STM JOURNALS

Trends in
Mechanical Engineering & Technology

https://journals.stmjournals.com/tmet

ISSN: 2231-1793 (Online)
ISSN: 2347-9965 (Print)
Volume 15, Issue 2, 2025
May–August
DOI (Journal): 10.37591/TMET

Review TMET

Comprehensive Analysis of Advanced Methods, Materials and Technologies for Portable Water Purifier in Domestic and Industrial Applications

Ravikant Nanwatkar[1,*], Sahil Umbarkar[2], Sujal Thakur[2], Shrikant Raut[2]

Abstract

Safe drinking water is still a major problem in developing countries, especially in areas with water scarcity, pollution or poor infrastructure. Portable water purifiers have come to the fore as solutions that are realistic to narrow this gap providing flexibility and accessibility in household and industrial environments as well. In this study, promising techniques, materials and technologies used in portable water treatment equipment design have been reviewed. We review important purification technologies, such as membrane processes (microfiltration, ultrafiltration, and reverse osmosis), UV and LED-based disinfection, activated carbon adsorption, and new nanomaterial-mediated processes such as photo catalysis and nanofiltration. Special focus is laid on advanced polymeric materials such as graphene oxide, carbon nanotubes, zeolites, silver nanoparticles, performance enhancement, antimicrobial action, and sustainability. Beyond the technological advances, the study reviews the latest developments in hybrid systems combining several purification stages for high-quality water and energy effectiveness. The implementation of smart sensors and IoT-based monitoring for real-time monitoring of water quality is also presented. In addition, the design requirement and performance criteria for its application in domestic and industrial sectors are compared introducing the importance of factors such as scalability, low-cost, low energy consumption and compliance to international water safety standards. Case studies and systems' comparisons are included for performance criteria, such as flow rate, contaminant removal efficiency, life cycle, and environmental impact. Of interest are not only the challenges on service and user accessibility, and material decay, but also the potential for sustainable deployment and design catered particularly for off-grid and emergency contexts. The results highlight the urgency of continued innovation and collaborative science in the development of next-generation personal water purification systems that are compatible with global health, environmental and economic priorities. The purpose of this review is to provide reference material for all stakeholders engaged in water purification technologies and their implementation.

Keywords: Safe drinking water, microfiltration, ultrafiltration, reverse osmosis, silver nanoparticles

***Author for Correspondence**
Ravikant Nanwatkar
E-mail: ravikant.nanwatkar@sinhgad.edu

[1]Assistant Professor, Department of Mechanical Engineering, Sinhgad Technical Education Society's NBN Sinhgad Techical Institutes Campus, Ambegaon, Savitribai Phule Pune University, Pune, Maharashtra, India
[2]U.G Students, Department of Mechanical Engineering, Sinhgad Technical Education Society's NBN Sinhgad Techical Institutes Campus, Ambegaon, Savitribai Phule Pune University, Pune, Maharashtra, India

Received Date: June 04, 2025
Accepted Date: June 20, 2025
Published Date: July 02, 2025

Citation: Ravikant Nanwatkar, Sahil Umbarkar, Sujal Thakur, Shrikant Raut. Comprehensive Analysis of Advanced Methods, Materials and Technologies for Portable Water Purifier in Domestic and Industrial Applications. Trends in Mechanical Engineering & Technology. 2025; 15(2): 8–19p.

INTRODUCTION

Importance of Clean Water in Domestic and Industrial Applications

Water is arguably one of the most crucial economical resources needed for domestic and industrial uses as primary needs for the improvement of humans, sustenance of the environment and population growth. Household sanitation is a major concern in almost all hypothetical as well as real cases, particularly for their availability of safe drinking water, their health status, and hygiene [1, 2]. Water is also important for preparation of food and water, washing, and washing utensils as well as cleaning, which affects health status and quality of life of individuals in a community. Water is an essential liquid in industries for such purposes as in manufacturing processes, cooling purposes, electricity production, production of pharmaceuticals, production of processed food and many other industries where high-quality water is required [3, 4]. Polluted water might cause deterioration of equipment, lower quality products to be manufactured thereby reducing durability of products and increased operational costs besides effects on the environment. Also, the water quality standards have to be met in industries to raise the minimum level of pollution when affecting ecosystems [5, 6]. As the international situations of water shortage and water pollution become worse and worse, the application of sophisticated water treatment technologies is inevitable for water purification and the satisfactory provision of water for both human use and industrial purposes. The purity of water also helps in the reduction of wastewater discharge and utilization of additional manpower hence resulting in sustainability, efficient use of resources and more benefits in the longer run (Figure 1).

Overview of Water Purification Needs and Challenges

Water purification is an important way of making water easy to use by both human beings and industries to meet their various demands without posing risks to their health or making their operations unproductive due to impure water (Table 1). The reason why there is a necessity of water purification is attributed to high water pollution from industries, agriculture, and urban centers which release metals, bacteria, chemical, and plastics into the water bodies [7–9]. In domestic uses, water is needed for drinking, preparation of meals and other purposes that require clean water, including washing utensils, clothes and body among other uses and since contaminated water can cause diseases ranging from simple gastrointestinal illness, organ damage to long-term illnesses.

