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MEMBRANE TECHNOLOGY FOR LOW-COST SMALL WATER TREATMENT IN DEVELOPING COUNTRIES

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ABSTRACT

The use of membrane technology for inexpensive small-scale water treatment in developing nations is examined in this research study. The project aims to address the pressing need for easily available, safe drinking water in areas where centralized water systems are frequently insufficient or non-existent. The most efficient and cost-effective methods for decentralized water treatment are determined by this report through a review of the literature, an analysis of case studies, and an evaluation of different membrane technologies, including Reverse Osmosis (RO), microfiltration (MF), ultrafiltration (UF), and nanofiltration (NF). Important results show that Gravity-Driven Membrane (GDM) systems are very beneficial in terms of sustainability, upkeep, and cost. Nevertheless, issues like membrane fouling and the requirement for prior treatment continue to exist. The study concludes with actionable recommendations for scaling up decentralized membrane systems, emphasizing the critical role of both public *and private sector engagement. Future opportunities in membrane innovation are discussed, highlighting the promise of advanced, adaptive solutions to improve water accessibility across underserved populations.*

Keywords: Membrane Technology, Decentralized Water Treatment, Gravity Driven Filtration, Water Accessibility, Low-Cost Systems

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1. Introduction

One of the biggest problems in many developing nations is access to clean, safe drinking water. Access to safely managed drinking water remains a critical challenge in many low- and middle-income countries, with over two billion individuals globally lacking reliable and safe water services. This deficit significantly contributes to the prevalence of waterborne illnesses, imposing a substantial public health burden. The situation is further compounded by the accelerating impacts of climate change, rapid urbanization, and population growth, all of which exert mounting pressure on existing water infrastructure and limited freshwater resources [1].

Drinking water that is safe is crucial for good health, personal hygiene, and general well-being. It is essential for cooking, drinking, and keeping things hygienic. Lack of consistent access to clean water in developing nations causes serious health problems like cholera and diarrhea, which are especially dangerous for young people and can have high death rates [2]. Because it takes longer to get water from frequently unsafe sources, the time and effort spent doing so limit opportunities for learning and productive activities, which in turn impede economic development [3]. Membrane technology is an effective solution for water treatment, capable of removing contaminants such as pathogens, chemicals, and particulates. Various membrane processes, including microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO), provide different levels of filtration suitable for various water treatment needs [4]. These technologies are particularly beneficial for decentralized water systems, which are essential in areas lacking reliable centralized infrastructure [5,6]. Recent advancements in membrane technology, marked by significant cost reductions and the emergence of gravity-driven filtration systems, have substantially improved the feasibility of deploying these technologies in cost-sensitive and decentralized applications.

Thus, this study investigates the viability of membrane technology as a cost-effective solution for small-scale water treatment systems in developing regions. It aims to evaluate the performance and economic feasibility of various membrane-based approaches for decentralized water purification. The research also examines real-world examples of successful deployments in resource-limited contexts to derive actionable insights. In addressing the practical and systemic challenges associated with the implementation of membrane technologies, it proposes context-sensitive strategies for overcoming technical, financial, and institutional barriers. Furthermore, it provides evidence-based recommendations to guide policymakers, engineers, and local stakeholders in improving water quality and access through membrane-based interventions. Finally, the study explores emerging trends and technological innovations that could enhance the scalability and efficiency of membrane solutions for potable water supply in underserved communities. By addressing these dimensions, the research contributes to global initiatives aimed at expanding access to safe drinking water, thereby supporting improvements in public health, socio-economic development, and overall well-being in low-income settings.

2. Methodology

This study employs a mixed-methods research design integrating a comprehensive literature review, qualitative case study analysis, and thematic synthesis to evaluate the applicability of membrane technologies for low-cost, small-scale water treatment systems in developing countries. The objective was to systematically assess the technical performance, cost-effectiveness, implementation challenges, and social acceptability of various membrane-based water treatment approaches in decentralized settings.

An extensive literature review was conducted to identify, extract, and synthesize peer-reviewed articles, technical reports, and relevant publications from academic databases such as Scopus, Web of Science, and Google Scholar. Selection criteria included: (i) relevance to membrane technology for drinking water treatment; (ii) focus on applications in developing countries; (iii) publication within the last 15 years to ensure technological currency; and (iv) methodological quality, prioritizing empirical and field-based studies. The review encompassed four primary membrane types: MF, UF, NF, and RO, as well as hybrid and gravity-driven membrane systems. Complementing the literature analysis, three qualitative case studies from rural regions in South Africa, Kenya, and Sri Lanka were examined in depth to understand real-world implementation outcomes. These cases were selected based on diversity in geographic context, technology type, and community scale. For each case, project documentation and evaluation reports were analyzed to extract insights on system performance, community engagement, maintenance practices, and sustainability factors.

Data from the literature and case studies were thematically analysed using a structured coding framework. Themes were developed inductively, focusing on technical efficiency, cost, maintenance burden, energy requirements, and community-level factors. A comparative matrix was constructed to evaluate membrane technologies against key performance indicators. The analysis also included an assessment of policy and institutional mechanisms supporting or hindering deployment. This multi-layered methodology ensures triangulation of findings, enhances the robustness of the conclusions, and provides a well-rounded basis for the practical recommendations offered in this study. All findings were synthesized to inform a framework for selecting and implementing membrane-based decentralized water systems in low-resource environments.

