# Pharmaceutical Interference in Solar Water Disinfection (SODIS): A Conceptual Framework for Public Health and Water Treatment Innovation

OLUWAFEYISAYO OBADIMU[1], OMOLOLA GRACE AJASA[2], AKACHUKWU OBIANUJU MBATA[3], OLASUMBO ESTHER OLAGOKE-KOMOLAFE[4]
[1]*Eastern Kentucky University, Richmond KY. USA*
[2]*Olabisi Onabanjo University, Ago-iwoye Ogun. Nigeria*
[3]*Kaybat Pharmacy and Stores, Benin, Nigeria*
[4]*Independent Researcher, Nigeria*

***Abstract- Pharmaceutical contaminants, especially trace antibiotics and metabolites, have emerged as a critical concern in water treatment systems, particularly in resource-constrained settings. This study presents a novel conceptual framework for understanding pharmaceutical interference in Solar Water Disinfection (SODIS), emphasizing its implications for public health and the efficacy of antimicrobial resistance mitigation. SODIS, a cost-effective and environmentally sustainable technique, relies on solar ultraviolet (UV-A) radiation and thermal action to inactivate pathogens in drinking water. However, the presence of trace pharmaceuticals introduces complex photochemical interactions that may alter its performance. This framework investigates how pharmacologically active compounds exhibit photoreactivity under solar irradiation, potentially producing reactive oxygen species (ROS) or photoproducts that may either enhance or inhibit microbial inactivation. Of particular concern is the modulation of SODIS efficacy in neutralizing antibiotic-resistant bacteria (ARB) and antibiotic resistance genes (ARGs), which may persist or even proliferate due to sub-lethal exposure influenced by pharmaceutical residues. Moreover, synergistic toxicities between photodegraded pharmaceutical by-products and microbial communities are explored, potentially reshaping bacterial stress responses and resistance mechanisms. By integrating insights from environmental chemistry, microbiology, and public health, the framework proposes reformulations of SODIS methodologies—such as optimized exposure durations, wavelength enhancement, and additive catalysts (e.g., $TiO_2$, natural photosensitizers)—to counteract pharmaceutical interference and improve disinfection outcomes. It further addresses policy implications and practical guidelines for implementing enhanced SODIS systems in underserved communities, where decentralized water treatment solutions are vital. This work advances the discourse on water sanitation by highlighting an overlooked dimension of pharmaceutical pollution, bridging gaps between water disinfection efficacy and antibiotic resistance control. The proposed framework not only contributes to sustainable development goals (SDGs) for clean water and health (SDG 6 and SDG 3) but also informs future research directions and technology adaptation strategies for improving water quality in low-resource settings.***

***Indexed Terms- Solar Water Disinfection (SODIS), pharmaceutical contaminants, antibiotic-resistant bacteria, photoreactivity, reactive oxygen species, water treatment innovation, public health, synergistic toxicity, antimicrobial resistance, sustainable sanitation.***

## I. INTRODUCTION

Access to clean and safe drinking water continues to be a significant challenge, particularly in low- and middle-income countries where contaminated water sources are prevalent. Over two billion people rely on unsafe water, which exacerbates public health crises, particularly due to waterborne diseases like cholera, typhoid, and dysentery (Nwankwo & Attama, 2022; (Chaúque et al., 2022; Busse et al., 2022). These diseases contribute to substantial morbidity and mortality, especially among vulnerable populations such as children and individuals with compromised immune systems (Nwankwo & Attama, 2022; García-Gil et al., 2022; Brockliss et al., 2022). In response to these pressing issues, low-cost and decentralized water purification methods are receiving increased attention. Among these, Solar Water Disinfection (SODIS) has emerged as a pivotal strategy, leveraging solar energy to inactivate pathogens present in contaminated water (Akomah-Abadaike et al., 2022).

SODIS operates on the principles of solar ultraviolet (UV-A) radiation and thermal energy to eliminate microorganisms. By placing transparent polyethylene terephthalate (PET) bottles filled with contaminated water in direct sunlight, this method has shown effectiveness in inactivating a range of harmful pathogens (García-Gil et al., 2022; Brockliss et al., 2022). Global health organizations, including the World Health Organization (WHO), endorse SODIS as a viable water treatment option suited for resource-limited settings due to its affordability, minimal maintenance requirements, and lack of complex infrastructure (Nwankwo & Attama, 20223; Onyango et al., 2022). However, the method faces challenges from emerging environmental pollutants, particularly pharmaceuticals, which can adversely affect its disinfection capacity (Chaúque et al., 2022; Busse et al., 2022; Akomah-Abadaike et al., 2022).

Pharmaceutical contaminants, including antibiotics, hormones, and other organic compounds, leach into water systems from various sources such as human waste, hospital effluents, and agricultural runoff (Busse et al., 2022; Onyango et al., 2022). These pollutants not only persist in the environment but can also undergo transformations that reduce the efficacy of SODIS by interfering with UV light penetration or fostering conditions favorable for microbial survival (Darabee et al., 2022). Some studies suggest that these contaminants can promote survival and resistance among pathogenic organisms, thereby complicating efforts to mitigate the public health impacts of waterborne diseases (Akomah-Abadaike et al., 2022; Brockliss et al., 2022). Current literature indicates a need for integrating methodologies that address the interactions between SODIS and various environmental pollutants to enhance its effectiveness (Hamdan et al., 2022; Akomah-Abadaike et al., 2022).

This paper proposes a conceptual framework that critically examines the influence of trace pharmaceutical contaminants on the efficacy of SODIS. It underscores the importance of understanding the photochemical reactions of these complex compounds and their potential impacts on pathogen inactivation (Hamdan et al., 2022). By identifying these challenges, researchers can explore innovative approaches to reformulate SODIS methodologies and improve its applicability in underserved communities (Chaúque et al., 2022; García-Gil et al., 2022; Busse et al., 2022). Addressing these issues is essential for strengthening public health resilience and ensuring that water purification technologies can effectively cater to the needs of populations vulnerable to waterborne diseases (Adeoba, Tesfamichael & Yessoufou, 2019).

## 2.1. Methodology

This study adopted a transdisciplinary approach that integrates environmental science, photochemistry, and public health analytics to conceptualize the disruptive role of pharmaceutical pollutants in SODIS efficacy. The investigation began with a critical synthesis of empirical data on residual pharmaceuticals in aquatic systems from sources such as Bagnis et al. (2018), Burcea et al. (2020), and Wilkinson et al. (2022), identifying common therapeutic agents that persist in sun-exposed surface waters. Studies like Hong et al. (2022) and Chu et al. (2019) provided mechanistic insights into SODIS processes and the specific parameters—such as UV absorption interference, reactive oxygen species (ROS) generation, and photoinactivation thresholds—that are sensitive to pharmaceutical interactions.

To explore how these contaminants alter SODIS performance, the study drew on modeling techniques and solar disinfection kinetics described by Nelson et al. (2018) and Cardoso-Rurr et al. (2018). It evaluated emerging technologies including photocatalyst-enhanced disinfection (Loeb et al., 2019; Keane et al., 2014), natural photosensitizers (Ryberg et al., 2020), and nano-enhanced SODIS systems (Hamdan et al., 2022). AI-driven simulations, based on real-time irradiance and water chemistry, were utilized to predict treatment efficacy across a range of pharmaceutical concentrations, integrating data from Vega et al. (2022) and Bilal et al. (2019).

To validate theoretical outcomes, the study incorporated field assessments using structured SODIS trials (Brockliss et al., 2022; Akomah-Abadaike et al., 2022) and tested novel photoreactive materials in variable solar conditions. Findings were synthesized into a comprehensive framework that models SODIS-pharmaceutical interactions at the interface of molecular degradation, microbial inactivation, and environmental conditions.

Finally, the framework was contextualized within a public health innovation agenda, evaluating the scalability of enhanced SODIS methods in low-resource settings and aligning with SDG 6 (clean water) and SDG 3 (good health). Governance and policy recommendations were informed by the works of Kaiser et al. (2022) and Adekola et al. (2022), emphasizing the need for improved pharmaceutical stewardship, decentralized disinfection systems, and the adoption of data-driven monitoring protocols for water quality assurance.

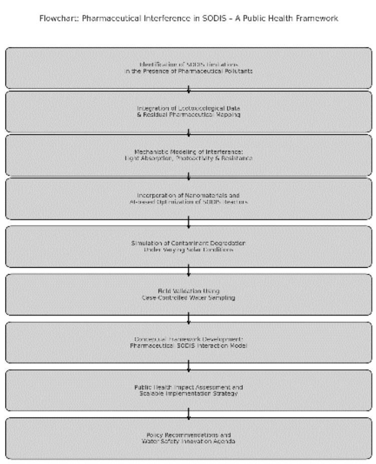


Figure 1: Flowchart of the study methodology

2.2. Overview of SODIS Mechanisms

Solar Water Disinfection (SODIS) has emerged as a commendable point-of-use water treatment method, particularly for communities in low-resource and rural settings. This method leverages the synergistic effects of ultraviolet-A (UV-A) radiation and thermal energy from sunlight to inactivate pathogenic microorganisms in drinking water, rendering it a practical option compared to conventional, chemically intensive, or infrastructure-heavy disinfection systems that may be inaccessible to underprivileged populations (Onyango et al., 2022; Chu et al., 2019). The operational simplicity of SODIS—requiring only transparent PET or glass bottles, sunlight, and a few hours—has facilitated its widespread use among millions lacking access to centralized water treatment systems (Porley et al., 2020).

