ISSN: 2976-7687

Journal of Waste Management & Recycling Technology

SCIENTIFIC Research and Community

Review Article

Open Access

Rainwater Treatment and Reuse Using Membrane Technology

Siva Sathyanarayana Movva

President, Innovations for Water Corp, USA

ABSTRACT

The concept and acceptance of water reuse has steadily increased, particularly in regions that rely on unpredictable water supplies and in industrial applications that benefit from a secondary source of recycled process water. Due to the current global water scarcity crisis, addressing the pressing need for ensuring water safety and sustainable usage has become paramount. Rainwater, as a clean energy source, presents a crucial avenue for consideration in terms of treatment and reuse methods. Membrane technology, known for its compact size, effective treatment capabilities, and affordability, has emerged as a favored approach for wastewater treatment and is increasingly gaining attention in rainwater treatment. This review aims to examine past research on rainwater treatment using membrane technology, identifying key research gaps to guide future exploration and technological advancements. It provides a comprehensive overview of various membrane technologies employed in rainwater treatment, analyzing post-treatment water quality and practical feasibility. Membrane fouling is recognized as a primary challenge, yet ongoing research is delving into surface modifications and process optimizations to mitigate this issue. Moreover, the quest for novel membrane materials and the investigation of diverse technology combinations for rainwater treatment remain active areas of study. The potential future applications of these efforts hold promise for addressing water scarcity concerns.

***Corresponding author**

Siva Sathyanarayana Movva, President, Innovations for Water Corp, USA.

Received: January 05, 2024; **Accepted:** January 11, 2024; **Published:** January 22, 2024

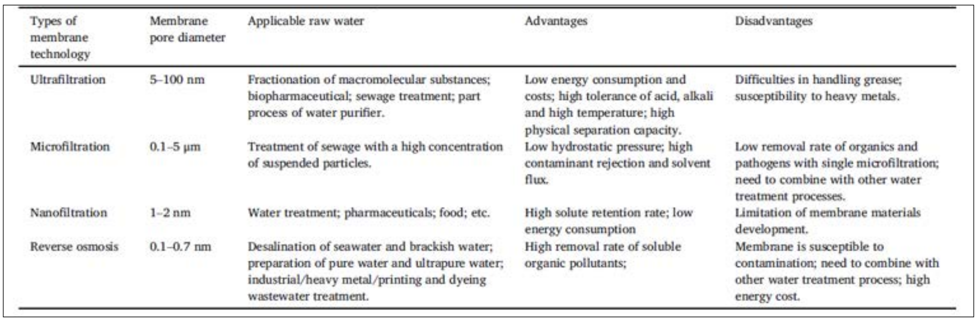
Keywords: Rainwater Treatment, Membrane Technology, Water Quality, Practical Feasibility

Introduction

Due to global water scarcity, climate change, and population growth, there's a rising demand for water. Predictions suggest a 40% global water deficit by 2030. This drives exploration of sustainable water management. Surface and groundwater face challenges like pollution and exploitation limitations. Groundwater contamination, e.g., arsenic, worsens the problem. Rainwater, a renewable resource, gains traction as an alternative. Rainwater harvesting (RWH) systems alleviate scarcity and strain on urban drainage. Examples like domestic RWH and greywater systems in Ireland replace significant public water usage. Integrating RWH with urban agriculture shows health, social, and sustainability benefits. Rainwater typically meets WHO standards but can change upon contact with storage or catchment surfaces. Rooftop rainwater faces contamination risks from particulate matter and roofing materials. Research suggests Total Suspended Solids (TSS) concentration differs based on roofing material, with concrete roofs having higher levels. However, TSS levels in rainwater usually remain below drinking water standards. Rainwater tank NO3 levels typically stay around 1 mg/L, meeting WHO standards, as NO2 levels are below 3 mg/L. However, NH4+ concentrations from various roofing materials fail Chinese drinking water standards. Roof runoff can also be tainted by bird and rodent droppings, raising nitrogen, phosphorus, and microorganism levels. Rainwater from wooden shingle tile roofs contains elevated TOC, NO3, and SO4^2-. Coliforms are detectable, requiring treatment per WHO standards. Urban areas may introduce heavy metals, while rural areas may have pesticide residues. Road pavement materials affect runoff quality, with contamination risks including organic compounds and pathogens like Pseudomonas aeruginosa and Cryptosporidium. Treatment is crucial for safe rainwater use.

