RESEARCH AND REVIEWS IN SUSTAINABILITY

Drinking Water Purification Techniques and the Emerging Environmental Challenges

REVIEW

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ABSTRACT

Water is a fundamental resource vital to the survival and well-being of all living organisms. Ensuring access to clean and safe drinking water has been a central concern of human societies since the earliest civilizations. Over time, the methods and technologies for water treatment have evolved significantly, which reflects advances in science, engineering, and public health. Today, drinking water treatment systems serve as a cornerstone of modern infrastructure and are designed to remove contaminants and safeguard populations against waterborne diseases and environmental pollutants. This paper explores current treatment technologies—including chlorination, flocculation, filtration, biological filtration, adsorption, and emerging technologies and nanotechnology-based approaches—to highlight their effectiveness and limitations. It also examines challenges such as emerging pollutants, temperature fluctuations, toxic sludge generation, and climate change. The discussion underscores the urgent need for innovative technologies, sustainable practices, and robust regulatory frameworks to ensure access to safe and clean drinking water. Addressing these issues is critical in protecting public health and conserving water resources for future generations.

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INTRODUCTION

The rapid pace of industrialization and population growth has led to the deterioration of both water quality and availability (Sarker *et al.*, 2021). Water sources are increasingly being contaminated by industrial discharges, agricultural runoff, and untreated sewage. Such pollution introduces hazardous substances that make water unsafe for the aquatic ecosystem and human use. This, in turn, adversely affects the aquatic environment like rivers and oceans, which are essential for sustaining life, and consequently poses risks to human health (Bhattarai and Bhasin, 2022). Industrial wastewater is particularly hazardous due to its high concentration of toxins that can seep into groundwater and nearby water bodies. Many areas of groundwater and surface water have been polluted with heavy metals and persistent organic pollutants, thus triggering health concerns (Kristanti *et al.*, 2021; Mawari *et al.*, 2022). If used for irrigation, this contaminated water can degrade crop quality and introduce harmful chemicals into the food chain, ultimately contributing to diseases such as lung cancer, weakened immune system, and liver and kidney damage (Musa Khan, Bano and Ishaq Khan, 2022).

Access to clean and safe drinking water is a fundamental human need and serves as a critical component of public health. Despite global advancements, approximately 1.1 million people still lack access to safe drinking water. In many developing countries, communities rely on surface water, groundwater (e.g., wells), and harvested rainwater—sources that are often susceptible to contamination by pathogenic microorganisms such as *Escherichia coli* and *Pseudomonas spp.* These pathogens contribute significantly to the global burden of waterborne diseases. According to the World Health Organization (WHO), over 1 million deaths annually are attributed to diarrheal illnesses linked to the consumption of contaminated water and seafood. Besides harmful microbes, toxic heavy metals like lead (Pb), nickel (Ni), cadmium (Cd), and chromium (Cr(VI)) also increase public health risks, contributing to serious health problems. For example, in Eluru, India, an outbreak of neurological symptoms in over 500 residents was linked to elevated levels of Pb and Ni in the water, highlighting the acute danger posed by metal contamination (Atikpo *et al.*, 2021). Prolonged mining operations in Kabwe, Zambia had caused elevated Pb concentrations in drinking water, contributing to developmental delays and neurological disorders among children (Siame *et al.*, 2023). Research conducted in Lahore, Pakistan identified elevated levels of Pb and Cd in groundwater, leading to cancer risks and skin health issues (Iqbal *et al.*, 2024). Furthermore, excessive Cr(VI) in drinking water posed carcinogenic risks to the local population in Badagry, Nigeria (Oloruntoba, Wada and Adejumo, 2022).

The lack of safe drinking water remains a leading cause of waterborne disease outbreaks worldwide. To address this challenge, effective drinking water treatment technologies tailored to local environmental and infrastructural conditions are essential. This paper explores various potential drinking water treatment methods aimed at improving water quality and ensuring reliable access to safe, potable water, ultimately safeguarding human health and improving quality of life.

METHODOLOGY

Relevant literature published between 2020 and 2025 was systematically identified through searches in Scopus and Web of Science. The search strategy used combinations of the following keywords: *"Disinfection By-products"*, *"Drinking Water Treatment"*, *"Nanomaterials"*, *"Drinking Water"*, *"Emerging Pollutants"*, and *"Water Purification"*. Studies were included if they were peer-reviewed and addressed drinking water purification methods or emerging environmental challenges, particularly those related to disinfection by-products, nanomaterials, or emerging pollutants. Publications falling outside the defined timeframe or lacking direct relevance to drinking water treatment were excluded from the review. Data from eligible studies were extracted on treatment techniques, targeted contaminants, and performance outcomes. A narrative synthesis was then conducted to integrate and compare the findings, and to organize studies by treatment category (e.g., chemical disinfection, adsorption, membrane filtration, nanomaterial-based technologies).

METHODS OF WATER TREATMENT

Various water treatment methods have been employed to improve water quality and reduce health risks associated with contaminated sources in developing countries. Common water treatment methods include chlorination, flocculation, filtration, and biological filtration (Mazhar *et al.*, 2020; Rahim, Sunarsih and Budiati, 2024).

CHLORINATION

Chlorination remains one of the most widely implemented methods for disinfecting drinking water treatment systems. This process commonly utilizes sodium hypochlorite (NaClO) as the active disinfectant agent (Kesar and Bhatti, 2022). NaClO acts by disrupting the structural integrity of microbial cell membranes and denaturing essential proteins, ultimately causing microbial cell death (Nizer, Inkovskiy and Overhage, 2020). The efficiency of this disinfection method extends across a broad spectrum of pathogenic microorganisms, including viruses; under controlled conditions (pH 7.0–7.2, chlorine dose 0.2–3 mg/L, and temperature around 5 °C), all viruses examined demonstrated hypersensitivity or high sensitivity to chlorination, with complete inactivation achievable at a CT value of 10 mg·min/L (Kong *et al.*, 2021). Recent advancements in molecular methods, such as high-throughput amplicon sequencing, have allowed for more detailed assessments of chlorination efficiency by tracking microbial community changes before and after treatment (Pinar-Méndez *et al.*, 2022). These methods allow for detailed profiling of microbial communities before and after treatment, thereby providing insights into residual microbial populations, resistance patterns, and treatment optimization. Studies employing these tools have highlighted not only the effectiveness of chlorination but also the potential for selection of chlorine-resistant taxa under suboptimal dosing conditions (Hwang *et al.*, 2012).

Previous research has examined how microbial communities change in drinking water systems following chlorination and found that certain microbial groups can survive the disinfection process. These chlorine-resistant taxa tend to persist particularly when chlorine levels are inconsistently maintained at effective concentrations. This finding supports the concern that inadequate or suboptimal chlorination may not only fail to eliminate all pathogens but also unintentionally favor the survival and proliferation of resistant organisms, thus posing a risk to water safety and public health. Despite its proven efficacy, chlorination must be carefully managed to avoid the formation of harmful by-products and ensure optimal disinfection performance. Compounds such as trihalomethanes and haloacetic acids, which can form during chlorination, have been associated with adverse health effects. Notably, much of the past concerns have focused on their potential carcinogenicity (Mazhar *et al.*, 2020).