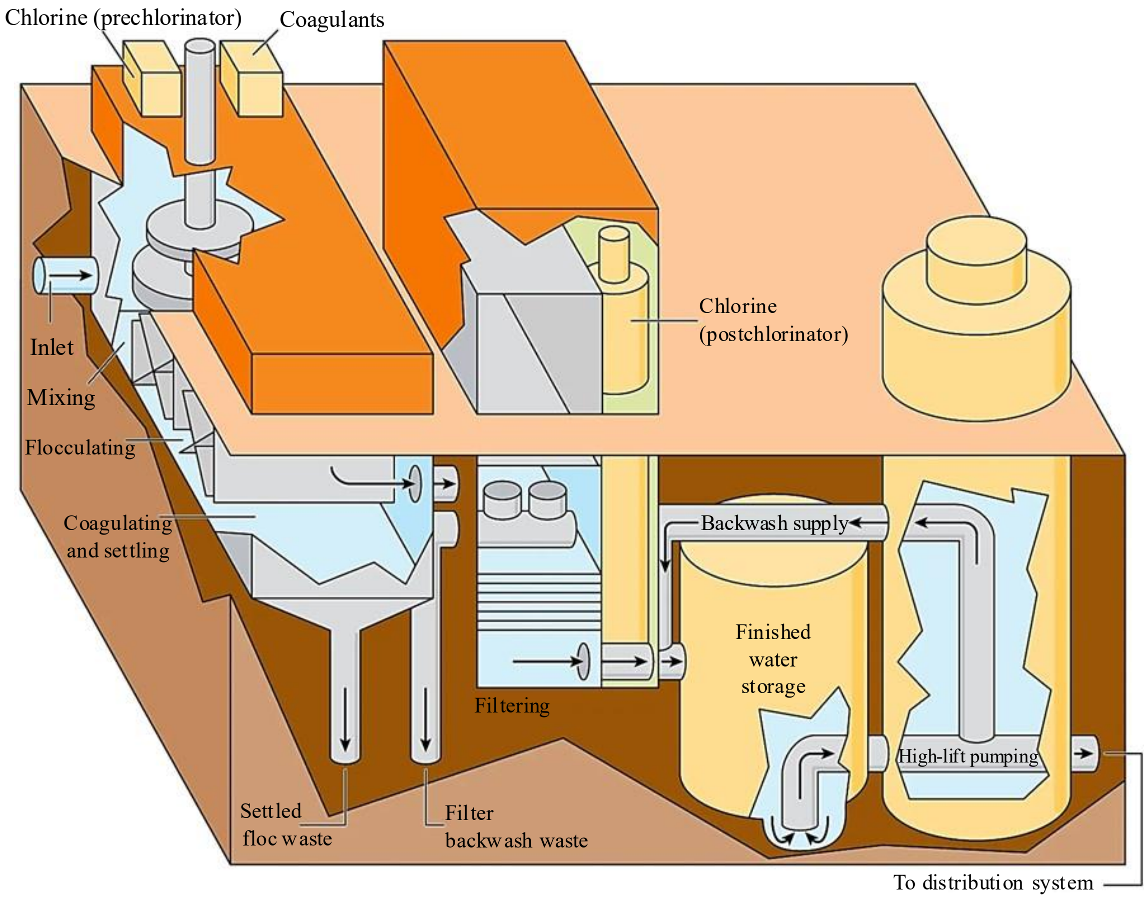

Figure 1. Water treatment [1].

Table 1. Overview of water purification needs and challenges.

Aspect	Details
Global Need	Over 2 billion people lack safe drinking water (WHO, 2023).
Domestic Demand	Clean water for drinking, cooking, hygiene; especially in rural areas.
Industrial Demand	Purified water for manufacturing, cooling, and cleaning processes.
Key Challenges	Contaminants (biological, chemical, heavy metals), high purification costs.
Technological Gaps	Inadequate low-cost, portable, and energy-efficient systems.
Environmental Concerns	Waste from purification processes, plastic filters, energy use.
Policy and Infrastructure	Lack of infrastructure, regulations, and maintenance in low-income areas.

Since water is used extensively in the industries, heating, paper and pulp, power generation, pharmaceutical industries, food industries, and most other industries where water is used, it is very important for industrial water treatment to make sure that water supply is of high quality [10–12]. Nevertheless, there are some drawbacks of attaining high-quality purification; costs of acquiring advanced filtration systems, the amount of energy that is used, disposal of filters that are used and the issue of applying different purification technologies in order to meet increasing demand. Also, the water sources have differences in contamination hence the need for flexibility and multiple stage treatment as the viewer. Current studied methods in an effort to overcome these challenges include, energy efficient desalination, water reuse and recycling, and nanotechnology for water filtration. These are the following several barriers to unimaginative materials, effective monitoring solutions, and environment friendly purification methods that are required in the present engineering solution to provide clean water for the ever-increasing demands [13–17].

PURPOSE AND SCOPE OF THE STUDY

This study seeks to carry out a detailed review on the latest techniques, materials, and technologies employed in portable water purification for domestic as well as industrial purposes. Based on the effects of the pollution of water and the current statistics involving water scarcity, there is a need for better and more efficient technologies that address the purification of water hence providing better and cheaper water for purification [18–20]. The objective of this research work is to assess the effectiveness of purification techniques like membrane filtration, adsorption, electrochemical and photo catalytic methods and evaluate the application of new materials including nano materials, graphene oxide and biofilter for enhanced purification of water. Furthermore, there will be the evaluation of novel technologies such as smart purification IoT, energy efficient desalination, and self-cleaning filtration for availability and usability in real life settings [21–23]. However, as we are going to review the small-scaled home applications and large-scale industries applications of all these technologies besides the technical efficiency, we will also consider the economic feasibility, environmental concern, scalability and maintainability. To that end, this study is formulated with the goal of highlighting the opportunities and challenges of current and future purification approaches in order to benefit the various scholars, producers, decision-makers, and related parties associated with water purification [24–26]. In the end, the results of the study shall help in formulating effective and efficient water purification methods that favor water safety and purification for various uses hence ensuring reduction of the impacts on the economic and environmental setting.