2.1 Decentralized water systems and their importance

Water treatment and distribution systems that function independently of centralized infrastructure are referred to as decentralized water systems [7]. These systems are made to supply drinkable water straight to locations that require it, like individual homes, small towns, or designated facilities. Since centralized water supply infrastructure is frequently insufficient, unstable, or non-existent in developing nations, decentralized water systems are especially crucial. They provide a scalable and adaptable way to increase access to clean drinking water, particularly in peri-urban and rural areas where centralized systems might not be practical because of logistical, financial, or geographic limitations [8].

2.2 Comparative Evaluation of Membrane-Based Decentralized Technologies

Membrane technologies are water purification methods that use semi-permeable membranes to separate contaminants from water based on particle size, pressure, or chemical properties [9]. Membrane-based technologies play a pivotal role in decentralized water treatment systems by providing reliable and energy-efficient solutions for small-scale applications [10]. Microfiltration is a membrane-driven water treatment process that employs porous membranes with pore sizes typically ranging from 0.1 to 10 µm, enabling the effective separation of suspended solids and microorganisms from aqueous solutions [11]. MF systems operate under low pressure, offering advantages in terms of operational simplicity and cost-efficiency, thereby rendering them particularly suitable for implementation in resource-limited settings. However, due to their limited ability to remove dissolved contaminants and pathogens, MF units are commonly integrated with complementary treatment technologies to ensure compliance with potable water quality standards [12].

Ultrafiltration (UF) is a pressure-driven membrane separation technique that effectively excludes viruses, bacteria, colloids, and macromolecular organic compounds based on size exclusion and molecular weight cut-off [13]. UF technologies offer superior filtration performance compared to MF, particularly in the removal of microbial pathogens. Owing to their high separation efficiency, operational simplicity, and cost-effectiveness, UF membranes have been widely adopted in municipal water treatment, decentralized systems, and point-of-use applications [14]. Their compatibility with gravity-driven configurations and minimal reliance on chemical additives render them especially advantageous in off-grid and rural water supply contexts. Nanofiltration (NF) membranes, characterized by nominal pore diameters between 0.001 and 0.01 μm, offer selective permeability that enables the effective rejection of divalent ions, larger monovalent ions, low-molecular-weight organic compounds, viruses, and emerging micropollutants, positioning them as a versatile solution in advanced water and wastewater treatment applications [9]. NF membranes offer a versatile solution for water treatment applications, particularly effective in water softening, selective pesticide removal, and the attenuation of colour and odor. Compared to RO, NF systems exhibit a looser membrane structure that permits partial retention of divalent salts and organic solutes, allowing beneficial ions or nutrients to remain in the treated water, an advantage in contexts such as agricultural reuse [15]. While NF operates under moderate pressure and demonstrates improved energy efficiency relative to RO, it remains more cost-intensive and maintenance-demanding than MF or UF, rendering it more appropriate for decentralized or specialized pollutant-targeting systems [16].

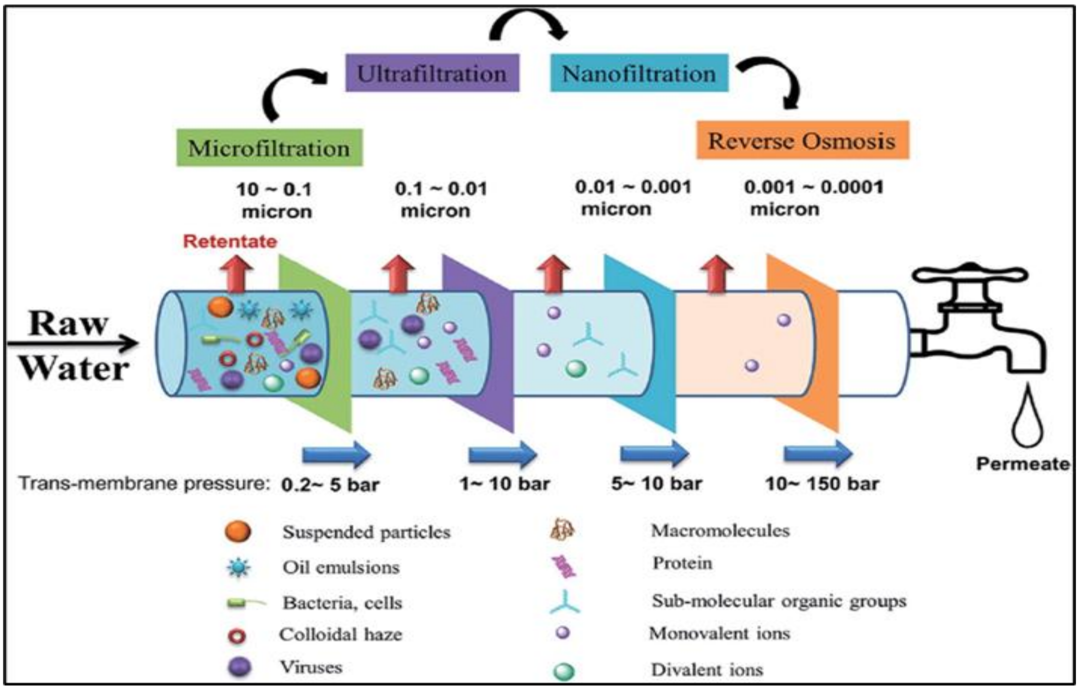

Fig 1: Schematic Representation of Membrane Filtration Processes for Water Purification