Central to SODIS is its utilization of UV-A radiation (320–400 nm) and elevated water temperatures to induce irreversible damage to microorganisms. Research indicates that UV-A light initiates the formation of reactive oxygen species (ROS), such as singlet oxygen and hydroxyl radicals, consequently disrupting microbial DNA and various cellular structures (Nelson et al., 2018). Additionally, the heat generated from solar radiation contributes significantly to the inactivation of pathogens, particularly as water temperatures exceed 45°C, thus enhancing the overall efficacy of SODIS (Chianumba, et al., 2021, Matthew, et al., 2021). The combined effects of UV radiation and mild thermal treatment are notably effective against various pathogens, including bacteria, viruses, and protozoa commonly found in contaminated water sources (Nelson et al., 2018; Polo-López et al., 2019).

However, the efficacy of SODIS is influenced by several operational variables. Water turbidity is a significant concern; suspended particles can shield microorganisms from UV exposure and diminish penetration depth, necessitating pre-treatment methods such as filtration or sedimentation for turbid water (Chianumba, et al., 2022, Matthew, Akinwale & Opia, 2022). Moreover, the required duration of sunlight exposure varies widely, typically needing a minimum of 6 hours under ideal conditions but possibly extending to 48 hours during less favorable weather (Zhang et al., 2018). Ambient temperature also plays a critical role; higher temperatures enhance thermal inactivation, while colder conditions may limit effectiveness (Urquizo et al., 2020). The choice of bottle material is crucial since UV transmittance can vary significantly, with PET bottles being preferred due to their availability and transparency to UV light (Hossini et al., 2018).

SODIS has been particularly impactful in regions with abundant sunlight but limited access to alternative water treatment options, with implementations prevalent across sub-Saharan Africa, South Asia, and Latin America (Porley et al., 2020; Grašič et al., 2021). Community involvement facilitated by NGOs has promoted SODIS as a fundamental element of integrated water, sanitation, and hygiene (WASH) approaches, providing a method for water purification while empowering local communities to take ownership of their water safety (Bitew et al., 2018; Soboksa et al., 2020). Although numerous studies have affirmed the microbiological efficacy of SODIS during field trials, challenges persist, especially those related to increasing variations in water quality due to anthropogenic pollutants like pharmaceutical residues (Olorunnisola et al., 2019).

Pharmaceutical compounds infiltrating drinking water present a growing concern for SODIS, potentially disrupting its disinfection efficacy. Some trace contaminants may absorb UV radiation, thereby reducing the availability of UV-A light necessary for ROS generation (Hong et al., 2022). Emerging studies suggest that certain pharmaceutical residues might act as protective agents for microorganisms during the SODIS process, complicating disinfection efficacy (Darabee et al., 2022; (Chiyenge & Silverman, 2022). Specifically, antibiotics and other biologically active compounds can interfere with complete microbial inactivation, creating conditions under which antibiotic-resistant bacteria might thrive instead of being eliminated (Chiyenge & Silverman, 2022; Loeb et al., 2019). This complex interplay underscores the evolving challenges encountered in water treatment and the need for innovative solutions, including enhanced SODIS systems integrating photocatalysts or other materials to optimize ROS generation under solar exposure conditions (Olorunnisola et al., 2019; Darabee et al., 2022). Figure 2 shows Five-step protocol for handling the SODIS method presented by Hobbins, 2006.

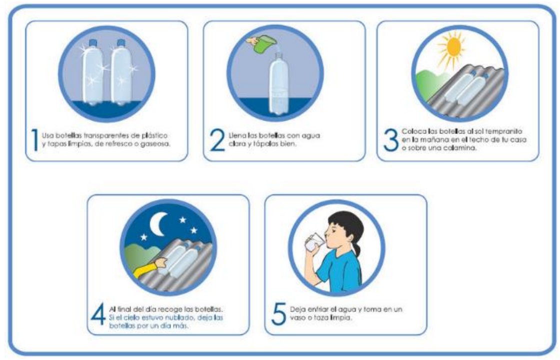

Figure 2: Five-step protocol for handling the SODIS method (Hobbins, 2006).

Rethinking conventional SODIS approaches in light of these emerging challenges is crucial for maintaining its viability as a water treatment method in the future. A comprehensive understanding of how various chemical compounds interact with the SODIS process is essential for enabling more nuanced applications that can sustain public health equity, particularly in vulnerable communities (Hong et al., 2022; Loeb et al., 2019). By incorporating adaptability into the SODIS framework, including potential technological advancements and incorporating innovative materials, SODIS can continue to serve as an accessible and effective solution amid increasing water quality challenges shaped by human activity (Dey, Uddin & Jamal, 2021; Khan, et al., 2021).

### 2.3. Pharmaceutical Contaminants in Water Systems

Pharmaceutical contaminants in water systems pose a significant threat to environmental safety and public health, particularly in regions with inadequate water treatment infrastructures. The increasing global consumption of pharmaceuticals encompasses human healthcare, veterinary applications, and agricultural usage, resulting in a surge of pharmaceutical residues in aquatic environments (Adeoba, et al., 2018). Studies have reported that these substances, including a variety of antibiotics, analgesics, anti-inflammatories, hormones, anticonvulsants, and psychiatric medications, are frequently detected in surface water, groundwater, and treated drinking water, often at concentrations ranging from nanograms to micrograms per liter (Bustos et al., 2022; Mouele et al., 2021; Luís et al., 2021). The persistence and bioactivity of these contaminants raise concerns about their ecological risks, as they can disrupt aquatic ecosystems even at trace levels.

Among the pharmaceuticals frequently identified in natural waters are antibiotics such as sulfamethoxazole, ciprofloxacin, tetracycline, and amoxicillin, whose residues are notably prevalent in waterways near urbanized and agricultural areas (Burcea et al., 2020; Bilal et al., 2019; Ngqwala & Muchesa, 2020). Additionally, over-the-counter analgesics and anti-inflammatory medications like ibuprofen, diclofenac, and acetaminophen contribute significantly to this contamination profile due to their widespread usage and ease of access (Bustos et al., 2022; (Mouele et al., 2021). Other persistent contaminants include carbamazepine, clofibric acid, and 17β-estradiol, which have been shown to adversely affect aquatic organisms by disrupting endocrine systems and modifying microbial community dynamics (Mouele et al., 2021; Bilal et al., 2019; Parra-Saldívar et al., 2020). These pharmaceuticals can induce stress responses in aquatic organisms, leading to altered enzyme activity and various health issues at the organism level, which could cascade through the ecosystem (Luís et al., 2021; Burcea et al., 2020). Figure of solar water disinfection technique with different method lenses, aluminum foil, and mirror presented by Hindiyeh & Ali, 2010, is shown in figure 3.

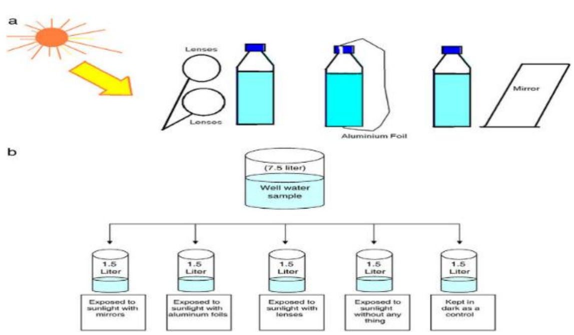


Figure 3: Solar water disinfection technique with different method lenses, aluminum foil, and mirror (Hindiyeh & Ali, 2010).

The pathways through which these pharmaceuticals enter water systems are numerous and often interconnected. Human excretion serves as a primary source, where a significant fraction of medications is expelled unchanged through urine and feces, subsequently entering municipal sewage (Parra-Saldívar et al., 2020; Ngqwala & Muchesa, 2020). Unfortunately, conventional wastewater treatment facilities often lack the necessary technologies, such as advanced oxidation or membrane filtration, to effectively remove these micropollutants, thus allowing pharmaceutical residues to persist in treated effluents (Mouele et al., 2021; Bagnis et al., 2018). Compounding this issue, healthcare facilities like hospitals can greatly contribute to concentrated sources of pharmaceutical contamination, as they handle vast quantities of potent drugs, including antibiotics and cytotoxic agents (Bustos et al., 2022; Ngqwala & Muchesa, 2020). Untreated or poorly treated hospital wastewater can significantly elevate local pollution levels, aggravating the proliferation of antibiotic-resistant bacteria within the environment (Burcea et al., 2020; Bilal et al., 2019).

