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Nanotechnology-Based Water Treatment for Rural and Resource-Constrained Environments: A Systematic Review

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Abstract

The increasing demand for clean water, coupled with the declining reliability of conventional water sources, has intensified the need for alternative and sustainable treatment solutions, particularly in rural communities. This study explored the potential of nanotechnology as an approach for treating contaminated surface and alternative water sources. A systematic literature review, guided by the PRISMA principles, was conducted to examine studies published between 2015 and 2025. The review identified four main nanotechnology-based treatment techniques: membrane separation, adsorption, catalysis, and multifunctional nanomaterials. Adsorption and membrane separation were found to be the most commonly applied methods for removing heavy metals and organic pollutants, while catalytic processes were mainly used for disinfection and contaminant degradation. The findings also show a growing shift towards hybrid systems that combine multiple techniques to improve overall treatment efficiency. The study highlights the potential of nanotechnology to improve water quality in rural communities that rely on sources such as harvested rainwater, boreholes, and surface water. However, its wider use is still limited by the high cost of materials, difficulties in scaling up beyond laboratory studies, and ongoing concerns about the potential toxicity of nanoparticles and their long-term persistence in the environment. Overall, the study provides a comprehensive synthesis of current advancements in nanotechnology-based water treatment and highlights its relevance in promoting sustainable water management and supporting water security in resource-constrained settings.

Keywords
Water, nanotechnology, water treatment, water quality, treatment

1. Introduction
Water treatment plays a critical role in public health and sustainable water resource management by ensuring the safety and suitability of water for diverse domestic, agricultural, and industrial applications, particularly under conditions of increasing scarcity and contamination pressure. Water availability, accessibility and quality directly impact the well-being of all living creatures (Wokem and Lawson-Jack 2015). Due to the increasing strain brought on by the growing human population, industrialisation, civilisation, and environmental changes, as well as agricultural

practices, water scarcity is widespread worldwide, particularly in water-rich regions. Access to potable water is, consequently, an unavoidable issue that calls for investigation into innovative, less expensive water purification methods, while accounting for energy needs and environmental effects (Kumar et al. 2014; Suthar and Gao 2017).

According to the World Health Organization (WHO) (2023), one of the most serious health issues facing the globe today is pollution and contamination of water, despite existing standards in place to check these issues. In developing nations, the contamination has been mostly caused by municipal and industrial wastewater discharge that has not been properly managed (Schweitzer and Noblet 2018; Lin et al. 2022). Only 20% wastewater worldwide had been adequately treated by 2015, with a 2016 United Nations report pointing out that approximately 70% industrial effluent is disposed of in developing countries without being destroyed (UNESCO 2016). Among the pollutants identified to compromise water quality are pathogens, organic pollutants, heavy metals and industrial discharge (Anabtawi et al. 2022).

In response to these growing challenges, nanotechnology is increasingly being explored in water treatment because it offers new ways of targeting contaminants at a very small scale, often achieving results that conventional methods struggle to deliver (Bhati and Rai 2017; Westerhoff et al. 2016). This advanced technology has shown significant potential in wastewater purification processes, offering cost-effective, efficient, and credible results to address global water scarcity (Sharma 2021). Furthermore, nanotechnology application to wastewater treatment and pollution remediation has shown great potential (Madhura et al. 2019).

Notwithstanding its global potential, the application of nanotechnology for water purification has not been fully explored in countries such as South Africa (SA), which often face severe drought conditions, inadequate water treatment infrastructure and a poor record of water conservation (Viljoen and van der Walt 2018). Historically, a large portion of SA was denied access to the provision of basic services such as water and sanitation, due to the apartheid and colonial governments that kept people separated from each other, evicted them from their ancestral lands and denied people participation in the nation's economy (Rathilall and Akpan 2025). As a result, residents of these rural communities depend on municipal water tanker supplies, boreholes, springs, and stagnant water, as well as local rivers and harvested rainwater (HRW) as an alternate source for domestic activities (Owen and Goldin 2015; Matimolane et al. 2023).

These alternative water storage methods are often contaminated or inadequately treated, thereby increasing health risks and highlighting the need for affordable and efficient purification methods (Martínez-García et al. 2022; Rathilall and Akpan 2025). In some cases, they combine water from different sources in the same container, based on availability, to meet their required volume. For instance, a resident can harvest rainwater, and in the same storage container, store water fetched from the river, and water from municipal tanker supply. These water sources can be contaminated in their original states, and the combination can breed more complex pathogens unsafe for human consumption.