Reverse osmosis (RO) represents a leading-edge membrane separation technology that employs semi-permeable membranes to effectively eliminate a wide spectrum of contaminants from water, including dissolved salts, heavy metals, microbial agents, and organic pollutants, thereby rendering it highly applicable for seawater desalination, advanced wastewater treatment, and the production of ultra-pure water [17]. Due to its superior separation efficiency and broad-spectrum contaminant rejection capabilities, reverse osmosis (RO) has become a critical technology for water treatment, particularly in regions challenged by salinity or severe pollution [17].

Table 1: Comparative Characteristics of various membrane-based decentralized technologies

Technology	**Pore Size**	**Removes**	**Typical Use**
Microfiltration (MF)	0.1 – 10 µm	Bacteria, suspended solids, and protozoa	Pre-treatment, household filters
Ultrafiltration (UF)	0.01 – 0.1 µm	Viruses, colloids, bacteria, and turbidity	Potable water, decentralized systems
Nanofiltration (NF)	0.001 – 0.01 µm	Divalent ions, organic molecules	Water softening, industrial use

Reverse Osmosis (RO)	< 0.001 µm	Salts, heavy metals, and all contaminants	Desalination, high-purity water

3. Types of Centralized Systems

Point-of-Use (POU) Systems: Point-of-use (POU) water treatment technologies are decentralized systems that purify water directly at the site of consumption, predominantly within individual households. Engineered to process limited volumes adequate for drinking and culinary purposes, these systems encompass household filtration units, compact purifiers, and small-scale membrane technologies. Due to their cost-effectiveness, ease of installation, and low operational complexity, POU systems represent a viable solution for ensuring safe water access at the domestic level [18].

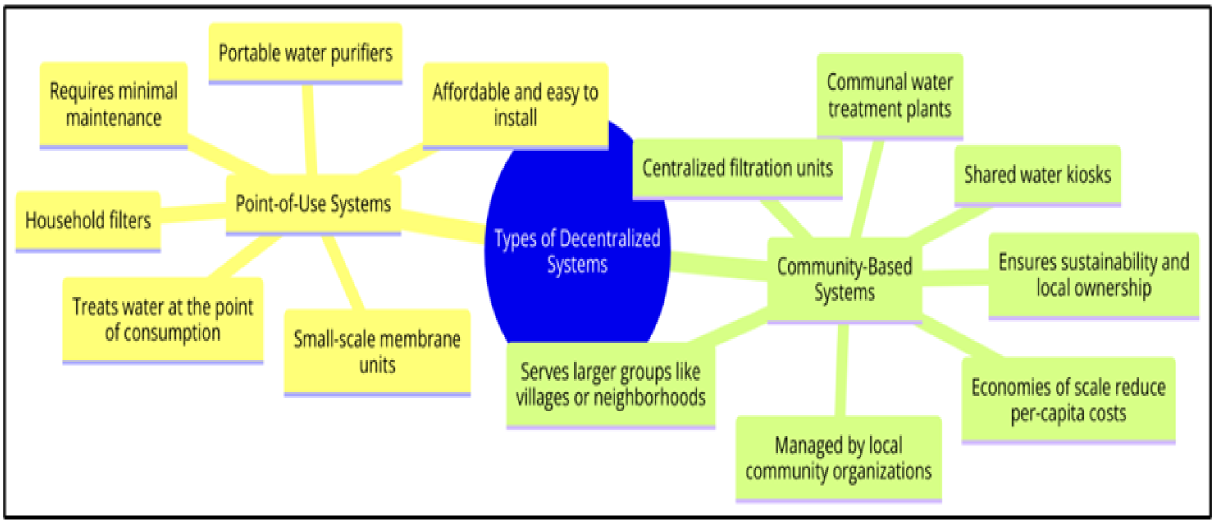

Fig 2: Types of Decentralized Systems

Community-Based Systems: Community-based systems serve a larger group of users, such as a village or a neighbourhood. These systems are designed to treat and distribute water to multiple households or a small community. Examples include communal water treatment plants, shared water kiosks, and centralized filtration units within a community. Community-based systems benefit from economies of scale, which can reduce per-capita costs and improve overall efficiency. They are often managed by local community organizations or cooperatives, which helps ensure sustainability and local ownership [19].

3.1 Key features of Decentralized Systems

Flexibility and Scalability: Decentralized water systems are scalable and adaptable to the unique requirements of a locality. Depending on the population's size and the resources available, they are easily scaled up or down. Because of its adaptability, it can be gradually expanded upon and adjusted to changing conditions, like population growth or seasonal variations in the availability of water [20].