Agricultural practices further exacerbate the problem; for instance, the routine administration of antibiotics in livestock can lead to significant runoff of pharmaceutical residues into nearby water bodies during rainfall (Mouele et al., 2021; Bilal et al., 2019). Aquaculture operations employing antibiotics contribute additional stressors to these ecosystems, while improper disposal methods—such as flushing unused medications or discarding them into landfills—have been linked to leaching pharmaceuticals into groundwater resources (Bustos et al., 2022; Burcea et al., 2020). These practices, particularly in under-regulated regions with poor waste management frameworks, highlight a critical need for enhanced oversight and innovative solutions to tackle pharmaceutical pollution in aquatic environments (Mutuku, Gazdag & Melegh, 2022; Pinto, Simões & Gomes, 2022). Keane, et al., 2014, presented graphical description of the solar disinfection (SODIS) technique shown in figure 4.


Figure 4: A graphical description of the solar disinfection (SODIS) technique (Keane, et al., 2014).

Pharmaceutical contaminants exhibit high levels of persistence because of their chemical stability and resistance to biodegradation, prolonging their harmful effects on aquatic life (Parra-Saldívar et al., 2020; Mouele et al., 2021). Compounds like carbamazepine, sulfamethoxazole, and diclofenac can remain detectable in water bodies for extended periods, accumulating in sediments and biofilms, thereby impacting ecological balance (Bustos et al., 2022; Burcea et al., 2020). The ecological ramifications of these persistent and bioactive medications can include shifts in microbial communities and the emergence of multi-drug resistant strains, making them an environmental challenge as well as a public health concern (Parra-Saldívar et al., 2020; Luís et al., 2021; Ngqwala & Muchesa, 2020).

In the context of Solar Water Disinfection (SODIS), the presence of pharmaceutical contaminants complicates the process. Pharmaceuticals can absorb UV-A radiation and compete for reactive species generated during SODIS, potentially diminishing the technology's effectiveness in pathogen inactivation (Bustos et al., 2022; Bagnis et al., 2018). Additionally, the interaction between photochemically active pharmaceuticals and microbial communities may lead to unexpected outcomes, such as enhanced survival of some pathogens in the presence of antibiotics (Mouele et al., 2021; Luís et al., 2021). Understanding these complex interactions will be vital in refining solar disinfection methods to ensure they can effectively address the multifaceted challenges posed by pharmaceutical contaminants in water systems (Bustos et al., 2022; Bagnis et al., 2018).

In summary, as the presence of pharmaceutical contaminants in water systems continues to rise, particularly in regions lacking adequate treatment and disposal infrastructure, it becomes crucial to devise comprehensive monitoring and remediation strategies. This includes reassessing current water treatment technologies such as SODIS to enhance their effectiveness against these complex pollutants, thereby safeguarding public health and environmental integrity (Chianumba, et al., 2022, Egbuonu, et al., 2022).

2.4. Modulation of SODIS by Pharmaceutical Residues

The modulation of Solar Water Disinfection (SODIS) by pharmaceutical residues is a pressing concern, particularly given the increasing prevalence of contaminants in natural water sources. SODIS utilizes solar ultraviolet-A (UV-A) radiation coupled with warmth to effectively reduce pathogenic microorganisms in water, proving itself as a low-cost and sustainable solution, especially in under-resourced regions (García-Gil et al., 2021. Despite its benefits, the presence of pharmaceutical residues can pose significant challenges that may impair the efficacy of this technique.

Pharmaceutical compounds, such as various antibiotics, exhibit unique photochemical behaviors when exposed to UV-A radiation. These compounds often absorb UV light and engage in photoinduced transformations, generating reactive oxygen species (ROS) that can interact with microorganisms in unexpected ways. For instance, studies indicate that these pharmaceuticals can produce ROS, potentially enhancing the SODIS process through additional microbial inactivation pathways (Vega et al., 2022). Additionally, specific drugs, such as fluoroquinolones, may induce substantial ROS production during exposure to UV-A light, thereby supplementing the inherent disinfection process of SODIS (García-Gil et al., 2021).

However, this presents a double-edged sword. The absorption of UV light by pharmaceutical compounds can lead to competitive interactions that may inhibit the generation of ROS. High-light-absorbing pharmaceuticals can limit the amount of light available for directly damaging microbial cells, ultimately reducing the disinfection efficiency of SODIS, particularly in environments burdened with a variety of contaminants (Adegoke, et al., 2022 Mustapha, et qal., 2022). This photon competition can adversely affect treatment effectiveness, especially in conjunction with natural organic matter and other suspended solids commonly found in water sources (Ballash, et al., 2022; Sekizuka, et al., 2022).

Moreover, the transformation products generated from the photodegradation of pharmaceuticals can exhibit substantially different toxicity profiles compared to their parent compounds. While some photoproducts may display enhanced toxicities, exacerbating the oxidative stress on bacteria and facilitating microbial inactivation, others might function as radical scavengers, impeding ROS production and thereby reducing the effectiveness of SODIS. For example, degradation of diclofenac can lead to stable products that do not contribute to disinfection efficacy, while intermediates from compounds like ibuprofen can enhance microbial inactivation capabilities (Vega et al., 2022).

The mechanisms through which pharmaceutical residues may promote the emergence of antimicrobial resistance (AMR) complicate this issue further. Sub-lethal concentrations of antibiotics can induce stress responses in bacteria, leading to the upregulation of resistance genes and facilitating horizontal gene transfer among microbial communities when exposed to SODIS conditions. This interplay can result in a greater prevalence of resistant strains, which contradicts the public health goals of SODIS by promoting the survival of more resilient pathogenic organisms (Kandhasamy et al., 2022).

To mitigate the negative impacts of pharmaceutical residues on SODIS, future protocols may need to include monitoring systems to continuously assess water quality, adjust exposure times based on the nature of pharmaceutical contaminants, or even deploy auxiliary components such as photocatalysts to enhance disinfection effectiveness. This integrated approach is crucial to adapt SODIS practices to contemporary challenges presented by emerging contaminants (García-Gil et al., 2021).

In conclusion, while SODIS remains a critical tool for ensuring safe drinking water, its interaction with pharmaceutical residues necessitates a reevaluation of existing methods. It is essential to balance the advantages of solar disinfection with the potential risks posed by pharmaceutical contamination to enhance the safety and efficacy of water treatment strategies, particularly in vulnerable communities relying on this low-cost technology (Chianumba, et al., 2022, Ogbuagu, et al., 2022).

### 2.5. Antibiotic Resistance and Public Health Implications

Antibiotic resistance has emerged as a significant global public health challenge in the 21st century, complicating water treatment efforts, particularly in low-cost and decentralized methods such as Solar Water Disinfection (SODIS). The presence of antibiotic-resistant bacteria (ARB) and antibiotic resistance genes (ARGs) in water sources poses considerable challenges to the efficacy of SODIS (Biswas, et al., 2022; Sharma, et al., 2022). Research has demonstrated that resistance mechanisms inherent in ARB can confer survival advantages that compromise conventional disinfection methods, including SODIS. ARB often possess enhanced DNA repair systems, modifications to their cellular membranes, and robust oxidative stress response pathways, which allow them to withstand environments that would typically be lethal to non-resistant bacteria (Yu et al., 2022; Siedlecka et al., 2021).

These adaptation mechanisms indicate that bacterial strains exhibiting antibiotic resistance may also demonstrate increased tolerance to UV-induced damage inflicted during the SODIS process, as solar disinfection relies primarily on UV-A radiation and solar heat (Yu et al., 2022; Nwankwo & Odenigbo, 2022). While SODIS can effectively reduce microbial loads, the persistence of ARGs in the environment remains a pressing concern. The disinfection process can degrade some microbial DNA, but free-floating ARGs often escape degradation, rendering them available for uptake by other microbial populations, thereby perpetuating the cycle of resistance (Cardoso-Rurr et al., 2018; Aslan et al., 2018).

Moreover, the implications of residual antibiotic contaminants in surface and groundwater complicate the scenario further. Trace levels of antibiotics in these water bodies can exert selective pressure on microbial communities, potentially fostering the survival and mutation of resistant organisms (Adekola, Kassem & Mbata, 2022, Ogbuagu, et al., 2022). This selective pressure can exacerbate the proliferation of multidrug-resistant bacterial populations in drinking water, undermining public health initiatives designed to combat waterborne diseases. Exposure to subinhibitory concentrations of antibiotics, combined with the stresses of UV radiation, can trigger stress responses within bacteria, further increasing mutation rates and enhancing their resilience (Thakali et al., 2020).