ADVANCED PURIFICATION METHODS

Membrane Filtration Technologies (Reverse Osmosis, Ultrafiltration, Nanofiltration)

Among membrane filtrations such as Reverse Osmosis, Ultrafiltration, and Nanofiltration, these technologies play an important role in water treatment applications for desalinating, wastewater treatment, and industrial treatment (Figure 2). Most importantly, Reverse Osmosis has the capacity to reject nearly all dissolved solute, bad bacteria, viruses and so on which makes it a viable process for producing potable water. Ultra filtration has a relatively more massive pore size that makes it suitable for removal of suspended solids, bacteria and organic macromolecules and is widely used in the food and beverage industry.

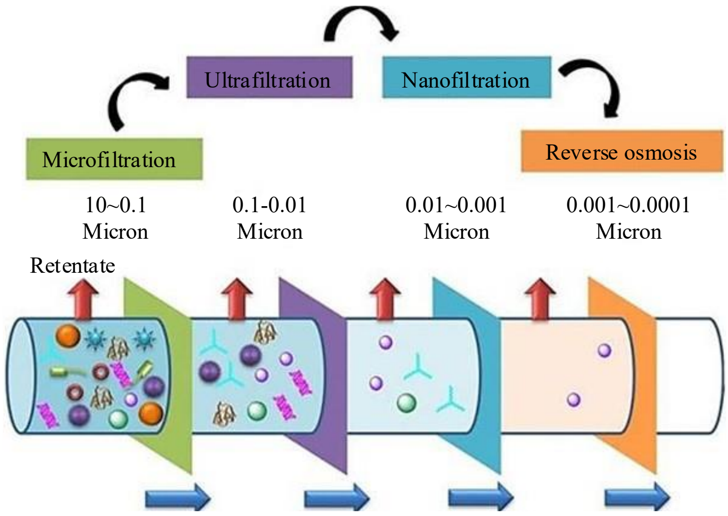

Figure 2. Membrane filtration technology.

Nanofiltration is situated in between RO and UF and has the capabilities of removing divalent ions, organic materials, and certain salts and is thus used in softening water and water reuse. These four membrane filtration technologies work on the basis of permeability criterion, where certain options are selected in order to meet the technological needs depending on size, charge, and chemical nature of the pollutant present in the water; and are indeed general and essential in solving problems related to water quality and use of water resource.

Adsorption Techniques (Activated Carbon, Biochar, Zeolites)

Activated Carbon, Biochar, and Zeolites have had significance proven records of usage in the adsorption of pollutants from water, air, and industrial effluents. Activated Carbon provides more surface area and porosities where organic compounds, heavy metals and volatile organic compounds (VOC) can be adsorbed which serve as its key uses for water and air filtration. In this sense, biochar is very effective similar to activated carbon and is often used as an environmental remedial material due to its renewable source derived from biomass and also enhancing soil health. Zeolites are microporous minerals with a specific crystalline framework that includes occasionally interconnected cavities; they are primarily used in processes based on ion exchange to filter out and for the removal of the heavy metals, ammonia and other ionized impurities from water and wastewater. These adsorption materials operate on the principle of pollutions, receptive and reactive surfaces where they are fixed, making them ideal in solving environmental issues such as pollution due to their cheapness, effectiveness as well as the possibility of their use in many fields.

Electrochemical Methods (Electrocoagulation, Capacitive Deionization)

Electrocoagulation and Capacitive Deionization (CDI) are the electrochemical methods that focus on the use of electrical energy in water treatment processes (Figure 3). Electrocoagulation is a process that uses electrical current to produce coagulants directly on site, which distribute electronic charges which leads to the coagulation and flocculation of the pollutants, solids, heavy metals, and any suspended matter in water. This method is most useful in industrial water reclamation and the elimination of oils, dyes and heavy metals from the water. CEDI, on the other hand, utilizes electric fields to attract and remove ions from water through ion adsorption onto the electrodes and it is suitable for desalinating water and water softening without involving a lot of energy. CDI is receiving increasing interest for the removal of salts and ions, with the benefits over the conventional ion exchange, such as higher energy efficiency, faster regeneration, and extrinsic scalability. These two methods are among the most advanced electrochemical methods that would help in facilitating efficient water treatment; this is through ensuring that water is purified efficiently, at a reduced cost; while at the same time, minimizing the impact that the process has on the environment.

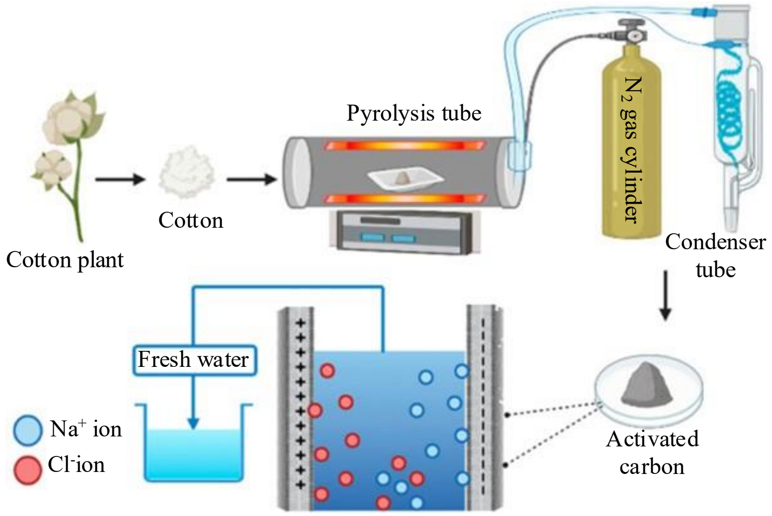

Figure 3. Capacitive Deionization.