Cost-Effectiveness: In areas with dispersed populations, decentralized systems may prove to be more economical than centralized ones. The systems can be installed gradually, and the initial capital cost is typically less [21]. Decentralized systems also frequently require less infrastructure for the distribution of water, which lowers overall costs.

Independence from Central Infrastructure: Decentralized systems operate independently of centralized water supply networks, which is crucial in regions where such infrastructure is lacking or unreliable. They provide a reliable source of potable water even in remote or underserved areas, reducing dependence on distant or intermittent central supplies [22].

Reduced Vulnerability to Contamination: By treating water closer to the point of use, decentralized systems minimize the risk of contamination during distribution. Centralized systems can be vulnerable to contamination due to aging infrastructure, leaks, and long distribution pipelines. Decentralized systems ensure that treated water is delivered directly to the end-users, maintaining its quality and safety [23,24].

Community Engagement and Ownership: Decentralized water systems often involve local communities in their operation and maintenance. This fosters a sense of ownership and responsibility, which can enhance the sustainability and effectiveness of the system. Community involvement also facilitates local capacity building and empowers residents to manage their own water resources.

Environmental Benefits: Decentralized systems can have lower environmental impacts compared to large-scale centralized systems. They often use fewer chemicals and less energy, particularly when integrated with renewable energy sources like solar power. Additionally, decentralized systems can promote water conservation and sustainable water management practices within communities.

3.2 Gravity-Drive Membrane systems and its benefits

Gravity-driven membrane systems (GDMS) represent a promising low-cost solution for decentralized water treatment in developing countries. These systems rely on gravity rather than external pressure to drive water through the membrane, significantly reducing the energy requirement and operational costs. They are particularly well-suited for areas with limited access to electricity or other energy sources [25]. GDMS are particularly well-suited for remote communities, rural areas, and regions affected by disasters, where centralized water infrastructure is either unavailable or prone to failure. Their straightforward design, coupled with their modular structure, enables easy scalability and flexibility to accommodate varying environmental conditions [26].

Despite the promising potential of GDMS, significant challenges persist in optimizing its performance for extended use in decentralized environments. Factors such as membrane fouling can severely compromise both the durability and operational efficiency of the system, hindering its long-term effectiveness. The study by Liu et al. (2025) [27] shown that integrating pre-treatment strategies, such as biological filtration or using hybrid systems like gravity-driven membrane bioreactors, can significantly reduce fouling and enhance system performance. Additionally, the scalability and modularity of GDMS make them particularly suited for decentralized water treatment systems [28]. These systems can be easily adapted to the specific needs of a community, with the ability to expand or contract based on population size or varying water demands.

Research by Ding et al. (2017) [29] emphasize that integrating GDMS systems with renewable energy sources, such as solar power, enhances their applicability in remote regions that lack access to conventional power grids. Furthermore, Advances in membrane materials, including the creation of coatings with enhanced resistance to fouling and the development of membranes with higher throughput capabilities, are progressively enhancing the robustness and reliability of Gas-Driven Membrane Separation (GDMS) for decentralized water treatment applications [30]. These advancements, combined with their environmental benefits, underscore the growing potential of GDMS in contributing to sustainable water management in underserved regions.

Some of the benefits of GDMS offers some benefits which are 1) Energy Efficiency: Gravity-driven systems do not require electricity or pumps, making them highly energy-efficient. This feature is crucial for remote areas where power supply is unreliable or non-existent. 2) Low Operational Costs: The absence of energy costs and the minimal maintenance requirements of gravity-driven systems contribute to their low operational costs. This makes them an affordable option for low-income communities. 3) Simplicity and Ease of Use: Gravity-driven systems are made to be easy to use and require little technical know-how to maintain and operate. Because of their simplicity, local communities can effectively manage the systems. 4) Reliability and Durability: These systems are more dependable and long-lasting because they are constructed with sturdy materials and straightforward mechanics. This guarantees a steady supply of pure water for a long time. 5) Scalability and Flexibility: Gravity-driven membrane systems can be easily scaled to meet the needs of different populations, from individual households to small communities. Their modular design allows for gradual expansion as the demand for clean water grows.

