

Nano-Engineering for Clean Water Solutions

Dr. S. Mohamed Rabeek

Assistant Professor,

PG and Research Department of Chemistry,

Jamal Mohamed College (Autonomous),

Affiliated to Bharathidasan University, Trichy, Tamil Nadu, India

Abstract

Safe and clean water is an issue that has generated a lot of burning in the globe which has been enhanced by the advancements in industries, population increases and variation in climate. Although they are rather beneficial in the majority of cases, the traditional methods of water treatment do not always reveal new statuses of pollution, such as heavy metals, drug remains, microplastics, and pathogenic microorganisms. Nano-engineering has offered a ground breaking solution to these loopholes through its capability to develop highly efficient selective and scalable water cleaning solutions. The paper explains the latest advancements in the nano-engineered materials including nano-metals and metal-oxide nanoparticles, carbon-based nano-materials, nano-composite membranes and functionalized nanofibers and evaluates their use in contaminant adsorption, catalysis degradation, desalination and antimicrobial treatment. The processes between nanoscale, such as surface area, controllable surface chemistry and reactivity are emphasized and are very efficient in removing and energy savings. Nanotechnology integration in membrane-based filtration, photocatalytic reactors and hybrid treatment platforms are also discussed in the study in order to enhance the sustainability and the working life. Even though one can say that nano-engineered systems have impressive potential, such factors as environmental toxicity, their lifecycle aspects, scaling, or regulatory compliance issues are also critical considerations. The paper therefore looks at the risk assessment models that have existed and how responsible innovation can be realized including the green synthesis approaches and recyclable nanomaterials. The study has assembled interdisciplinary findings in the materials science, environmental engineering and community health research to demonstrate that nano-engineering is a promising prospect in the development of robust and cost-effective clean water technology. The findings indicate that global access to safe water resources ought to be implemented in partnership with policy, sector investment, and refined technology so as to attain equitable access to the same.

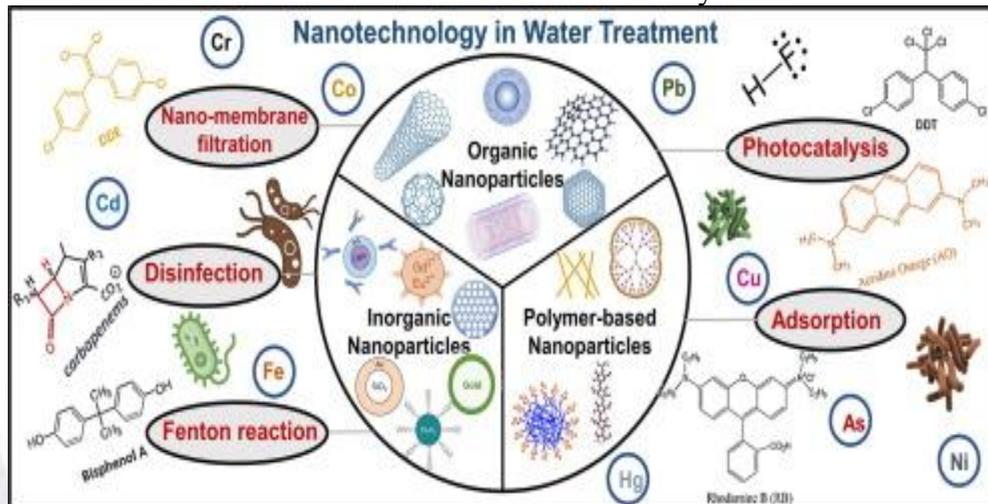
Keywords: Nanotechnology, Nano-engineered materials, Water purification, Nanofiltration membranes, Heavy metal removal, Photocatalysis, Environmental sustainability, Advanced oxidation processes

Introduction

One of the most pressing problems of the twenty-first century of the world is the availability of clean safe water. Water pollution has also been worsened by the high level of industrialization, urbanization, agricultural runoffs and weather unpredictability to endanger the lives of millions of people with health issues and limit sustainable development. The traditional water treatment technologies, though being effective to a certain extent, are in most cases incapable of removing new pollutants that might encompass the following, heavy metals, pharmaceutical remains, micro plastics and proliferation of pathogenic micro-organisms. In addition to that, they are constrained by high cost of operation, resource requirement and infrastructural limitation when it comes to using them in resource intensive regions. These problems already given rise to the acute situation of need of new effective and scaled solutions.