With its large surface areas and altered characteristics, nanotechnology offers significant treatment prospects for improving the quality of water from these sources (Yaqoob et al. 2020). By integrating nanotechnology-based purification techniques, it becomes possible to enhance water safety in rural communities and promote sustainable water resource management. However, some societal and ethical concerns around the potential effect of nanoparticles (NPs) on humans and the entire ecosystem have been raised. There are concerns regarding the long-term health effects of NPs, such as toxicity or bioaccumulation in the human body, as NPs may linger in water systems and endanger aquatic life, simultaneously upsetting ecosystems (Aithal and Aithal 2016). There are also fears with regard to the environmental effects, transparency in their use, possible hazards to communities, and the suitability of regulatory frameworks to guarantee safety and ethical issues.

The study aim was, therefore, to highlight the effectiveness of nanotechnology for water treatment, and identify various nanotechnology-based options available for contaminated water treatment.

2. Methods

This study adopted a systematic literature review (SLR) methodology to explore and analyze the latest developments on nanotechnology and surface water treatments. The SLR approach is aimed at identifying and understanding key trends and knowledge gaps within the existing academic literature. This method involves a comprehensive and methodical review of relevant studies to synthesize findings and provide a coherent overview of the subject matter as described by Xiao and Watson (2019). The objective of the SLR is to produce a thorough, unbiased, and reliable synthesis of a broad range of relevant research, and integrating the findings into a cohesive narrative. This is achieved through a meticulous and transparent review process, ensuring that the synthesis is both valid and comprehensive (Snyder 2019).

2.1 Data Collection

The data collection and review process adhered to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure a transparent and replicable methodology, encompassing the stages of identification, screening, eligibility, and inclusion (Shaheen et al. 2023; Snyder 2019). The study identified relevant literature from prominent academic research databases, including Springer Link, Scopus, and Science Direct. The inclusion focused on studies addressing nanotechnology techniques for water-treatment, including associated methods and processes. Conversely, the exclusion criteria ensured studies focusing on conventional water treatment methods were excluded. The inclusion criteria applied in the database search strategy are detailed in Table 1.

Table 1. Database search strategy

Criteria	**Inclusion**
Keywords	water, treatment, nanotechnology, nanomaterials, membrane, adsorption, catalysis
Article types	Peer Reviewed
Language	English
Year	2015-2025

As can be seen in Table 1, the keywords used in the search field were "water AND treatment AND nanotechnology AND nanomaterials AND membrane AND adsorption AND catalysis". The Boolean operators were included in the keywords to refine the search strategy. The full search strings were adapted for each database (Springer Link, Scopus, and Science Direct) to account for database-specific indexing and search functionalities. The review focused exclusively on peer-reviewed articles and comprehensive review papers published in reputable journals within the fields of nanotechnology techniques for water-treatment, including its associated methods and processes. This selection was made to enhance the credibility of the study, as such sources provide detailed methodological explanations, support the transparency of results, and enable the reproducibility and extension of research. Furthermore, peer-reviewed articles are central to trustworthy research since independent experts evaluate the study design, methods, analysis, and citations before publication (Munn et al. 2018). The time frame covering the period from 2015 to 2025 was selected to include the most recent and relevant studies that reflect current practices and advancements in wastewater treatment processes. To maintain the quality and relevance of the review, non-English articles were excluded. This decision was based on the need for language consistency and the availability of translation resources, which could otherwise introduce potential biases or inaccuracies in the interpretation of findings (Shaheen et al. 2023).

The PRISMA guidelines were followed in a systematic process, and the study selection process is presented in Figure 1 using a PRISMA flow diagram.