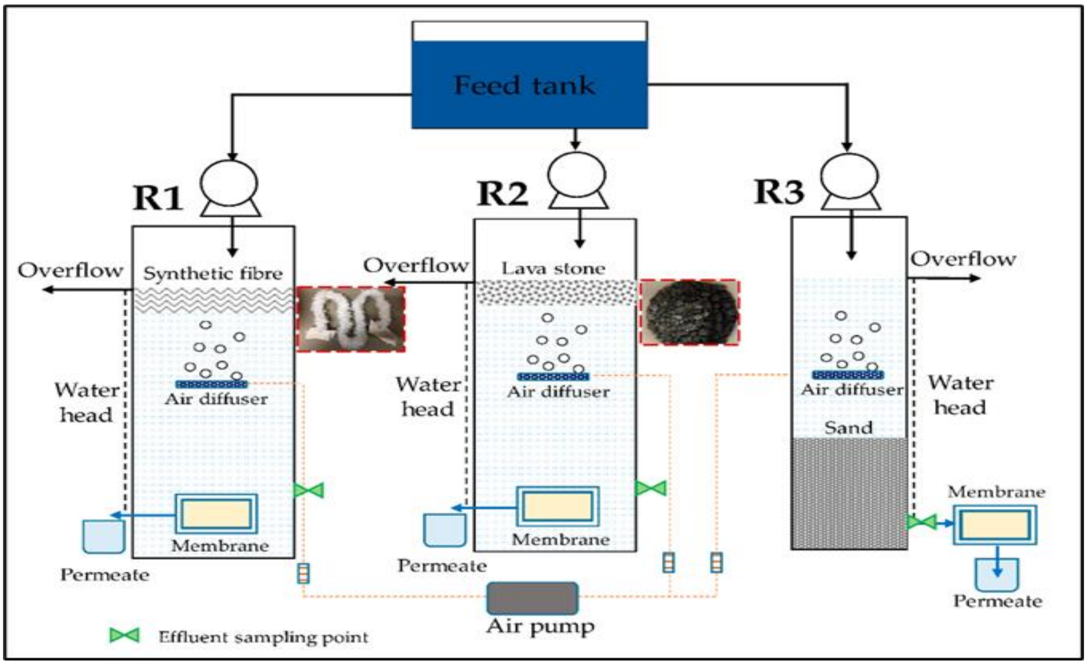

Fig 3 Gravity-Driven Membrane Systems

4. Case Studies

The study by Momba et al. (2009) [8] Conducted a conducted across 55 small-scale water treatment plants within five district municipalities of the Eastern Cape province in South Africa, aiming to assess water quality and disinfection practices in rural water systems. The findings indicated that most plants utilized traditional treatment methods, including coagulation, flocculation, sedimentation, filtration, and chlorination, but were still unable to meet the required water quality standards. Although some plants achieved acceptable turbidity levels, microbial contamination was widespread, with only 18% of the plants adhering to microbiological quality standards for drinking water. Key challenges identified included insufficient operator training, inadequate technical knowledge, poor communication, and ineffective chemical dosing, all contributing to the plant's inability to consistently deliver safe drinking water. The study further revealed that bacterial regrowth in distribution systems led to compromised water quality at the point of consumption. Despite the widespread use of chlorination, many plants struggled to maintain adequate chlorine residuals, resulting in high concentrations of total and faecal coliforms in the treated water. These issues were exacerbated by a lack of proper maintenance and the absence of standardized operational procedures. In conclusion, the study emphasized the need for significant improvements in operator education, system management, and regular quality monitoring, alongside enhanced communication and technical support at the local government level to ensure a sustainable and safe water supply.

Further, the study by Maryna Peter (n.d.) [31] aimed at developing an innovative household water treatment solution utilizing gravity-driven membrane (GDM) technology. The Gravity-Driven Membrane Disinfection (GDMD) project was rigorously tested in Kenya, where the α-prototype of the GDMD filter was evaluated under real-world conditions. This field study focused on assessing the performance and effectiveness of the GDM system in purifying water sourced from local supplies, which often contained significant levels of bacteria and other pollutants. The experiment involved filtering water with elevated concentrations of Escherichia coli to determine the system's efficacy in providing safe drinking water. Feedback from local users led to refinements in the system, ensuring it was tailored to the specific requirements of Kenyan households, with an emphasis on affordability, ease of use, and low maintenance.

The research by Ranasinghe et al. (2023) [32] developed an innovative solar water distillation system to tackle the water purification challenges in Sri Lanka, particularly in its dry and coastal areas. These regions are plagued by water contamination, mainly due to elevated levels of heavy metals such as arsenic and cadmium, which are further compounded by the excessive use of agrochemicals. To address the pressing need for clean drinking water, the study introduced a novel solar distillation unit incorporating several design advancements. The system featured a double-sloped solar still, a flat-plate solar collector for preheating the water, and added innovations such as heat-retaining sand layers under the still and sponge cubes to expand the evaporation surface area and reduce surface tension. Through testing five distinct configurations, the researchers found that combining these enhancements increased the system's efficiency by 138%, outperforming traditional models. This breakthrough holds promise for improving water quality and alleviating water scarcity issues in similar regions worldwide, where solar energy can be harnessed for water purification.

5. Challenges and Solutions

Common Challenges in Implementing Membrane Technology in Developing Countries are ***Cost:*** The initial cost of purchasing and installing membrane systems can be prohibitively high for many communities in developing countries. The expenses related to the procurement, transportation, and installation of membrane units often surpass the financial capabilities of local populations and governments. ***Maintenance:*** Maintenance of membrane systems requires regular cleaning, replacement of filters, and technical expertise. In remote or underserved areas, the lack of trained personnel and access to spare parts can lead to system failures and reduced effectiveness. ***Sustainability:*** Ensuring the long-term sustainability of membrane systems poses a significant challenge. Factors such as membrane fouling, energy requirements, and the need for ongoing financial investment can impact the durability and reliability of these systems. ***Water Quality Variability:*** The variability in the quality of raw water sources, including high levels of turbidity, organic matter, and microbial contamination, can affect the performance of membrane systems. Membrane fouling and clogging are common issues that arise due to poor water quality. ***Social and Cultural Barriers:*** Acceptance of new technologies can be hindered by social and cultural factors. Communities may be resistant to adopting unfamiliar systems, and there may be a lack of awareness about the benefits and proper use of membrane technology.

