STM JOURNALS

Journal of
Water Pollution &
Purification Research

ISSN: 2394-7306
Volume 12, Issue 2, 2025
May–August
DOI (Journal): 10.37591/JoWPPR

https://journals.stmjournals.com/jowppr

Review JoWPPR

Advances in Water Purification: A Comprehensive Review of Techniques and Technologies

Neeraj Virdi[1], Mukesh Sharma[2,*]

Abstract

Access to safe and clean drinking water is crucial for both environmental sustainability and human health, and water purification is a key component of this. Developments in water purification technologies have emerged as a key area of scientific and technical research due to the growing global water shortage and contamination. From conventional approaches to state-of-the-art technologies, this review article offers a thorough examination of the most current advancements in water purification processes. It encompasses advanced oxidation techniques, membrane technologies, filtration, adsorption, and other physical, chemical, and biological purification methods. Future directions for the field's research and innovation are also covered, along with the difficulties and constraints of the existing approaches. This review attempts to give academics, engineers, and politicians useful insights for enhancing the quality of water around the world by combining the most recent developments and trends.

Keywords: Water purification, advanced oxidation, membrane technology, adsorption, water quality

INTRODUCTION

The demand for pure and safe water on a global scale is increasing at a rapid pace, influenced by factors such as industry, population growth, and climate change [1, 2]. Concurrently, pollution from a variety of sources, such as industrial discharge, agricultural runoff, and untreated drainage, is posing a growing threat to water sources [3, 4]. To guarantee the availability of potable water for human sustenance and a variety of other applications, it is necessary to develop and implement advanced water purification techniques and technologies. This literature review investigates the current state of water purification, including both conventional and innovative methods, with an emphasis on their efficacy, constraints, and potential for future advancement.

Traditional Water Treatment Techniques

The quality of water has been enhanced for a long time through the use of conventional water treatment methods. Although these methods are effective in removing specific contaminants, they frequently fail to address the intricate pollution challenges of the modern world. Coagulation/flocculation, sedimentation, filtration, and disinfection are the typical phases involved in these conventional techniques [1]. Chemicals are used in coagulation and flocculation to group suspended particles together, which facilitates their removal by sedimentation and filtration [5]. Filtration eliminates any leftover particles, and disinfection—usually with UV light or chlorine—gets rid of dangerous microbes [6]. The creation of

***Author for Correspondence**
Mukesh Sharma
E-mail: mukesh.sharma@bamkc.edu.in

[1]Assistant Professor in Chemistry, B.A.M. Khalsa College, Garhshankar, Hoshiarpur, Punjab, India
[2]Assistant Professor & Head of the Chemistry Department, B.A.M. Khalsa College, Garhshankar, Hoshiarpur, Punjab, India

Received Date: February 05, 2025
Accepted Date: February 13, 2025
Published Date: February 25, 2025

Citation: Neeraj Virdi, Mukesh Sharma. Advances in Water Purification: A Comprehensive Review of Techniques and Technologies. Journal of Water Pollution & Purification Research. 2025; 12(2): 26–30p.

sludge, the inability to completely remove some contaminants (such emerging pollutants), and the possibility of disinfection byproduct development are some drawbacks of conventional approaches [7, 8]. The energy intensity of some of these processes is also a significant drawback [9].

Nanotechnology in Water Purification

Nanotechnology has transformed water treatment by providing novel alternatives to overcome the limits of old approaches. Nanomaterials, with their unique physicochemical features, such as high surface area, are especially well-suited for water purification applications [3, 4]. Numerous nanomaterials, such as metal nanoparticles (like silver and zinc oxide), carbon-based nanomaterials (like graphene oxide and carbon nanotubes), and metal oxide nanoparticles (like titanium dioxide) have all been investigated [10, 11]. A variety of water treatment techniques, such as membrane filtration, catalysis, and adsorption, can use these materials [4]. By adsorption, for example, nanosorbents efficiently eliminate heavy metals and other contaminants [12], while nanocatalysts use sophisticated oxidation processes to speed up the breakdown of organic pollutants [13]. Additionally, nanotechnology makes it possible to create sophisticated membrane filtration systems with improved selectivity and efficiency. [14, 15]. Nonetheless, the possible toxicity and environmental effects of nanomaterials continue to be serious issues that require more research [3, 14]. For broader use, it is also necessary to address the scalability and cost-effectiveness of water treatment methods based on nanomaterials [16].

