or resistance gene prevalence. Regulatory agencies should adopt guidelines for detecting microplastic particles and resistance genes in drinking water sources, using tools such as micro-FTIR spectroscopy for plastic characterization and qPCR-based assays for tracking AMR determinants. Including these indicators in national water safety plans will help ensure that public health interventions remain responsive to environmental realities, particularly in areas that depend on SODIS and other decentralized treatment systems.

These domestic efforts must be nested within broader global commitments, particularly those articulated under Sustainable Development Goal 6 (clean water and sanitation for all) and the global AMR action plans coordinated by the World Health Organization (WHO), the Food and Agriculture Organization (FAO), and the World Organisation for Animal Health (WOAH). SDG 6 emphasizes the importance of improving water quality by reducing pollution, eliminating dumping, and minimizing the release of hazardous materials. Microplastic pollution—especially from pharmaceutical sources—undermines this target by introducing new vectors for microbial resistance and by impairing low-cost disinfection strategies that are essential for rural and underserved populations (Kelvin-Agwu, et al., 2023, Kolawole, et al., 2023, Nnagha, et al., 2023).

To advance SDG 6 in a microplastic era, countries must commit to measuring and mitigating plastic leakage from pharmaceutical supply chains. This includes supporting research on the environmental fate of pharmaceutical packaging, funding pilot programs that test biodegradable alternatives, and mainstreaming environmental impact assessments in pharmaceutical regulation. International trade and regulatory bodies such as the World Trade Organization (WTO) and the International Conference on Harmonisation of Technical Requirements for Pharmaceuticals for Human Use (ICH) can play a vital role by integrating sustainability criteria into pharmaceutical product approvals and harmonizing standards for packaging design across borders (Al Hasan, Matthew & Toriola, 2024, Ikese, et al., 2024, Nwokediegwu,et al., 2024).

In parallel, the global AMR action agenda must expand to include environmental drivers of resistance evolution. Current AMR strategies emphasize responsible antibiotic use in human and veterinary medicine, infection prevention, and the development of new antimicrobials. However, the role of environmental microplastics as platforms for resistance gene exchange remains underexplored (Balogun, et al., 2024, Ezeamii, et al., 2024, Mbata, Ogbewele & Nwosu, 2024). The One Health framework—central to the AMR action plan—must extend its scope to incorporate plastic waste management and water treatment technologies. Member states should be encouraged to report on the presence of pharmaceutical microplastics in national AMR surveillance systems and to invest in environmental interventions that reduce the selection pressure for resistance traits.

Global collaboration can also facilitate the transfer of technology and best practices related to microplastic monitoring and mitigation. Many low- and middle-income countries lack the analytical infrastructure to detect and respond to microplastic contamination and biofilm-associated resistance. Multilateral development agencies, including the United Nations Environment Programme (UNEP), the United Nations Development Programme (UNDP), and the Global Environment Facility (GEF), should prioritize funding for capacity-building initiatives that strengthen laboratory networks, promote knowledge exchange, and support community-based water safety interventions (Tomoh, et al., 2024, Ugwu, et al., 2024, Usuemerai, et al., 2024). Joint programming across agencies—linking health, environment, industry, and infrastructure—can accelerate the development of integrated policies that reflect the systemic nature of the problem.

Importantly, policy design must be inclusive and participatory, reflecting the lived experiences of communities most affected by microplastic-contaminated water and weakened disinfection systems. Local governments and civil society organizations should be empowered to contribute to policy dialogues and implementation planning (Kelvin-Agwu, et al., 2023, Kolawole, et al., 2023, Nnagha, et al., 2023). Water users, particularly in rural areas that rely on SODIS, must be consulted on the feasibility of proposed interventions, from packaging return schemes to household filtration technologies. Gender-sensitive approaches are especially critical, as women and girls are often responsible for water collection and household hygiene in many parts of the world. Their insights can guide the development of culturally appropriate and operationally feasible policies.