The proposed solution to overcome these challenges is ***Cost Reduction Strategies:*** To mitigate the high initial costs, governments and NGOs can provide subsidies or financial assistance programs. Additionally, the use of locally available materials and the development of low-cost membrane manufacturing techniques can help reduce expenses. Implementing modular systems that can be scaled up gradually can also spread out the financial burden over time. ***Training and Capacity Building:*** Establishing training programs for local technicians and community members can ensure proper maintenance and operation of membrane systems. Partnerships with technical schools and vocational training centres can help build local expertise. Creating a network of service providers who can supply spare parts and perform maintenance can further support system sustainability. ***Enhancing Sustainability:*** The energy costs of membrane systems can be decreased by integrating renewable energy sources, like solar or wind power. It's also critical to create strong pre-treatment procedures to lessen fouling and increase membrane longevity. System reliability can be improved by community involvement in the form of regular maintenance schedules and monitoring. ***Addressing Water Quality Issues:*** Implementing pre-treatment steps, such as sedimentation, coagulation, and sand filtration, can improve the quality of water entering the membrane system. Developing membranes with higher resistance to fouling and better performance under variable water conditions can also address these challenges. ***Community Engagement and Education:*** Including the community in the planning and implementation phases from the beginning can help boost acceptance and a sense of ownership for the technology. Social and cultural barriers can be addressed through educational campaigns that emphasize the advantages of membrane systems and provide training on how to use them properly.

5.1 Future Prospects

1. Advanced Membrane Materials:

Research is ongoing to develop advanced membrane materials that offer superior performance and durability. Innovations such as nanocomposite membranes, which incorporate nanoparticles into the membrane matrix, are showing promise in enhancing permeability, selectivity, and resistance to fouling.[6] These advanced materials can significantly improve the efficiency and lifespan of membrane systems.

2. Hybrid Membrane Systems:

Membrane technology combined with other water treatment techniques is becoming more and more popular in hybrid systems. Comprehensive treatment solutions can be achieved, for instance, by combining membrane filtration with sophisticated oxidation or biological treatment techniques. These hybrid systems enhance overall water quality by efficiently handling a greater variety of contaminants.

3. Energy-Efficient Membrane Processes:

The development of energy-efficient membrane processes is a key trend. Innovations such as forward osmosis, which utilizes natural osmotic pressure differences, and pressure-retarded osmosis, which generates energy during the water treatment process, are being explored. These energy-efficient processes can reduce operational costs and make membrane technology more sustainable.

4. Smart Membrane Systems:

The integration of smart technologies with membrane systems is an emerging trend. Smart membranes equipped with sensors and automation capabilities can monitor water quality in real-time, detect fouling, and optimize operation parameters. These intelligent systems can enhance the reliability and efficiency of water treatment processes.

5.2 Potential Advancements and Innovations

1. Graphene-Based Membranes:

Graphene, a material known for its exceptional strength and conductivity, is being explored for use in membrane technology. Graphene-based membranes have the potential to provide ultra-fast water filtration while maintaining high selectivity for contaminants. This innovation could revolutionize water treatment by offering highly efficient and robust membrane systems.

2. Antifouling and Self-Cleaning Membranes:

Research is focused on developing antifouling and self-cleaning membranes that can maintain their performance over longer periods. Techniques such as surface modification, incorporation of antimicrobial agents, and the use of stimuli-responsive materials are being investigated. These advancements can reduce maintenance requirements and extend the lifespan of membrane systems.

3. Modular and Portable Membrane Units:

The design of modular and portable membrane units is an area of innovation that can enhance the accessibility and scalability of membrane technology. These units can be easily transported, assembled, and adapted to different water treatment needs, making them ideal for emergency response and remote communities.

4. Solar-Powered Membrane Systems:

Harnessing solar energy to power membrane systems is a promising advancement. Solar-powered desalination and filtration units can provide sustainable water treatment solutions in off-grid areas. Continued research in this area aims to improve the efficiency and cost-effectiveness of solar-powered membrane systems.

5.3 Future Research Directions and Areas of Improvement

Future research in membrane technology should prioritize enhancing the durability of membrane materials to endure harsh operating conditions, improving their resistance to chemical degradation, mechanical stress, and biofouling, thus extending their lifespan. Another critical area of focus is reducing the costs associated with membrane production, installation, and maintenance, through the development of cost-effective manufacturing techniques, the use of locally sourced materials, and innovative financing models, particularly for developing countries. Additionally, research should aim to advance pre-treatment processes that effectively remove suspended solids, organic matter, and other foulants to protect membranes and prolong their operational life. Increased field testing and pilot projects are also necessary to assess the performance of innovative membrane technologies in real-world settings, providing valuable insights into system reliability, user acceptance, and long-term sustainability. Finally, research should examine the policy and regulatory frameworks required to support the adoption of membrane technology, identifying implementation barriers, creating standards for membrane performance, and advocating for policies that promote sustainable water treatment solutions.