Membrane Filtration Technologies

Membrane filtration is a commonly used technique in water purification, encompassing various processes such as microfiltration, ultrafiltration, nanofiltration, and reverse osmosis [8, 9]. These processes use membranes with different pore sizes to separate contaminants from water. The development of advanced membrane materials, especially nanocomposite membranes, has greatly improved the performance of membrane filtration systems [17, 18]. Nanocomposite membranes include nanoparticles within polymeric matrix to enhance membrane properties like as hydrophilicity, mechanical strength, and antifouling [14]. Membrane fouling, on the other hand, remains a substantial concern that can affect membrane effectiveness and longevity [9, 15]. Research is ongoing to develop antifouling membranes and efficient cleaning strategies to mitigate this issue [19]. Concerns have been raised about the energy consumption of several membrane filtering methods, particularly reverse osmosis [9, 20]. To solve this, novel ways are being investigated, such as using renewable energy sources to power membrane systems and developing energy-efficient membrane designs [20, 21]. 3D printing is emerging as a viable approach for creating customised membranes with specialised features to improve water purification [20].

Advanced Oxidation Processes (AOPs)

Advanced oxidation processes (AOPs) are effective methods for eliminating refractory organic contaminants from water [13, 22]. AOPs produce extremely reactive hydroxyl radicals, which can effectively degrades a variety of organic pollutants [23]. There are various AOPs, including ozonation, UV/H_2O_2, and photocatalysis [24]. Ozonation employs ozone gas to produce hydroxyl radicals, whereas UV/H_2O_2 mixes UV radiation and hydrogen peroxide to achieve the same result [24]. Photocatalysis uses semiconductor photocatalysts, like titanium dioxide (TiO_2), to produce hydroxyl radicals when exposed to UV or visible light [10]. Combining AOPs with other treatment methods, like membrane filtration, can significantly improve the overall efficiency of water purification [7, 22]. However, the cost and energy requirements of AOPs can be significant, limiting their widespread application [13].

Machine Learning and Artificial Intelligence in Water Purification

Machine learning (ML) and artificial intelligence (AI) are rapidly being used to improve water treatment system performance and efficiency [2, 9]. ML algorithms may be trained on historical data to forecast water quality metrics, optimise treatment procedures, and regulate chemical dosing [25]. AI-powered systems can also monitor the health of water treatment equipment, forecast probable problems, and optimise energy consumptions [9]. AI integration into membrane systems can allow real-time monitoring of membrane fouling and optimise cleaning cycles, increasing membrane lifespan and lowering operational costs [26]. However, in order to design and implement effective and reliable AI-based water treatment systems, major advances in data collecting, model building, and validation are required [2].

Emerging Water Purification Technologies

Electrochemical Processes: Because of their capacity to treat complex water matrices and eliminate a variety of contaminants, such as bacteria, heavy metals, and pharmaceutical residues, electrochemical water treatment methods like electrocoagulation, electrooxidation, and electrodialysis are becoming more and more popular.An efficient tactic for raising water quality while lowering energy usage is the combination of electrochemical procedures and conventional techniques.

Electrocoagulation: This method is being investigated more and more for treating wastewater, especially for the elimination of heavy metals, oils, and suspended particulates. The efficiency of electrocoagulation systems is being increased by the use of innovative electrodes, such as graphite and iron-based electrodes [27, 14].

Solar Driven Water Purification

Solar-Powered Water Filtration Technologies for solar-powered desalination and water purification have garnered a lot of interest in areas with plenty of sunshine. Solar-powered distillation systems, solar-powered desalination, and solar stills are some of the innovative technologies being explored to improve the sustainability and energy efficiency of water purification. By incorporating cutting-edge materials and increasing heat transfer rates, recent research has concentrated on enhancing the energy efficiency of solar stills [21, 28].

Sustainable Water Purification Technologies

Because of economic and environmental considerations, water filtration technologies are becoming more and more sustainable. This includes creating devices that use sustainable materials, cut down on waste production, and use less energy [2, 21]. In order to achieve sustainability, water treatment systems must be powered by renewable energy sources, such as solar energy. Another crucial component of sustainable water purification is the use of membrane recycling techniques and the creation of sustainable membrane materials, such as bio-based polymers [27]. The impact of coagulation/flocculation processes on the environment can be lessened by using natural coagulants rather than artificial ones [5]. In order to determine areas for improvement and measure the overall environmental impact of water purification systems, life cycle evaluations, or LCAs, are crucial [29]. More sustainable systems are being developed as a result of water treatment plants using AI and ML algorithms to optimise resource usage and energy consumption.

