Applied Chemical Engineering (2025) Volume 8 Issue 3 ISSN: 2578-2010 (O)
doi: 10.59429/ace.v8i3.5665

ORIGINAL RESEARCH ARTICLE

Sustainable Solutions and Innovations in Sand Filtration for Safe Drinking Water in Arid Areas

Ahmed Elshaikh[1*], Ahmed Osman[2], Maher Abdalla[3], Elsiddig Elsheikh[4], Jamal Mabrouki[5]

[1] *Water Research Center, University of Khartoum, Khartoum, 11111, Sudan*

[2] *WASH officer, Danish Refugee Council (DRC), Gadaref, 11111, Sudan*

[3] *WASH department, Danish Refugee Council (DRC), Gadaref, 11111, Sudan*

[4] *Department of Applied Biology, College of Sciences, University of Sharjah, 27272, United Arab Emirates*

[5] *Faculty of Science, Mohammed V University, Rabat, 10100, Morocco*

***Corresponding author:** Ahmed Elshaikh, ahmedhayaty@live.com

ABSTRACT

Sand filtration stands as a time-tested method for water treatment, yet advancements in technology continue to enhance its effectiveness and efficiency. This paper explores the latest innovations and applications aimed at improving sand filtration for the provision of safe drinking water. Through a comprehensive evaluation of recent developments, this study identifies key innovations in filter media, design modifications, and operational strategies that optimize sand filtration performance. Moreover, it examines the diverse applications of innovative sand filtration techniques in addressing and improving water quality in various contexts. Considering the evaluation of efficiency, scalability, and sustainability of these advancements, this research provides valuable insights into optimizing sand filtration for safe drinking water with focus on rural areas. Finally, through a synthesis of analytical insights and practical case studies, this paper provides a comprehensive overview of the state-of-the-art in sand filtration technology, offering valuable insights for researchers, practitioners, and policymakers seeking to adopt sustainable solutions for the promotion of safe water for rural development.

Keywords: Sand filtration; drinking water; innovations; water quality

ARTICLE INFO

Received: 8 May 2025
Accepted: 29 July 2025
Available online: 18 August 2025

1. Introduction

Safe drinking water stands as a cornerstone of human health and well-being, holding immense significance across various spheres of life. Its paramount importance lies in safeguarding public health by preventing waterborne diseases and illnesses, particularly in vulnerable communities where access to clean water is limited[1]. Beyond health, safe drinking water is a linchpin for social and economic development, fostering thriving communities by enabling agricultural productivity, industrial activities, and commerce[2,3]. Moreover, it plays a pivotal role in environmental sustainability, ensuring the preservation of ecosystems and biodiversity by maintaining the quality and availability of freshwater sources[4]. Its multifaceted importance underscores the urgent need for concerted efforts to ensure universal access to clean water, not only as a fundamental human right but also as a linchpin for achieving the broader goals of public health, social equity, economic prosperity, and environmental stewardship[5,6].

Sand filtration has long been recognized as a robust and sustainable method for improving water quality, particularly in decentralized and rural settings. Quantitative studies have shown that well-maintained slow sand filters can achieve bacterial removal efficiencies exceeding 99% under optimal conditions[7,8]. For instance, Stauber et al. (2021)[9] demonstrated that household slow sand filters reduced E. coli concentrations by 93–99%, while also showing increasing virus removal over time due to biofilm development. In addition to microbial reduction, sand filters have proven effective in removing turbidity and suspended solids, with removal efficiencies often exceeding 95% in both slow and rapid filter designs[10]. Qualitatively, these systems are favored in low-resource settings due to their low energy requirements, passive operation, and long lifespan. The simplicity of design and potential for local maintenance make sand filtration an attractive solution in arid and developing regions where centralized water treatment infrastructure is lacking.

In addition to its immediate health benefits, safe drinking water serves as a catalyst for broader societal progress. It underpins educational opportunities by alleviating the burden of water collection, particularly on children, thereby allowing them to attend school regularly and pursue academic success[11,12]. Furthermore, equitable access to clean water promotes social justice by addressing disparities based on socio-economic status, ethnicity, or geography, thereby contributing to the realization of basic human rights. Moreover, in the face of climate change, ensuring the availability of safe drinking water becomes increasingly vital for building resilience against water scarcity and extreme weather events[13,14].

Given the unique challenges faced by rural communities, sand filtration has emerged as a preferred technology due to its low cost, ease of maintenance, and effectiveness in removing pathogens from surface and groundwater sources. Sand filtration stands as a time-tested method for purifying water, renowned for its simplicity, effectiveness, and reliability. Dating back centuries, this technique utilizes layers of sand to remove impurities and contaminants from water, making it safe for consumption[7,15]. As water percolates through the sand bed, physical, chemical, and biological processes work synergistically to trap suspended particles, pathogens, and organic matter, resulting in clearer, cleaner water. Its widespread adoption across diverse contexts, from household filtration systems to large-scale water treatment plants, attests to its enduring relevance and efficiency in addressing water quality challenges[16].

Innovations and applications in sand filtration represent a crucial frontier in advancing water treatment technologies, with profound implications for public health, environmental sustainability, and economic development. These advancements not only enhance the efficiency and effectiveness of water purification processes but also expand the scope of sand filtration to address emerging challenges. As such, ongoing innovations in sand filtration hold the promise of improving water quality, safeguarding public health, and fostering sustainable development on a global scale[17-21].