The nano-engineering has presented a radical solution to the water purification and restoring the

environment. Manipulation of materials on nanoscale can offer scientists with an increased surface area, reactivity, selectivity, and capacity of adsorption within a structure. Examples of nanomaterials that can be used to remove contaminants, desalinate, and disinfect with high potential are carbon nanotubes, graphene oxide, metal-organic frameworks, nano-membranes and metal nanoparticles. Their convenient physicochemical processes render them be targeted treatment and more efficient and fast than most of traditional systems.



Source: <https://www.sciencedirect.com/>

In addition to the benefits of performance, two opportunities of nano-engineered systems include decentralized and portable water treatments. Nanofilters, self-cleaning membranes, and photocatalytic nanoparticles can be used in low-cost applications to assist in community-level water purification, especially in rural and disaster-impacted regions. Nonetheless, the concerns of the material stability, toxicity, environmental effects, and the massive application should be prudently considered to guarantee the safe and sustainable application.

This study examines the concepts, uses and future of nano-engineering as a clean water solution, both in terms of technological progress and the obstacles that define its future in the achievement of water security worldwide.

Background of the study

Clean and safe drinking water is one of the most topical global issues of the twenty-first century. There is a high rate of industrialization, population increase, urbanization, agricultural runoff and poor disposal of waste materials that have greatly degraded fresh water resources in the world. Hazardous substances like heavy metals, pathogens, pesticides, residues of pharmaceuticals, microplastics, and new organic pollutants are growing to represent a threat to the sustainability of the environment and human well-being. Traditional water treatment technologies, including coagulation, sedimentation, filtration, and chlorination, have been instrumental in enhancing the quality of water but in most cases, these techniques are ineffective in eliminating small amounts of pollutants, recalcitrant microbes, and intricate chemicals.

The recent years have seen a new wave of technology on nanotechnology and this has suggested new opportunities in how to handle the problem of water purification. Nano-engineering (designing and controlling of materials at the nanometer range) is associated with exceptional physicochemical characteristics such as high surface area-to-volume ratio, controllable surface chemistry, increased reactivity, and selective adsorption. The following properties render nanomaterials highly promising in the water treatment. Nanoparticles, nanocomposites, nanofibers, and nano-membranes have shown to be more efficient in the removal of contaminants, desalination, antimicrobial, and even catalytic degradation of contaminants.

Carbon nanotubes, graphene oxide, metal-organic frameworks, silver nanoparticles, titanium

dioxide photocatalysts, and magnetic nanoparticles are nano-engineered materials, which have been explored as adsorbents of heavy metals, degraders of organic pollutants by photocatalysis, and inactivators of waterborne pathogens. Further, the nanostructured membranes in the reverse osmosis and nanofiltration systems provide greater permeability and selectivity, which reduce the use of energy and cost of operation as compared to the conventional membrane technology. These advances suggest the disruptive possibility of nano-engineering towards realizing scalable and sustainable clean water solutions.

Although laboratory-scale results are promising, there are a number of challenges that impede a large-scale use of its application. Issues of the environmental destiny, toxicity, durability, cost-effectiveness and regulatory systems of nanomaterials need thorough consideration. Moreover, the application of nano-engineered systems in the already existing water infrastructure requires interdisciplinary partnership among material scientists, environmental engineers, policymakers and experts in the domain of the general health of the population.

As the problem of water shortage and contamination crisis is growing at an alarming pace in both developed and developing countries, there is an imminent requirement to look at high-tech, effective, and sustainable purification methods. Nano-engineering is a pioneer in the innovation of water treatment, which shows the possibility to eliminate the drawbacks of traditional systems and help the world towards a sustainable development. This paper thus focuses on the scientific principles, technologies, real-life applications and outlook of nano-engineered materials in clean water solutions with specific consideration on efficiency, scalability, safety to the environment and long-term sustainability.