6. Conclusion

The research paper underscores the critical role of membrane technologies in tackling water treatment issues, especially in regions with limited access to centralized systems, such as many developing countries. The study highlights the potential of gravity-driven membrane systems (GDMS) and various other membrane-based technologies, including microfiltration, ultrafiltration, nanofiltration, and reverse osmosis, as viable decentralized solutions for water purification. These technologies offer significant advantages, such as cost-effectiveness, energy efficiency, and scalability; however, challenges like membrane fouling, high initial investment costs, and the necessity for efficient pre-treatment methods persist. The paper suggests that overcoming these challenges requires advances in membrane material development, strategies for reducing operational costs, improvements in pre-treatment techniques, and increased field testing via pilot programs. Additionally, the integration of renewable energy sources like solar power, along with enhancing community engagement and capacity-building efforts, is essential to ensuring the long-term viability and acceptance of these systems. Lastly, the study emphasizes the need for a supportive policy and regulatory environment to promote the widespread adoption of membrane technology, contributing to global initiatives aimed at improving public health and driving socio-economic development in underserved areas.

References

[1] Arnal, J. M., García-Fayos, B., Verdú, G., & Rodrigo, I. (2001). Design of a membrane-based desalination plant for irrigation. Desalination, 138(1-3), 93-101. https://doi.org/10.1016/S0011-9164(01)00259-4

[2] Basu, R., & Main, H. (2001). Water management in India: Performance and challenges. Journal of Cleaner Production, 9(1), 1-12. https://doi.org/10.1016/S0959-6526(00)00035-7

[3] Brick, T., Primrose, B., Chandrasekhar, R., Roy, S., Muliyil, J., & Kang, G. (2004). Water contamination in urban south India: Household storage practices and their implications for water safety and health. International Journal of Hygiene and Environmental Health, 207(5), 473-480. https://doi.org/10.1078/1438-4639-00313

[4] Cath, T. Y., Childress, A. E., & Elimelech, M. (2006). Forward osmosis: Principles, applications, and recent developments. Journal of Membrane Science, 281(1-2), 70-87. https://doi.org/10.1016/j.memsci.2006.05.048

[5] Ciochetti, D. A., & Metcalf, R. H. (1984). Pasteurization of naturally contaminated water with solar energy. Applied and Environmental Microbiology, 47(2), 223-228. https://doi.org/10.1128/AEM.47.2.223-228.1984

[6] Gadgil, A. (1998). Drinking water in developing countries. Annual Review of Energy and the Environment, 23(1), 253-286. https://doi.org/10.1146/annurev.energy.23.1.253

[7] Xiao Y, Fang L, Hipel KW. Centralized and Decentralized Approaches to Water Demand Management. *Sustainability*. 2018; 10(10):3466. https://doi.org/10.3390/su10103466

[8] Momba, M. N. B., Tyafa, Z., & Brouckaert, B. M. (2005). Safe drinking water still a dream in rural areas of South Africa. Case Study: The Eastern Cape Province. Water SA, 31(4), 663-670. https://doi.org/10.4314/wsa.v31i4.5128

[9] Akinyemi, B. T., Ogundele, O. D., & Afolabi, A. B. (2023). Advancements in sustainable membrane technologies for enhanced remediation and wastewater treatment: A comprehensive review. *Acadlore Transactions on Geosciences*, *2*(4), 196-207. http://dx.doi.org/10.56578/atg020402

[10] Capodaglio, A. G., Cecconet, D., & Molognoni, D. (2016, September). Small communities decentralized wastewater treatment: Assessment of Technological Sustainability. In *Proceedings, 13th IWA Specialized Conference on Small Water and Wastewater Systems & 5th IWA Specialized Conference on Resources-Oriented Sanitation. Athens, Greece*.

[11] Madaeni, S. S. (1999). The application of membrane technology for water disinfection. *Water Research*, *33*(2), 301-308. https://doi.org/10.1016/S0043-1354(98)00212-7

[12] Fane, A. G., Wang, R., & Hu, M. X. (2015). Synthetic membranes for water purification: status and future. *Angewandte Chemie International Edition*, *54*(11), 3368-3386. https://doi.org/10.1002/anie.201409783

[13] Charcosset, C. (2016). Ultrafiltration, microfiltration, nanofiltration and reverse osmosis in integrated membrane processes. *Integrated membrane systems and processes*, 1-22. https://doi.org/10.1002/9781118739167.ch1

[14] Huttinger A, Dreibelbis R, Roha K, Ngabo F, Kayigamba F, Mfura L, Moe C. Evaluation of Membrane Ultrafiltration and Residual Chlorination as a Decentralized Water Treatment Strategy for Ten Rural Healthcare Facilities in Rwanda. *International Journal of Environmental Research and Public Health*. 2015; 12(10):13602-13623. https://doi.org/10.3390/ijerph121013602

[15] Mohammad, A. W., Teow, Y. H., Ang, W. L., Chung, Y. T., Oatley-Radcliffe, D. L., & Hilal, N. (2015). Nanofiltration membranes review: Recent advances and future prospects. *Desalination*, *356*, 226-254. https://doi.org/10.1016/j.desal.2014.10.043