The aim of this paper is to assess the efficacy of cutting-edge sand filtration methods in enhancing water quality and mitigating the presence of emerging contaminants. Through a comprehensive evaluation of the performance, scalability, cost-effectiveness, and environmental sustainability of innovative sand filtration approaches, this research aims to provide valuable insights and recommendations for the implementation of these techniques in diverse water treatment settings, thereby contributing to the advancement of sustainable and resilient water management practices for rural development.

2. Methodology

The methodology of this paper adopts rigorous analytical method to assess existing sand filtration techniques in rural settings, evaluating their efficacy and identifying key challenges and limitations associated with traditional filtration methods. This analytical framework involves thorough literature examinations data case analysis to gain a comprehensive understanding of the current landscape of sand filtration technology (**Figure 1**). Within this framework aimed at achieving sustainability, understanding the current status and desired destination is crucial. This comprehension enables the identification of opportunities and challenges, facilitating the maximization of profits while minimizing losses.

Figure 1. Framework for sustainable sand filtration system.

This paper seeks to pinpoint gaps and areas ripe for innovation and sustainable solutions within the realm of sand filtration technology. The methodology begins with identifying the existing sand filtration techniques and their efficacy in rural settings, and then analyze the challenges and limitations associated with traditional filtration methods. Following this, the paper delves into the identification of gaps and opportunities for innovation in sand filtration technology, aimed at fostering sustainable solutions for safe drinking water in rural communities.

This study employs a systematic review methodology to synthesize current innovations in sand filtration technologies with a focus on applications in arid and rural contexts. Literature was collected from peer-reviewed databases including Scopus, Web of Science, and PubMed, as well as gray literature such as field reports from NGOs and development agencies, covering the period from 2000 to 2025. Case studies were included based on criteria such as relevance to arid environments, filtration system scale (household or community), and documentation of performance metrics, resulting in 38 cases selected for analysis.

2.1. Flow regime and the characteristics of the filter media

Sand filters operate under various flow regimes most notably slow, rapid, and intermittent flow which significantly influence their performance, design, and operational sustainability. Slow sand filtration, characterized by low flow rates (typically <0.4 $m^3/m^2/h$), allows for extended contact time and biological activity, leading to high removal efficiency of pathogens and turbidity. In contrast, rapid sand filters operate at higher flow rates (5–15 $m^3/m^2/h$) and rely more on mechanical straining and require frequent backwashing. Intermittent filters, often used in decentralized systems, alternate between resting and dosing periods, facilitating both physical and biological treatment. The choice of flow regime must be aligned with the water quality objectives, maintenance capacity, and environmental context especially in arid and low-resource settings.

The effectiveness of sand filtration also depends heavily on the physical and hydraulic characteristics of the filter media. Critical parameters include grain size distribution, effective size (commonly denoted as d_{10}), uniformity coefficient (UC), porosity, and depth of the media layers. Fine sand, for example, offers greater surface area and microbial removal but can increase head loss and clogging risk, while coarse sand promotes higher flow but may compromise filtration efficiency. The media's mineral composition also plays a role in adsorption and biological colonization. Optimal design must balance removal efficiency, flow rate, maintenance frequency, and media availability factors that are especially crucial when deploying sustainable water treatment technologies in remote or arid environments.

Recent advancements in sand filtration have focused on tackling emerging contaminants such as PFAS and micro-plastics. For instance, studies have demonstrated that modified "super sand" filters can remove up to 87% of PFAS under laboratory conditions with influent concentrations typical of contaminated groundwater. Similarly, enhanced bio-sand filters using coated media have shown removal efficiencies exceeding 90% for micro-plastic particles less than 5 microns in size[22,23].

2.2. Principles of sand filtration

The fundamental principles underlying sand filtration revolve around physical, chemical, and biological processes that collectively remove impurities and contaminants from water[16]. Firstly, physical filtration occurs as water passes through the porous bed of sand, with particles larger than the pore size being physically trapped. This process effectively removes suspended solids, sediments, and larger microorganisms[7]. Secondly, chemical processes such as adsorption and precipitation play a crucial role in removing dissolved contaminants. Finally, biological filtration involves the activity of microorganisms present in the sand bed, which can biodegrade organic matter and metabolize certain contaminants[24] (see **Figure 2**).

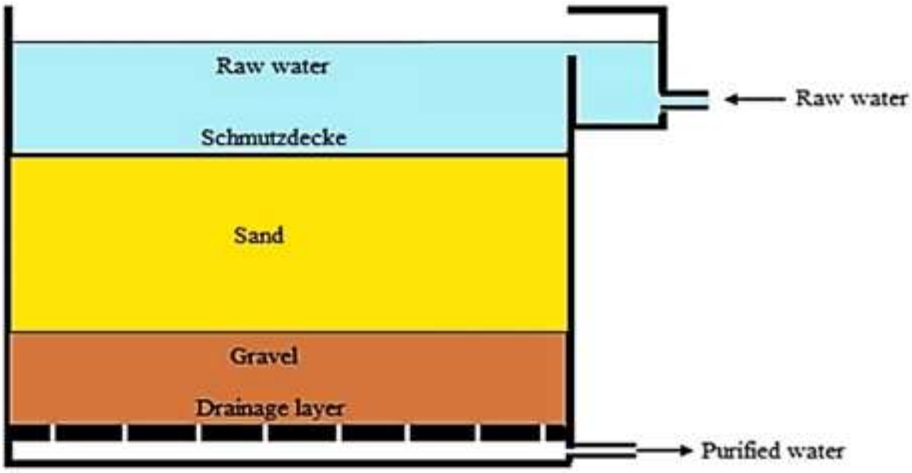

Figure 2. Diagram illustrating a typical layout for a sand filtration system[7].