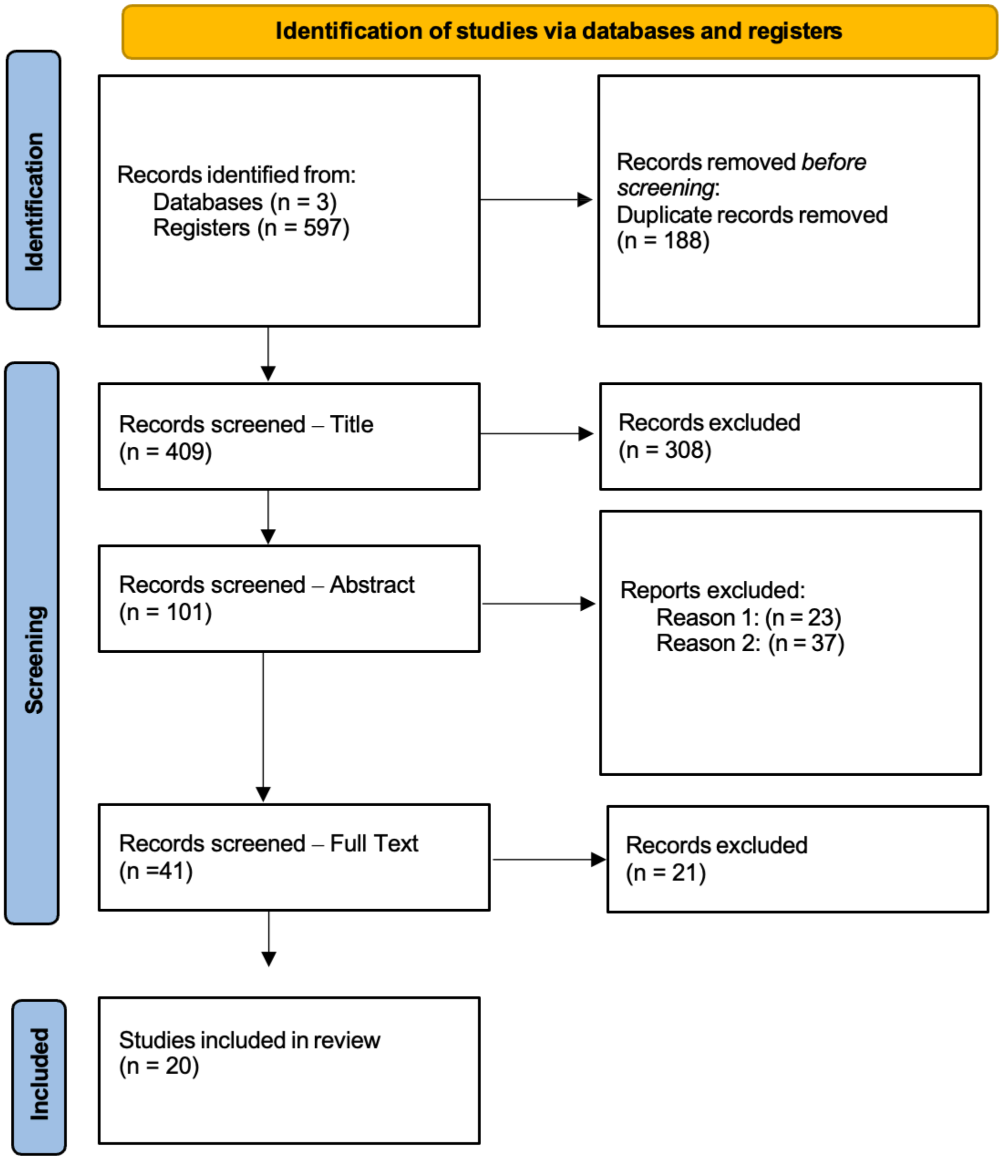

Figure 1. PRISMA diagram

As shown in Figure 1, a total of 597 articles were identified through an exhaustive search of selected databases. After removing 188 duplicates using EndNote software, 409 articles remained for screening. These were then reviewed by title, which reduced the number to 101 articles. The abstracts were screened next, leaving 41 articles that were relevant to the study. Finally, a full-text review was conducted, and 20 articles were included in the final review based on their relevance and quality.

The screening process was conducted in stages, including title screening, abstract review, and full-text assessment, based on the predefined inclusion and exclusion criteria. The screening and selection of the studies were conducted by two reviewers, and any differences in study selection were discussed and resolved to ensure consistency in the final inclusion.

2.2 Data Analysis

Qualitative data analysis techniques were utilized to systematically interpret and derive meaningful insights from the qualitative data collected. The extracted data was captured and arranged in Microsoft Excel in terms of author details, study design, methodology, and key findings related to the application of nanotechnology in water treatment.

Thereafter the data was analysed using thematic synthesis to identify recurring patterns and arrange the themes as they appeared (Shuster et al. 2018). This approach enabled the identification and examination of key themes and patterns within the textual data, as supported by Snyder (2019). It further facilitated a comprehensive understanding of the various applications, treatment methods, and technological advancements associated with nanotechnology in water treatment. Data organisation and reference management were conducted using EndNote to ensure efficient handling and retrieval of sources.

2.3 Quality Assessment

According to Xiao and Watson (2019), quality assessment in systematic reviews often involves evaluating the internal validity of studies, with a study considered internally valid if it is free from significant methodological biases. The quality assessment procedures employed in this study were designed to ensure a high level of methodological rigour, thereby contributing to the reliability and validity of the research outcomes (Shaheen et al. 2023). The PICO (Population, Intervention, Comparison, and Outcome) method was employed to address the diverse approaches and goals of the identified articles, to create a clear, focused research question and eligibility criteria. PICO reduces ambiguity and selection bias, clarifies what evidence is relevant, and makes synthesis and interpretation more straightforward to ensure their reliability when applied at the start of an SLR (Tufanaru et al. 2017; Page et al. 2021). The evaluation identified three possible outcomes: low risk, where the article is straightforward and interpretable, indicating no possibility of bias; unclear risk, where the manuscript raises questions needing further explanation by the review author; and high risk, where the results are not fully understood (Page et al. 2021; Munn et al. 2018). To further enhance the robustness and fairness of the results, the study utilized multiple databases, reducing the risk of database-specific biases. Additionally, comprehensive reporting of findings from the selected studies was undertaken to provide a balanced and accurate representation of the research landscape. Steps were also taken to address potential biases, such as publication bias and selection bias, through transparent reporting and methodological rigour.