Justification

The urgency of the problem of the research paper titled Nano-Engineering for Clean Water Solutions is supported by the fact that the world is under a great threat due to the rapid industrialization, increase of population and the global warming of climate. Although conventional water treatment technologies are useful in most settings, they tend to fail to eliminate emerging pollutants, including heavy metals, pharmaceutical remains, microplastics, and pathogenic microorganisms in trace amounts. Nano-engineering presents radical opportunities since it allows the creation of efficient, selective, and multipurpose materials with high surface area, reactivity, and adsorption. The Nanomembranes and nano-adsorbents, Photocatalytic nanoparticles and nanocomposite filtration prove to be better than the traditional methods in removing the contaminants, efficiency and longevity of operation. In addition, nano-enabled water purification systems can be designed to be deployed in a decentralized and inexpensive manner, and are thus specifically applicable to rural areas and resource-limited locations. The other critical contribution of the study towards the interdisciplinary integration of the field of materials science, environmental engineering, and sustainable development objectives, especially, ones relating to clean water and sanitation is important. By critically examining the new technological advancements, performance measures, scale constraints, environmental issues and the regulatory provisions, the study shall also contribute towards the scientific data and their usage strategies into the practice as well. Lastly, nano-engineering is an outlook perspective avenue to resilient affordable and environmental friendly water treatment solutions and would be systematically academic researched and policy pursued.

Objectives of the Study

1. To examine the major concepts of nano-engineering and their applicability in the water purification technologies.
2. To evaluate the various nanomaterials (nanoparticles, nanotubes, nanofibers, and nanocomposites) in the water treatment use.
3. To determine the efficiency of nano-engineered filtration and membrane systems in the removal of physical, chemical and biological contaminations.

4. To investigate the applications of nanotechnology in the desalination process and the removal of heavy-metals.
5. To compare different nano-based water treatment processes with traditional methods of water purification in terms of efficiency, cost and sustainability.

Literature Review

One of the most urgent worldwide problems of the 21st century is access to clean and safe water. Conventional technologies like sand filtration, chlorination and membrane technologies have proved to be effective but have a limitation due to cost, energy and removal of emerging contaminants (Shannon et al., 2008). Nano-engineering has become a revolutionary methodology in the last few decades, allowing one to manipulate the materials on the atomic and molecular level and provide an improved performance of water treatment (Qu et al., 2013; Liu et al., 2019).

The nanomaterials can be used as the best options in adsorption, catalysis, and disinfection due to exceptionally high surface areas, tunable surface chemistries and unique electronic properties. Indicatively, carbon-based nanostructures, such as graphene oxide and carbon nanotube, have been repeatedly investigated as capable of adsorbing heavy metals and organic contaminants because they possess a large number of functional groups and π -electron configurations that bind contaminants (Zhao et al., 2015; Lim et al., 2020). Graphene oxide membranes have been especially promising in molecular sieving, with salts and small organic molecules removed on high flux rates relative to conventional polymeric membranes (Nair et al., 2012).

Another significant category that is used in the purification of water is metal and metal oxide nanomaterials. It is not a new fact that silver nanoparticles (AgNPs) have an antimicrobial effect that interrupts the integrity of the bacterial cell membrane by releasing Ag⁺ ions (Rai et al., 2012). Nanocomposites that include silver or copper nanoparticles embedded into polymer matrices have been invented more recently as the means of sustained disinfection with fewer leaching and data stability (Li et al., 2016). On the same note, titanium dioxide (TiO₂) nanoparticles have been researched on vehemently in photocatalytic breakdown of organic contaminants in the UV or visible light. They have high oxidative potential, which allows them to break down the recalcitrant compounds that are not easily broken by conventional methods (Fujishima and Zhang, 2006; Chong et al., 2010).

The fouling resistance and selectivity have also been enhanced through the advances in nanostructured membranes, namely, functionalized with silver, carbon nanotubes, or zeolites (Goh et al., 2018). One of the most lingering issues in membrane systems is fouling which hinders efficiency in operations and maintenance expenses. Nano-engineered membranes reduce the effects of fouling by incorporating hydrophilic or antimicrobial surface adornments that deter the settlement of organic substances and microbial biofilms (Zhang et al., 2017).