FLOCCULATION

The flocculation process is typically applied to enhance the removal of suspended solids. Flocculation involves adding agents—such as polyaluminum chloride—to wastewater to aggregate fine particles into larger clusters, or flocs, which can be more easily removed through sedimentation or filtration (Esteki *et al.*, 2024). Traditionally, a wide range of flocculants has been employed in water treatment processes, primarily including inorganic salts like aluminum sulfate (alum) and organic polymers like polyacrylamide (Ghernaout, 2020; Maćczak, Kaczmarek and Ziegler-Borowska, 2020). These flocculants facilitate the aggregation of suspended particles into larger flocs, thus enhancing sedimentation and removal efficiency. Inorganic flocculants are valued for their cost-effectiveness and strong charge neutralization capacity, while organic polymers are recognized for producing larger, more stable flocs and functioning effectively at lower dosages (Maćczak, Kaczmarek and Ziegler-Borowska, 2020).

Recent innovations include magnetic flocculation, which uses magnetic particles or composite materials to enhance the flocculation process. When exposed to a magnetic field, these materials facilitate rapid sedimentation, making the treatment process more efficient. Magnetic flocculation also offers the benefit of lower chemical usage while improving the removal of pollutants from water (Hu *et al.*, 2024). Previous study demonstrated an effective method for removing microplastics from water using magnetic nano-Fe_3O_4 particles (Shi *et al.*, 2022). These nanoparticles bind to common plastics like polyethylene (PE) and polystyrene (PS), allowing for easy removal with a magnet. The technique achieved over 80% removal efficiency in both pure and environmental water samples, showing strong potential for treating microplastic contamination in drinking water. Researchers at RMIT University developed a magnetic nanomaterial featuring a nano-pillar structure composed of carbon-coated iron oxide (CC-FeO) integrated with two-dimensional metal–organic frameworks (2D-MOFs) (Haris *et al.*, 2023). This innovative adsorbent effectively attracts and removes microplastics and dissolved pollutants (i.e., methylene blue) from water. The process achieved 100% removal of microplastics and methylene blue simultaneously within an hour, offering a sustainable and efficient solution for improving drinking water quality.

FILTRATION

Filtration technologies have significantly evolved by incorporating advanced materials and hybrid systems to address environmental challenges and enhance pollutant removal. Among the most popular systems are ceramic microfiltration membranes, known for their durability and resistance to extreme conditions. However, these systems are still prone to fouling, which necessitates regular cleaning and pretreatment (Haris *et al.*, 2023). Carbon-based nanomaterials, such as carbon nanotubes and graphene, have emerged as powerful filtration media due to their superior adsorption capacity and antimicrobial properties. These materials are especially effective in removing heavy metals and pathogens from water (Chadha *et al.*, 2022). A recent study introduced a regeneratable graphene-based water filter comprising of graphene oxide (GO) and claisen graphene (CG) in a 90:10 weight ratio (Schmidt, Dou and Sydlik, 2023). This advanced filter exhibited significantly higher heavy metal adsorption capacity than conventional activated charcoal. It achieved removal efficiencies of 90% for Pb, 70% for Cd, and 90% for mercury (Hg) in contaminated water. More importantly, the filter can be regenerated using hot water (80°C) or vinegar while maintaining its performance over multiple reuse cycles. This reusable design presents a sustainable and cost-effective approach to household water purification.

BIOLOGICAL FILTRATION

Biological filtration is a sustainable and cost-effective method for removing contaminants from drinking water. It relies on the formation of microbial biofilms on filter media such as sand or granular activated carbon. These biofilms support microbial communities that actively degrade organic pollutants, reduce nutrient loads, and eliminate pathogens (Bai, Dinkla and Muyzer, 2022). Biological filtration is used to remove ammonium from water through the nitrification process, which depends on factors like water quality and filtration parameters. A pilot study at a drinking water treatment plant used nitrifying biofilters to assess how filtration rate affects nitrification efficiency. Under optimal conditions, biofilm formation took approximately 70 days in water with ~1 mg/L of ammonium (NH_4^+), high dissolved oxygen (>9 mg/L), a filtration rate under 1 m/h, temperatures above 12°C, and pH between 7.8–8.0. Once biofilms were fully developed, the system achieved over 95% NH_4^+ removal across filtration rates from 0.5 to 8.4 m/h, even as ammonium concentrations increased (1–2.5 mg/L) and temperatures dropped (13 to 7°C) (Dragić, Drljača and Zoric, 2024). A summary of drinking water treatment methods and removal rates is presented in Table 1.

ADSORPTION

Maximizing the performance of adsorption processes largely depends on the careful selection of appropriate adsorbents. An effective adsorbent is generally characterized by a high adsorption capacity, rapid adsorption kinetics, ease of separation or recovery from aqueous media, as well as high porosity with small pore diameters, which enhance surface area availability and consequently improve adsorption efficiency (Abegunde *et al.*, 2020). A wide range of materials has been employed as adsorbents for diverse applications, including water purification, catalysis, desiccation, and sensing. Among the most widely investigated adsorbents are activated carbon, cellulose, natural minerals, silica, biopolymers, and nanomaterials.

Adsorbents such as silica, zeolites, and activated carbon are particularly attractive owing to their low cost, natural abundance, and excellent adsorption performance (Zhu *et al.*, 2021). Among them, activated carbon (AC) is the most widely utilized adsorbent for water decontamination, primarily due to its exceptionally high surface area and strong affinity toward heavy metals and dye molecules. Various forms of activated carbon, including granular activated carbon, powdered activated carbon, and activated carbon cloth, have been employed for pollutant removal from aqueous systems. Similarly, zeolites—typically aluminosilicates or aluminophosphates—also demonstrate notable adsorption capacity for heavy metals. Natural zeolites, in particular, are regarded as one of the most economical alternatives among commercially available adsorbents, owing to both their cost-effectiveness and inherently high porosity, which further enhances their adsorption potential (Chmielewská *et al.*, 2019). Silica-based materials have gained significant attention as promising sorbents, offering a broad range of applications. Their inherently large surface area, along with uniform and evenly distributed pores, makes them highly effective. Functionalized silica, in particular, has been widely applied as an efficient adsorbent for the removal of heavy metal ions and other hazardous contaminants (Chua *et al.*, 2021; Da'na *et al.*, 2017).