In conclusion, the disruption of SODIS by pharmaceutical microplastics and the associated spread of antimicrobial resistance call for a paradigm shift in policy and governance. Addressing these challenges requires cross-sector regulation that integrates pharmaceutical sustainability, plastic waste management, and water safety. Clear packaging standards, robust segregation systems, and comprehensive AMR surveillance must be implemented at the national level, while global collaboration under the umbrella of SDG 6 and the AMR action plan can provide the strategic coherence

and technical resources needed for systemic change (Ajibola, et al., 2024, Fagbenro, et al., 2024, Nwokediegwu,et al., 2024). Only through such coordinated, interdisciplinary governance can we safeguard public health, environmental integrity, and the future of decentralized water purification systems in an increasingly complex ecological landscape.

IX. CONCLUSION AND FUTURE RESEARCH DIRECTIONS

The investigation into the impact of pharmaceutical packaging-derived microplastics on the efficacy of solar water disinfection (SODIS) reveals a critical and emerging intersection between environmental contamination, microbial ecology, and public health. At the heart of this study is the recognition that microplastics, especially those originating from discarded pharmaceutical materials, are not inert pollutants but active substrates that promote biofilm formation and horizontal gene transfer. These biofilm-microplastic complexes reduce the penetrative capacity of solar UV radiation and suppress the generation or effectiveness of reactive oxygen species—two of the key mechanisms by which SODIS achieves microbial inactivation. Furthermore, the sorption of residual pharmaceutical compounds onto plastic surfaces introduces additional challenges by selectively enriching resistant microbial populations and contributing to the persistence of antibiotic resistance genes in aquatic environments.

This conceptual framework expands the existing understanding of SODIS beyond its physical parameters and brings to light the broader systems-level vulnerabilities introduced by global plastic pollution and pharmaceutical waste mismanagement. It also advances a critical discourse on the indirect but profound role that material science and industrial waste streams play in shaping microbial resistance and disinfection failure. The resilience of biofilms, the enhanced gene exchange facilitated by mobile genetic elements within microplastic environments, and the metabolic adaptability of bacteria exposed to sublethal UV stress collectively redefine the boundaries within which solar disinfection can be considered reliable.

In light of these insights, there is an urgent need for rigorous empirical research to validate and quantify the theoretical relationships proposed. Experimental studies must be conducted under environmentally realistic conditions, simulating microplastic contamination and measuring microbial inactivation outcomes using SODIS. Investigations should focus on the specific chemical composition and aging processes of pharmaceutical microplastics, their propensity to adsorb antibiotic residues, and their influence on the structure, diversity, and gene dynamics of associated microbial biofilms. Moreover, the development of molecular tools for real-time monitoring of antibiotic resistance genes and microplastic-biofilm formation in SODIS-treated water would enhance the reliability and safety assessment of this disinfection method. Interdisciplinary innovation must also be encouraged, integrating expertise from microbiology, environmental engineering, material science, public health, and policy design to co-develop sustainable solutions.

Moving forward, the resilience of water disinfection systems must be anchored in their ability to adapt to complex and evolving environmental stressors, including those not previously considered in conventional treatment design. Achieving equity in global access to safe water means ensuring that low-cost technologies like SODIS are not only available but also effective under real-world conditions increasingly shaped by anthropogenic pollution and ecological disruption. The communities that rely most heavily on SODIS—often in marginalized or underserved regions—should not bear the burden of silent failures brought on by unaddressed microplastic contamination or resistance gene proliferation. Instead, these communities must be at the center of research, policy, and innovation efforts aimed at safeguarding and enhancing water disinfection technologies.

In conclusion, reimagining SODIS in a microplastic era is not merely a scientific or technical endeavor; it is an ethical and environmental imperative. It requires a paradigm shift in how we understand and respond to the interconnected threats of pollution, resistance, and water insecurity. By committing to integrated research, responsive policy, and inclusive innovation, we can build more resilient and equitable water treatment solutions for the future—solutions that honor both the promise of technological simplicity and the complexity of the ecosystems in which they operate.

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