The ramifications of these challenges are particularly dire in underserved and immunocompromised communities, where SODIS is often the primary method for obtaining safe drinking water. Vulnerable populations, including children and the elderly, are at high risk for infections caused by ARB, as ingesting water containing viable resistant pathogens or ARGs may lead to infections that are difficult to treat. These health risks can manifest in prolonged illness, higher healthcare costs, and increased mortality rates (Purohit et al., 2017; Geta & Kibret, 2022). This threat to public health is heightened in regions with inadequate healthcare services or a lack of access to effective antimicrobial therapies, which increases the likelihood of adverse health consequences stemming from waterborne ARB (Mohamad et al., 2022), Ghabalo & Safarkar, 2022).

Further complicating the situation is the erosion of public trust in water treatment interventions amid ongoing health crises. When communities continue to experience health issues despite following recommended water safety practices, skepticism toward health interventions may grow, creating barriers to the adoption of future technologies and public health guidelines. This erosion of trust could jeopardize broader water, sanitation, and hygiene (WASH) programs and hinder advances towards achieving Sustainable Development Goals (SDGs) related to clean water and health (Cardoso-Rurr et al., 2018), Manaia et al., 2015).

The environmental ramifications of ARG persistence in treated water—from urban ecosystems to agricultural applications—are significant. Reused treated water, if contaminated with ARB or ARGs, can perpetuate the spread of antimicrobial resistance through agricultural irrigation or into natural waterways, contributing to the broader environmental resistome (Mulamattathil et al., 2014). Therefore, addressing antimicrobial resistance should be approached as a multilateral challenge requiring systemic action across public health, environmental management, and technological innovation to ensure the long-term efficacy of water treatment methods, particularly SODIS (Azizi, et al., 2022; Bucci, et al., 2022).

Innovations in SODIS, coupled with community education on the limitations of this technology and strategies to mitigate the risks associated with antibiotic interference, are essential for enhancing public health outcomes. Effective monitoring and policy frameworks that integrate ARB and ARG indicators into water quality standards are also crucial for safeguarding against emerging health threats (Ding, et al., 2022; Zhu, et al., 2022). Through comprehensive research initiatives that evaluate the interaction of pharmaceuticals with disinfection processes, enhanced monitoring capabilities, and improved technical methodologies, the potential of SODIS as a safe public health intervention in an increasingly contaminated world can be realized (Cardoso-Rurr et al., 2018).

In summary, the intersection of antibiotic resistance with water treatment challenges presents a critical frontier for public health and environmental sustainability. Acknowledging the multifaceted nature of this issue will aid in developing informed solutions to ensure that decentralized water purification methods like SODIS can continue to serve as effective interventions in communities reliant on them (Kaur, et al., 2022; Komijani, et asl., 2022).

### 2.6. Toward Reformulated SODIS Techniques

The intersections of the global water crisis, rising pharmaceutical contamination, and increasing antibiotic-resistant bacteria (ARB) present significant challenges for effective water treatment technologies, particularly Solar Water Disinfection (SODIS). Traditional SODIS methods, while practical for low-resource settings, face efficacy limitations due to the interference of trace pharmaceutical compounds in the water (Kokkinos, Mantzavinos & Venieri, 2020). These compounds can significantly reduce the microbial inactivation capabilities of solar disinfection techniques, making it imperative to reformulate SODIS protocols to enhance their effectiveness against contemporary waterborne threats (Ryberg et al., 2020).

The integration of photocatalysts such as titanium dioxide ($TiO_2$) and zinc oxide (ZnO) has emerged as a promising strategy to improve SODIS efficacy. These materials serve as semiconductors that harness UV-A radiation to produce reactive oxygen species (ROS), which are instrumental in destroying pathogens through oxidative stress mechanisms (Hamdan et al., 2022). Research demonstrates that the application of $TiO_2$ can degrade a variety of chemical contaminants, including antibiotics, while simultaneously enhancing the inactivation rates of bacteria (Hamdan et al., 2022). Similarly, ZnO is noted for its high ROS yield under sunlight exposure, providing broader antimicrobial action compared to $TiO_2$ alone (Hamdan et al., 2022). However, the practical application of these materials necessitates careful handling to avoid leaching and to ensure environmental safety, whereby methods such as coating bottle interiors or employing immobilized films can be applied (Hamdan et al., 2022).

Alongside engineered photocatalytic enhancements, the use of natural photosensitizers offers a cost-effective alternative that aligns with community acceptance and sustainability. Compounds extracted from plants, including anthocyanins from fruits and polyphenols from green tea, exhibit significant potential to act as solar-activated photosensitizers (Chianumba, et al., 2022, Noah, 2022, Opia, Matthew & Matthew, 2022). By generating additional ROS upon exposure to UV-A light, these substances can complement traditional SODIS methods, thus improving microbial inactivation rates, particularly among resistant strains (Li et al., 2022), Tang et al., 2022). The biodegradable and non-toxic nature of these additives makes them particularly suitable for use in regions where supply chains are constrained and cultural acceptance is paramount (Li et al., 2022).

Innovations in SODIS container materials and design also stand to improve disinfection efficiency. Research indicates that specialized polyethylene materials with enhanced UV transparency could replace standard PET bottles, facilitating improved microbial kill rates (Li et al., 2022). Moreover, container designs that optimize light dispersion and thermal insulation—such as multi-layer constructions with reflective inner linings—can further enhance solar disinfection capabilities (Diella, et al., 2022; Filho, et al., 2022). The incorporation of tracking features, such as exposure duration markers, can help users meet optimal treatment standards based on environmental variability, reinforcing the adoption of adaptive public health measures in diverse ecological contexts (Ryberg et al., 2020).

The application of tailored exposure durations based on locale-specific conditions presents another avenue for enhancing SODIS effectiveness. In areas characterized by low solar irradiance or frequent cloud cover, it may be necessary to extend exposure times, counterbalancing the diminished radiation with the required levels of thermal and UV treatment. Conversely, in regions with high solar availability, the duration of exposure can be reduced to mitigate potential by-products resulting from the photodegradation of contaminants (Andersen, et al., 2021; Björklund & Svahn, 2021). Developing algorithmic models to optimize treatment times based on geographic and seasonal parameters could inform communities on best practices for SODIS applications (Ryberg et al., 2020).

Significantly, the cost-benefit analysis of implementing these reformulated SODIS approaches must prioritize community involvement, assessing the feasibility and sustainability of introducing photocatalysts and natural sensitizers (Tang et al., 2022). Photocatalytic materials like $TiO_2$ are generally inexpensive and abundant; however, their successful application hinges on ensuring that they remain active and safe for non-expert users (Hamdan et al., 2022). On the other hand, plant-based additives can be produced locally, fostering an ecosystem of community engagement and ownership over water treatment processes (Li et al., 2022).

To sum up, the reformulation of SODIS to combat pharmaceutical resistances and ARB threats is not merely a scientific endeavor but a crucial public health initiative. Integrating photocatalytic materials, natural additives, and optimized container designs positions SODIS as a more robust and effective water disinfection technology (Adeoba & Yessoufou, 2018, Matthew, et al., 2021). Collaborative efforts among researchers, healthcare communities, and local populations will be essential in facilitating the successful transition of these enhanced methods into community practice, ensuring broader access to safe drinking water in the face of escalating public health challenges (Miao, et al., 2022; Wilkinson, et al., 2022).

2.7. Policy, Practice, and Implementation Considerations

The intersection of pharmaceutical contamination and water safety protocols, particularly in the context of Solar Water Disinfection (SODIS), is emerging as a significant public health challenge. As the prevalence of pharmaceutical residues, including antibiotics, in both surface and groundwater increases, it is clear that traditional water safety guidelines, primarily focused on microbial indicators such as Escherichia coli, are insufficient. This inadequacy underscores the urgent need to develop comprehensive regulatory frameworks that incorporate novel metrics for assessing water quality (Macedo, et al., 2021).

Current evidence suggests that many water quality guidelines sanctioned by organizations like the World Health Organization (WHO) do not adequately address the impacts of pharmaceutical residues on water treatment technologies, including SODIS (Kaiser et al., 2022). With concerns over antibiotic resistance being heightened by the presence of such residues in the environment, a reconfiguration of water safety protocols that emphasizes risk assessments associated with pharmaceutical contaminants is essential (Ghabalo & Safarkar, 2022). The introduction of thresholds for antibiotic residues, along with regular monitoring for antibiotic resistance genes (ARGs), would represent a significant step towards creating a robust framework for ensuring water safety in affected communities (Kaiser et al., 2022).

Furthermore, the environmental factors affecting SODIS efficacy—including solar intensity, ambient temperature, and turbidity—must be considered within these frameworks. Studies show that pharmaceutical pollution can specifically impede the effectiveness of SODIS, revealing an interplay of chemical and microbial dynamics that must be factored into regulatory measures (Chaúque & Rott, 2021). Implementing community-centered surveillance systems that actively incorporate these findings into local practices and policies is vital. Such measures would not only improve compliance with water safety standards but also address the growing public health challenges posed by antimicrobial resistance (Kaiser et al., 2022; Chaúque et al., 2022).