Sand filtration is a versatile method employed across a spectrum of settings, each tailored to meet specific needs. From large-scale municipal water treatment plants ensuring the provision of safe drinking water to entire communities, to point-of-use and point-of-entry filtration systems installed in households for individual purification needs.

Large-scale Municipal Water Treatment Plants: These systems are engineered for large-scale applications, catering to the water needs of entire communities or urban areas. They typically involve extensive sand filtration processes within centralized water treatment facilities to ensure the supply of clean water to the population[25,26]. Schematic diagram of the large-scale Sand Filters is shown in **Figure (3)**.

Point-of-Use Filtration Systems for Households: These filtration systems are designed to be installed directly at the point where water is used or enters a building. Point-of-use systems are installed at individual faucets or appliances. The household is responsible for the operation and maintenance of the system to ensure its functionality and hygienic operation[25,27]. **Figure (4)** illustrates the key components of the filter.

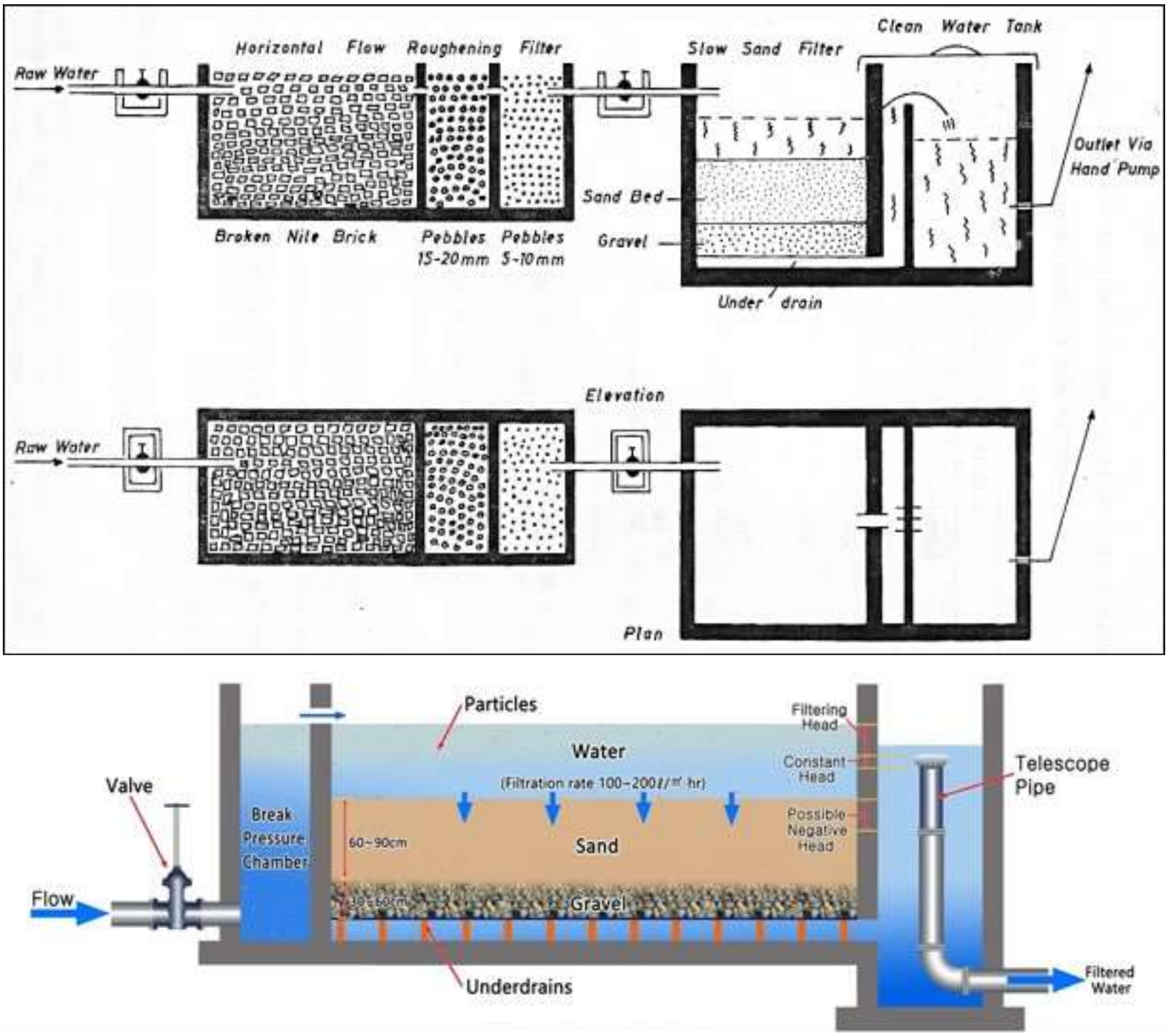

Figure 3. Horizontal flow slow sand filter for small villages[8,25].