3. Results and Discussion

The thematic analysis identified four main nanotechnology-based techniques used in water treatment, namely membrane separation, adsorption, catalysis, and multifunctional nanomaterials. As shown in Table 2, studies published between 2015 and 2025 apply these techniques across different contexts, including drinking water, wastewater, and harvested rainwater treatment.

Table 2. Summary of author contributions to water treatment

Author	**Study Focus Area**	**Technique**			
		Membrane separation	Adsorption	Catalysis	Multifunctional nanomaterials
Zhang *et al.* (2023)	Covalent organic framework-immobilized wood membrane for high performance nanofiltration	X			
He *et al*. (2020)	Conventional drinking water treatment process removal of CX3R-type disinfection by-product precursors from rainwater		X		X
Figoli *et al.* (2017)	Nanotechnology in drinking water purification	X	X		X
Surendhiran *et al.* (2017)	Silver–magnetic nanocomposites for water purification				X
Samuel and Mathew (2015)	Filtration system of rainwater harvested drinking water	X	X		
Dudziak and Kudlek (2019)	Membrane filtration to remove hardness in wastewater effluent	X			

Mabudi *et al*. (2025)	Metal-based NPs to enhance wastewater treatment				X
Fiorentino *et al.* (2021)	Conventional vs solar driven AOPs in roof-harvested rainwater disinfection			X	
Nalwanga *et al.* (2018)	SODIS as a suitable treatment technology of roof-harvested rainwater			X	
Sharma (2021)	Nanotechnology for water purification	X	X		X
Martínez-García *et al.* (2022)	Solar reactors for harvested rainwater			X	
Rathod *et al*. (2024)	Green NPs and the nanotechnology role in wastewater treatment				X
Bouzayani and Sanromán (2024)	Environmental remediation of wastewater using polymer-supported heterogeneous Fenton catalysts			X	
Vinayagam *et al.* (2024)	AOPs for degradation of pollutants from wastewater			X	
Olawade *et al*. (2024)	NPs for microbial control in water		X		X
Elhenawy *et al.* (2024)	Emerging nanomaterials for drinking water purification				X
Li *et al.* (2024)	Graphene-based adsorbents for wastewater treatment		X		
Mohammad *et al.* (2015)	Nanofiltration membranes review; desalination	X			
Motitswe *et al.* (2022)	Adsorptive materials for removal of toxic metals in wastewater		X		
Kang *et al.* (2024)	Graphene Membrane for Water-Related Environmental Application	X	X		

From Table 2, it is evident that adsorption and membrane separation are the most commonly used approaches, particularly for the removal of contaminants such as heavy metals and organic pollutants. Catalytic processes, including advanced oxidation processes (AOPs), solar disinfection (SODIS), and Fenton-based reactions, appear less frequently but are mainly applied for disinfection and pollutant degradation. Multifunctional nanomaterials are also widely reported, with several studies showing their ability to combine adsorption, separation, and catalytic functions within a single system. In addition, some studies apply more than one technique, which suggests a growing focus on integrated or hybrid treatment approaches to improve overall efficiency. This indicates a clear research preference for well-established physical separation methods, while catalytic and transformation-based approaches remain less developed in applied and real-world contexts. The next section discusses each of these themes in more detail and highlights their role in advancing nanotechnology-based water treatment.

3.1 Membrane Separation

Nanotechnology improves membrane separation through microfiltration, ultrafiltration, and nanofiltration (NF), as well as reverse osmosis (RO), by embedding or coating membranes with NPs, nanosheets or nanofibres. These nanofillers create tailored transport channels, increase permeability, add antifouling or antimicrobial functions, and permit selective removal of salts, heavy metals, organics and pathogens while managing fouling and mechanical stability (Mohammad et al. 2015). Deemed the most common membrane technology for water treatment, NF involves passing a fluid through a membrane that serves as a sieve to separate contaminants. The fluid and certain monovalent ions are the only substances that can travel through the membrane, which traps debris on the opposite side (Sharma 2021).

NF is used in the purification of dairy products, drinking water filtration, and reducing colour, tannins, and turbidity. In addition, inorganic salts and tiny organic molecules can be effectively separated by NF membranes. Other than food uses, NF is also known to be effective in desalination, water and wastewater treatment (Mohammad et al. 2015). The challenge in its use, is that NF membranes cost a little more than other membranes. Both industrial and residential water treatment can be managed using NF, because the nanomaterials on the nanofilters target pollutants such as viruses, pesticides, copper (Cu), and fluorides, while the nanofilters trap the wastes and germs (Figoli et al. 2017).