Table 2 presents the performance of silica, zeolite, and AC in reducing various water pollutants, with results compared against the permissible limits for drinking water. The data indicate that the effectiveness of each adsorbent varies considerably depending on the type of pollutant. For ammonium, zeolite achieved the best performance, reducing the concentration from 5.50 mg/L to 1.50 mg/L, which exactly meets the permissible limit. In contrast, silica and AC showed limited efficiency, with final concentrations still exceeding the acceptable threshold, highlighting zeolite's strong ion-exchange capacity for ammonium removal. For iron, silica significantly outperformed the other adsorbents by

METHOD	POLLUTANTS	REMOVAL EFFICIENCY	REFERENCE
Chlorination	Viruses	Complete inactivation at CT value of 10 mg·min/L	(Kong *et al.*, 2021)
Flocculation (magnetic Fe_3O_4)	Microplastics (PE, PS)	> 80% removal in lab & environmental samples	(Shi *et al.*, 2022)
Flocculation (CC-FeO + 2DMOF nanocomposite)	Microplastics & methylene blue dye	≈ 100% removal within 1 h	(Haris *et al.*, 2023)
Filtration (GO/CG graphene filter)	Pb, Cd, Hg	Pb 90%; Cd 70%; Hg 90%	(Schmidt, *et al.*, 2023)
Biological filtration (nitrifying biofilter)	NH_4^+	> 95% across 0.5 – 8.4 m h^{-1} flow rates	(Dragić, *et al.*, 2024)

Table 1 Drinking water treatment methods and removal rates.

POLLUTANT	C_i (mg/L)	SILICA ADSORBENT	ZEOLITE ADSORBENT	ACTIVATED CARBON ADSORBENT	DRINKING WATER STANDARD (mg/L)
		C_{out} (mg/L)	C_{out} (mg/L)	C_{out} (mg/L)	
Ammonium	5.50	4.70	1.50	3.50	1.50
Iron	0.55	0.10	0.50	0.35	0.3
Phosphate	4.00	2.80	1.20	0.25	N/A
COD	200	70.0	180	21.00	0
Turbidity*	100*	81.0*	N/A	9.7*	5*

Table 2 Adsorption performance of silica, zeolite, and AC in reducing pollutant concentrations. (Malekmohammadi *et al.*, 2016).
Remarks: (*) is in NTU (nephelometric turbidity unit), N/A is no data available, C_i is initial concentration, C_{out} is final concentration.

reducing the concentration to 0.10 mg/L, well below the permissible limit of 0.3 mg/L. This suggests that silica, with its high surface reactivity, has a strong affinity for iron ions, whereas zeolite and AC were less effective. In the case of phosphate, AC proved to be the superior adsorbent, lowering the concentration from 4.0 mg/L to 0.25 mg/L, while zeolite also achieved substantial reduction (1.20 mg/L). Silica, however, demonstrated only moderate removal (2.80 mg/L), indicating that surface functionalization may be critical for phosphate adsorption.

With respect to organic pollutants, as measured by COD, AC exhibited a remarkable reduction from 200 mg/L to 21.0 mg/L, far surpassing the performance of silica (70.0 mg/L) and zeolite (180 mg/L). This underscores the well-known advantage of AC's high surface area and microporous structure in adsorbing a broad range of organic molecules. A similar trend was observed for turbidity, where AC reduced values to 9.7 NTU, approaching but not attaining the permissible limit of 5 NTU, whereas silica achieved only partial removal (81.0 NTU) and no data were reported for zeolite.

Overall, the data highlight that no single adsorbent is universally effective for all pollutants. Zeolite is highly effective for ammonium due to its ion-exchange capacity, silica is particularly suitable for iron removal, and AC demonstrates superior performance for phosphate, COD, and turbidity reduction. Nevertheless, it is also evident that neither silica nor AC consistently achieved permissible levels for ammonium and turbidity, indicating inherent limitations. These findings suggest that integrated or hybrid adsorbent systems may be required to meet stringent drinking water standards across multiple pollutant categories, rather than relying on a single material.

While silica, zeolite, and AC each demonstrate specific strengths in pollutant removal, the data also reveal significant limitations when applied individually. For example, silica, although highly effective for iron removal, performs poorly for phosphate and turbidity reduction. Zeolite shows strong affinity for ammonium but provides only moderate removal for other pollutants. AC, despite its superior performance for COD, phosphate, and turbidity, does not consistently achieve permissible levels for ammonium and turbidity. These inconsistencies suggest that the adsorption efficiency of conventional adsorbents is pollutant-specific and may not be sufficient to meet comprehensive drinking water standards when used alone.

This gap points to the need for hybrid or composite adsorbent systems that combine the complementary properties of different materials. For instance, coupling AC with zeolite or silica could simultaneously enhance organic matter removal while improving ion-exchange capacity for ammonium and iron. Moreover, the functionalization of adsorbents with tailored surface groups or nanomaterials offers a promising direction to improve selectivity and adsorption kinetics. Recent studies on nanocomposites, biochar-based hybrids, and functionalized mesoporous silica have shown enhanced performance due to increased surface reactivity and synergistic effects between components.

Future research should therefore focus on developing cost-effective, sustainable, and multifunctional adsorbents that integrate high porosity, selective ion-exchange capacity, and broad-spectrum adsorption ability. Such advances would not only overcome the limitations observed in traditional adsorbents but also provide more reliable solutions for meeting stringent global water quality standards.

In summary, silica, zeolite, and AC each exhibit distinct advantages as adsorbents for water treatment, with their effectiveness strongly influenced by pollutant type. Zeolite demonstrates superior ammonium removal through ion-exchange mechanisms, silica shows high efficiency for iron due to its surface affinity, and AC remains the most versatile option, particularly for phosphate, COD, and turbidity reduction. However, none of these adsorbents alone is capable of achieving comprehensive pollutant removal at levels consistently below permissible drinking water standards. This limitation underscores the necessity of moving beyond conventional single-material systems toward hybrid and functionalized adsorbents. Integrating the complementary properties of these materials, particularly through composite structures or nanomaterial modification, holds great promise for developing cost-effective, sustainable, and multifunctional sorbents. Such approaches are likely to play a pivotal role in advancing water purification technologies and ensuring compliance with increasingly stringent environmental regulations.

EMERGING TECHNOLOGIES AND NANOTECHNOLOGY-BASED APPROACHES

Nanotechnology has emerged as a rapidly developing field in drinking water treatment, offering significant potential to enhance existing production processes. Among various nanomaterials, titanium dioxide (TiO_2) and silver (Ag) nanoparticles have attracted considerable attention due to their demonstrated antimicrobial properties and broad-spectrum effectiveness against pathogens. Despite this potential, the application of nanoparticle (NP)-based technologies in drinking water production remains limited compared to their wider use in other fields such as environmental remediation, wastewater treatment, and the agri-food sector, including food packaging. Nevertheless, future advancements are expected to expand the integration of nanomaterials, particularly nanoparticles, into advanced water treatment processes. In contemporary drinking water treatment, nanotechnology can play a pivotal role in pathogen disinfection, heavy metal removal, point-of-use purification, and the reduction of natural organic matter (NOM). Current applications of nanoparticles in this sector predominantly focus on disinfection, adsorption-based heavy metal removal, nanofiltration, and the elimination or detoxification of organic contaminants, highlighting their versatility as multifunctional treatment agents.