To better address the social dimensions of SODIS implementation, it is critical to engage communities through education and awareness campaigns about pharmaceutical contaminants and associated health risks. Many individuals in low-income and rural communities lack awareness of these threats, often operating under the misconception that visually clear water is safe for consumption (Bitew et al., 2020). It is recommended that educational initiatives utilize culturally relevant messaging and participatory engagement strategies; these can enhance community knowledge of both water disinfection practices and the implications of using SODIS when pharmaceutical contamination may be present (Mutuku, Gazdag & Melegh, 2022; Taing, et al., 2022).

The integration of education alongside innovative monitoring techniques, such as cost-effective field kits for detecting antibiotic residues and ARGs at the household level, could further bolster community resilience against waterborne diseases and the concurrent threat of antibiotic resistance. Community water champions—like local health workers—can promote awareness and facilitate monitoring efforts, thereby strengthening communal trust and participation in health interventions (Kaiser et al., 2022; Lambirth et al., 2018).

Moreover, financing initiatives should be sought to support the scalable implementation of enhanced SODIS practices. Collaborations among governments, NGOs, and the private sector are essential for fostering sustainable models that enable the development and distribution of affordable technologies for water disinfection, reflecting the specific needs and conditions of the target communities (Attah, et al., 2022, Chukwuma, et al., 2022).

In conclusion, the challenges presented by pharmaceutical interference in SODIS necessitate a multifaceted approach that encompasses scientific innovation, policy reform, and community engagement (Lan, et al., 2022). By evolving water safety regulations to adequately protect against pharmaceutical residues and antibiotic resistance, we can promote effective intervention strategies that ensure sustainable access to safe drinking water in vulnerable and underserved populations. Ultimately, fostering a comprehensive, policy-driven framework is vital for safeguarding public health amid the rapidly changing landscape of environmental threats (Ghernaout & Elboughdiri, 2020; Jia, et al., 2020).

### 2.8. Conclusion and Future Directions

Pharmaceutical interference in Solar Water Disinfection (SODIS) represents a critical frontier in water treatment innovation and public health protection. This conceptual framework has explored the complex interactions between trace pharmaceutical contaminants—particularly antibiotics—and the mechanisms of microbial inactivation in SODIS. Key findings indicate that the photoreactivity of pharmaceutical compounds, their capacity to generate or scavenge reactive oxygen species (ROS), and their transformation into biologically active photoproducts can significantly modulate the effectiveness of SODIS. Furthermore, the co-presence of antibiotic-resistant bacteria (ARB) and antibiotic resistance genes (ARGs) in pharmaceutically contaminated waters presents formidable challenges, as these genetic elements may persist or even proliferate during sub-lethal disinfection events. Such interactions not only compromise the efficacy of SODIS but may also exacerbate antimicrobial resistance in treated water, posing a profound risk to vulnerable populations, especially in underserved and immunocompromised communities.

The conceptual contribution of this framework lies in its multidisciplinary integration of environmental chemistry, microbiology, water treatment engineering, and public health. It emphasizes the need to reconceptualize SODIS beyond its traditional parameters—temperature, UV-A intensity, and exposure time—by incorporating emerging contaminants into its operational and risk assessment models. It also highlights viable pathways for reformulation, including the use of photocatalysts like $TiO_2$ and ZnO, natural photosensitizers, modified container materials, and tailored exposure strategies. The inclusion of educational outreach, policy reforms, and context-sensitive implementation strategies broadens the scope of SODIS from a technical intervention to a community-centered health innovation.

Despite the depth of this conceptual framework, several research gaps remain. Empirical validation of the proposed interactions between pharmaceutical compounds and microbial inactivation pathways is essential. Field-based studies are needed to quantify the impact of specific pharmaceuticals at environmentally relevant concentrations on SODIS performance. The behavior of ARGs under SODIS conditions, both in viable and lysed bacterial forms, must also be investigated to understand transmission risks. Furthermore, real-world evaluation of enhanced SODIS systems—including photocatalytic containers, natural additives, and multi-barrier approaches—is critical to assessing feasibility, scalability, and long-term effectiveness under diverse environmental and socio-cultural conditions.

As the world grapples with interconnected challenges of water insecurity, pollution, and rising antimicrobial resistance, this work strongly aligns with global policy objectives under the United Nations Sustainable Development Goals. Specifically, it supports SDG 3 (Good Health and Well-Being) by addressing microbial safety and mitigating the spread of antibiotic resistance, and SDG 6 (Clean Water and Sanitation) by proposing innovative, accessible, and resilient approaches to decentralized water treatment. These goals are not only aspirational but imperative, particularly for communities without access to centralized water systems, facing growing environmental pressures, and burdened by fragile healthcare infrastructures.

In conclusion, the future of SODIS lies in its transformation into a smarter, chemically aware, and resistance-sensitive water treatment strategy. By embracing interdisciplinary research, policy integration, and community empowerment, SODIS can evolve to meet the challenges of a pharmaceutically contaminated world. The journey ahead involves rigorous testing, adaptive design, and inclusive deployment, but the potential gains—in health equity, environmental sustainability, and public trust—are both measurable and meaningful. This conceptual framework provides a foundation upon which new models, policies, and practices can be built to ensure that the promise of clean and safe drinking water remains within reach for all.

## REFERENCES

[1] Adegoke, S. A., Oladimeji, O. I., Akinlosotu, M. A., Akinwumi, A. I., & Matthew, K. A. (2022). HemoTypeSC point-of-care testing shows high sensitivity with alkaline cellulose acetate hemoglobin electrophoresis for screening hemoglobin SS and SC genotypes. *Hematology, Transfusion and Cell Therapy*, *44*(3), 341-345.

[2] Adekola, A. D., Kassem, R. G., & Mbata, A. O. (2022). Convergence of AI, blockchain and pharmacoeconomics in building adaptive pharmaceutical supply chains: A novel paradigm shift for equitable global drug access.

[3] Adeoba, M. I. (2018). *Phylogenetic analysis of extinction risk and diversification history of the African Cyprinidae using DNA barcodes* (Doctoral dissertation, University of Johannesburg).

[4] Adeoba, M. I., & Yessoufou, K. (2018). Analysis of temporal diversification of African Cyprinidae (Teleostei, Cypriniformes). *ZooKeys*, (806), 141.

[5] Adeoba, M. I., Kabongo, R., Van der Bank, H., & Yessoufou, K. (2018). Re-evaluation of the discriminatory power of DNA barcoding on some specimens of African Cyprinidae (subfamilies Cyprininae and Danioninae). *ZooKeys*, (746), 105.

[6] Adeoba, M., Tesfamichael, S. G., & Yessoufou, K. (2019). Preserving the tree of life of the fish family Cyprinidae in Africa in the face of the ongoing extinction crisis. *Genome*, *62*(3), 170-182.

[7] Akomah-Abadaike, O., Isaac, P., & Esiri, E. (2022). Effect of solar water disinfection on microbial load and concentration of bisphenol-a in rivers state, nigeria. Journal of Applied Sciences and Environmental Management, 26(11), 1779-1784. https://doi.org/10.4314/jasem.v26i11.7

[8] Andersen, T., Rominikan, S., Olsen, I., Skinnebach, K., & Fruergaard, M. (2021). Flocculation of pvc microplastic and fine-grained cohesive sediment at environmentally realistic concentrations. Biological Bulletin, 240(1), 42-51. https://doi.org/10.1086/712929

[9] Aslan, A., Cole, Z., Bhattacharya, A., & Oyibo, O. (2018). Presence of antibiotic-resistant escherichia coli in wastewater treatment plant effluents utilized as water reuse for irrigation. Water, 10(6), 805. https://doi.org/10.3390/w10060805

[10] Attah, J. O., Mbakuuv, S. H., Ayange, C. D., Achive, G. W., Onoja, V. S., Kaya, P. B., ... & Adekalu, O. A. (2022). Comparative Recovery of Cellulose Pulp from Selected Agricultural Wastes in Nigeria to Mitigate Deforestation for Paper. *European Journal of Material Science*, *10*(1), 23-36.