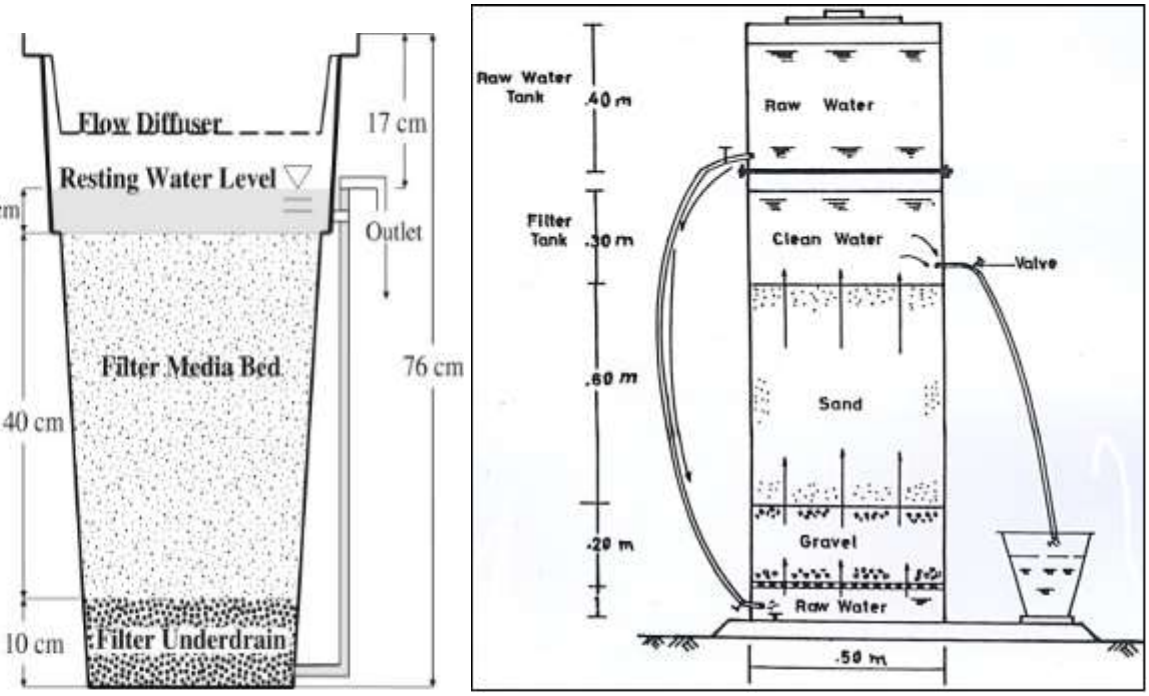

Figure 4. Up-Word flow Sand Filter for individual Household[8,25].

To better illustrate the practical differences between filtration system scales, **Table 1** provides a side-by-side comparison of household and large-scale sand filtration technologies. The comparison includes key performance indicators such as contaminant removal efficiency, operational and maintenance challenges, infrastructure requirements, and training needs. This overview highlights how the choice of filtration system must align with local context, available resources, and community needs, reinforcing the importance of scale-appropriate water treatment solutions in both rural and semi-urban settings.

Table 1. Comparison of large-scale vs. household sand filtration systems (source: link).

Parameter	Household Sand Filtration	Large-Scale (Community or Municipal) Sand Filtration
Typical Contaminant Removal Rates	• Bacteria (E. coli): 90–95% • Turbidity: 80–90% • Protozoa: 80–90%	• Bacteria (E. coli): 98–99% • Turbidity: 95–98% • Protozoa: 95–98%
Flow Rate	10–30 L/hour	1,000–10,000+ L/hour
Maintenance Requirements	Frequent manual cleaning (weekly to bi-weekly); user-dependent	Requires trained operators; less frequent but more technical
Cost	Low initial cost (~$15–50 per unit); minimal operational costs	Higher capital cost (~$1,000–$15,000); ongoing O&M costs
Infrastructure Needs	Minimal; can be constructed locally using buckets, sand, gravel	Requires civil works, plumbing, pressure regulation, sedimentation tanks
Training Needs	Basic training for users; vulnerable to misuse	Operator training required; performance is more consistent
Suitability	Ideal for dispersed households or small-scale rural use	Suitable for centralized service in villages, schools, health centers
Resilience to Environmental Stress	Variable—performance drops under turbidity spikes or floods	More robust with pre-treatment and protective housing

2.3. Challenges of sand filtration in rural areas

Sand filtration remains one of the most practical and widely adopted methods for water treatment, particularly in rural regions of developing countries where access to safe drinking water is often scarce. Despite its proven efficiency in removing contaminants, the implementation of sand filtration systems in these areas faces a range of challenges that must be carefully addressed. These obstacles include, but are not limited to:

Policy and institutional factors: these challenges encompass issues such as the lack of supportive regulatory frameworks and limited institutional capacity for planning and oversight. Additionally, the absence of clear guidelines for water quality standards and monitoring further complicates the implementation process. Addressing these barriers requires collaborative efforts between government agencies, non-profit organizations, and local communities to develop tailored solutions that promote sustainable development[28].

Infrastructure Limitations: rural areas often lack the necessary infrastructure for implementing sand filtration systems. This includes issues such as limited access to electricity, inadequate plumbing, and insufficient space for constructing filtration facilities. Without proper infrastructure, it becomes challenging to set up and maintain sand filtration systems effectively[29].

Operation and Maintenance: Sand filtration systems require regular maintenance and skilled operation to ensure optimal performance. In rural areas where there may be a lack of trained personnel and technical expertise, maintaining these systems becomes a significant challenge. Additionally, sourcing spare parts and chemicals for system upkeep can be difficult in remote locations[30].

Financial Constraints: implementing sand filtration systems in rural areas requires substantial financial investment, including the initial setup costs and ongoing maintenance expenses. Many rural communities may lack the financial resources to fund such projects independently. Securing funding from government agencies or non-profit organizations can be challenging, further complicating the implementation process[29].