Nanomaterials, particularly NPs such as ZnO, CuO, TiO_2, and Mn_3O_4, have been shown to exhibit strong adsorption capacities for arsenic in drinking water treatment (Arora, 2021). Despite their promising laboratory-scale results, large-scale commercialization remains limited due to the high production costs of these nanomaterials, which likely explains the absence of widely implemented nano-based adsorption columns for arsenic removal in groundwater and surface water systems. This gap is increasingly critical as global drinking water demand continues to rise, requiring treatment technologies that are not only highly efficient but also economically viable and operationally simple. The potential of tetravalent manganese feroxyhyte nanoparticles for As(V) removal has been demonstrated, where the polymerization of metal-oxyhydroxyl chains increased the availability of adsorption sites and enhanced arsenic uptake (Pinakidou *et al.*, 2016). Their experiments reported removal efficiencies ranging between 2.1% and 2.5%. Other heavy metals such as Pb, Cd, and Ni have also been shown to be effectively adsorbed using CeO_2-, Fe-, and Ag-based nanoparticles (Bettini *et al.*, 2014), reinforcing the broad applicability of nanoscale materials.

Nevertheless, the translation of such laboratory findings to real drinking water systems remains challenging. Nano-based adsorption may underperform under real water conditions due to the presence of competing ions and complex water chemistry, which can substantially reduce adsorption efficiency, as highlighted by Simeonidis *et al.*, 2015. Despite these challenges, their work with magnetite nanoparticles showed promise: Cr(VI) concentrations of 50 µg L^{-1} were reduced to below 10 µg L^{-1} within 5 hours, even at pH > 7.5, with an adsorption capacity of 2 µg mg^{-1}. Importantly, the nanoparticles were synthesized from inexpensive iron salts ($FeSO_4$ and $Fe_2(SO_4)_3$), yielding a treatment cost of approximately 3.5 EUR/kg (dry basis) and an estimated annual cost of 5 EUR per inhabitant, demonstrating the potential for low-cost scalability.

Taken together, these findings underscore both the promise and the limitations of nanoparticle-based adsorption in drinking water treatment. While nanomaterials provide superior adsorption capacities and selectivity for contaminants such as As, Pb, Cd, Ni, and Cr, issues related to high production costs, incomplete performance data, and reduced efficiency under realistic water chemistries remain major barriers to commercialization. Future research must therefore focus on cost reduction strategies, long-term stability assessments, and hybrid systems that integrate nanoparticles with conventional adsorbents to achieve both technical efficiency and economic feasibility for large-scale drinking water applications.

Nanomaterials, particularly NPs such as ZnO, CuO, TiO_2, and Mn_3O_4, have been shown to exhibit strong adsorption capacities for arsenic in drinking water treatment. Nevertheless, their large-scale application remains constrained by high production costs and uncertainties regarding long-term stability and environmental safety. Future research is therefore expected to focus on the development of green synthesis routes, strategies to improve regeneration and reusability, as well as comprehensive risk and safety assessments, in order to facilitate sustainable and practical implementation of NP-based technologies in real water treatment systems.

CHALLENGES IN DRINKING WATER TREATMENT

Modern water treatment systems face numerous significant challenges that compromise their effectiveness and pose serious risks to public health and the environment. These challenges include the presence of emerging contaminants in water systems, temperature variations driven by climate change and urban heat islands, the generation of toxic sludge during coagulation processes, and the global impact of climate change on water resources.

EMERGING CONTAMINANTS IN WATER SYSTEMS

One of the primary concerns in modern water treatment is the increasing presence of emerging contaminants, including pharmaceuticals, pesticides, and microplastics (Nadia Morin-Crini *et al.*, 2022). These pollutants are not traditionally regulated and have only recently been recognized for their potential harm to human health and ecosystems. They enter water sources through multiple pathways, including untreated or partially treated wastewater, agricultural runoff containing chemical residues, and industrial discharges that release synthetic compounds. Due to their complex chemical structures and persistence in the environment, these substances are often resistant to removal by conventional water treatment systems, which are not designed to target such micro-pollutants (Nzereogu *et al.*, 2024). As a result, they can remain in treated water, subsequently raising concerns about long-term exposure and environmental accumulation. Addressing this issue requires advanced treatment technologies, such as activated carbon adsorption, advanced oxidation processes, and membrane filtration, along with updated regulations and monitoring strategies (Shahid *et al.*, 2021).

TEMPERATURE VARIATION DRIVEN BY CLIMATE CHANGE AND URBAN HEAT

Another major challenge in water treatment is the impact of temperature variations, which directly influence both the treatment process and the distribution of drinking water (Mishra, 2023). Rising temperatures, often driven by climate change and urban heat island effects, can significantly affect the chemical and biological stability of treated water. One of the most critical consequences is the accelerated decay of chlorine, a common disinfectant used to eliminate harmful pathogens (Calero Preciado *et al.*, 2021). As chlorine degrades more rapidly at higher temperatures, its residual concentration in the water distribution system diminishes, thereby reducing disinfection efficiency and increasing the risk of microbial contamination. In addition to chemical degradation, elevated temperatures also create favorable conditions for microbial regrowth and biofilm formation within pipes and storage tanks (Agudelo-Vera *et al.*, 2020; Calero Preciado *et al.*, 2021). Biofilms can harbor pathogens and protect them from disinfectants, posing a serious threat to water quality and public health, especially at the point of use. These temperature-related issues are particularly concerning in regions experiencing frequent heatwaves or lacking climate-resilient infrastructure. To address these risks, it is essential to develop and implement responsive system designs (Carbonari *et al.*, 2025), such as temperature-adaptive disinfection strategies, improved pipe materials, and real-time monitoring technologies. Furthermore, robust regulatory frameworks and proactive management practices are needed to ensure the delivery of safe drinking water under changing climate conditions.

GENERATION OF TOXIC SLUDGE DURING COAGULATION PROCESSES

The generation of toxic sludge during coagulation processes remains a significant environmental and operational concern in water treatment. Traditional coagulants like aluminum and iron salts are effective in removing turbidity and suspended solids but produce large volumes of non-biodegradable sludge that often contains residual metals, ultimately posing disposal challenges especially in regions with limited infrastructure (Patchaiyappan and Devipriya, 2021). Improper sludge management can result in heavy metal leaching, environmental contamination, and additional health risks. Moreover, such sludge can hinder biological treatment processes and increase operating costs. In response, biocoagulants and bioflocculants derived from natural sources like plant extracts, microbial metabolites, and marine organisms have gained attention as eco-friendly alternatives. These materials offer benefits such as biodegradability, lower toxicity, and potential reuse of the resulting sludge as biofertilizer (Badawi, Salama and Mostafa, 2023). However, limitations like raw material inconsistency, seasonal variability, limited shelf life, and scalability issues currently restrict their widespread application (Kurniawan *et al.*, 2020). To address these constraints, ongoing research is focused on optimizing extraction and production methods, improving coagulation efficiency, and integrating bio-based solutions into existing treatment frameworks.