Samuel and Mathew (2015) created, developed, and assessed a drinking water filtration system that is inexpensive to buy, requires no power or upkeep, and operates independently. Natural resources such as sand and gravel were used in their study, together with three types of charcoal; wood charcoal, anthracite, and (coconut) shell charcoal that functioned as adsorbents to evaluate as filter media. Similarly, Zhang et al. (2023) successfully eliminated organic contaminants from water by creating a TpPa-wood NF membrane using large covalent organic frameworks (COFs) in their natural condition. With a 600 L m-2 h-1 treatment rate, the TpPa-wood membrane has a 97% efficiency. This success rate was attained due to the natural micropores of the synthesised COFs, the chemical reaction between the COFs and the cellulose in wood, the mechanical properties of wood, and the low-tortuous wood channels.

Dudziak and Kudlek (2019) comprehensively assessed the efficacy of membrane filtration, specifically NF and RO in eliminating hardness ions (calcium and magnesium) from treated municipal wastewater effluent. The pilot-scale experimental setup reveals that both NF and RO effectively diminish water hardness, with RO attaining more than 90% and NF achieving 85% removal efficiency, particularly for magnesium ions. The processed water complies with reuse regulations, specifically for industrial use. The study validates membrane technology effectiveness for tertiary wastewater treatment but fails to address long-term membrane performance and cost considerations, underscoring the necessity for future research on economic viability, fouling resistance, and integration with supplementary treatment methods.

Figoli et al. (2017) examined nanotechnology use in drinking water filtration, highlighting the efficacy of nanomaterials such as carbon nanotubes (CNTs), metal oxides, and composites in eliminating impurities including heavy metals, pathogens, and organic pollutants. These materials utilise methods including adsorption, photocatalysis, and antibacterial activity to improve purification efficiency. The authors emphasised nanotechnology benefits, such as elevated surface area and reactivity, which facilitate its application in decentralised water treatment. Nonetheless, the study also highlights problems including nanoparticle stability, possible toxicity, and elevated production costs. However, most studies focus on short-term performance, with limited evidence on long-term operational sustainability in real-world settings.

3.2 Adsorption

Adsorption is a surface phenomenon in which molecules of an adsorbate (substance) adhere to a solid surface (adsorbent). Temperature, the adsorbent and adsorbate type, the presence of additional contaminants, and particle size, as well as contact time, and the chemical environment are some variables that impact the adsorption process (Motitswe et al. 2022).

The unique characteristics of nanomaterials, including their small size, catalytic potential, high reactivity, and increased surface area, as well as a significant number of active sites for interaction with different contaminants, have made nanomaterials effective adsorbent materials. Nanostructured adsorbents such as graphene derivatives, CNTs, metal-oxide NPs, and functionalised magnetic particles, along with nanoscale zero-valent iron (nZVI) variants, offer a high surface area and tunable surface chemistry for rapid capture of heavy metals, dyes, organics and some emerging contaminants (Motitswe et al. 2022).

Li et al. (2024) reviewed recent progress in the use of graphene-based materials for wastewater treatment, focusing on their synthesis, adsorption characteristics, and pollutant removal mechanisms. Their paper discusses how structural features such as high surface area, tunable surface chemistry, and abundant functional groups enhance adsorption of both inorganic contaminants such as heavy metals and organic pollutants, for example, dyes and pharmaceuticals. The authors compare preparation methods including chemical oxidation, hydrothermal, and composite formation techniques, noting their influence on performance and regeneration ability. They conclude graphene-based adsorbents offer high efficiency and reusability but highlight challenges such as production cost, scalability, and potential environmental risks that must be addressed for practical application.

He et al. (2020) centred their research on dissolved organic matter elimination, and the subsequent disinfectant byproduct (DBP) decrease after disinfection, in a study on traditional drinking water treatment procedures for surface and groundwater. In addition to lowering the production and toxicity of DBPs such as trihalomethanes, halo-aldehydes, haloacetonitriles, and haloacetamides during the chloramination process, He et al. (2020) assessed how well these treatments removed CX3R-type DBP precursors from the water. Granular activated carbon (GAC) and sand filtration (SF) both successfully eliminated DBP precursors, according to the results, while GAC was superior to SF. Conversely, coagulation-sedimentation treatment did not result in any DBP precursor elimination.

Kang et al. (2024) present a comprehensive review of graphene-based membranes including graphene, graphene oxide (GO), reduced graphene oxide (rGO) and hybrid composites for water and wastewater treatment. Beyond their molecular sieving ability, these membranes exhibit strong adsorption properties resulting from abundant surface functional groups, π–π interactions and tunable surface chemistry. The review explains how rGO membranes combine high surface area with residual oxygen functionalities, allowing simultaneous filtration and adsorption of heavy metals, dyes and organic contaminants.