Photocatalysis and UV Treatment (Titanium Dioxide-based purification, UV-C Sterilization)

Photocatalysis and UV treatment technologies are more innovative ways of handling water and air pollution through the use of light energy in the form of Titanium Dioxide-based purification and UV-C sterilization (Figure 4 (a and b)). Titanium Dioxide or TiO_2, being a type of photocatalyst, it produces hydroxyl radicals and other reactive oxygen species when exposed to UV light, thus, effectively eliminating organic materials, bacteria and viruses in water. Titanium dioxide photocatalysis purification is especially useful in removing substances that are hazardous when it comes to water and air treatment as a clean and cost efficient method. UV-C sterilization is one of the effective techniques using short-wavelength ultraviolet radiation to destroy microorganisms' ability to both spread diseases and reproduce through the destruction of their DNA. UV-C is currently applied to water treatment, food and beverage processing, as well as in hospitals among other places because of its effectiveness and non-chemical nature. Each method provides cost-effective and energy saving, easy to operate ways of disinfecting water, and cleaning up the environment in order to support sustainable pollution management and human benefits.

Biological Methods (Biofiltration, Microbial Fuel Cells)

The two biological treatment systems include Bio filtration and Microbial Fuel Cells, which are environmentally friendly techniques that apply the natural biological functions to eliminate pollutants from both water and air (Figure 5 (a and b)). Microbial Fuel Cells harness bacteria to oxidize pollutants in the wastewater while at the same time carrying out electricity generation hence providing a twofold advantage of wastewater treatment and electricity generation. MFCs have been considered for their applications in treating industrial effluents in addition to the use in the decentralized system. Bio filtration, on the other hand, is the use of biofilms or microorganisms to eliminate aerosols or water before it filters through a particular medium. This method is often applied to remove VOCs and controlling odor in industries as well as wastewater treatment by microbial action on organic matters. Thereby both processes are based on the natural filtration capabilities of microorganisms, MFCs and biofiltration are energy efficient with low costs and implemented as an environmentally friendly approach compared to other treatment methods. These biological methods are used to enhance the application of green technologies for abatement of pollution and utilization of secondary resources.

ADVANCED MATERIALS USED IN WATER PURIFIERS

Nanomaterials (Graphene Oxide, Carbon Nanotubes, Metal-Organic Frameworks)

These include Graphene Oxide (GO), Carbon Nanotubes (CNTs) and Metal-Organic Frameworks (MOFs) where functionalization is defining themselves as promising materials in different environmental and water treatment applications resulting from high surface area and distinctive structure.

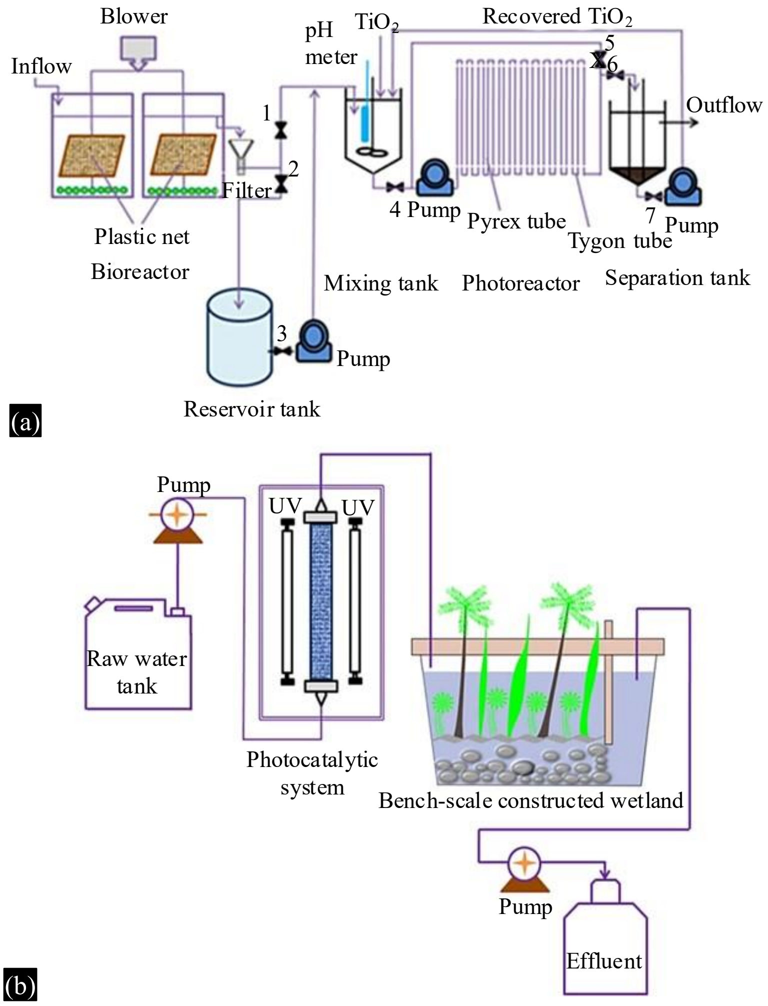

Figure 4. (a) Photocatalysis and (b) UV treatment.