GLOBAL IMPACT OF CLIMATE CHANGE ON WATER RESOURCES

Climate change significantly impacts global water resources by altering rainfall patterns, increasing the frequency of droughts, and intensifying extreme weather events, all of which compromise water availability and quality. These changes are particularly detrimental to developing countries, where limited water treatment infrastructure heightens vulnerability to waterborne diseases such as cholera and typhoid. For instance, in Malawi, the combination of tropical storms and heavy rainfall in 2022 led to the country's largest cholera outbreak, with over 36,000 cases and 1,200 deaths reported by early 2023. Similarly, in Kenya, prolonged drought conditions have been linked to increased cholera cases due to compromised sanitation and water scarcity (Alam, 2023). To address these challenges, experts advocate for a holistic approach to sustainable water management under climate stress. This includes the integration of advanced technologies, resilient infrastructure, community engagement, and effective water governance. Nature-based solutions, such as constructed wetlands and rainwater harvesting systems, have shown promise in enhancing water resilience (Barman, Rajak and Jha, 2024). Additionally, initiatives like Odisha's adaptive governance framework aim to foster climate-resilient development by strengthening climate-risk management and promoting community-driven adaptation strategies (Meher, 2024). Implementing such comprehensive strategies is crucial for safeguarding water resources and public health amidst ongoing climate change.

FUTURE RESEARCH DIRECTIONS

Future research on drinking water purification must go beyond incremental technological advances and embrace a more systemic, multidisciplinary perspective. One critical direction involves the integration of circular economy principles into water treatment research. Conventional treatment processes typically focus on removing contaminants to achieve compliance with regulatory standards, but they often overlook opportunities for resource recovery. Future technologies should therefore not only purify water but also reclaim valuable materials such as phosphorus, nitrogen, and trace metals. For example, phosphorus recovery from wastewater streams could support sustainable fertilizer production, while selective adsorption and nanomaterial-based filtration systems may allow the extraction of rare earth elements from industrial effluents. Embedding such resource recovery strategies into treatment design would simultaneously improve environmental sustainability, reduce waste generation, and create new economic opportunities.

A second research priority lies in the development of decentralized and point-of-use treatment systems, particularly in low-resource and rural settings where centralized treatment infrastructure is either absent or unreliable. The future of global water security will increasingly depend on portable, adaptable, and cost-effective systems capable of providing safe drinking water during emergencies, climate-related disasters, or in remote communities. Solar-driven disinfection units, compact adsorption filters using biochar or nanocomposites, and membrane-based kits represent promising approaches. These systems must be designed with affordability, robustness, and ease of maintenance in mind, ensuring that vulnerable populations are not excluded from technological benefits.

Another promising area of research is the integration of renewable energy with water treatment technologies. The energy-intensive nature of many advanced purification techniques, including membrane filtration and advanced oxidation processes, raises concerns about carbon footprints and operational costs. Coupling these systems with renewable energy sources such as solar, wind, or biomass could significantly reduce environmental impacts while enhancing resilience in off-grid or energy-scarce regions. Recent work in solar photocatalysis, particularly with TiO_2-based nanomaterials, demonstrates the feasibility of harnessing solar energy for pathogen inactivation and degradation of organic pollutants. Future studies should emphasize hybrid systems that co-optimize energy and water treatment efficiencies, ultimately contributing to the dual goals of climate change mitigation and water security.

In parallel, the concept of digital twins and smart water infrastructure is expected to transform the water sector. Digital twin technologies, which create dynamic, virtual replicas of physical systems, can simulate treatment performance under varying environmental conditions and contaminant loads. By integrating real-time monitoring data with artificial intelligence, digital twins could predict system failures, optimize chemical dosing, and improve resilience against shocks such as sudden pollution events or heatwaves. Such predictive systems could be particularly transformative for utilities operating under resource constraints, enabling preventive maintenance and adaptive responses at lower cost.

The future of drinking water treatment research must also confront socioeconomic and equity considerations, which remain underexplored in the technical literature. While high-income regions experiment with sophisticated nanotechnology and smart infrastructure, large portions of the global population still lack access to basic clean water. Future studies should therefore examine affordability, accessibility, and community-level adaptability of emerging technologies. Participatory approaches, where local populations are actively engaged in the co-design and testing of technologies, can enhance cultural acceptance and ensure that innovations address real-world needs. Moreover, policies must be aligned with research to prevent technological disparities from widening global inequities in access to safe drinking water.

Emerging contaminants, particularly pharmaceuticals, endocrine-disrupting chemicals, and microplastics, pose another domain for intensified research. While many current studies demonstrate removal efficiencies under laboratory conditions, their persistence in real water matrices often undermines treatment success. Future investigations must prioritize multifunctional hybrid technologies that combine adsorption, advanced oxidation, and membrane separation in integrated systems. Hybrid bio-nano composites, catalytic membranes, and bioelectrochemical systems are promising directions that could address the complex chemical diversity of these contaminants more effectively than single-method approaches.

A further critical consideration is the long-term sustainability, safety, and environmental risk assessment of new technologies. Nanomaterials, for example, offer extraordinary efficiency for pollutant removal, yet their potential release into aquatic systems raises concerns about ecotoxicity and human health impacts. Systematic studies on life cycle assessment, regeneration potential, and safe disposal methods of emerging materials are urgently required. Green synthesis methods using plant extracts, microbial processes, or biopolymers offer a potential pathway to safer nanomaterial production, but scalability and cost remain significant hurdles. Addressing these gaps will ensure that future technologies are not only efficient but also environmentally and socially responsible.

Another critical dimension for future research is the incorporation of climate resilience into water purification technologies. Climate change not only alters the quantity and distribution of water resources but also affects their quality through rising temperatures, flooding, salinity intrusion, and the increased mobilization of contaminants. These conditions can undermine the stability of traditional treatment processes and accelerate the decay of disinfectants. Future treatment systems should therefore be designed with adaptive capabilities that can perform reliably under fluctuating environmental conditions. For example, modular purification units capable of withstanding temperature extremes, or systems that combine physical, chemical, and biological mechanisms in a flexible architecture, may provide resilience in the face of climate variability. By embedding climate adaptation into technology design, research can ensure that drinking water purification systems remain robust and effective in a rapidly changing global environment.

Equally important is the recognition that the future of water purification cannot be solved by engineering and materials science alone. Instead, interdisciplinary collaboration will be essential to bridge technical innovation with social, environmental, and economic priorities. Environmental scientists, engineers, data specialists, public health experts, and social scientists must work together to design systems that not only meet technical performance criteria but also align with community needs, governance structures, and long-term sustainability. Such cross-disciplinary approaches can also accelerate the translation of laboratory findings into field applications by ensuring that the social acceptability and policy implications of new technologies are considered from the outset.