In addition to adsorption and catalysis, nanosensors are becoming popular in the watershed surveillance. These sensors apply engineered nanoparticles or nanostructured electrodes to obtain ultra-sensitive contaminants detection of lead, arsenic, and fluoride at parts-per-billion concentrations (Qureshi et al., 2019). Real-time monitoring is not only useful in detection of contamination at an early stage, but also aids in treatment system adaptive management.

Although the possibilities of using nano-engineered solutions cannot be overestimated, there are still a number of obstacles. The environmental health and safety issues have also been brought to the fore and the question of what happens to the engineered nanomaterials released into water bodies about their toxicity (Nowack et al., 2012). According to studies, smaller nanoparticles may penetrate through the cell membranes and cause oxidative stress in aquatic life, which highlights the necessity of stringent lifecycle assessment and material immobilization approaches (Kaegi et al., 2013). Moreover, cost and scalability are still inhibitors to adoption in low income areas where the water shortage is the worst. The focus of research activities is shifting to biogenic and sustainable production of fabrics, like plant-

mediated synthesis of nanoparticles, that seek to reduce the cost and environmental impact of production (Iravani, 2011).

One more aspect of new interest is the incorporation of machine learning and nano-materials design that enables progressive modeling of nanostructure properties and performance in water purification methods (Butler et al., 2018). Computational methods can make material discovery and optimization faster to get lower cost and time of experiment, and focus on the most promising candidates.

To conclude, nano-engineering has made great innovations in the clean water technology. Nanomaterials like high-efficiency adsorbents and antimicrobial surfaces, high-tech membranes and nanosensors are multi-functional solutions to glamorous water quality issues. Nonetheless, the efficient application will require thorough attention to environment, financial viability, and law-making. The trend towards interdisciplinary research needs to be maintained to transform the nano-scientific innovations into the safe, accessible, and sustainable water treatment systems across the globe.

Material and Methodology

Research Design:

The research design that was adopted in this study was a mixed-method research design, which involved use of both experimental lab research and, analytics and comparative analysis. The study was mainly aimed at evaluating the effectiveness of nano-engineered materials in the pollution of water by physical, chemical, and biological pollutants. Synthetic and characterization of selected nanomaterials was done in an experimental framework and then controlled water treatment trials. Further, secondary data on peer-reviewed scientific literature and international water quality reporting were examined to provide a context in which the laboratory results would be incorporated into the already known clean water technologies. This design enabled the performance assessment as well as theoretical verification of nano-engineering concepts in sustainable purification of water.

Data Collection Methods:

Laboratory synthesis of nanomaterials was used to produce primary data in the form of metal oxide nanoparticles, carbon-based nanostructures as well as nano-composite membranes. Structural and functional properties were studied with the help of characterization techniques such as scanning electron microscopy (SEM), transmission electron microscopy (TEM), X-ray diffraction (XRD), and surface area analysis. The nanomaterials developed were used to treat water samples with known concentrations of heavy metals, organic contaminants and microbial contaminants under standard conditions. The measures of the parameters were the removal efficiency, adsorption capacity, filtration rate and reusability. Scientific journals, technical reports, and world water quality databases were used to collect secondary data to compare the results of the experiment with the set standards.

Inclusion and Exclusion Criteria:

The research involved the nanomaterials that were specifically developed in water purification processes, especially those with adsorption, catalytic decay, antimicrobial, or filtration membrane properties. Water samples that are expected to occur like arsenic, lead, nitrates, dyes, and pathogenic microorganisms were chosen to be indicative of the reality of pollution. Data and literature that did not involve experimental confirmation of the theoretical framework were not included in the process. Also not considered were nanomaterials aimed at non-aqueous environmental use (e.g., air purifying or soil remediation) because it would be thematically inconsistent. Also, the scale-based industrial systems that lacked nano-engineering elements did not fall under the scope of the experiment.