Behavioral and Cultural Factors: changing behaviors and cultural practices related to water usage and hygiene can be challenging in rural communities. Even with access to sand filtration systems, community members may continue to rely on traditional water sources or engage in practices that compromise water quality. Educating and raising awareness among community members about the importance of clean water and proper sanitation is crucial but can be met with resistance[28].

Climate Change and Sustainability: ensuring the long-term sustainability of sand filtration systems in rural areas is a significant challenge. Factors such as environmental degradation, climate change, and population growth can impact the availability and quality of water sources over time. Implementing sustainable practices, such as watershed management and rainwater harvesting, alongside sand filtration can help address these challenges but require careful planning and community involvement[31].

Tackling these challenges effectively is crucial for ensuring dependable access to clean water in rural areas. Effective strategies may involve investing in innovative and smart technologies, providing technical support and fostering community engagement to ensure system sustainability.

2.4. Case studies

Several studies have demonstrated the effectiveness of sand filtration systems under various flow regimes and media configurations. (See **Table 2**).

Table 2. Summary of selected studies on sand filtration systems.

Filter Type	Flow Regime	Media Characteristics	Removal Efficiency	Reference
Slow Sand Filter	Slow gravity (< 0.25 $m^3/m^2/h$)	Fine sand, depth ~1 m	> 99% removal of bacteria and viruses under optimized conditions	[7]
Household Slow Sand Filter	Intermittent	Fine sand (d_{10} ≈ 0.20 mm)	~93–99% E. coli; increasing virus removal over time	[32]
Slow Sand Filter	Gravity (0.19–0.4 m/h)	Fine sand layer with biofilm	> 99% coliform and Giardia removal	[33]
Rapid Sand Filter	Rapid (multiple $m^3/m^2/h$)	Coarse sand + gravel, depth ~0.6–1 m	~50% bacteria-reduction; high turbidity removal	[34]
Rapid Sand Filter	4.3 m/h	Lava sand (d ~ 0.2 cm), sedimentation pretreatment	96–98.6% turbidity removal from high NTU influent	[10]

Innovations in Sand Filtration Technology

Sand filtration technology has long been employed as a cost-effective and sustainable method for water treatment. However, in recent years, significant innovations have emerged, promising to revolutionize the efficacy, efficiency, and accessibility of sand filtration systems. The following points explores these innovations, their potential impact, and the implications for addressing global water crises.

Advancements in Filtration Media

Traditionally, sand has been the primary filtration media used in sand filtration systems. However, recent innovations have expanded the range of filtration media, introducing materials such as activated carbon, zeolite, and biochar. These alternative media offer enhanced adsorption properties, increased surface area, and improved contaminant removal capabilities. Additionally, advancements in nanotechnology have led to the development of nanostructured materials that exhibit superior filtration performance, allowing for the removal of even smaller particles and contaminants[35].

Research in the field of water filtration has achieved a significant advancement with the introduction of "super sand." This innovation entails applying graphite oxide coating to sand grains, resulting in enhanced filtration capabilities. According to reports, super sand surpasses traditional sand filters by efficiently removing harmful contaminants like mercury from water. Studies indicate that super sand can filter contaminants up to five times more effectively than conventional sand filters[36].

The integration of membrane technologies signifies a notable progression in improving the functionality of sand filtration systems used in water purification. This integration elevates the overall filtration efficiency and efficacy of sand filtration systems. Through incorporating membranes, which serve as a dual-filtration system, the comprehensive removal of contaminants is ensured, leading to elevated water quality standards and enhanced protection against waterborne diseases[37].

Modular and Scalable Designs

Innovations in modular and scalable designs have transformed sand filtration technology, making it highly adaptable to various environments and applications. Modular filtration units can be effortlessly assembled, disassembled, and adjusted in size to cater to specific water treatment requirements[38]. This flexibility facilitates the deployment of sand filtration systems in remote or temporary settings, such as during disaster relief operations or within mobile water treatment units, where rapid installation and versatility are paramount. Furthermore, decentralized modular designs reduce dependence on centralized water treatment infrastructure, bolstering resilience and sustainability. Additionally, the adoption of solar energy further enhances the sustainability of sand filtration systems, providing a renewable and environmentally friendly power source for operations, especially in off-grid or remote locations[29].

Integration of Smart Technologies

The integration of smart technologies into sand filtration systems represents a significant advancement in water treatment technology. This integration involves the incorporation of various sensors, data analytics algorithms, and automation features to enhance the efficiency, reliability, and effectiveness of filtration processes. The integration of smart technologies and innovation in sand filtration system include:

- **Sensor Technology:** Sensors play a crucial role in modern sand filtration systems by monitoring key water quality parameters in real-time at various points within the filtration process. Moreover, advanced sensors have the capability to detect specific contaminants or pollutants, enabling the implementation of targeted treatment strategies[39].
- **Data Analytics and Monitoring:** Data analytics algorithms are integral components of sand filtration systems, leveraging information collected by sensors to discern patterns, trends, and anomalies in water quality parameters. Real-time monitoring dashboards further empower operators by offering visual representations of key performance indicators, facilitating swift intervention and informed decision-making to uphold water quality standards and system integrity[40].
- **Automation and Control Systems:** Automation features in sand filtration systems play a pivotal role in optimizing performance and ensuring system integrity. Moreover, remote monitoring and control capabilities empower operators to manage and oversee filtration systems from any location with internet connectivity, enhancing operational efficiency, flexibility, and responsiveness to changing conditions or demands[40].
- **Integration with IoT and Cloud Platforms:** Integration with Internet of Things (IoT) platforms is pivotal in enhancing connectivity and communication within sand filtration systems. Furthermore, leveraging cloud-based platforms for data storage enabling collaboration and data sharing among multiple stakeholders. Moreover, historical data stored in the cloud can be leveraged for trend analysis, performance benchmarking, and regulatory compliance reporting[41].