At the policy level, governance frameworks must evolve in tandem with technological advancements. Current regulations in many countries lag behind the emergence of novel contaminants such as pharmaceuticals and microplastics. Future research should therefore support the development of regulatory standards that address these emerging threats and provide guidelines for the safe deployment of advanced technologies, particularly nanomaterials. Policymakers, industry stakeholders, and the scientific community must work collaboratively to ensure that technological innovations are accompanied by transparent governance, risk communication, and equitable implementation. Without such alignment, even the most advanced purification systems risk remaining confined to experimental settings rather than being scaled for global impact.

Taken together, future research in drinking water purification must move toward holistic, integrated solutions that bridge technical innovation with social, environmental, and economic considerations. Circular economy strategies, decentralized systems, renewable energy integration, digital intelligence, equity-focused design, multifunctional treatment approaches, climate resilience, and sustainability assessments will all play pivotal roles in shaping the next generation of water purification technologies. By embedding these priorities into the research agenda, the scientific community can contribute to resilient, inclusive, and sustainable solutions for one of humanity's most pressing challenges.

CONCLUSION AND OUTLOOK

The purification of drinking water remains both a fundamental public health necessity and a growing environmental challenge. This review has highlighted the evolution of conventional treatment methods, including chlorination, flocculation, filtration, biological filtration, and adsorption, while also examining their respective strengths and limitations. These approaches continue to serve as the backbone of modern drinking water treatment systems; however, they are increasingly confronted with new and complex contaminants such as pharmaceuticals, pesticides, microplastics, and heavy metals. Moreover, global pressures including climate change, rapid urbanization, and the generation of toxic sludge further complicate the capacity of current technologies to safeguard public health and ensure water security.

The analysis also emphasizes that no single treatment method is universally effective across all contaminant categories. Chlorination, while highly effective for pathogen inactivation, risks the formation of harmful disinfection by-products. Flocculation and filtration provide reliable removal of suspended solids, yet their efficiency is constrained by issues such as fouling, sludge generation, and the persistence of dissolved organic and emerging contaminants. Biological filtration is sustainable and cost-effective but requires careful optimization of biofilm development and operational conditions. Adsorption, especially using materials such as activated carbon, zeolites, and silica, demonstrates considerable versatility but is limited by pollutant-specific selectivity and the inability to consistently meet stringent drinking water standards. These limitations underscore the need for integrated or hybrid systems that combine complementary mechanisms to achieve comprehensive purification.

Beyond conventional approaches, nanotechnology has emerged as a transformative frontier. Nanomaterials such as TiO_2, Ag, ZnO, CuO, and Mn_3O_4 demonstrate exceptional antimicrobial and adsorptive properties, positioning them as highly promising candidates for advanced water purification. Nevertheless, significant barriers remain, including high production costs, potential ecotoxicity, and performance inconsistencies under real-water conditions. As discussed, future research must focus on overcoming these constraints through green synthesis methods, improved regeneration and reusability, and comprehensive safety assessments aligned with international regulatory frameworks. Integrating nanomaterials into hybrid treatment systems also holds promise for achieving multifunctionality, simultaneously addressing microbial pathogens, heavy metals, and organic contaminants.

Importantly, drinking water purification research must now be contextualized within broader global trends. Climate change not only threatens water availability through droughts and extreme weather events but also exacerbates risks of contamination and infrastructure failure. Population growth and urban expansion will further intensify water demand, requiring treatment solutions that are scalable, adaptable, and resilient. Emerging contaminants challenge the adequacy of current monitoring frameworks, highlighting the need for real-time sensing, predictive analytics, and smart water systems that integrate digital technologies with treatment processes.

Looking forward, the future of drinking water purification depends on a holistic approach that integrates technological innovation with sustainability, governance, and equity. Circular economy strategies that couple purification with resource recovery, decentralized point-of-use systems that extend safe water access to vulnerable populations, renewable energy-powered treatment technologies, and AI-driven optimization all represent critical frontiers for research and practice. Equally, social dimensions—such as affordability, community acceptance, and policy support—must be embedded into the design and deployment of future systems.

In conclusion, achieving universal access to clean and safe drinking water will require a paradigm shift from reliance on single, conventional methods toward the development of integrated, sustainable, and adaptive treatment solutions. By bridging material science, engineering innovation, environmental sustainability, and social responsibility, future water purification systems can rise to the dual challenge of protecting public health and ensuring water security in an era of unprecedented environmental change.

DATA ACCESSIBILITY STATEMENT

The data supporting the findings of this review are entirely sourced from publicly available literature as cited in the present article. No original datasets were generated, and no unpublished data were used.

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The authors have no competing interests to declare.

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REFERENCES

Abegunde, S.M., Idowu, K.S., Adejuwon, O.M. and **Adeyemi-Adejolu, T.** 2020. A review on the influence of chemical modification on the performance of adsorbents. *Resources, Environment and Sustainability*, 1: pp. 100001. DOI: https://doi.org/10.1016/j.resenv.2020.100001

Agudelo-Vera, C., Avvedimento, S., Boxall, J., Creaco, E., de Kater, H., Di Nardo, A., Djukic, A., Douterelo, I., Fish, K.E., Iglesias Rey, P.L., Jacimovic, N., Jacobs, H.E., Kapelan, Z., Martinez Solano, J., Montoya Pachongo, C., Piller, O., Quintiliani, C., Ručka, J., Tuhovčák, L. and **Blokker, M.** 2020. Drinking water temperature around the globe: Understanding, policies, challenges and opportunities. *Water*, 12(4): pp. 1049. DOI: https://doi.org/10.3390/w12041049

Alam, M. 2023. How climate change affects waterborne diseases. Wellcome, 11 November 2023, [https://wellcome.org/search?search=How+climate+change+affects+waterborne+diseases and last accessed 13 July 2025].

Arora, R. 2021. Nano adsorbents for removing the arsenic from waste/ground water for energy and environment management—A review. *Materials Today Proceedings*, 45(6): pp. 4437–4440. DOI: https://doi.org/10.1016/j.matpr.2020.12.546

Atikpo, E., Okonofua, E.S., Uwadia, N.O. and **Michael, A.** 2021. Health risks connected with ingestion of vegetables harvested from heavy metals contaminated farms in Western Nigeria. *Heliyon*, 7(8): pp. e07716. DOI: https://doi.org/10.1016/j.heliyon.2021.e07716

Badawi, A.K., Salama, R.S. and **Mostafa, M.M.M.** 2023. Natural-based coagulants/flocculants as sustainable market-valued products for industrial wastewater treatment: a review of recent developments. *RSC Advances*, 13(28): pp. 19335–19355. DOI: https://doi.org/10.1039/d3ra01999c

Bai, X., Dinkla, I.J.T. and **Muyzer, G.** 2022. Microbial ecology of biofiltration used for producing safe drinking water. *Applied Microbiology and Biotechnology*, 106(13–16): pp. 4813–4829. DOI: https://doi.org/10.1007/s00253-022-12013-x

Barman, A., Rajak, F. and **Jha, R.** 2024. Integrating wetlands as nature-based solutions for sustainable built environments a comprehensive review. *Engineering, Technology and Applied Science Research*, 14(6): pp. 18670–18680. DOI: https://doi.org/10.48084/etasr.8923

Bettini, S., Pagano, R., Valli, L. and **Giancane, G.** 2014. Drastic nickel ion removal from aqueous solution by curcumin-capped Ag nanoparticles. *Nanoscale*, 6: 10113–10117. DOI: https://doi.org/10.1039/C4NR02583K

Bhattarai, K.R. and **Bhasin, M.** 2022 Water Pollution is the main problem for human health. *Journal of Algebraic Statistics*, 13(2): pp. 2812–2817. https://publishoa.com.