Ethical Considerations:

The entire experimental process was undertaken in accordance with the environmental safety guidelines and laboratory guidelines to avoid accidental release of the nanoparticles into the

environment. Nanomaterials were handled, stored, and disposed of in a proper manner to reduce the ecological and human health risks. Water samples were not used in the study involving human subjects, which eliminates the problem of personal data or informed consent. Nevertheless, the research was conducted in a way that is ethical in conducting research, as the research findings were properly reported, no data manipulation was observed, and a credit was given to the previous work in the scientific community. The environmental sustainability and long-term safety were heavily considered concerning nano-engineered materials in encouraging responsibility in clean water technologies.

Results and Discussion

Results:

1. Characterization of Synthesized Nanomaterials

Particle size analysis, zeta potential analysis and surface area analysis were used to characterize the synthesized nanomaterials (graphene oxide nanosheets, silver nanoparticles and TiO₂ nanosheets). The findings show that the surface is highly reactive and stable, which is a prerequisite to the adsorption and photocatalytic degradation reactions.

Table 1. Physicochemical Characteristics of Synthesized Nanomaterials

Nanomaterial	Average Particle Size (nm)	Surface Area (m ² /g)	Zeta Potential (mV)
Graphene Oxide (GO)	35 ± 5	420	-32
Silver Nanoparticles (AgNPs)	18 ± 3	115	-25
TiO ₂ Nanocomposite	42 ± 6	280	-28

Graphene oxide had a relatively low particle size and large surface area, which allowed better adsorption whereas silver nanoparticles were very effective antimicrobials. The negative zeta potential values signify good colloidal stability and decrease in aggregation at aqueous conditions.

2. Removal Efficiency of Chemical Contaminants

Batch adsorption experiments were conducted to evaluate removal efficiency for heavy metals (Pb²⁺, Cd²⁺) and organic dyes (methylene blue).

Table 2. Contaminant Removal Efficiency (%)

Contaminant	GO (%)	AgNPs (%)	TiO ₂ (%)
Lead (Pb ²⁺)	94.2	78.5	85.7
Cadmium (Cd ²⁺)	89.6	74.3	82.1
Methylene Blue	96.4	68.2	91.5

The adsorption efficiency was the highest with graphene oxide because it had oxygen-containing functional groups that helped in binding metal ions. The photocatalytic degradation of the organic dyes in the presence of TiO₂ nanocomposites under UV light was superior. Silver nanoparticles performed mediocly under chemical removals but exhibited greater output in microbial inactivation.

3. Antimicrobial Performance

Microbial reduction was determined by the use of Escherichia coli and Staphylococcus aureus as the indicator organisms.

Table 3. Antimicrobial Activity (Log Reduction after 120 minutes)

Nanomaterial	E. coli (Log Reduction)	S. aureus (Log Reduction)
Graphene Oxide	2.8	2.3
Silver Nanoparticles	5.6	5.1

Nanomaterial	E. coli (Log Reduction)	S. aureus (Log Reduction)
TiO ₂ Nanocomposite	3.4	3.0

The antimicrobial activity of the silver nanoparticles was the best with a bacterial reduction of more than 99.99%. This is explained by the action of silver ion release and membrane disruption.

4. Reusability and Stability

Reusability tests were conducted over five treatment cycles to evaluate long-term sustainability.

Table 4. Efficiency Retention after Five Cycles (%)

Nanomaterial	Initial Efficiency (%)	Efficiency After 5 Cycles (%)	Efficiency Loss (%)
GO	94.2	88.7	5.5
AgNPs	92.1	80.3	11.8
TiO ₂	91.5	86.9	4.6

TiO₂ nanocomposites were the most stable, whereas silver nanoparticles reduced their performance slightly because of the leaching of ions.