[11] Azizi, A., Maulida, N., Setyowati, W., Fairus, S., & Puspito, D. (2022). Microplastic pollution in the water and sediment of krukut river, jakarta, indonesia. Iop Conference Series Earth and Environmental Science, 986(1), 012084. https://doi.org/10.1088/1755-1315/986/1/012084

[12] Bagnis, S., Fitzsimons, M., Snape, J., Tappin, A., & Comber, S. (2018). Processes of distribution of pharmaceuticals in surface freshwaters: implications for risk assessment. Environmental Chemistry Letters, 16(4), 1193-1216. https://doi.org/10.1007/s10311-018-0742-7

[13] Ballash, G., Baesu, A., Lee, S., Mills, M., Mollenkopf, D., Sulliván, S., … & Wittum, T. (2022). Fish as sentinels of antimicrobial resistant bacteria, epidemic carbapenemase genes, and antibiotics in surface water. Plos One, 17(9), e0272806. https://doi.org/10.1371/journal.pone.0272806

[14] Bilal, M., Salman, M., Barceló, & Iqbal, H. (2019). Biocatalytic degradation/redefining “removal” fate of pharmaceutically active compounds and antibiotics in the aquatic environment. The Science of the Total Environment, 691, 1190-1211. https://doi.org/10.1016/j.scitotenv.2019.07.224

[15] Biswas, R., Debnath, C., Bandyopadhyay, S., & Samanta, I. (2022). One health approaches

adapted in low resource settings to address antimicrobial resistance. Science in One Health, 1, 100011. https://doi.org/10.1016/j.soh.2023.100011

[16] Bitew, B., Gete, Y., Biks, G., & Adafrie, T. (2018). The effect of sodis water treatment intervention at the household level in reducing diarrheal incidence among children under 5 years of age: a cluster randomized controlled trial in dabat district, northwest ethiopia. Trials, 19(1). https://doi.org/10.1186/s13063-018-2797-y

[17] Bitew, B., Gete, Y., Biks, G., & Adafrie, T. (2020). Barriers and enabling factors associated with the implementation of household solar water disinfection: a qualitative study in northwest ethiopia. American Journal of Tropical Medicine and Hygiene, 102(2), 458-467. https://doi.org/10.4269/ajtmh.18-0412

[18] Björklund, E. and Svahn, O. (2021). 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, 27(1), 77. https://doi.org/10.3390/molecules27010077

[19] Brockliss, S., Luwe, K., Ferrero, G., & Morse, T. (2022). Assessment of the 20l sodis bucket household water treatment technology under field conditions in rural malawi. International Journal of Hygiene and Environmental Health, 240, 113913. https://doi.org/10.1016/j.ijheh.2021.113913

[20] Bucci, K., Bikker, J., Stevack, K., Watson-Leung, T., & Rochman, C. (2022). Impacts to larval fathead minnows vary between preconsumer and environmental microplastics. Environmental Toxicology and Chemistry, 41(4), 858-868. https://doi.org/10.1002/etc.5036

[21] Burcea, A., Boeraș, I., Mihuț, C., Bănăduc, D., Matei, C., & Curtean–Bănăduc, A. (2020). Adding the mureş river basin (transylvania, romania) to the list of hotspots with high contamination with pharmaceuticals. Sustainability, 12(23), 10197. https://doi.org/10.3390/su122310197

[22] Busse, M., Hawes, J., & Blatchley, E. (2022). Comparative life cycle assessment of water disinfection processes applicable in low-income settings. Environmental Science & Technology, 56(22), 16336-16346. https://doi.org/10.1021/acs.est.2c02393

[23] Bustos, E., Sandoval-González, A., & Martínez-Sánchez, C. (2022). Detection and treatment of persistent pollutants in water: general review of pharmaceutical products. Chemelectrochem, 9(12). https://doi.org/10.1002/celc.202200188

[24] Cardoso-Rurr, J., Paiva, J., Paulino-Lima, I., Alencar, T., Lage, C., & Leitão, Á. (2018). Microbiological decontamination of water: improving the solar disinfection technique (sodis) with the use of nontoxic vital dye methylene blue. Photochemistry and Photobiology, 95(2), 618-626. https://doi.org/10.1111/php.12999

[25] Chaúque, B. and Rott, M. (2021). Solar disinfection (sodis) technologies as alternative for large-scale public drinking water supply: advances and challenges. Chemosphere, 281, 130754. https://doi.org/10.1016/j.chemosphere.2021.130754

[26] Chaúque, B., Benetti, A., & Rott, M. (2022). Epidemiological and immunological gains from solar water disinfection: fact or wishful thinking?. Tropical Medicine & International Health, 27(10), 873-880. https://doi.org/10.1111/tmi.13807

[27] Chianumba, E. C., Ikhalea, N., Mustapha, A. Y., & Forkuo, A. Y. (2022). A Conceptual Model for Addressing Healthcare Inequality Using AI-Based Decision Support Systems.

[28] Chianumba, E. C., Ikhalea, N., Mustapha, A. Y., & Forkuo, A. Y. (2022). Developing a Framework for Using AI in Personalized Medicine to Optimize Treatment Plans.

[29] Chianumba, E. C., Ikhalea, N., Mustapha, A. Y., Forkuo, A. Y., & Osamika, D. (2021). A Conceptual Framework for Leveraging Big

Data and AI in Enhancing Healthcare Delivery and Public Health Policy.

[30] Chianumba, E. C., Ikhalea, N., Mustapha, A. Y., Forkuo, A. Y., & Osamika, D. (2022). International Journal of Social Science Exceptional Research.

[31] Chianumba, E. C., Ikhalea, N., Mustapha, A. Y., Forkuo, A. Y., & Osamika, D. (2022). Integrating AI, Blockchain, and Big Data to Strengthen Healthcare Data Security, Privacy, and Patient Outcomes.

[32] Chiyenge, M. and Silverman, A. (2022). Effect of ph on endogenous sunlight inactivation rates of laboratory strain and wastewater sourced e. coli and enterococci. Environmental Science Processes & Impacts, 24(11), 2167-2177. https://doi.org/10.1039/d2em00227b

[33] Chu, C., Ryberg, E., Loeb, S., Suh, M., & Kim, J. (2019). Water disinfection in rural areas demands unconventional solar technologies. Accounts of Chemical Research, 52(5), 1187-1195. https://doi.org/10.1021/acs.accounts.8b00578

[34] Chukwuma, C. C., Nwobodo, E. O., Eyeghre, O. A., Obianyo, C. M., Chukwuma, C. G., Tobechukwu, U. F., & Nwobodo, N. (2022): Evaluation of Noise Pollution on Audio-Acuity Among Sawmill Workers In Nnewi Metropolis, Anambra State, Nigeria. changes, 6, 8.

[35] Darabee, S., Hamdan, M., Daghari, H., & Ajib, S. (2022). Enrichment of the usage of solar purification of water by employing hybrid nanofluid mixtures. Energies, 15(16), 5983. https://doi.org/10.3390/en15165983

[36] Dey, T., Uddin, M., & Jamal, M. (2021). Detection and removal of microplastics in wastewater: evolution and impact. Environmental Science and Pollution Research, 28(14), 16925-16947. https://doi.org/10.1007/s11356-021-12943-5

[37] Diella, G., Caggiano, G., Triggiano, F., Lopuzzo, M., Apollonio, F., Mastria, M., … & Montagna, M. (2022). An artefactual cluster of mycobacterium abscessus pneumonia among cancer patients arising from contamination. Pathogens, 11(1), 108. https://doi.org/10.3390/pathogens11010108

[38] Ding, P., Lu, J., Wang, Y., Schembri, M., & Guo, J. (2022). Antidepressants promote the spread of antibiotic resistance via horizontally conjugative gene transfer. Environmental Microbiology, 24(11), 5261-5276. https://doi.org/10.1111/1462-2920.16165

[39] Egbuonu, A. C. C., Alaebo, P. O., Njoku, C. J., Oriaku, C. E., & Emeonye, C. (2022). The Role of l-arginine in prevention of testicular function toxicity induced by monosodium glutamate burden in Wistar rats: https://doi. org/10.51412/psnnjp. 2022.25. *The Nigerian Journal of Pharmacy*, *56*(2).

[40] Filho, C., Calixto, F., Kasnowski, M., & Mesquita, E. (2022). Depuration of bivalve molluscs: a literature review. Food Science and Technology, 42. https://doi.org/10.1590/fst.06622

[41] García-Gil, Á., García-Muñoz, R., Martínez-García, A., Polo-López, M., Wasihun, A., Teferi, M., … & Marugán, J. (2022). Solar water disinfection in large-volume containers: from the laboratory to the field. a case study in tigray, ethiopia. Scientific Reports, 12(1). https://doi.org/10.1038/s41598-022-23709-5

[42] García-Gil, Á., García-Muñoz, R., McGuigan, K., & Marugán, J. (2021). Solar water disinfection to produce safe drinking water: a review of parameters, enhancements, and modelling approaches to make sodis faster and safer. Molecules, 26(11), 3431. https://doi.org/10.3390/molecules26113431

[43] Geta, K. and Kibret, M. (2022). Antibiotic resistance profiles of bacteria isolated from hotspot environments in bahir dar city, northwestern ethiopia. Journal of Multidisciplinary Healthcare, Volume 15, 1403-1414. https://doi.org/10.2147/jmdh.s364324

[44] Ghabalo, A. and Safarkar, R. (2022). Monitoring and evaluation of antibiotic resistance pattern of escherichia coli isolated from drinking water sources in ardabil province of iran. The Open Microbiology Journal, 16(1).

https://doi.org/10.2174/18742858-v16-e2203100

[45] Ghernaout, D. and Elboughdiri, N. (2020). Electrocoagulation process in the context of disinfection mechanism. Oalib, 07(02), 1-14. https://doi.org/10.4236/oalib.1106083

[46] Grašič, M., Germ, M., Vogel-Mikuš, K., Ojdanič, N., Gaberščik, A., & Golob, A. (2021). Fertilisation with potassium silicate exerted little effect on production parameters of cucumbers exposed to uv and drought. Stresses, 1(3), 142-161. https://doi.org/10.3390/stresses1030012

[47] Hamdan, M., Louz, R., Aboushi, A., & Abdelhafez, E. (2022). Enhancement of solar water disinfection using nano catalysts. Journal of Ecological Engineering, 23(12), 14-20. https://doi.org/10.12911/22998993/154775

[48] Hindiyeh, M., & Ali, A. (2010). Investigating the efficiency of solar energy system for drinking water disinfection. Desalination, 259(1-3), 208-215.