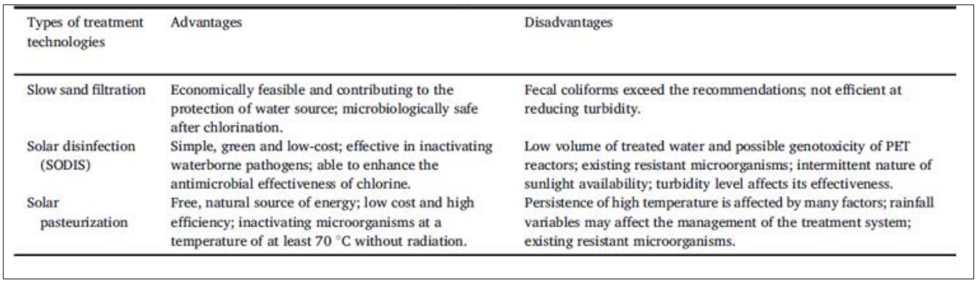
Membrane processes are widely used in water treatment due to their small footprint, high efficiency, and capacity for permeated water, making them advantageous for distributed rainwater collection systems. These technologies maximize rainwater treatment to meet reuse standards and facilitate household purification. Various membrane types and characteristics are outlined in Table 1. Membrane systems were notably effective during the 2000 Sydney Olympic Games, where polypropylene hollow fiber microfiltration (MF) membranes pretreated rainwater by removing pollutants and pathogens before desalination with RO techniques. The resulting water was chlorinated for toilet flushing. Membrane technology, with its efficacy, simplicity, and compatibility with other systems, holds promise for emergency water supply. Research indicates its capability to meet or exceed domestic water quality standards, fully utilizing rainwater. Dispersed membrane systems, primarily MF, UF, or RO-based, are emerging, with UF systems already on the market. However, membrane fouling remains a significant challenge, although measures such as chemical cleaning and pretreatment can mitigate it effectively.

Table 1: Types and Characteristics of Different Membrane Technologies



Types of membrane technology	Membrane pore diameter	Applicable raw water	Advantages	Disadvantages
Ultrafiltration	5–100 nm	Fractionation of macromolecular substances; biopharmaceutical; sewage treatment; part process of water purifier.	Low energy consumption and costs; high tolerance of acid, alkali and high temperature; high physical separation capacity.	Difficulties in handling grease; susceptibility to heavy metals.
Microfiltration	0.1–5 µm	Treatment of sewage with a high concentration of suspended particles.	Low hydrostatic pressure; high contaminant rejection and solvent flux.	Low removal rate of organics and pathogens with single microfiltration; need to combine with other water treatment processes.
Nanofiltration	1–2 nm	Water treatment; pharmaceuticals; food; etc.	High solute retention rate; low energy consumption	Limitation of membrane materials development.
Reverse osmosis	0.1–0.7 nm	Desalination of seawater and brackish water; preparation of pure water and ultrapure water; industrial/heavy metal/printing and dyeing wastewater treatment.	High removal rate of soluble organic pollutants;	Membrane is susceptible to contamination; need to combine with other water treatment process; high energy cost.

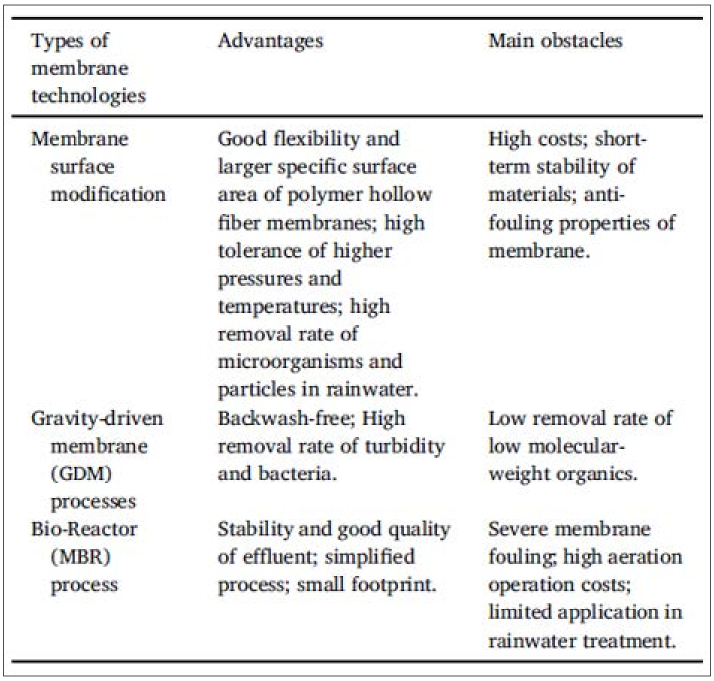
Table 2: Characteristics and Trends of other Rainwater Treatment Technologies