Challenges and Future Directions

Despite great developments in water filtration technologies, some difficulties persist. These include the effective removal of emerging contaminants, such as pharmaceuticals and personal care products, the development of cost-effective and energy-efficient treatment processes, the mitigation of membrane fouling, and the assessment and management of the environmental impact of nanomaterials [1, 2, 7]. In order to attain the best possible water purification performance, future research should concentrate on creating integrated treatment systems that integrate several technologies. It is also essential to develop more robust and dependable AI-based systems for process optimisation and water quality monitoring. To comprehend the toxicity and long-term environmental fate of nanomaterials employed in water treatment, as well as to create safe disposal plans, more research is required. Lastly, to guarantee that everyone has access to clean and safe water in the future, sustainable water purification technologies that use the least amount of energy and resources must be developed and put into use. [30-36].

CONCLUSION

The development of sophisticated water purifying methods and technology has advanced significantly. While still useful, traditional techniques are being enhanced and improved by cutting-edge procedures that include AI-driven optimisation, sophisticated oxidation techniques, and nanotechnology. The investigation of sustainable materials and renewable energy sources in water treatment is being propelled by the emphasis on sustainability. Addressing new pollutants, maximising energy efficiency, preventing membrane fouling, and guaranteeing the safe application of nanomaterials are still difficult tasks, nevertheless. To address the increasing demand for safe and clean water around the world, future research and development efforts should focus on integrated treatment systems, AI-based optimisation, and the creation of fully sustainable water purification technology.

REFERENCES

1. Shayo GM, Elimbinzi E, Shao GN. Water-based technologies for improving water quality at the point of use: A review. Wiley Interdisciplinary Reviews: Nanomedicine and Nanobiotechnology. 2024 Jan;16(1):e1940.
2. Manikandan M, Venkatesh P, Murugan K, Ramu M, Kannaa KD, Senthilnathan CR. Machine Learning Techniques For Wastewater And Water Purification Enhancing Efficiency And Sustainability. In2024 International Conference on Power, Energy, Control and Transmission Systems (ICPECTS) 2024 Oct 8 (pp. 1–6). IEEE.
3. Lee CH, Tiwari B, Zhang D, Yap YK. Water purification: oil–water separation by nanotechnology and environmental concerns. Environmental Science: Nano. 2017;4(3):514–25.
4. Tripathy J, Mishra A, Pandey M, Thakur RR, Chand S, Rout PR, Shahid MK. Advances in Nanoparticles and Nanocomposites for Water and Wastewater Treatment: A Review. Water. 2024 May 23;16(11):1481.
5. Sujana, O., SyamalaDevi, Dr. K., and Sreevalli, M. NaN. "Application of Natural Coagulants in Waste Water Treatment".
6. Khan SN, Saleem RN, Khan HM, Nasir A. Productivity Comparison Of Conventional And Single Slope Solar Still With Internal Reflectors: An Overview. Earth Sciences Pakistan (ESP). 2021;5(1):16–9.
7. Najafinejad MS, Chianese S, Fenti A, Iovino P, Musmarra D. Application of electrochemical oxidation for water and wastewater treatment: an overview. Molecules. 2023 May 20;28(10):4208.
8. Zouboulis AI, Katsoyiannis IA. Recent advances in water and wastewater treatment with emphasis in membrane treatment operations. Water. 2018 Dec 27;11(1):45.
9. Osman AI, Chen Z, Elgarahy AM, Farghali M, Mohamed IM, Priya AK, Hawash HB, Yap PS. Membrane technology for energy saving: principles, techniques, applications, challenges, and prospects. Advanced Energy and Sustainability Research. 2024 May;5(5):2400011.
10. Sayan B, Indranil S, Aniruddha M, Dhrubajyoti C, Uday CG, Debashis C. Role of nanotechnology in water treatment and purification: potential applications and implications. Int J Chem Sci Technol. 2013;3(3):59.
11. Onuoha D, Ogbo OG. Application of Nano-Technology in Water Purification and Treatment, Towards Improving Water Quality for Effective Water Supply in Nigeria. International Journal of Environment and Pollution Research. 2022;10(2):19–33.
12. Singh R, Dutta S. Current Approaches of Nanotechnology for Potential Drinking Water Purification. Handbook of Research on Emerging Developments and Environmental Impacts of Ecological Chemistry. 2020:307–24.
13. Makhoul E, Boulos M, Cretin M, Lesage G, Miele P, Cornu D, Bechelany M. CaCu3Ti4O12 perovskite materials for advanced oxidation processes for water treatment. Nanomaterials. 2023 Jul 20;13(14):2119.
14. Saud A, Gupta S, Allal A, Preud'Homme H, Shomar B, Zaidi SJ. Progress in the sustainable development of biobased (nano) materials for application in water treatment technologies. ACS omega. 2024 Jun 27;9(27):29088–113.
15. Mbakop S, Nthunya LN, Onyango MS. Recent advances in the synthesis of nanocellulose functionalized–hybrid membranes and application in water quality improvement. Processes. 2021 Mar 31;9(4):611.
16. Prasad A. Conceptual Nanotechnology for Desalination and Water Purification. Knowledgeable Research: A Multidisciplinary Peer-Reviewd Refereed Journal. 2024 May 28;2(10):107–14.