[16] Yang J, Monnot M, Ercolei L, Moulin P. Membrane-Based Processes Used in Municipal Wastewater Treatment for Water Reuse: State-Of-The-Art and Performance Analysis. *Membranes*. 2020; 10(6):131. https://doi.org/10.3390/membranes10060131

[17] Greenlee, L. F., Lawler, D. F., Freeman, B. D., Marrot, B., & Moulin, P. (2009). Reverse osmosis desalination: water sources, technology, and today's challenges. *Water research*, *43*(9), 2317-2348. https://doi.org/10.1016/j.watres.2009.03.010

[18] Mintz, E. D., Bartram, J., Lochery, P., & Wegelin, M. (2001). Not just a drop in the bucket: Expanding access to point-of-use water treatment systems. American Journal of Public Health, 91(10), 1565-1570. https://doi.org/10.2105/AJPH.91.10.1565

[19] Cherunya PC, Janezic C, Leuchner M. Sustainable Supply of Safe Drinking Water for Underserved Households in Kenya: Investigating the Viability of Decentralized Solutions. *Water*. 2015; 7(10):5437-5457. https://doi.org/10.3390/w7105437

[20] Leigh NG, Lee H. Sustainable and Resilient Urban Water Systems: The Role of Decentralization and Planning. *Sustainability*. 2019; 11(3):918. https://doi.org/10.3390/su11030918

[21] Sobsey, M. D. (2002). Managing water in the home: accelerated health gains from improved water supply (pp. 7-70). Geneva: World Health Organization. https://iris.who.int/handle/10665/67319

[22] Tsegaye S, Missimer TM, Kim J-Y, Hock J. A Clustered, Decentralized Approach to Urban Water Management. *Water*. 2020; 12(1):185. https://doi.org/10.3390/w12010185

[23] van Duuren D, van Alphen H-J, Koop SHA, de Bruin E. Potential Transformative Changes in Water Provision Systems: Impact of Decentralised Water Systems on Centralised Water Supply Regime. *Water*. 2019; 11(8):1709. https://doi.org/10.3390/w11081709

[24] Pasciucco, F., Pecorini, I., & Iannelli, R. (2022). Planning the centralization level in wastewater collection and treatment: a review of assessment methods. *Journal of Cleaner Production*, *375*, 134092. https://doi.org/10.1016/j.jclepro.2022.134092

[25] Schumann, P., Andrade, J. O., Jekel, M., & Ruhl, A. S. (2020). Packing granular activated carbon into a submerged gravity-driven flat sheet membrane module for decentralized water treatment. *Journal of Water Process Engineering*, *38*, 101517. https://doi.org/10.1016/j.jwpe.2020.101517

[26] Nguyen, T. T., Nguyen, D. V., Salmani, H. J., Nguyen, H. V., Fareed, H., Nguyen, P. T. T. H., & Bui, X. T. (2025). Gravity-driven membrane filtration: Fouling control and its application for water and wastewater treatment. In *Low Cost Water and Wastewater Treatment Systems: Conventional and Recent Advances* (pp. 327-346). Elsevier. https://doi.org/10.1016/B978-0-443-23662-4.00005-6

[27] Liu, W., Yang, Y., Lu, Z., Li, T., Li, X., & Sun, Y. (2025). Impact of variable hydrostatic pressure and intermittent operation on filtration performance and biofouling layer in gravity-driven membrane system for practical decentralized water supply. *Separation and Purification Technology*, *355*, 129668. https://doi.org/10.1016/j.seppur.2024.129668

[28] Othman NH, Alias NH, Fuzil NS, Marpani F, Shahruddin MZ, Chew CM, David Ng KM, Lau WJ, Ismail AF. A Review on the Use of Membrane Technology Systems in Developing Countries. *Membranes*. 2022; 12(1):30. https://doi.org/10.3390/membranes12010030

[29] Ding, A., Wang, J., Lin, D., Tang, X., Cheng, X., Li, G., ... & Liang, H. (2017). In situ coagulation versus pre-coagulation for gravity-driven membrane bioreactor during decentralized sewage treatment: Permeability stabilization, fouling layer formation and biological activity. *Water research*, *126*, 197-207. https://doi.org/10.1016/j.watres.2017.09.027

[30] Pronk, W., Ding, A., Morgenroth, E., Derlon, N., Desmond, P., Burkhardt, M., ... & Fane, A. G. (2019). Gravity-driven membrane filtration for water and wastewater treatment: a review. *Water research*, *149*, 553-565. https://doi.org/10.1016/j.watres.2018.11.062

[31] Peter, M. (2015). Gravity-driven membrane disinfection for household water treatment. *Eawag: Dübendorf, Switzerland*.

[32] Ranasinghe, M. K. N. K., Kahandage, P. D., Kosgollegedara, E. J., & Weerasooriya, G. V. T. V. (2023). Design and implementation of an advanced solar water distillation system for the efficient purification of contaminated water into clean drinking water. *Journal of Dry Zone Agriculture*, *9*(2). http://dx.doi.org/10.4038/jdza.v9i2.74

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