- **Artificial intelligence algorithms:** Artificial intelligence (AI) algorithms play a crucial role in optimizing the performance of sand filtration systems by analyzing data patterns to predict system failures, enhance filtration efficiency, and minimize energy consumption. Through sophisticated data analysis techniques, AI algorithms can identify correlations and trends in sensor data, enabling early detection of potential equipment malfunctions or operational issues[42].

Recent advancements in smart technologies have opened new opportunities to enhance the efficiency, monitoring, and sustainability of sand filtration systems, particularly in remote and arid regions. These technologies include the integration of IoT (Internet of Things) sensors for real-time water quality monitoring, automated backwashing systems, and predictive maintenance using machine learning. For instance, systems equipped with turbidity and pressure sensors can optimize filter cleaning cycles, reduce water wastage, and ensure consistent filtration performance without constant human supervision. The adoption of GSM-enabled controllers has further allowed decentralized communities to receive performance alerts and maintenance updates remotely.

A notable case study is the implementation of a smart bio-sand filter system in Rajasthan, India[43], where IoT-based turbidity sensors were used to monitor filter clogging and trigger automated maintenance alerts. This resulted in a 30% improvement in operational uptime and a measurable reduction in microbial contamination. Similarly, in Morocco's semi-arid Doukkala region, a pilot project[44] integrated solar-powered sensors into community sand filtration units, allowing for remote water quality tracking and improved resource planning. These case studies highlight the potential of combining traditional sand filtration with digital innovations to address sustainability and maintenance challenges in water-stressed environments.

Strategies for lifecycle management and sustainability

Lessons learned and best practices gleaned from sand filtration applications can guide replication efforts and inform the implementation of similar projects in various contexts. **Figure 5** below outlines the fundamental elements from literature that are essential for lifecycle sustainability for Sand Filtration system.

Figure 5. The primary components for lifecycle management and sustainability.

This diagram likely outlines components such as monitoring and evaluation mechanisms, resource allocation strategies, stakeholder engagement initiatives, and measures for mitigating environmental impact and promoting social responsibility throughout the project's lifecycle. Ensuring the success of sand filtration projects hinges on careful consideration of several key factors.

Firstly, site selection and design must undergo thorough evaluation, taking into account variables like water quality, hydraulic conditions, land availability, and accessibility. Through meticulously assessing these aspects, project planners can optimize system performance and durability, laying a solid foundation for effective water purification efforts. Secondly, the selection and preparation of sand media play a pivotal role in filtration efficiency. It's essential to choose sand with appropriate grain size, uniformity, and cleanliness to prevent clogging and maximize contaminant removal. Properly preparing the sand media further enhances filtration effectiveness, contributing to the overall success of the system[45].

Regular maintenance and monitoring constitute another critical aspect of sand filtration projects. Implementing a robust maintenance plan, including routine backwashing, media inspection, and replacement, ensures sustained performance over time. Additionally, continuous monitoring of influent and effluent water quality parameters allows for prompt identification of any issues and timely intervention to maintain optimal filtration outcomes[29]. Community engagement and capacity building are fundamental for fostering project ownership, acceptance, and sustainability. Through involving local communities and stakeholders throughout the project lifecycle, project planners can ensure that the initiative aligns with community needs and preferences. Providing training and capacity-building opportunities empowers communities to take an active role in operating and maintaining sand filtration systems, thereby enhancing long-term project success[46].

Flexibility and adaptability are essential principles when replicating sand filtration projects in diverse contexts[47]. Acknowledging and integrating local environment and climate change into project design and implementation ensure that initiatives resonate with the community and garner sustainable future.

In recent years, the concept of the circular economy has gained traction in water treatment technologies, including sand filtration. Applying circular economy principles to sand filters involves reusing, recycling, or repurposing filtration materials to extend their lifecycle and reduce environmental impact. For example, spent sand media can be regenerated through thermal or chemical treatment for reuse, or repurposed in construction materials such as bricks or road sub-base layers. In some community systems, waste sludge from pre-treatment units is being composted or safely disposed using decentralized sludge management approaches. These practices not only reduce operational costs but also minimize waste, making sand filtration systems more sustainable and environmentally friendly. Integrating circular economy strategies supports long-term viability, especially in resource-constrained rural areas where supply chains for new materials are limited.

3. Conclusion and recommendations

In conclusion, the sustainability of water treatment projects, especially those utilizing sand filtration systems, necessitates a holistic approach that addresses various critical components. This includes establishing a strong connection between technology selection and ongoing operation and maintenance, ensuring that the chosen solutions align with the specific needs and capacities of the community. Moreover, community involvement throughout all stages of the project is paramount, emphasizing the importance of participatory approaches that empower local stakeholders to actively engage in decision-making and take ownership of project management. Through fostering transparent communication, flexible management strategies, and institutional support, water treatment initiatives can enhance their chances of long-term success and contribute to lasting improvements in public health and environmental conservation.