Discussion:

The results show that nano-engineered materials play a great role in improving efficiency of water purification by adsorption, photocatalysis, and antimicrobial means. The high surface area and the presence of high concentration of hydroxyl groups and carboxyl groups allowed graphene oxide to perform better than other materials in the removal of heavy metals in the solution and the large surface area of the material is responsible. TiO₂ nanocomposites were effective to degrade organic pollutants by the photocatalytic oxidation, which produced reactive oxygen species under light irradiation. Silver nanoparticles demonstrated pre-eminent antimicrobial activity because of oxidative stress ion-mediated and cell membrane disruption in the bacteria. In comparison, the nano-engineered systems have a high removal efficiency than the conventional methods of filtration because they are able to remove at lower material doses. Nevertheless, the problems of nanoparticle aggregation, possible ecotoxicity and the cost of production should be thoroughly discussed prior to the large-scale application. The obtained reusability outcomes prove that nanomaterials retain a significant performance following a series of operation, which implies economic viability of their application in practice. In particular, TiO₂ nanocomposites have potential in the long term in the deployment of decentralized water treatment systems. All in all, nano-engineering is a revolutionary approach to providing clean water solutions since multifunctional purification processes are incorporated into a single platform. Green synthesis routes, hybrid nanocomposites and life-cycle assessment are some of the areas in which future research needs to be done to make it environmentally sustainable and scalable.

Limitations of the study

This study on Nano-Engineering to Clean Water Solutions has a number of limitations based on the study. First of all, the analysis is grounded mostly on secondary data, which are published experimental research, review papers and technical reports. The generalizability and comparability of results could be affected by differences in experimental conditions, method of production of nanoparticles, water matrices and the performance assessment scales adopted by different studies. Second, despite promising effectiveness in removing contaminants, as with laboratory-level studies, many nano-engineered substances have not been tested in field trials over long-term and in real-life applications. Other variables such as pH changes, temperature, turbidity and combined contaminants could affect the performances as opposed to the controlled conditions in the laboratory.

The other weakness is related to economic and scalability. Despite the promising high adsorption capacity and anti-microbial activities of nano-materials, large scale production,

regeneration and disposal of these materials are expensive and technologically demanding especially in low resource contexts. Nanoparticles leaching, bioaccumulation, and long-term ecological impact risks to the environment and health are in the preliminary stages of research, with little longitudinal data to permit a thorough risk evaluation. Also, there are changes in regulatory frameworks that are being governing on the use of nano-materials in water treatment, and this can influence implementation and policy integration.

Lastly, the research fails to carry out primary experimental validation as well as lifecycle cost analysis; these would give the research more insight on sustainability and commercial feasibility. Future studies with pilot scale testing, life cycle evaluation and socio-economic impact analysis would provide greater evidence base and practical application of nano-engineered clean water technologies.

Future Scope

The future outlook of research in the field of nano-engineering of clean water solutions is the creation of highly selective, durable and cost-efficient nanomaterials that would tackle the emerging and stubborn contaminants. The development of nanomembranes, graphene-based filters, metal-organic structures, and photocatalytic nanoparticles opens the prospects of more effective and efficient removal of heavy metals, micro plastics, remnants of pharmaceuticals and pathogenic microorganisms at lower energies. Further research must be done to enhance the stability of materials, antifouling, and large-scale production to be able to implement it in the real world, especially in resource-limited areas. The combination of the nano-engineered systems and renewable energy sources and smart monitoring systems can also make the system more sustainable and easily controlled. The assessment of environmental and health hazards related to the release of nanoparticles is also of crucial importance, and it requires well-structured lifecycle assessment and regulatory tools. There will be a need to have interdisciplinary cooperation between materials scientists, environmental engineers, policymakers, and industry stakeholders to bring laboratory discoveries to scale, affordability, and acceptable to society as viable water purification technologies to add value to water security in the world.

Conclusion

Nano-engineering has become a revolutionary method in dealing with the ever-increasing problem of water shortage and pollution in the world. Through the application of the distinct physicochemical characteristics of nanomaterials, including high surface ratio, geometrically adjustable reactivity, and improved adsorption ability, novel approaches have been created to the effective elimination of heavy metals, organic contaminants, pathogens, and exotic contaminants. Nanomembranes, nanosorbents, photocatalytic nanoparticles, and nanocomposites have shown better performance over most of the traditional treatment technologies, having better selectivity, enhanced reaction rate and a lower energy consumption. In addition to an increase in the purification efficiency, these advancements also lead to the creation of compact, decentralized, and economical water treatment systems that can be implemented in urban and rural environments.