Fabrication methods such as pore etching, cross linking and surface functionalisation are discussed in relation to adsorption capacity and selectivity. While laboratory studies show high permeability and pollutant removal efficiency, challenges such as GO swelling, fouling and limited regeneration hinder real world use. Kang et al. (2024) recommend developing stable composite supports, optimising surface chemistry for reusable adsorption and conducting standardised testing and environmental assessment to advance graphene-based membranes toward practical and sustainable deployment. This suggests that adsorption efficiency is highly dependent on material properties and water conditions, limiting direct comparability across studies.

3.3 Catalysis

Nanocatalysts such as Titanium dioxide (TiO2), graphitic carbon nitride (g-C3N4), doped metal oxides, and metal-organic frameworks (MOF)-derived catalysts, as well as iron (Fe)-based NPs and heterogeneous Fenton/peroxymonosulfate (PMS) activators accelerate oxidative breakdown of recalcitrant organics and disinfect microbes (Bouzayani and Sanromán 2024). They are used in photocatalytic reactors, photo-Fenton and persulfate activation systems, with nanoscale engineering shown to improve light absorption, charge separation and catalytic cycles.

Despite strong laboratory performance, catalytic processes remain less widely applied due to operational complexity and sensitivity to environmental conditions. An example would be Martínez-García et al. (2022), who reported on using solar disinfection reactors for rainwater treatment in rural sub-Saharan Africa (SSA) communities. Their studies in Uganda and Spain demonstrated effective microbial and bacterial load reduction in HRW, supporting its potential as a safe drinking water source, underscoring the importance of continuous monitoring and technological innovation in rainwater management practices.

This supports Nalwanga et al. (2018), whose study employed solar water disinfection equipment at a rural settlement in Southern Uganda to examine the quality of HRW over a 12-month period. Their results, based on 50 households that used rooftop rainwater harvesting and different storage systems, showed although HRW generally complied with drinking water regulations, many samples had high levels of microbiological contamination, making the water unfit for human consumption without treatment. The study found solar reactor use could reduce the health hazards related to drinking untreated rainwater.

Fiorentino et al. (2021) investigated nanotechnology use in solar photo Fenton (SPF) processes in Italy, such as solar-driven advanced oxidation processes (SODAOP), sunlight/peroxide, and sunlight/chlorine (SCL) for disinfection, was further investigated. When compared to traditional disinfection techniques such as UV-C radiation and chlorination, their study discovered SPF and SCL were more successful in lowering bacteria burdens, emphasising how cutting-edge treatment technology can enhance water safety.

Bouzayani and Sanromán (2024) surveyed polymer-supported heterogeneous Fenton catalysts for wastewater treatment, concentrating on hydrogels as the polymer hosts that immobilise catalytically active metals. The review encapsulates preparation methods and catalyst designs, and reports performance data for degrading organic pollutants. These authors identified iron oxides (FeO) and copper-based materials as the most used active phases (with limited work on ruthenium), and discuss strategies to enhance metal loading and activity, as well as approaches for catalyst recovery and reuse. They noted, notwithstanding promising lab-scale degradation results, key challenges remain material stability, metal leaching, regeneration, and scale-up in real wastewater, with greener synthesis routes, stronger immobilisation to reduce leaching, and testing in realistic matrices to advance practical application recommended.

Vinayagam et al. (2024) reviewed AOPs for removing pharmaceuticals from wastewater, covering electrooxidation, ozonation, sonolysis, and radiation, along with electroFenton photolysis and photocatalysis. They showed operating conditions (current density, pH, electrode and electrolyte choice, influent concentration) strongly influence removal; despite many lab studies reporting high parent compound removal, incomplete mineralisation, transformation products, and matrix effects, as well as high energy and cost limit field application. These authors recommend process optimisation, coupling AOPs with biological or hybrid treatments, and pilot scale technoeconomic and environmental assessment.

3.4 Multifunctional Nanomaterials

Nanomaterials are deployed as antimicrobial agents, with silver (Ag), copper (Cu), titanium dioxide (TiO_2) electrochemical/optical nanosensors for in-field water quality monitoring, and as selective sorbents for resource recovery such as targeted ion capture. There are also hybrid devices that combine sensing and treatment, for example, electrochemical disinfection on nanostructured electrodes. Silver NPs a technique in nanotechnology, are a nanotechnology technique frequently used to purify water, because they are extremely poisonous to microorganisms and provide efficient microbiological defence against bacteria, viruses, and fungi. Due to its extremely high efficacy in the purification process, the silver NPs approach has been widely utilised to disinfect drinking water (Surendhiran et al. 2017). Moreover, owing to their strong and broad-spectrum antibacterial action and minimal toxicity to humans, silver NPs have also been shown to be efficient water filters in home water treatment systems.