Types of treatment technologies	Advantages	Disadvantages
Slow sand filtration	Economically feasible and contributing to the protection of water source; microbiologically safe after chlorination.	Fecal coliforms exceed the recommendations; not efficient at reducing turbidity.
Solar disinfection (SODIS)	Simple, green and low-cost; effective in inactivating waterborne pathogens; able to enhance the antimicrobial effectiveness of chlorine.	Low volume of treated water and possible genotoxicity of PET reactors; existing resistant microorganisms; intermittent nature of sunlight availability; turbidity level affects its effectiveness.
Solar pasteurization	Free, natural source of energy; low cost and high efficiency; inactivating microorganisms at a temperature of at least 70 °C without radiation.	Persistence of high temperature is affected by many factors; rainfall variables may affect the management of the treatment system; existing resistant microorganisms.

Characteristics of Efficient Membrane Technology Field

This part presents traditional and novel membrane technologies and their application in rainwater treatment. Characteristics of novel membrane technologies for rainwater treatment are summarized in Table 3.



Types of membrane technologies	Advantages	Main obstacles
Membrane surface modification	Good flexibility and larger specific surface area of polymer hollow fiber membranes; high tolerance of higher pressures and temperatures; high removal rate of microorganisms and particles in rainwater.	High costs; short-term stability of materials; anti-fouling properties of membrane.
Gravity-driven membrane (GDM) processes	Backwash-free; High removal rate of turbidity and bacteria.	Low removal rate of low molecular-weight organics.
Bio-Reactor (MBR) process	Stability and good quality of effluent; simplified process; small footprint.	Severe membrane fouling; high aeration operation costs; limited application in rainwater treatment.

Table 3: Characteristics of Novel Membrane Technologies for Rainwater Treatment

Application of Traditional Membrane Technology

Advancements in materials and chemical engineering have broadened the application of membrane technology from traditional sewage treatment to specialized and unconventional contaminated sewage treatment, ensuring water security. Common membrane technologies like reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF), and microfiltration (MF) are categorized based on pore diameter, tailored to different pollutants. For instance, MF membranes have pore diameters of 0.1–5 µm, while UF membranes range from 5–100 nm. Membrane selection depends on permeability and particle removal through physical separation, offering advantages like smaller footprint, reduced operation control, and lower chemical usage for drinking water treatment. Filtration performance relies on raw water quality and application purpose; simpler processes suffice for lower quality demands, while advanced treatments are necessary for higher quality standards.

Microfiltration

Traditional membrane separation tech is widely used in rainwater collection and treatment. Microfiltration (MF) effectively treats sewage with high suspended particle concentration, removing solids, bacteria, etc., at low pressure. However, MF alone has limitations in rainwater reuse, often requiring surface modification or other treatments. Dobrowsky et al. tested a PVA nanofiber membrane/activated carbon column system, achieving over 99% reduction in E. coli and other bacteria. Yet, potential pathogens may remain, necessitating further optimization. Direct membrane filtration for rainwater treatment is still in early stages but advancing. As MF membrane costs decrease, future research should focus on enhancing filtration and anti-pollution performance, potentially as a pretreatment method for rainwater treatment

Ultrafiltration

Ultrafiltration (UF) surpasses MF in filtration accuracy, effectively removing bacteria, suspended solids, colloids, and harmful substances from water. Widely applied in rainwater management, UF membranes repel macromolecular substances. Oosterom et al. discovered that rainwater, low in mineral elements, doesn't need desalination. MF or UF technology removes colloids and suspended solids, disinfects, and produces demineralized water at lower energy and cost than RO. Farago et al. confirmed UF plant feasibility for rainwater management, environmentally friendly and value-generating. Ortega et al. combined MF and UF membranes for rainwater treatment, showing high removal efficiency for various pollutants. UF withstands high temperatures and chemical resistance, but faces challenges with grease and heavy metals, requiring further research. Pretreatment steps like coagulation are crucial to mitigate membrane fouling. Future efforts should focus on developing high-performance UF membranes and enhancing functions through modification and coupling.