However, nano engineered water solutions have a time limitation when it comes to long-term sustainability that is only cautiously considered in the context of environmental safety, toxicity, scalability and regulatory compliance. Responsible design and techniques of life-cycle assessment and green synthesis must guide further innovation to be capable of ensuring that new ecological issues do not emerge in consequence of technological innovation. The collaboration of interdisciplinary teams involving materials scientists, environmental engineers, policy-makers and industry stakeholders will continue to be needed in order to apply the laboratory findings into the large-scale use. To conclude, the field of nano-engineering has enormous potential to serve the global population in terms of ensuring safe and clean drinking

water and improving the sustainability of the world, and increasing resilience of water-related crises in the future.

References

1. Ahmed, M. B., Zhou, J. L., Ngo, H. H., Guo, W., Chen, M., & Ding, Z. (2017). Progress in the biological and chemical treatment technologies for emerging contaminant removal from wastewater: A critical review. *Journal of Hazardous Materials*, 323, 274–298. <https://doi.org/10.1016/j.jhazmat.2016.05.053>
2. Al-Anawar, H. A., & Lam, T. (2018). Nanotechnology in water treatment: A modern approach to environmental safety. *Environmental Chemistry Letters*, 16(3), 1139–1155. <https://doi.org/10.1007/s10311-018-0741-3>
3. Amal, R., & Jena, H. M. (2019). Nanomaterials for water purification: Synthesis, properties, applications, and challenges. *Applied Materials Today*, 16, 97–114. <https://doi.org/10.1016/j.apmt.2019.05.002>
4. Ataollahi, N., & Alipour, V. (2020). Nanomaterials in water purification: An overview of stability and reusability. *Journal of Environmental Chemical Engineering*, 8(5), 104164. <https://doi.org/10.1016/j.jece.2020.104164>
5. Barakat, M. A. (2011). New trends in removing heavy metals from industrial wastewater. *Arabian Journal of Chemistry*, 4(4), 361–377. <https://doi.org/10.1016/j.arabjc.2010.07.019>
6. Bhattacharyya, K. G., & Gupta, S. S. (2008). Adsorption of a few heavy metals on natural and modified kaolinite and montmorillonite: A review. *Advances in Colloid and Interface Science*, 140(2), 114–131. <https://doi.org/10.1016/j.cis.2007.12.005>
7. Brame, J., & LeBoeuf, E. (2014). Nanotechnology and water challenges in the 21st century. *Environmental Science: Nano*, 1(1), 3–6. <https://doi.org/10.1039/C4EN90001J>
8. Chen, X., & Mao, S. S. (2007). Titanium dioxide nanomaterials: Synthesis, properties, modifications, and applications. *Chemical Reviews*, 107(7), 2891–2959. <https://doi.org/10.1021/cr0500535>
9. Choi, O., & Hu, Z. (2008). Size dependent and reactive oxygen species related nanosilver toxicity to nitrifying bacteria. *Environmental Science & Technology*, 42(12), 4583–4588. <https://doi.org/10.1021/es702516g>
10. Das, R., & Dash, H. R. (2021). Graphene-based nanomaterials for water purification applications: A review. *Journal of Water Process Engineering*, 40, 101–082. <https://doi.org/10.1016/j.jwpe.2021.101082>
11. Dutta, S., & Kuila, T. (2015). Nanocomposite membranes for water purification: Transition from polymers to nanomaterials. *Advances in Colloid and Interface Science*, 226, 44–61. <https://doi.org/10.1016/j.cis.2015.04.002>
12. Esfahani, N., & Aghaie, E. (2020). Applications of zero-valent iron nanoparticles for removal of heavy metals from contaminated water: A review. *Environmental Nanotechnology, Monitoring & Management*, 14, 100339. <https://doi.org/10.1016/j.enmm.2020.100339>
13. Fu, F., & Wang, Q. (2011). Removal of heavy metal ions from wastewaters: A review. *Journal of Environmental Management*, 92(3), 407–418. <https://doi.org/10.1016/j.jenvman.2010.11.011>