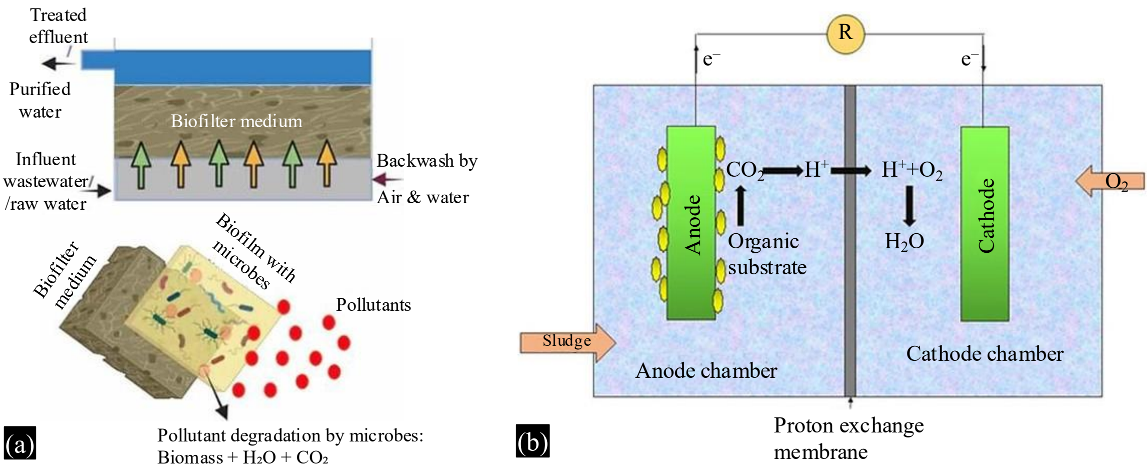

Figure 5. (a) Bio filtration, (b) Microbial fuel cells.

Graphene oxide being hydrophilic in nature and having large surface area is thus excellent in adsorption and filtration of organic pollutants, heavy metals, and microorganisms from water. Carbon nanotubes are extremely strong, electrically conductive, and have large surface area, and therefore efficient in desalination, heavy metals removal and in water purification due to their high adsorption capacity through selectivity. Metal-Organic Frameworks also known as MOFs are porous materials formed from connecting metal ions and organic ligands and are characterized by vast surface area, adjustable porosity and high adsorption capability for gases, ions and organic molecules, and contaminants. These nanomaterials have the immense potential of innovating the field of filtration and purification of water hence introducing the necessary solution to the issues of water scarcity, water pollution and sustainability globally.

Smart Polymers and Hydrogels

Smart polymers and hydrogels are also known as intelligent or responsive materials that are capable of changing their properties upon exposure to certain stimuli like pH, temperature, ionic strength, etc., and have their utility in many fields like water treatment, drug delivery system and environmental monitoring. The smart polymers or stimuli-responsive polymers are of great interest and have the property of swelling and deswelling in response to certain stimuli or an environment depending on situations in which they are to be used; for example, in controlled/sustained-release delivery systems or responsive filters for water purification with a view of varying permeability according to the quality of water. An application of hydrogels is related to water purification techniques because they have polymer chains that are connected in 3D networks, and these networks are capable of absorbing huge amounts of water. Due to their ability to moderately swell in contact with water, biocompatibility as well as ability to adapt to varying conditions they are especially suitable for use in the areas such as wastewater management, detection of contaminants, and formation of self-healing materials. Smart polymers and hydrogels have a critical role to play in environmental technologies since they offer flexible, effective, and sufficiently sustainable approaches to environmental issues such as pollution and resources management.

Composite and Hybrid Materials

The use of composite and hybrid materials that integrate two or more dissimilar materials to make an improved product is showing high potential in the sphere of water treatment and environmental management. These materials take the advantages of each constituent in order to provide high performance in adsorption, filtration and contaminant elimination. For instance, the composites that are prepared with inorganic materials like metal oxides and organic polymers have the advantage of a large surface area, chemical stability, and selectivity for topical adsorption which make it appropriate for the removal of some heavy metals, organic pollutants, and pathogens. Nanomaterials such as the carbon nanotubes or graphene incorporated with the standard filtering media improve the filter capacity and versatility of the filtration systems. Different types of materials in composites and hybrids also provide the opportunity of making materials that respond to more than one stimulus, for example, temperature, solution pH, or concentration of ions. It is evident from these new materials that these materials will be of great value in the future of either drinking water or wastewater treatment for both affordable high performance for a variety of water quality concerns.

TECHNOLOGICAL INNOVATIONS IN PORTABLE WATER PURIFIERS

IoT-based Smart Purifiers (Real-time Monitoring, AI Optimization)

Smart purifiers with IoT and AI built-in are much more effective as they help innovate the idea of water and air purification through implementation of sensors and intelligent artificial technology to constantly maximize the result of the purification and to adapt to individual needs. These smart systems utilize IoT sensors which make it possible to track the key parameters including quality of water, its temperature, pH level, and even the levels of pollutants at a given time to let the users be informed of the status of purification cycles. AI algorithms process this data continuously, adjust purification methods and algorithms, parameters such as flow rate or filter regeneration, etc. Also, the use of artificial intelligence in analyzing data results in the prediction of maintenance requirements, for example, the replacement of filters, and allows for immediate changes for the improvement of positive purification results. Overall, IoT-based smart purifiers are real-time, remote, and optimized, which enhances user experience of the water and air purifier as well making it to be adaptive to the changing environmental conditions that are sustainable in various environmental setups.