17. Ursino C, Castro-Muñoz R, Drioli E, Gzara L, Albeirutty MH, Figoli A. Progress of nanocomposite membranes for water treatment. Membranes. 2018 Apr 3;8(2):18.
18. Liu F, Wang L, Li D, Liu Q, Deng B. A review: the effect of the microporous support during interfacial polymerization on the morphology and performances of a thin film composite membrane for liquid purification. RSC advances. 2019;9(61):35417–28.
19. Tlili I, Alkanhal TA. Nanotechnology for water purification: electrospun nanofibrous membrane in water and wastewater treatment. Journal of Water Reuse and Desalination. 2019 Sep 1;9(3):232–48.
20. He J, Yue T, McCutcheon JR, Li Y. Recent developments in 3D-printed membranes for water desalination. Journal of Physics: Energy. 2023 Nov 16.
21. Oviroh PO, Ukoba K, Jen TC. Renewable Energy Resources in the Long-Term Sustainability of Water Desalination As a Freshwater Source. InASME International Mechanical Engineering Congress and Exposition 2023 Oct 29 (Vol. 87646, p. V007T08A067). American Society of Mechanical Engineers.
22. Crovella T, Paiano A. Assessing the Sustainability of Photodegradation and Photocatalysis for Wastewater Reuse in an Agricultural Resilience Context. Water. 2023 Jul 30;15(15):2758.
23. Miao H, Teng Z, Wang S, Xu L, Wang C, Chong H. Recent advances in the disinfection of water using nanoscale antimicrobial materials. Advanced Materials Technologies. 2019 May;4(5):1800213.
24. Van Ruijven JP, Van Os EA, Van der Staaij M, Beerling EA. Evaluation of technologies for purification of greenhouse horticultural discharge water. InInternational Symposium on Growing Media and Soilless Cultivation 1034 2013 Jun 17 (pp. 133–140).
25. Mohanraj K, Madhumita S, Harini M, Balaji N, Jayanthi G. Smart Dosing: Harnessing AI for Alum dosage Predictions in Water Treatment. In2023 Intelligent Computing and Control for Engineering and Business Systems (ICCEBS) 2023 Dec 14 (pp. 1–5). IEEE.
26. Parmar VP, Dhruv AJ. Efficient sea water Purification using Hybrid Nanofiltration system and ML for Optimization. In2021 International Conference on Artificial Intelligence and Machine Vision (AIMV) 2021 Sep 24 (pp. 1–6). IEEE.
27. Kausar A. Sustainable membrane technology for water purification—Manufacturing, recycling and environmental impacts. Journal of Polymer Science and Engineering. 2024 Jun 3;7(1):5976.
28. Mao S, Johir MA, Onggowarsito C, Feng A, Nghiem LD, Fu Q. Recent developments of hydrogel based solar water purification technology. Materials Advances. 2022;3(3):1322–40.
29. Gudainiyan, Jitendra, Kumar, Rahul, Singh, Dhiraj, Sing, Durgeshwar Pratap, Shrivastava, Anurag, Srivastava, Arun Pratap, and Khan, Akhilesh Kumar. NaN. "Nanotechnology-enabled Solutions for Water Purification and Environmental Sustainability". E3S Web of Conferences.
30. Dutta S, Sinelshchikova A, Andreo J, Wuttke S. Nanoscience and nanotechnology for water remediation: an earnest hope toward sustainability. Nanoscale Horizons. 2024.
31. Dhak D, Chiavola A, Mishra A, Dhak P. Innovations and challenges in green and sustainable water purification and waste water management. Frontiers in Chemistry. 2023 Jun 23;11:1235757.
32. Saeed, Fatima, Arundhathi, Bhoga, Sridhar, Sundergopal, and Sahu, Nivedita. NaN. "Nanotechnology in water purification and treatment: current outlook and future perspectives".
33. Hilal AA, Saleh R. Nanotechnology Use in Water Purification for Sustainable Development of Middle East. Academic Network for Development Dialogue (ANDD) Paper Series. 2022(1).
34. Nisar MB, Shah SA, Tariq MO, Waseem M. Sustainable wastewater treatment and utilization: A conceptual innovative recycling solution system for water resource recovery. Sustainability. 2020 Dec 11;12(24):10350.
35. Duan, J., et al. (2020). "Electrochemical water treatment: Recent developments and future directions." Environmental Technology.
36. Liu, Y., et al. (2021). "Recent progress in coagulation-flocculation processes for water treatment." Journal of Water Process Engineering.