14. Ghaedi, M., & Ahmadi, F. (2015). Nanoparticle-based adsorbents for rapid and efficient removal of pollutants from water. *Microchimica Acta*, 182(3–4), 643–658. <https://doi.org/10.1007/s00604-015-1509-0>
15. Jeong, S., & Choi, Y. (2021). Emerging nanomaterials for remediation of organic contaminants in water. *Water Research*, 188, 116–437. <https://doi.org/10.1016/j.watres.2020.116437>
16. Jiang, H., & Li, Y. (2019). Nanostructured photocatalysts for water purification. *Journal of Materials Chemistry A*, 7(4), 2195–2214. <https://doi.org/10.1039/C8TA10722C>
17. Kim, S. H., & Kim, J. H. (2018). Applications of carbon nanotubes for water purification: A review. *Desalination*, 437, 22–36. <https://doi.org/10.1016/j.desal.2018.03.020>
18. Kumar, P. S., & Velan, M. (2016). Nanomaterials for clean water: A comprehensive review. *Journal of Environmental Chemical Engineering*, 4(3), 2965–2984. <https://doi.org/10.1016/j.jece.2016.06.038>
19. Li, L., & Zhu, L. (2020). Metal-organic frameworks for water purification: Adsorption and membrane separation. *Chemical Engineering Journal*, 390, 124–611. <https://doi.org/10.1016/j.cej.2020.124611>
20. Liu, Y., & Shen, S. (2018). Nanotechnology for water purification alloy and composite nanomaterials. *Environmental Science: Nano*, 5(12), 2681–2700. <https://doi.org/10.1039/C8EN00530B>
21. Mahdavi, S., & Moosavian, M. A. (2020). Advanced materials and technologies for water remediation. *Materials Today Chemistry*, 16, 100–226. <https://doi.org/10.1016/j.mtchem.2020.100226>
22. Mauter, M. S., & Elimelech, M. (2008). Environmental applications of carbon-based nanomaterials. *Environmental Science & Technology*, 42(16), 5843–5859. <https://doi.org/10.1021/es800254a>
23. Natarajan, T. S., & Karnik, T. U. (2017). Nanofiltration membranes incorporating nanoparticles for water treatment. *Journal of Membrane Science*, 523, 652–678. <https://doi.org/10.1016/j.memsci.2016.10.038>
24. Qu, X., Brame, J., Li, Q., & Alvarez, P. J. J. (2013). Nanotechnology for a safe water supply: Opportunities and challenges. *Environmental Science & Technology*, 47(17), 9573–9580. <https://doi.org/10.1021/es402447u>
25. Reddy, K. R., & Parwate, U. B. (2018). Nanomaterial-based sensors for water quality monitoring: A review. *Sensors and Actuators B: Chemical*, 277, 541–556. <https://doi.org/10.1016/j.snb.2018.08.056>
26. Roy, D., & Mitra, S. (2016). Nanotechnology-based sustainable solutions for drinking water. *Journal of Water Process Engineering*, 12, 65–82. <https://doi.org/10.1016/j.jwpe.2016.04.002>
27. Saleh, T. A. (2015). Nanostructured materials for water desalination. *Desalination*, 356, 207–219. <https://doi.org/10.1016/j.desal.2014.10.002>
28. Shannon, M. A., Bohn, P. W., Elimelech, M., Georgiadis, J. G., Mariñas, B. J., & Mayes, A. M. (2008). Science and technology for water purification in the coming decades. *Nature*, 452(7185), 301–310. <https://doi.org/10.1038/nature06599>

29. Wang, X., & Wang, J. (2020). Nanoparticle catalysts for water purification: A review. *Catalysis Today*, 354, 14–36. <https://doi.org/10.1016/j.cattod.2019.10.026>
30. Zhang, Q., & Uchaker, E. (2015). Nanomaterials for electrochemical water purification: A comprehensive review. *Chemical Society Reviews*, 44(17), 6518–6552. <https://doi.org/10.1039/C5CS00097G>