Energy-efficient and Renewable Energy-powered Purifiers (Solar Desalination, Piezoelectric Filters)

Renewable energy and energy-efficient technologies in purification are relatively new concepts which have been tagged under sustainable technologies in water purification especially in remote and resource limited areas. Solar desalination uses the energy from the sun either directly in the form of solar thermal or indirectly through photovoltaic systems to heat sea water in order to evaporate it and condense the pure water and leave the salts behind. They include solar stills and multiple effect distillation as well as solar powered reverse osmosis that can be used at domestic and small industrial levels (Table 2). "Piezoelectric filters", on the other hand, use materials that can produce an electrical charge when subjected to mechanical stress in some other type of low power filters. These filters are able to employ vibration, fluid pressure or motion to initiate the piezoelectric effect, to achieve micro-filtration or even catalysis for destruction of pollutants at an incredibly low energy cost. The combination of such systems in portable water purifiers similarly increases energy use efficiency in addition to acting in accordance with future environmental goals for sustainability and environmentally friendly creations. These technologies offer a sustainable solution toward decentralized use of water and are effective as the conventional technologies since they minimize the use of energy and are environment friendly especially due to the increasing costs of energy resources and effects caused by climate change.

Self-cleaning and Low-maintenance Systems

Consequently, self-cleaning and low-maintenance systems are considered as promising innovations for portable water purification technologies concerning filter fouling, operational downtime and high maintenance cost related to traditional cleaning techniques employed in purification technologies. These systems employ such advanced materials and mechanical systems in their design that minimizes the need of frequent cleaning and replacement of the components, and they offer longer durability in service. Films such as Titania or titanium dioxide when incorporated on the surface of the filters allows UV light to enter and destroys biofilms and organic pollutants on the filter membranes thus reducing clogging and bacterial growth. Other systems also use ultrasonic cleaning to wash out contaminate materials through vibration of the membrane without its disassembly in order to increase its permeability. Further, there are new Nanocoatings in development to be able to prevent the formation of oils, dirt, and biological growths on filtering surfaces and prevent fouling. In smart purification systems, fouling conditions are real-time measured, and the implemented backwash or flush processes are initiated.

Table 2. Comparative analysis: Domestic vs. industrial water purification.

Aspect	Domestic Applications	Industrial Applications
Purpose	Drinking, cooking, hygiene	Manufacturing, cooling, processing, cleaning
Water Quality Standard	High (potable standard, free of pathogens and toxins)	Varies by industry (may require ultra-pure or recycled water)
Volume Requirement	Low to moderate (l/day)	High (hundreds to thousands of l/day)
Purification Methods	RO, UV, activated carbon, ceramic filters	RO, NF, UF, ion exchange, distillation, chemical treatments
Energy Consumption	Low to moderate	High
System Size and Portability	Compact, often portable	Large-scale, fixed installations
Maintenance	Minimal, user-level maintenance	Requires skilled personnel and regular monitoring
Cost Sensitivity	High (cost-effective solutions preferred)	Secondary to performance and compliance
Regulatory Compliance	Local health and safety standards	Industry-specific regulations (e.g., FDA, EPA, ISO)
Waste Management	Typically negligible or household-level disposal	Must manage chemical and sludge waste according to regulations

These aspects come in handy especially where reaching a technician for maintenance services may be a luxury you cannot afford. The wonders of such self-reliant technologies also reduce the need for human interaction, guarantee a constant purification quality, and longevity of the machines, low water consumption and high energy provision, making them the key to attaining the next generation of sustainable and people-friendly purification devices.

CHALLENGES AND FUTURE PERSPECTIVES

Affordability and Accessibility

Unquestionably, one of the greatest pressures for sustainable development and application of portable water purification systems is “cost and availability” of such systems in low-income populated and remote areas. However, most of the advanced methods like membrane filtration, nanomaterials, photocatalytic treatment, and smart IoT-based systems have high efficiency and innovation rate, but their basic implementation issues involve high initial cost, complicated infrastructure, and technicality which makes their usability highly impossible for the underfed communities. These materials, for instance, include graphene oxide, carbon nanotubes, and metal-organic frames which may be costly to produce and maintain; AI and IoT may require energy, internet connection and professional workforce. Further, costs like replacement of filters and sensors and membranes are part of the recurring expenditure that cannot be easily manageable for most of the families or small scale industries. Safety is also limited by variations in water quality in different regions which need variation approaches of purification that could not exist on the market or are very expensive depending on the types of contamination. To address these challenges, the future technologies should aim at the application of affordable, discrete, and scalable concepts like biodegradable filters, solar driven systems or smart systems available on open source platforms that are not only sophisticated in their working but also sensible according to economic viability and relativity of the approaches. It is only through collective efforts from the government, nonprofit organizations, academics and water manufacturers that the expensive costs of treating water can be covered, the public can be informed and leads to fair distribution of purified water with safe technologies.

Waste Management and Environmental Impact

The central issues of efficient waste disposals, reducing the adverse effects on the environment are relevant while incorporating new purification methods of water technologies. Some of the industries that are used in portable water purifiers are nanomaterials, activated carbon, smart polymers and other advanced materials which although are very efficient in the filtration of water, they present some challenges in the environment after usage since they are non-biodegradable, toxic, and accumulate in the ecosystems. Improper disposal of employed filters, membranes and chemical contaminants results in secondary pollution which defeats the purpose of purification. These large scale purification plants produce large amounts of sludge and concentrated waste products that need to be disposed of with the help of certain methods of treatment. In particular, some of the purification techniques can be very energy demanding and thus if not driven by renewable energy, will lead to emission of carbon. Thus, concepts used in construction or technologies, while purifying water, should not harm the environment by using harmful material, excessive energy, and not using filter regeneration technology, recycling material wastes and the right procedures of waste disposal.