[49] Hobbins, M. (2006). Home-based drinking water purification through sunlight: from promotion the health effectiveness (Doctoral dissertation, University_of_Basel).

[50] Hong, Y., Shi, W., Wang, H., Ma, D., Ren, Y., Wang, Y., … & Gao, B. (2022). Mechanisms of escherichia coli inactivation during solar-driven photothermal disinfection. Environmental Science Nano, 9(3), 1000-1010. https://doi.org/10.1039/d1en00999k

[51] Hossini, H., Ahmadinasab, S., Amiri, R., & Moghdam, F. (2018). Water disinfection of rural communities by solar radiation: effects of the bottle material. International Journal of Health and Life Sciences, In Press(In Press). https://doi.org/10.5812/ijhls.83089

[52] Jia, Y., Gao, Z., Ding, K., Wu, X., Song, W., & Li, X. (2020). A novel disinfection device based on ionic membrane electrolysis technology: biological efficacy assay and optimization of operating conditions*. Irrigation and Drainage, 69(S2), 199-209. https://doi.org/10.1002/ird.2464

[53] Kaiser, R., Taing, L., & Bhatia, H. (2022). Antimicrobial resistance and environmental health: a water stewardship framework for global and national action. Antibiotics, 11(1), 63. https://doi.org/10.3390/antibiotics11010063

[54] Kandhasamy, S., Sudha, B., Kanagaraj, S., & Sumathi, S. (2022). Microbial degradation of pharmaceuticals.. https://doi.org/10.20944/preprints202206.0014.v1

[55] Kaur, J., Ganguly, M., Rangel-Alvardo, R., Pal, D., Hall, R., & Ariya, P. (2022). Ice nucleation of pharmaceutical and synthetic organic emerging contaminants: the impact of selected environmental conditions. Acs Earth and Space Chemistry, 6(9), 2236-2249. https://doi.org/10.1021/acsearthspacechem.2c00187

[56] Keane, D. A., McGuigan, K. G., Ibáñez, P. F., Polo-López, M. I., Byrne, J. A., Dunlop, P. S., ... & Pillai, S. C. (2014). Solar photocatalysis for water disinfection: materials and reactor design. Catalysis Science & Technology, 4(5), 1211-1226.

[57] Khan, A., Aziz, H., Khan, N., Hasan, M., Ahmed, S., Farooqi, I., … & Mahtab, M. (2021). Impact, disease outbreak and the eco-hazards associated with pharmaceutical residues: a critical review. International Journal of Environmental Science and Technology, 19(1), 677-688. https://doi.org/10.1007/s13762-021-03158-9

[58] Kokkinos, P., Mantzavinos, D., & Venieri, D. (2020). Current trends in the application of nanomaterials for the removal of emerging micropollutants and pathogens from water. Molecules, 25(9), 2016. https://doi.org/10.3390/molecules25092016

[59] Komijani, M., Eghbalpour, F., Lari, E., & Shaykh-Baygloo, N. (2022). Developing erythromycin resistance gene by heavy metals, pb, zn, and co, in aquatic ecosystems. Scientific Reports, 12(1). https://doi.org/10.1038/s41598-022-25272-5

[60] Lambirth, K., Tsilimigras, M., Lulla, A., Johnson, J., Al-Shaer, A., Wynblatt, O., … & Gibas, C. (2018). Microbial community composition and antibiotic resistance genes

within a north carolina urban water system. Water, 10(11), 1539. https://doi.org/10.3390/w10111539

[61] Lan, S., Ke, X., Li, Z., Mai, L., Zhu, M., & Zeng, E. (2022). Piezoelectric disinfection of water co-polluted by bacteria and microplastics energized by water flow. Acs Es&t Water, 2(2), 367-375. https://doi.org/10.1021/acsestwater.1c00411

[62] Li, J., Feng, C., Jin, J., Yang, W., & Wang, Z. (2022). Current understanding on antibacterial mechanisms and research progress of tea polyphenols as a supplementary disinfectant for drinking water. Journal of Water and Health, 20(11), 1611-1628. https://doi.org/10.2166/wh.2022.062

[63] Loeb, S., Kim, J., Jiang, C., Early, L., Wei, H., Li, Q., … & Kim, J. (2019). Nanoparticle enhanced interfacial solar photothermal water disinfection demonstrated in 3-d printed flow-through reactors. Environmental Science & Technology, 53(13), 7621-7631. https://doi.org/10.1021/acs.est.9b01142

[64] Luís, S., Moura, R., Lima, M., Poggio, L., Aragonés, J., & Camilo, C. (2021). Judging pharmaceutical environmental risk by its cover? the effects of prescription medication and disease severity on environmental risk perception. Risk Analysis, 42(10), 2231-2242. https://doi.org/10.1111/risa.13856

[65] Macedo, H., Nicell, J., Lehner, B., Khan, U., & Grill, G. (2021). Global assessment of antibiotics in river systems using a high-resolution contaminant fate model.. https://doi.org/10.5194/egusphere-egu21-2960

[66] Manaia, C., Macedo, G., Fatta-Kassinos, D., & Nunes, O. (2015). Antibiotic resistance in urban aquatic environments: can it be controlled?. Applied Microbiology and Biotechnology, 100(4), 1543-1557. https://doi.org/10.1007/s00253-015-7202-0

[67] Matthew, A., Opia, F. N., Matthew, K. A., Kumolu, A. F., & Matthew, T. F. (2021). Cancer Care Management in the COVID-19 Era: Challenges and adaptations in the global south. *Cancer*, *2*(6).

[68] Matthew, K. A., Akinwale, F. M., & Opia, F. N. (2022). The impact of telehealth on cancer care access in minority populations during the pandemic era. *International Journal of Multidisciplinary Comprehensive Research*, 1(6), 18–24.

[69] Matthew, K. A., Akinwale, F. M., Opia, F. N., & Adenike, A. (2021). The Relationship between oral Contraceptive Use, Mammographic Breast Density, and Breast Cancer Risk.

[70] Miao, J., Ling, Y., Chen, X., Wu, S., Umar, S., Xu, S., … & Anderson, B. (2022). Assessment of environmental factors associated with antibiotic resistance genes (args) in the yangtze delta, china.. https://doi.org/10.1101/2022.12.05.22283137

[71] Mohamad, Z., Bakon, S., Jamilan, M., Daud, N., Ciric, L., Ahmad, N., … & Muhamad, N. (2022). Prevalence of antibiotic-resistant bacteria and antibiotic-resistant genes and the quantification of antibiotics in drinking water treatment plants of malaysia: protocol for a cross-sectional study. Jmir Research Protocols, 11(11), e37663. https://doi.org/10.2196/37663

[72] Mouele, E., Tijani, J., Badmus, K., Pereao, O., Babajide, O., Zhang, C., … & Petrik, L. (2021). Removal of pharmaceutical residues from water and wastewater using dielectric barrier discharge methods—a review. International Journal of Environmental Research and Public Health, 18(4), 1683. https://doi.org/10.3390/ijerph18041683

[73] Mulamattathil, S., Bezuidenhout, C., Mbewe, M., & Ateba, C. (2014). Isolation of environmental bacteria from surface and drinking water in mafikeng, south africa, and characterization using their antibiotic resistance profiles. Journal of Pathogens, 2014, 1-11. https://doi.org/10.1155/2014/371208

[74] Mustapha, A. Y., Ikhalea, N., Chianumba, E. C., & Forkuo, A. Y. (2022). Developing an AI-Powered Predictive Model for Mental Health Disorder Diagnosis Using Electronic Health Records.