Calero Preciado, C., Boxall, J., Soria-Carrasco, V., Martínez, S. and **Douterelo, I.** 2021. Implications of Climate Change: How does increased water temperature influence biofilm and water quality of chlorinated drinking water distribution systems? *Frontiers in Microbiology*, 12(658927). DOI: https://doi.org/10.3389/fmicb.2021.658927

Carbonari, A., Scarpab, M. and **Plazac, F.I.M.** 2025. Environmental control of urban covered courtyards in mediterranean climates – Comparison between different strategies. *Energy Catalyst*, 1: pp. 22–34. DOI: https://doi.org/10.61552/EC.2025.002

Chadha, U., Selvaraj, S.K., Vishak Thanu, S., Cholapadath, V., Abraham, A.M., Zaiyan, M., Manikandan, M. and **Paramasivam, V.** 2022. A review of the function of using carbon nanomaterials in membrane filtration for contaminant removal from wastewater. *Materials Research Express*. 9(012003): pp. 1–23. DOI: https://doi.org/10.1088/2053-1591/ac48b8

Chmielewská, E. 2019. Chapter 4—Natural zeolite: Alternative adsorbent in purification or post-treatment of waters. In Modified Clay and Zeolite Nanocomposite Materials: Environmental and Pharmaceutical Applications; Elsevier: Amsterdam, The Netherlands, 2019; pp. 87–112. DOI: https://doi.org/10.1016/B978-0-12-814617-0.00012-8

Chua, S.F., Nouri, A., Ang, W.L., Mahmoudi, E., Mohammad, A.W., Benamor, A. and **Ba-Abbad, M.** 2021. The emergence of multifunctional adsorbents and their role in environmental remediation. *Journal of Environmental Chemical Engineering*, 9: pp. 104793. DOI: https://doi.org/10.1016/j.jece.2020.104793

Da'na, E. 2017. Adsorption of heavy metals on functionalized-mesoporous silica: A review. *Microporous and Mesoporous Materials*, 247: 145–157. DOI: https://doi.org/10.1016/j.micromeso.2017.03.050

Dragić, D., Drljača, D. and **Zoric, S.** 2024. Start-up of biofilter for nitrification and effect of filtration rate on the ammonium removal efficiency in drinking water treatment on pilot plant. *Water Supply*, 24(4): pp. 1207–1223. DOI: https://doi.org/10.2166/ws.2024.038

Esteki, R., Ehrampoush, M.H., Nasab, H. and **Ebrahimi, A. A.** 2024. Investigating the improvement of the quality of industrial effluents for reuse with added processes: coagulation, flocculation, multi-layer filter and UV. *Scientific reports*, 14: pp. 3971. DOI: https://doi.org/10.1038/s41598-024-54310-7

Ghernaout, D. 2020. Water treatment coagulation: dares and trends. *OALib*, 07(08): pp. 1–18. DOI: https://doi.org/10.4236/oalib.1106636

Haris, M., Khan, M.W., Zavabeti, A., Mahmood, N. and **Eshtiaghi, N.** 2023. Self-assembly of C@FeO nanopillars on 2D-MOF for simultaneous removal of microplastic and dissolved contaminants from water. *Chemical Engineering Journal*, 455: pp. 140390. DOI: https://doi.org/10.1016/j.cej.2022.140390

Hu, Z., Wu, K., Wang, Z., Shah, K.J. and **Sun, Y.** 2024. Research progress of magnetic flocculation in water treatment. *Magnetochemistry*, 10(8): pp. 56. DOI: https://doi.org/10.3390/magnetochemistry10080056

Hwang, C.-L., Ling, F., Andersen, G.L., LeChevallier, M.W. and **Wen Tso Liu.** 2012. Microbial Community dynamics of an urban drinking water distribution system subjected to phases of chloramination and chlorination treatments. *Applied and Environmental Microbiology*, 78(22): pp. 7856–7865. DOI: https://doi.org/10.1128/aem.01892-12

Iqbal, H.H., Siddique, A., Qadir, A., Sajid Rashid Ahmad, Liess, M. and **Shahid, N.** 2024. Human health and ecology at risk: A case study of metal pollution in Lahore, Pakistan. *Environmental Sciences Europe*, 36(9): pp. 1–11. DOI: https://doi.org/10.1186/s12302-023-00824-2

Kesar, S. and **Bhatti, M.S.** 2022. Chlorination of secondary treated wastewater with sodium hypochlorite (NaOCl): An effective single alternate to other disinfectants. *Heliyon*, 8(11): pp. e11162. DOI: https://doi.org/10.1016/j.heliyon.2022.e11162

Kong, J., Lu, Y., Ren, Y., Chen, Z. and **Chen, M.** 2021. The virus removal in UV irradiation, ozonation and chlorination. *Water Cycle*, 2: pp. 23–31. DOI: https://doi.org/10.1016/j.watcyc.2021.05.001

Kristanti, R.A. 2021. Rhizofiltration for removal of inorganic and organic pollutants in groundwater: A review. *Biointerface Research in Applied Chemistry*. 11(4): pp. 12326–12347. DOI: https://doi.org/10.33263/briac114.1232612347

Kurniawan, S., Abdullah, S., Imron, M., Said, N., Ismail, N., Hasan, H., Othman, A. and **Purwanti, I.** 2020. Challenges and opportunities of biocoagulant/bioflocculant application for drinking water and wastewater treatment and its potential for sludge recovery. *International Journal of Environmental Research and Public Health*, 17(24): pp. 9312. DOI: https://doi.org/10.3390/ijerph17249312

Maćczak, P., Kaczmarek, H. and **Ziegler-Borowska, M.** 2020. Recent achievements in polymer bio-based flocculants for water treatment. *Materials*, 13(18). DOI: https://doi.org/10.3390/ma13183951

Malekmohammadi, S., Mirbagheri, A. and **Ehteshami, M.** 2016. Comparison of silica, activated carbon and zeolite adsorbents in the removal of ammonium, iron, COD, turbidity and phosphate pollutants, and investigating the effect of discharge on the removal of pollutants. *International Journal of Humanities and Cultural Studies*. 2016: pp. 667–679. http://www.ijhcs.com/index.php/ijhcs/index