Furthermore, the integration of smart technologies such as sensors, data analytics, and automation presents significant opportunities to enhance the efficiency and sustainability of sand filtration systems. Real-time monitoring capabilities enable proactive maintenance and optimization, while artificial intelligence algorithms offer insights for predictive maintenance and energy optimization. Automated control systems adjust filtration parameters dynamically, ensuring consistent performance even in the face of changing water quality conditions. Through harnessing the power of these technologies, water treatment projects can operate more effectively, reduce operational costs, and ultimately improve access to safe and clean drinking water for communities around the world.

Conflict of interest

The authors declare no conflict of interest.

References

1. O. B. Adesina, C. William, and E. I. Oke, "Evolution in Water Treatment: Exploring Traditional Self-Purification Methods and Emerging Technologies for Drinking Water and Wastewater Treatment: A Review," World News Nat. Sci., vol. 53, pp. 169–185, 2024.
2. S. M. Rasoolimanesh, N. Badarulzaman, A. Abdullah, and M. Behrang, "How governance influences the components of sustainable urban development?," J. Clean. Prod., vol. 238, p. 117983, 2019.
3. P. M. de Souza, A. K. Mahapatra, and E. P. da Silva, "Emerging Technologies for Water Decontamination: Ensuring Safe and Clean Water," Emerg. Trends Technol. Water Manag. Conserv., pp. 35–86, 2025.
4. J. Livingston, "Water scarcity & health in urban Africa," Daedalus, vol. 150, no. 4, pp. 85–102, 2021.
5. P. H. Gleick, "Water in crisis: paths to sustainable water use," Ecol. Appl., vol. 8, no. 3, pp. 571–579, 1998.
6. T. A. Tella, B. Festus, T. D. Olaoluwa, and A. S. Oladapo, "Water and wastewater treatment in developed and developing countries: Present experience and future plans," in Smart Nanomaterials for Environmental Applications, Elsevier, 2025, pp. 351–385.
7. K. Abdiyev et al., "Review of slow sand filtration for raw water treatment with potential application in less-developed countries," Water, vol. 15, no. 11, p. 2007, 2023.
8. M. A. Elliott, F. A. DiGiano, and M. D. Sobsey, "Virus attenuation by microbial mechanisms during the idle time of a household slow sand filter," Water Res., vol. 45, no. 14, pp. 4092–4102, 2011.
9. J. Stauber et al., "Application of bioavailability models to derive chronic guideline values for nickel in freshwaters of Australia and New Zealand," Environ. Toxicol. Chem., vol. 40, no. 1, pp. 100–112, 2021.
10. E. Yogafanny, A. Utami, E. A. Kristiati, and W. W. Nandari, "Rapid lava sand filtration for decentralized produced water treatment system in old oil well wonocolo," in Journal of the Civil Engineering Forum, 2018, vol. 5, no. 2, pp. 113–122.
11. P. Du and R. Eisenberg, "Catalysts made of earth-abundant elements (Co, Ni, Fe) for water splitting: recent progress and future challenges," Energy Environ. Sci., vol. 5, no. 3, pp. 6012–6021, 2012.V. Saxena, "Water quality, air pollution, and climate change: investigating the environmental impacts of industrialization and urbanization," Water, Air, Soil Pollut., vol. 236, no. 2, p. 73, 2025.
12. E. Arcipowski, J. Schwartz, L. Davenport, M. Hayes, and T. Nolan, "Clean water, clean life: Promoting healthier, accessible water in rural Appalachia," J. Contemp. Water Res. Educ., vol. 161, no. 1, pp. 1–18, 2017.
13. C. Hutete and M. M. Sibanda, "Water service provision and social equity in a South African rural district municipality," Africa's Public Serv. Deliv. Perform. Rev., vol. 10, no. 1, p. 12, 2022.
14. K. Ellis and W. E. Wood, "Slow sand filtration," Crit. Rev. Environ. Sci. Technol., vol. 15, no. 4, pp. 315–354, 1985.
15. E. Guchi, "Review on slow sand filtration in removing microbial contamination and particles from drinking water," Am. J. Food Nutr., vol. 3, no. 2, pp. 47–55, 2015.
16. D. K. Emslie, "Analysis of a sand filtration system with common filter media and innovative materials." University of British Columbia, 2019.
17. N. Khan, Z. A. Tabasi, J. Liu, B. H. Zhang, and Y. Zhao, "Recent advances in functional materials for wastewater treatment: from materials to technological innovations," J. Mar. Sci. Eng., vol. 10, no. 4, p. 534, 2022.
18. D. H. Manz and P. Eng, "BioSand water filter technology household concrete design," Retrieved Oct., vol. 22, p. 2008, 2007.
19. G. Tamakhu and I. M. Amatya, "Turbidity removal by rapid sand filter using anthracite coal as capping media," J. Innov. Eng. Educ., vol. 4, no. 1, pp. 69–73, 2021.
20. J. Wang, D. de Ridder, A. van der Wal, and N. B. Sutton, "Harnessing biodegradation potential of rapid sand filtration for organic micropollutant removal from drinking water: a review," Crit. Rev. Environ. Sci. Technol., vol. 51, no. 18, pp. 2086–2118, 2021.
21. M. Coccia and E. Bontempi, "New trajectories of technologies for the removal of pollutants and emerging contaminants in the environment," Environ. Res., vol. 229, p. 115938, 2023.