Emerging Trends (AI-driven Water Quality Monitoring, 3D Printed Filters)

New discoveries in portable water purification devices are rapidly associated with advanced technology like artificial intelligence which is used in monitoring the quality of the water as well as new innovation techniques such as 3D printing to produce filtration tools. Artificial Intelligence is being used to process real time data received from the various IoT sensors attached to turbidity, pH, temperature and contaminants in order to predict when maintenance is needed, to fine tune the system and impel greater purity. Besides, this intelligent monitoring not only increases the efficiency of the system but also maintains sustainability, as well as effectively provides convenience to the user. At the same time, 3D printing is changing the nature of filter products while offering much more extensive filter components with a higher constructive section and structure as well as better flow surfaces. These filters can be made of nanocomposite and biopolymers, which increases the efficiency of their performance and at the same time makes them eco-friendly. These trends together collectively present a new phase in the innovation for better, smarter, more efficient, and better variant water purification technologies for home use and industries.

CONCLUSION AND FUTURE SCOPE

Conclusions

This study reviews recent advancements in portable water treatment technology and in purification capsule design, materials, and methods. Key conclusions emphasize that even though some water purification methods (e.g. reverse osmosis (RO), ultrafiltration (UF), nanofiltration (NF)) are able to remove bacteria, viruses, salts, and suspended solids, they tend to resist removing dissolved inorganic chemicals. Low-cost adsorption procedures based on activated carbon, biochar and zeolites are in use, as well as electrochemical techniques including electro-coagulation and capacitive deionization (CDI), resulting advantageous for efficiently treating heavy metals, dyes, and salts with minimum energy consumption.

Non-chemical techniques such as photo catalysis and UV-C sterilization provide energy-efficient disinfection whereas biologically inspired techniques such as microbial fuel cells and bio filtration bring in environment friendly technologies with simultaneous possibility of dual usage like energy recovery. In terms of the materials, the purification performance of GO has been improved thanks to nano-materials, including carbon nanotubes (CNTs), graphene oxide (GO) and metal organic framework (MOF) with a high specific surface area and selective adsorption performance. Smart polymers and hydrogels provide functional adaptability for environmental and biotechnological applications, and composite and hybrid materials integrate functionalities for greater effectiveness.

In terms of technology, by merging IoT into smart purification systems means a real-time tracking and AI-based optimization, leading to low maintenance, eco-friendly designs running on renewable energy sources such as solar and piezoelectric filtration. These technologies are workable and able to be adapted to either domicile or industrial use as required, according to the complexity of the system and the level of investment. Promising developments are powering new applications from AI-driven predictive maintenance to innovative, low-cost production techniques, like thread printing, for affordable and effective purification.

Future Research Directions

This study implies that the important future research area for mobile water purification should involve identifying portable tap water technologies that are affordable, energy efficient and integrated methods with the environmental compatibility to be used at domestic and industrial level. Nanotechnology, smart polymers and bio-base filters represent promising future opportunities that could help to develop better filters that are efficient and at the same time environmentally friendly. Combining AI and IoT for continuous monitoring and self-controlled purification has much potential for the future smart purifiers. Moreover, advances like the filter by 3D printing and renewable energy-powered systems also add up to enhancing access to clean water especially in regions that have limited access to materials and resources. Further research on the material science elements of water treatment technologies of the future with the help of environmental engineering and data technology is critical to achieving the goal of access to safe water in the future.

REFERENCES

1. Abdiyev K, Azat S, Kuldeyev E, Ybyraiymkul D, Kabdrakhmanova S, Berndtsson R, Khalkhabai B, Kabdrakhmanova A, Sultakhan S. Review of Slow Sand Filtration for Raw Water Treatment with Potential Application in Less-Developed Countries. Water. 2023; 15: 2007. https://doi.org/10.3390/w15112007.