Nanofiltration

NF membranes offer a balance between UF and RO, boasting high solute retention and low energy usage. They excel in purifying surface and underground water, often meeting potable standards. Studies have successfully applied NF to rainwater treatment, showcasing its efficacy in removing organic and inorganic contaminants. For instance, Kose-Mutlu demonstrated NOM removal rates exceeding 99%. Yu et al. explored using NF alongside other methods for rainwater conversion to drinking water, reducing pathogens significantly. Despite advancements, further research is needed, especially in utilizing polymer materials and nanotechnology for enhanced NF membranes.

Reverse Osmosis (RO) and Forward Osmosis (FO)

RO technology uses pressure to drive water molecules through a dense membrane, separating solutions and removing impurities like salts, organic matter, and microorganisms up to 99.5%. Widely adopted in rainwater treatment, it's central to systems like Singapore's, where 30% of water demand is met by RO-based NEWater plants, expected to rise to 55% by 2060. RO effectively removes organic pollutants and suspended solids, but requires maintenance to prevent fouling and corrosion, which can compromise effectiveness. Its compact design leads to strong interactions between water, ions, and membrane molecules, increasing energy costs. Membrane fouling is a significant challenge during treatment. In contrast to reverse osmosis (RO), forward osmosis (FO) is a filtration process driven by osmotic pressure, avoiding the use of energy drives. Wang et al. studied FO's potential in treating and reusing rainwater for cooling water makeup. The FO membrane's water flux was 1.75 L/(m2•h) at 23°C, reducing to 0.65 L/(m2•h) when TDS concentration in the draw solution was diluted 4 times. Even at 50°C, the flux was 10 times higher than at 3°C, showing potential for cooling water dilution and reuse. However, FO technology needs further optimization to address challenges like reverse solute diffusion, concentration polarization, and membrane fouling. Conversely, RO technology in rainwater applications will focus on membrane module and process development.Both membrane processes have high energy costs due to osmotic pressure changes and membrane fouling, necessitating additional pressure and maintenance. Future research aims to develop new membrane materials, enhance process efficiency, reduce energy consumption, and mitigate fouling, promising significant advancements in this technology field.

Membrane Fabrication and Surface Modification

In water treatment, membrane technology is effective for separation, dependent on pore structure and surface properties. Surface modification is crucial for controlling selectivity, flux, and anti-fouling. Hydrophilicity enhances performance, counteracting hydrophobicity-related fouling. Polysulfone membrane modification improves water treatment capacity, fostering nanocomposite membrane innovation. Research focuses on polymer-based nanocomposites, addressing challenges in large-scale production. Polymer hollow fiber membranes offer flexibility and larger surface area, but surface modification complexities exist. Flat-sheet membranes are convenient for preparation but may have limitations in certain applications. Reinforced hollow fiber membranes show promise in various processes. Future research should prioritize low-cost, stable materials and monitor anti-fouling properties for consolidation in this field. Metal membrane filtration is emerging as a promising technology for purifying rainwater. Compared to polymer membranes, metal membranes offer greater durability against pressure, temperature, shock, and chemical oxidation, resulting in longer service life. Kim et al. introduced a novel method using metal membranes to treat contaminated rainwater, combined with ozone injection to prevent membrane fouling. Experimental findings showed significant reduction in coliforms, with 1 μm metal membranes achieving over 98% removal. Combining ozone treatment with metal membranes resulted in nearly complete coliform inactivation. Metal membranes also showed high efficiency in particle rejection, indicating their effectiveness in reducing microorganisms and particles in rainwater. Furthermore, Kim et al. demonstrated the feasibility of using metal membranes for greywater and rainwater treatment, proving their potential for non-potable water production inside buildings. Although research on metal membranes has been limited due to high costs and technological constraints, further exploration is essential to control operational expenses and enhance rainwater utilization. Ceramic membrane technology, with its superior hydrophilicity and anti-fouling properties compared to polymer membranes, holds promise for water treatment applications. However, its high initial cost hampers widespread adoption. Despite its potential, ceramic membranes are rarely used in rainwater treatment, necessitating research on cost-effective materials and fouling mechanisms. Pilot-scale evaluations and economic analyses are crucial for ensuring the sustainable implementation of ceramic membrane technology. In addition to the above technologies, further in-depth research on forwarding osmosis membranes, anion exchange membranes, poly (vinylidene fluoride) membranes, polyether sulfone membranes, etc. are underway in the field of water treatment. It's expected for these emerging technologies to be fully utilized in the field of rainwater harvesting and reuse.