Mabudi et al. (2025) examine the application of metal-based NPs to improve wastewater treatment methodologies. The authors investigated different metal NPs, including nZVI, Ag, and Cu, emphasising their efficacy in eliminating contaminants such as heavy metals, organic pollutants, and infections. Similarly, He et al. (2020) not only examine the modes of action of these NPs, including adsorption, reduction, and photocatalysis, they also assessed their efficacy in several treatment situations. The study delivers an exhaustive examination of the advantages and constraints of metal-based NPs, furnishing insights for forthcoming advancements in sustainable wastewater treatment methods.
Surendhiran, et al. (2017) likewise proposed silver–magnetic nanocomposites as an efficacious method for water purification, emphasising their dual role in pollutant extraction and magnetic recovery for reutilisation, thereby providing a promising, environmentally sustainable strategy for water treatment. With each of these metal oxides, silver nanocomposites are expected to provide a powerful and more affordable inorganic antibacterial substance. As a result, the final nanocomposites would be divided into two categories: silver (Ag) with copper oxide (CuO) and silver (Ag) with zinc oxide (ZnO). The antibacterial potential of these nanocomposites would be improved by their harmonious combination. Therefore, by producing related ions, each component of the nanocomposite will operate as an antibacterial agent and activate its unique antibacterial activity.

Olawade et al. (2024) appraised how NPs are used for microbial control in water treatment, focusing on silver (Ag), copper (Cu), and titanium dioxide (TiO_2) NPs and carbon-based materials such as GO and CNTs. These particles exhibit strong antimicrobial effects through cell membrane disruption, reactive oxygen species generation, and metabolic interference. Their study outlines these applications in drinking water disinfection, wastewater treatment, and anti-biofilm coatings, showing high pathogen removal efficiency. However, Olawade et al. (2024) caution NPs released into the environment can persist, bioaccumulate, and harm aquatic life. They accentuated the need for stricter regulation, life-cycle assessment, and long-term ecological studies to ensure safe and sustainable use in water purification.

Elhenawy et al. (2024), similarly, reviewed emerging nanomaterials for drinking water purification, focusing on carbon-based materials, metal (Ag, Fe), and metal oxide NPs (Titanium oxide [TiO2], zinc oxide [ZnO])), with nanostructured membranes used for adsorption, photocatalysis, disinfection and filtration. They emphasise the materials' high surface area, tunable chemistry and multifunctional properties but note concerns regarding nanoparticle release, toxicity, fouling, and regeneration, as well as cost. In addition, Elhenawy et al. (2024) call for greener synthesis methods, better immobilisation, pilot scale testing, and stronger environmental and regulatory assessments to enable safe and practical implementation.

Sharma (2021) examined the use of nanotechnology in water purification through different methods: adsorption (nanomaterials), nanomembranes (NF), and nanofabrication. Pre-treatment is accomplished by modifying nanomembranes using nanofibers. Since nanofiltration softens hard water, removes micropollutants and bacteria, and removes contaminants from surface and ground water, it is utilised in the manufacture of drinking water. The process of nanofabrication entails creating nanomaterials in treatment units, using either the top-down or bottom-up approaches in nanomaterial application as adsorbents, including dendrimers, CNTs, metal oxide NPs (TiO2, ZnO), as well as metal NPs (Fe and Ag). However, while nanotechnology is widely regarded as an effective approach for water purification and may be considered safe under controlled conditions (Sharma, 2021), its broader application remains debated due to concerns regarding the potential health and environmental risks associated with the high reactivity of NPs.

Rathod et al. (2024) investigate the synthesis and application of green NPs in wastewater treatment in their biotechnology study, highlighting sustainable, plant-derived approaches that employ natural extracts for nanoparticle manufacturing. The authors examine diverse green synthesis methods, accentuating their ecological advantages, economic efficiency, and scalability, relative to conventional chemical approaches. Their study highlights the promise of green nanoparticles as environmentally sustainable options in wastewater management, consistent with ecological sustainability and resource efficiency concepts.

Overall, these studies underline the importance of effective treatment and regular monitoring of contaminated water intended for consumption. These techniques, along with their applicable methods, benefits, active nanomaterials, and treatment outcomes are summarised in Table 3.