22. M. Ateia, H. Wei, and S. Andreescu, “Sensors for emerging water contaminants: overcoming roadblocks to innovation,” Environ. Sci. Technol., vol. 58, no. 6, pp. 2636–2651, 2024.
23. C. O. Lee, R. Boe-Hansen, S. Musovic, B. Smets, H.-J. Albrechtsen, and P. Binning, “Effects of dynamic operating conditions on nitrification in biological rapid sand filters for drinking water treatment,” Water Res., vol. 64, pp. 226–236, 2014.
24. BNHP, “The Blue Nile health project,” Sudan, 1998.
25. R. Rashid, I. Shafiq, P. Akhter, M. J. Iqbal, and M. Hussain, “A state-of-the-art review on wastewater treatment techniques: the effectiveness of adsorption method,” Environ. Sci. Pollut. Res., vol. 28, no. 8, pp. 9050–9066, 2021.
26. S. Satyam and S. Patra, “Innovations and challenges in adsorption-based wastewater remediation: A comprehensive review,” Heliyon, vol. 10, no. 9, 2024.
27. R. Tobias and M. Berg, “Sustainable use of arsenic-removing sand filters in Vietnam: psychological and social factors.” ACS Publications, 2011.
28. H. A. Lukacs, “From design to implementation: innovative slow sand filtration for use in developing countries.” Massachusetts Institute of Technology, 2002.
29. C. Zinn et al., “How are water treatment technologies used in developing countries and which are the most effective? An implication to improve global health,” J. Public Heal. Emerg., vol. 2, 2018.
30. P. A. Clark, C. A. Pinedo, M. Fadus, and S. Capuzzi, “Slow-sand water filter: Design, implementation, accessibility and sustainability in developing countries,” Med. Sci. Monit. Int. Med. J. Exp. Clin. Res., vol. 18, no. 7, p. RA105, 2012.
31. B. L. S. Freitas et al., “A critical overview of household slow sand filters for water treatment,” Water Res., vol. 208, p. 117870, 2022.
32. J. K. Maiyo, S. Dasika, and C. T. Jafvert, “Slow sand filters for the 21st century: A review,” Int. J. Environ. Res. Public Health, vol. 20, no. 2, p. 1019, 2023.
33. J. T. O’Connor and T. L. O’Connor, “Removal of microorganisms by rapid sand filtration,” H2O’C Eng. Columbia, Missouri, pp. 23–35, 2001.
34. T. Rahaman, M. I. Hossain, and S. Mousumi Akter, “Advanced Filtration Techniques in Environmental Engineering,” Rahaman, T. Hossain, MI, Sathi, MA Adv. Filtr. Tech. Environ. Eng. Am. J. Sci. Learn. Dev., vol. 3, no. 2, pp. 22–32, 2024.
35. Y. Nakazawa, Y. Matsui, Y. Hanamura, K. Shinno, N. Shirasaki, and T. Matsushita, “Identifying, counting, and characterizing superfine activated-carbon particles remaining after coagulation, sedimentation, and sand filtration,” Water Res., vol. 138, pp. 160–168, 2018.
36. K. Byeon and E. Jang, “Comparison of operational efficiency between sand-filtration process and membrane filtration process,” J. Korean Soc. Water Wastewater, vol. 31, no. 6, pp. 529–537, 2017.
37. S. T. Summerfelt, “Engineering design of modular and scalable recirculating systems containing circular tanks, microscreen filters, fluidized-sand biofilters, cascade aerators, and low-head or u-tube oxygenators,” AES Tech. Sess. 1 Open Pap., p. 1, 1996.
38. M. J. Adelman et al., “Stacked filters: novel approach to rapid sand filtration,” J. Environ. Eng., vol. 138, no. 10, pp. 999–1008, 2012.
39. J. W. Wouters and K. J. Agema, “RFID technology as cost-effective real-time process monitoring and control tool in continuous sand filters: two case studies,” HIC, 2018.
40. H. Y. El Sayed, M. Al-Kady, and Y. Siddik, “Management of smart water treatment plant using iot cloud services,” in 2019 International Conference on Smart Applications, Communications and Networking (SmartNets), 2019, pp. 1–5.
41. S. Narendran, B. R. Yakkala, J. C. R. Azariah, and A. Sivagami, “Combined Artificial Intelligence and Fuzzy logic Model for the process of groundwater treatment for irrigation and drinking purposes using filtration and other membrane process,” in IOP Conference Series: Earth and Environmental Science, 2021, vol. 945, no. 1, p. 12040.
42. J. Khurana, P. Choudhary, L. Gupta, R. Dutta, and A. Patwal, “Design of IoT based smart in-pipe drain monitoring system,” in AIP Conference Proceedings, 2022, vol. 2451, no. 1, p. 20050.
43. A. M. Bendaoud, K. A. Haddou, A. M. Taleb, and N. O. Belaidi, “Assessment of subsurface riverbed clogging by fine sediments in a semi-arid catchment of north-western Algeria,” African J. Aquat. Sci., vol. 46, no. 1, pp. 54–66, 2021.
44. J. Bové, J. Pujol, G. Arbat, M. Duran-Ros, F. R. de Cartagena, and J. Puig-Bargués, “Environmental assessment of underdrain designs for a sand media filter,” Biosyst. Eng., vol. 167, pp. 126–136, 2018.
45. D. F. Ogeleka and M. C. Emegha, “Effectiveness and Risk Assessment of Bio Sand Filters (BSF) technique in Rural Water Purification,” Chem. Res. J., no. 5(6), pp. 110–124, 2020.
46. S. Islam, “Performance of existing pond sand filters and design modification,” 2002.