2. Ravi Kant Upadhyay, Navneet Soin, Susanta Sinha Roy. Role of graphene/metal oxide composites as photocatalysts, adsorbents and disinfectants in water treatment: a review. RSC Adv. 2014; 4(8): 3823–3851. DOI:10.1039/C3RA45013A.
3. Jasaswini Tripathy, Akanshya Mishra, Mayank Pandey, Thakur Rakesh R, Sasmita Chand, Rout Prangya R, Shahid Muhammad K. Advances in nanoparticles and nanocomposites for water and wastewater treatment: a review. Water. 2024; 16(11): 1481. DOI:10.3390/w16111481.
4. Sheng Liu, Zi-Lin Su, Yi Liu, Lin-Ya Yi, Zhan-Li Chen, Zhen-Zhong Liu. Mechanism and purification effect of photocatalytic wastewater treatment using graphene oxide-doped titanium dioxide composite nanomaterials. Water. 2021; 13(14): 1915. DOI:10.3390/w13141915.
5. Yongchen Liu. Application of graphene oxide in water treatment. IOP Conf Ser: Earth Environ Sci. 2017; 94(1): 012060. DOI:10.1088/1755-1315/94/1/012060.
6. Ramesh Thiruvenkatachari, Saravanamuthu Vigneswaran, Shik Moon. A review on UV/TiO2 photocatalytic oxidation process. Korean J Chem Eng. 2008; 25(1): 64–72. DOI:10.1007/s11814-008-0011-8.
7. Ganjar Fadillah, Saleh Tawfik A, Hanik Munawaroh, Sayekti Wahyuningsih, Ari Handono Ramelan. Flow photocatalysis system-based functionalized graphene oxide-ZnO nanoflowers for degradation of a natural humic acid. Environ Sci Pollut Res. 2022; 29: 9883–9891. DOI:10.1007/s11356-021-16333-9.
8. Penghui Shao, Jiayu Tian, Wenxin Shi, Shanshan Gao, Fuyi Cui. Eco-friendly one-pot synthesis of ultradispersed TiO2 nanocrystals/graphene nanocomposites with high photocatalytic activity for dye degradation. J Mater Chem A. 2015; 3(39): 19913–19919. DOI:10.1039/C5TA05378A.
9. Rukia Fatima, Warsi Muhammad F, Sonia Zulfiqar, Ragab Sameh A, Imran Shakir, Sarwar Muhammad I. Nanocrystalline transition metal oxides and their composites with reduced graphene oxide and carbon nanotubes for photocatalytic applications. Ceram Int. 2020; 46(10): 16480–16492. DOI:10.1016/j.ceramint.2020.03.213.
10. Jun Yin, Baolin Deng. Polymer-matrix nanocomposite membranes for water treatment. J Membr Sci. 2015; 479: 256–275. DOI:10.1016/j.memsci.2015.01.068.
11. Wei Lau, Sabrina Gray, Teow Chong Matsuura, Delfin Emadzadeh, Jin Perng Chen, Ismail Ahmad A. A review on polyamide thin film nanocomposite (TFN) membranes: history, applications, challenges and approaches. Water Res. 2015; 80: 306–324. DOI:10.1016/j.watres.2015.04.037.
12. Das L, Das P, Bhowal A, Bhattachariee C. Synthesis of hybrid hydrogel nano-polymer composite using graphene oxide, chitosan and PVA and its application in waste water treatment. Environ Technol Innov. 2020; 18: 100664. DOI:10.1016/j.eti.2020.100664.
13. Kadhim RJ, Al-Ani FH, Al-Shaeli M, Alsalhy QF, Figoli A. Removal of dyes using graphene oxide (GO) mixed matrix membranes. Membranes. 2020; 10(12): 366. DOI:10.3390/membranes10 120366.
14. Kurniawan TA, et al. Functionalizing TiO2 with graphene oxide for enhancing photocatalytic degradation of methylene blue in contaminated wastewater. J Environ Manag. 2020; 270: 110871. DOI:10.1016/j.jenvman.2020.110871.
15. Mao M, Boopathi S, Thiruppathi AR, Wood PC, Chen A. Efficient dye removal and separation based on graphene oxide nanomaterials. New J Chem. 2020; 44(11): 4519–4528. DOI:10.1039/ C9NJ05895H.
16. Zhu M, Kurniawan TA, Song F, Ouyang T, Othman MHD, Rezakazemi M, Shirazian S. Applicability of BaTiO3/graphene oxide composite for enhanced photodegradation of methylene blue in synthetic wastewater under UV–vis irradiation. Environ Pollut. 2019; 255: 113182. DOI:10.1016/j.envpol.2019.113182.
17. Menachem Elimelech, Brady-Estévez Anna S, Seoktae Kang. A single-walled-carbon-nanotube filter for removal of viral and bacterial pathogens. Small. 2008; 4(3): 481–484. DOI:10.1002/smll. 200700620.
18. François Perreault, de Faria Andreia F, Siamak Nejati, Menachem Elimelech. Antimicrobial properties of graphene oxide nanosheets: why size matters. ACS Nano. 2015; 9(7): 7226–7236. DOI:10.1021/acsnano.5b03009.

19. Peng Zhang, Yawen Tong, Yong Liu, Vequizo Junie JM, Hongwei Sun. Heteroatom dopants promote two-electron reduction for photocatalytic production of H2O2 on polymeric carbon nitride. Angew Chem Int Ed. 2020, 59(37): 15596–15601. DOI:10.1002/anie.202005199.
20. Mohammed Nazim, Aftab Aslam Parwaz Khan, Asiri Abdullah M, Jae Hyun Kim. Exploring rapid photocatalytic degradation of organic pollutants with porous CuO nanosheets: synthesis, dye removal, and kinetic studies at room temperature. ACS Omega. 2021; 6(5): 3487–3496. DOI:10.1021/acsomega.0c05920.
21. Tae-Moon Tak, Tae-Hyun Bae. Effect of TiO2 nanoparticles on fouling mitigation of ultrafiltration membranes for activated sludge filtration. J Membr Sci. 2005; 256(1-2): 24–35. DOI:10.1016/j.memsci.2005.03.022.
22. Erika Nascimbén Santos, Zsuzsanna László, Cecilia Hodúr, Gangasalam Arthanareeswaran, Gábor Veréb. Photocatalytic membrane filtration and its advantages over conventional approaches in the treatment of oily wastewater: a review. Asia-Pac J Chem Eng. 2020, 15(5): e2467. DOI:10.1002/apj.2467.
23. Coelho François B, Candelario Victor M, Araújo Estêvão MR, Miranda Tânia LS, Giuliana Magnacca. Photocatalytic reduction of Cr(VI) in the presence of humic acid using immobilized Ce–ZrO2 under visible light. Nanomaterials. 2020; 10(4): 726. DOI:10.3390/nano10040726.
24. Hai HTN, Nguyen TT, Nishibori M, Ishihara T, Edalati K. Photoreforming of plastic waste into valuable products and hydrogen using a high-entropy oxynitride with distorted atomic-scale structure. Appl Catal B. 2025; 314: 121731. DOI:10.1016/j.apcatb.2024.121731.
25. Rouzafzay F, Shidpour R. Graphene@ZnO nanocompound for short-time water treatment under sun-simulated irradiation: effect of shear exfoliation of graphene using kitchen blender on photocatalytic degradation. J Alloys Compd. 2024; 798: 165–174. DOI:10.1016/j.jallcom.2023.165174.
26. Wellia Diana V, Syuadi Atika F, Rahma Resha M, Atika Syafawi, Rafli Habibillah M. Rind of Aloe vera extract for synthesis of titanium dioxide nanoparticles: properties and application in model dye pollutant degradation. Case Stud Chem Environ Eng. 2024; 9: 100358. DOI:10.1016/j.cscee.2024.100358.