Mawari, G., Kumar, N., Sarkar, S., Frank, A.L., Daga, M.K., Singh, M.M., Joshi, T.K. and **Singh, I.** 2022. Human health risk assessment due to heavy metals in ground and surface water and association of diseases with drinking water sources: A study from Maharashtra, India. *Environmental Health Insights*, 16: pp. 117863022211460. DOI: https://doi.org/10.1177/11786302221146020

Mazhar, M.A., Khan, N.A., Ahmed, S., Khan, A.H., Hussain, A., Rahisuddin, Changani, F., Yousefi, M., Ahmadi, S. and **Vambol, V.** 2020. Chlorination disinfection by-products in municipal drinking water – A review. *Journal of Cleaner Production*, 273: pp. 123159. DOI: https://doi.org/10.1016/j.jclepro.2020.123159

Meher, A. 2024. Framework for adaptive governance in odisha : a special reference to educational administration: Theory and practice framework for adaptive governance in Odisha: A special reference to climate change and disaster management. *Educational Administration: Theory and Practice*, 30(9): pp. 377–388. DOI: https://doi.org/10.53555/kuey.v30i9.7703

Mishra, R.K. 2023. Fresh water availability and it's global challenge. *Journal of Marine Science and Research*, 2(1): pp. 01–03. DOI: https://doi.org/10.58489/2836-5933/004

Musa Khan, N., Bano, A. and **Ishaq Khan, G.** 2022. Contaminated wastewater irrigation impacts on human health. *Pak-Euro Journal of Medical and Life Sciences*, 4(6): pp. 126–137. DOI: https://doi.org/10.31580/pjmls.v4iSpecial.1802

Morin-Crini, N., Lichtfouse, E., Liu, G., Balaram, V., Ribeiro, A.R.L., Lu, Z., Stock, F., Carmona, E., Teixeira, M.R., Picos-Corrales, L.A., Moreno-Piraján, J.C., Giraldo, L., Li, C., Pandey, A., Hocquet, D., Torri, G. and **Crini, G.** 2022. Worldwide cases of water pollution by emerging contaminants: A review. *Environmental Chemistry Letters*, 20: pp. 2311–2338. DOI: https://doi.org/10.1007/s10311-022-01447-4

Nizer, W.S. da C., Inkovskiy, V. and **Overhage, J.** 2020. Surviving reactive chlorine stress: responses of gram-negative bacteria to hypochlorous acid. *Microorganisms*, 8(8): pp. 1–27. DOI: https://doi.org/10.3390/microorganisms8081220

Nzereogu, S.K. 2024. A critical review on emerging organic micro pollutants: Fate and treatment methods. *International Journal of Advances in Engineering and Management (IJAEM)*, 6(09): pp. 239–258. DOI: https://doi.org/10.35629/5252-0609239258

Oloruntoba, E.O., Wada, O.Z. and **Adejumo, M** 2022. Heavy metal analysis of drinking water supply, wastewater management, and human health risk assessment across secondary schools in Badagry coastal community, Lagos State, Nigeria. *International Journal of Environmental Health Research*, 32(9): pp. 1897–1914. DOI: https://doi.org/10.1080/09603123.2021.1926438

Patchaiyappan, A. and **Devipriya, S.P.** 2021. Application of plant-based natural coagulants in water treatment. *Cost Effective Technologies for Solid Waste and Wastewater Treatment*, 14: pp. 1–27. DOI: https://doi.org/10.1016/B978-0-12-822933-0.00012-7

Pinakidou, F., Katsikini, M., Paloura, E., Simeonidis, K., Mitraka, E. and **Mitrakas, M.** 2016. Monitoring the role of Mn and Fe in the As-removal efficiency of tetravalent manganese feroxyhyte nanoparticles from drinking water: An X-ray absorption spectroscopy study. *Journal of Colloid and Interface Science*. 477: 148–155. DOI: https://doi.org/10.1016/j.jcis.2016.05.041

Pinar-Méndez, A., Wangensteen, O.S., Præbel, K., Galofré, B., Méndez, J., Blanch, A.R. and **García-Aljaro, C.** 2022. Monitoring bacterial community dynamics in a drinking water treatment plant: An integrative approach using metabarcoding and microbial indicators in large water volumes. *Water*, 14(9): pp. 1435. DOI: https://doi.org/10.3390/w14091435

Rahim, J., Sunarsih. and **Budiati, L.** 2024. Drinking water treatment system and the challenges faced by developing countries. *Malaysian Journal of Medicine and Health Sciences*, 20(2): pp. 293–299. DOI: https://doi.org/10.47836/mjmhs.20.2.38

Sarker, B., N. Keya, K., I. Mahir, F., M. Nahiun, K., Shahida, S. and **A. Khan, R.** 2021. Surface and ground water pollution: Causes and effects of urbanization and industrialization in South Asia. *Scientific Review*, 7(73): pp. 32–41. DOI: https://doi.org/10.32861/sr.73.32.41

Schmidt, S.J., Dou, W. and **Sydlik, S.A.** 2023. Regeneratable graphene-based water filters for heavy metal removal at home. *ACS ES and T Water*, 3(8): pp. 2179–2185. DOI: https://doi.org/10.1021/acsestwater.3c00010

Shahid, M.K., Kashif, A., Fuwad, A. and **Choi, Y.** 2021. Current advances in treatment technologies for removal of emerging contaminants from water – A critical review. *Coordination Chemistry Reviews*, 442: pp. 213993. DOI: https://doi.org/10.1016/j.ccr.2021.213993

Shi, X., Zhang, X., Gao, W., Zhang, Y. and **He, D.** 2022. Removal of microplastics from water by magnetic nano-Fe_3O_4. *Science of The Total Environment*, 802: pp. 149838. DOI: https://doi.org/10.1016/j.scitotenv.2021.149838

Siame, T., Muzandu, K., Kataba, A. and **M'Kandawire, E.** 2023. Comparative determination of human health risks associated with consumption of groundwater contaminated with lead in selected areas surrounding the former lead mine in Kabwe and non-mining areas in Lusaka, Zambia. *International Journal of Community Medicine and Public Health*, 10(11): pp. 4089–4095. DOI: https://doi.org/10.18203/2394-6040.ijcmph20233434

Simeonidis, K., Kaprara, E., Samaras, T., Angelakeris, M., Pliatsikas, N., Vourlias, G., Mitrakas, M. and **Andritsos, N.** 2015. Optimizing magnetic nanoparticles for drinking water technology: The case of Cr(VI). *Science of The Total Environment*. 535: 61–68. DOI: https://doi.org/10.1016/j.scitotenv.2015.04.033

Zhu, F., Zheng, Y.M., Zhang, B.G. and **Dai, Y.R.** 2021. A critical review on the electrospun nanofibrous membranes for the adsorption of heavy metals in water treatment. *Journal of Hazardous Materials*, 401: pp. 123608. DOI: https://doi.org/10.1016/j.jhazmat.2020.123608

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