Table 3. Summary of nanotechnology-based water treatment techniques and their applications

Techniques	Benefits	Applicable methods	Targeted contaminants	Conclusion
1. Membrane separation	Removes particles and microbes by size exclusion or membrane sieving	Nanofiltration (NF), thin-film nanocomposite membranes, electrospun nanofiber filters	Suspended solids, colloids, bacteria, some organics	High removal performance: fouling and nanoparticle release must be managed
2. Adsorption	Captures contaminants onto high-surface-area adsorbents or via reactive sequestration	Graphene- and carbon-based nano-adsorbents, mesoporous oxides, magnetic nanoparticles, nZVI	Heavy metals, dyes, organics, nutrients	Very fast and selective uptake; requires regeneration and safe handling of material
3. Catalytic and advanced oxidation/ reduction	Transforms or destroys pollutants through catalytic oxidation or reduction	Heterogeneous photocatalysis (TiO_2 and doped variants); electrocatalysis; AOPs with nanocatalysts, nanobubble-enhanced oxidation	Persistent organics, micropollutants, some pathogens	Can mineralise contaminants; performance depends on energy and catalyst stability
4. Antimicrobial, disinfection and anti-biofouling	Inactivates microbes and prevents biofilm formation on treatment surfaces	Ag/Cu NP coatings, photocidal TiO_2 coatings, antifouling surface grafting, nanobubble-assisted disinfection	Bacteria, viruses, biofilms	Effective at low doses; environmental/toxicity release risks must be evaluated

By synthesising these reviews from a broad range of studies, it advances understanding of the mechanisms, performance parameters, and design principles that govern these treatment techniques. The review demonstrates (Table 3) although membrane-based treatments are independently flawed, membrane-based technologies, particularly nanocomposite and hybrid membranes, have improved permeability, selectivity, and resistance to fouling, thereby enhancing water treatment efficiency.

Also emphasised is the continued relevance of adsorption as an adaptable approach for the removal of heavy metals, dyes, and organic pollutants, particularly through the use of advanced nanomaterials such as GO and MOFs. Catalytic and AOPs are, furthermore, identified as vital for degrading persistent contaminants, with nanocatalysts contributing to improved reaction kinetics, stability, and recyclability. Last, multifunctional nanomaterial integration offers synergistic effects by combining adsorption, catalysis, and separation processes within a single treatment platform, resulting in superior purification performance and environmental sustainability. Collectively, this comprehensive review not only consolidates current advancements but also identifies critical research gaps related to scalability, regeneration efficiency, and environmental safety, thereby providing a foundation for the development of next-generation, high-performance water treatment systems.

4. Conclusion

In conclusion, this systematic evaluation highlights the significant potential of integrating membrane separation, adsorption, catalysis, and multifunctional nanomaterials to advance water and wastewater treatment. The combined strategies deliver measurable gains in contaminant removal, selectivity, and operational flexibility, yet practical deployment remains constrained by challenges in scale-up, durability, regeneration, and environmental risk. For rural and resource-constrained contexts, adsorption-based systems and low-pressure membrane filtration are the most applicable due to their relatively low energy requirements, ease of operation, and adaptability to decentralised settings. Catalytic and advanced oxidation processes are more suitable in situations where microbial contamination or persistent organic pollutants are dominant, but they require controlled operating conditions and technical capacity, limiting their standalone use in rural environments. To bridge the gap between bench and field, future studies should emphasise pilot-scale validation, harmonised testing protocols, comprehensive life-cycle and ecotoxicological assessments, and robust techno-economic evaluations that reflect complex real feeds and regulatory demands. Progress will depend on close interdisciplinary collaboration among materials scientists, engineers, toxicologists, and policymakers to optimise multifunctional systems, while mitigating environmental and societal risks.

Recommendations

The following recommendations emerged from this study:

- Future studies should focus on developing and improving hybrid nanotechnology-based treatment systems, especially those that combine adsorption, membrane separation, and catalytic processes. While these approaches show potential for improving contaminant removal, more practical studies are needed to evaluate how well they perform and whether they can be applied on a larger scale.
- There is a need for pilot-scale and field-based studies, particularly in rural communities, to better understand how these nanotechnology-based treatment systems perform over time. This includes assessing their durability, maintenance requirements, and overall effectiveness under real-world conditions.
- Further research should also explore the development of cost-effective and locally suitable nanomaterials. Using locally available resources and environmentally friendly green synthesis methods could help improve affordability and accessibility, especially in resource-limited settings.
- In addition, future studies should consider developing context-specific nanotechnology solutions that address the varying quality of alternative water sources such as harvested rainwater, boreholes, and surface water. This would help ensure the effective removal of contaminants such as pathogens, heavy metals, and organic pollutants.
- More attention should be given to conducting detailed health and environmental risk assessments to determine the long-term safety of nanomaterials. This is particularly important in relation to toxicity, bioaccumulation, and their potential impact on the environment.
- Policymakers also have an important role to play in establishing clear regulations and water quality standards to guide the safe and responsible use of nanotechnology in water treatment.
- Lastly, awareness and capacity-building initiatives should be strengthened in rural communities. Improving knowledge about water quality management, safe storage practices, and the use of nanotechnology-based treatment methods can support better adoption and long-term sustainability.

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