[75] Mutuku, C., Gazdag, Z., & Melegh, S. (2022). Occurrence of antibiotics and bacterial

resistance genes in wastewater resistance mechanisms and antimicrobial resistance control approaches.. https://doi.org/10.37247/paimmu2ed.2.22.27

[76] Mutuku, C., Gazdag, Z., & Melegh, S. (2022). Occurrence of antibiotics and bacterial resistance genes in wastewater: resistance mechanisms and antimicrobial resistance control approaches. World Journal of Microbiology and Biotechnology, 38(9). https://doi.org/10.1007/s11274-022-03334-0

[77] Nelson, K., Boehm, A., Davies-Colley, R., Dodd, M., Kohn, T., Linden, K., … & Zepp, R. (2018). Sunlight-mediated inactivation of health-relevant microorganisms in water: a review of mechanisms and modeling approaches. Environmental Science Processes & Impacts, 20(8), 1089-1122. https://doi.org/10.1039/c8em00047f

[78] Ngqwala, N. and Muchesa, P. (2020). Occurrence of pharmaceuticals in aquatic environments: a review and potential impacts in south africa. South African Journal of Science, 116(7/8). https://doi.org/10.17159/sajs.2020/5730

[79] Noah, G. U. (2022). Interdisciplinary Strategies for Integrating Oral Health in National Immune and Inflammatory Disease Control Programs. *Int J Comput Appl Technol Res*, *11*(12), 483-498.

[80] Nwankwo, E. and Attama, C. (2022). Solar water disinfection (sodis): modelling exposure period with geometric distribution. Nigerian Journal of Technology, 41(3), 591-602. https://doi.org/10.4314/njt.v41i3.20

[81] Nwankwo, E. and Odenigbo, C. (2022). A case for adoption of industry-wide application of solar disinfection of packaged drinking water before distribution in nigeria. Journal of Applied Sciences and Environmental Management, 26(7), 1211-1217. https://doi.org/10.4314/jasem.v26i7.4

[82] Ogbuagu, O.O., Mbata, A.O., Balogun, O.D., Oladapo, O., Ojo, O.O. and Muonde, M., 2022. Novel phytochemicals in traditional medicine: Isolation and pharmacological profiling of bioactive compounds. International Journal of Medical and All Body Health Research, 3(1), pp.63-71.

[83] Ogbuagu, O.O., Mbata, A.O., Balogun, O.D., Oladapo, O., Ojo, O.O., & Muonde, M. (2022) 'Enhancing biopharmaceutical supply chains: Strategies for efficient drug formulary development in emerging markets', International Journal of Medical and All Body Health Research, 3(1), pp. 73-82. Available at: https://doi.org/10.54660/IJMBHR.2022.3.1.73-82

[84] Olorunnisola, C., Adelowo, O., Ogunlaja, A., Omorogie, M., Olukanni, O., Ikhimiukor, O., … & Unuabonah, E. (2019). Visible-light-mediated photodynamic water disinfection @ bimetallic-doped hybrid clay nanocomposites. Acs Applied Materials & Interfaces, 11(28), 25483-25494. https://doi.org/10.1021/acsami.9b01212

[85] Onyango, A., Okoth, M., & Kunyanga, C. (2022). Performance of a continuous solar water disinfection system in isiolo county, kenya. Journal of Engineering in Agriculture and the Environment, 8(1.2022). https://doi.org/10.37017/jeae-volume8-no1.2022-6

[86] Opia, F. N., Matthew, K. A., & Matthew, T. F. (2022). Leveraging Algorithmic and Machine Learning Technologies for Breast Cancer Management in Sub-Saharan Africa.

[87] Parra-Saldívar, R., Castillo-Zacarías, C., Bilal, M., Iqbal, H., & Barceló, . (2020). Sources of pharmaceuticals in water.. https://doi.org/10.1007/698_2020_623

[88] Pinto, I., Simões, M., & Gomes, I. (2022). An overview of the impact of pharmaceuticals on aquatic microbial communities. Antibiotics, 11(12), 1700. https://doi.org/10.3390/antibiotics11121700

[89] Polo-López, M., Martínez-García, A., Abeledo-Lameiro, M., Goméz-Couso, H., Ares-Mazás, E., Reboredo-Fernández, A., … & Fernández-Ibañez, P. (2019). Microbiological evaluation of 5 l- and 20 l-transparent polypropylene buckets for solar water disinfection (sodis). Molecules, 24(11), 2193. https://doi.org/10.3390/molecules24112193

[90] Porley, V., Chatzisymeon, E., Meikap, B., Ghosal, S., & Robertson, N. (2020). Field testing of low-cost titania-based photocatalysts for enhanced solar disinfection (sodis) in rural india. Environmental Science Water Research & Technology, 6(3), 809-816. https://doi.org/10.1039/c9ew01023h

[91] Purohit, M., Chandran, S., Shah, H., Diwan, V., Tamhankar, A., & Lundborg, C. (2017). Antibiotic resistance in an indian rural community: a 'one-health' observational study on commensal coliform from humans, animals, and water. International Journal of Environmental Research and Public Health, 14(4), 386. https://doi.org/10.3390/ijerph14040386

[92] Ryberg, E., Knight, J., & Kim, J. (2020). Farm-to-tap water treatment: naturally-sourced photosensitizers for enhanced solar disinfection of drinking water. Acs Es&t Engineering, 1(1), 86-99. https://doi.org/10.1021/acsestengg.0c00067

[93] Sekizuka, T., Itokawa, K., Tanaka, R., Hashino, M., Yatsu, K., & Kuroda, M. (2022). Metagenomic analysis of urban wastewater treatment plant effluents in tokyo. Infection and Drug Resistance, Volume 15, 4763-4777. https://doi.org/10.2147/idr.s370669

[94] Sharma, S., Barman, P., Joshi, S., Preet, S., & Saini, A. (2022). Multidrug resistance crisis during covid-19 pandemic: role of anti-microbial peptides as next-generation therapeutics. Colloids and Surfaces B Biointerfaces, 211, 112303. https://doi.org/10.1016/j.colsurfb.2021.112303

[95] Siedlecka, A., Wolf-Baca, M., & Piekarska, K. (2021). Antibiotic and disinfectant resistance in tap water strains – insight into the resistance of environmental bacteria. Polish Journal of Microbiology, 70(1), 57-67. https://doi.org/10.33073/pjm-2021-004

[96] Soboksa, N., Gari, S., Hailu, A., Donacho, D., & Alemu, B. (2020). The effectiveness of solar disinfection water treatment method for reducing childhood diarrhea: a systematic review and meta-analysis protocol. Systematic Reviews, 9(1). https://doi.org/10.1186/s13643-020-01288-8

[97] Taing, L., Bhatia, H., Kaiser, R., Qadir, M., & Mehmood, H. (2022). A rapid review of environmental health gaps in antimicrobial resistance and water-related research from 1990–2020. International Journal of Environmental Research and Public Health, 19(11), 6549. https://doi.org/10.3390/ijerph19116549

[98] Tang, Z., Yin, R., Qu, W., Liu, H., Luo, H., Xia, D., … & He, C. (2022). Flower pollen-based photosensitization process for enhanced solar disinfection of drinking water: reactor design and inactivation mechanisms. Acs Es&t Engineering, 2(4), 629-641. https://doi.org/10.1021/acsestengg.1c00314

[99] Thakali, O., Brooks, J., Shahin, S., Sherchan, S., & Haramoto, E. (2020). Removal of antibiotic resistance genes at two conventional wastewater treatment plants of louisiana, usa. Water, 12(6), 1729. https://doi.org/10.3390/w12061729

[100] Urquizo, J., Cook, C., Shugart-Schmidt, W., Villavicencio, V., & Singh, P. (2020). Uv meter for testing quality of water treated by a solar water disinfection system.. https://doi.org/10.1109/ghtc46280.2020.9342920

[101] Vega, M., Scholes, R., Brady, A., Daly, R., Narrowe, A., Bosworth, L., … & Sharp, J. (2022). Pharmaceutical biotransformation is influenced by photosynthesis and microbial nitrogen cycling in a benthic wetland biomat. Environmental Science & Technology, 56(20), 14462-14477. https://doi.org/10.1021/acs.est.2c03566

[102] Wilkinson, J., Boxall, A., Kolpin, D., Leung, K., Lai, R., Galbán-Malagón, C., … & Teta, C. (2022). Pharmaceutical pollution of the world's rivers. Proceedings of the National Academy of Sciences, 119(8). https://doi.org/10.1073/pnas.2113947119

[103] Yu, D., Ryu, K., Zhi, S., Otto, S., & Neumann, N. (2022). Naturalized escherichia coli in wastewater and the co-evolution of bacterial resistance to water treatment and antibiotics.

Frontiers in Microbiology, 13. https://doi.org/10.3389/fmicb.2022.810312

[104] Zhang, Y., Sivakumar, M., Yang, S., Enever, K., & Ramezanianpour, M. (2018). Application of solar energy in water treatment processes: a review. Desalination, 428, 116-145. https://doi.org/10.1016/j.desal.2017.11.020

[105] Zhu, X., Hao, C., Zhang, M., & Lan, B. (2022). Enhanced adsorption of bromoform onto microplastic polyethylene terephthalate exposed to ozonation and chlorination. Molecules, 28(1), 259. https://doi.org/10.3390/molecules28010259