GDM Process

Gravity-driven membrane (GDM) filtration processes, incorporating UF and MF membranes, are gaining attention for surface water and wastewater treatment. GDM operates via gravity flow in dead-end filtration mode, maintaining constant permeation volume without backwashing or chemical cleaning until hydrostatic pressure reaches 40–100 mbar. Flux stability is attributed to a biological filtering layer on the membrane surface, enhancing turbidity and microorganism removal. Studies by Ding et al. on rainwater treatment revealed effective removal of bacteria and turbidity, although DOC removal was limited. Further research is suggested for improving removal of low molecular-weight organics and stable flux values. Ding et al. enhanced GDM efficiency by combining granular activated carbon (GAC) pretreatment with the process, achieving significant removal of turbidity, DOC, heavy metals, and organic matter. Adsorption by GAC increased DOC removal efficiency to 37%. Tang et al. compared the performance of fresh and saturated GAC/GDM systems. The study found that combining GAC and GDM effectively removes dissolved organic compounds, achieving higher and more stable permeation flux compared to traditional GDM, suitable for decentralized and emergency water supply. However, drawbacks include reduced flux due to particle obstruction and denser filter cake. The static placement of GAC layer on the membrane suggests room for development. Ceramic membranes offer stable hydraulic performance, as demonstrated by GDCM systems, showing promise for ultra-low pressure filtration. GDCM microfiltration effectively treats roof rainwater, meeting water quality guidelines with stable water flux and no backwashing needed. However, GDCM technology faces challenges such as high costs and limited research in rainwater treatment. The authors suggest GDM combined with GAC has more research prospects than GDCM. In the GDM system, flat membranes offer higher and more stable flux, while hollow fiber membranes provide higher productivity per unit area, especially in limited spaces. This method enhances rainwater quality with high feasibility, saving energy, space, and maintenance costs while omitting backwashing. The resulting biofilm exhibits significant biological activity. The GDM system can be easily integrated with RWH systems, offering sustainability and feasibility. It outperforms conventional MF in low capacity scenarios, making it suitable for decentralized supply. The GDM process has significant application potential, with anticipated further development.

Membrane Bio-Reactor (MBR) Process

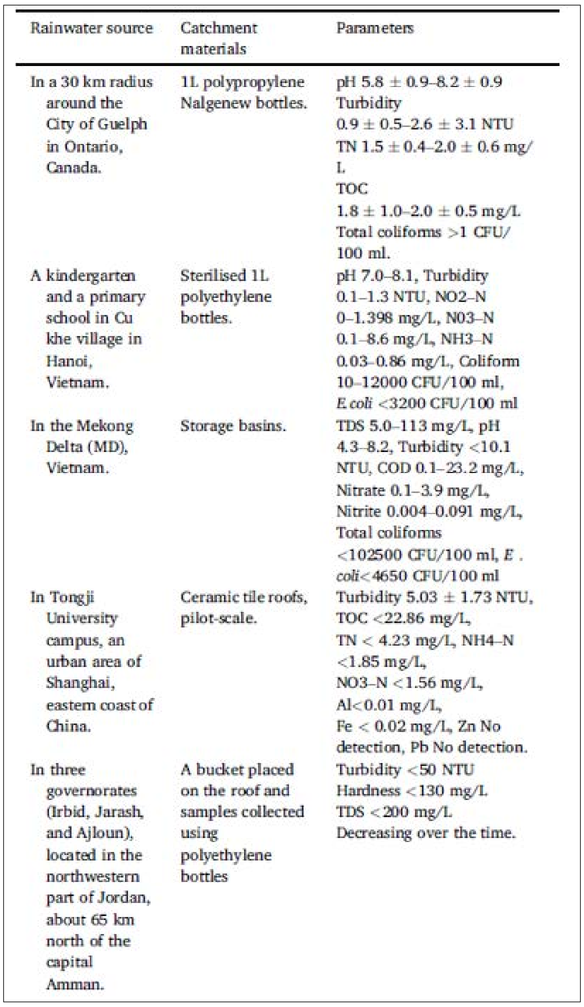
Membrane bioreactors (MBR) are usually combined with membrane separation technology and biodegradation and have been actively employed for municipal and industrial wastewater treatment. Compared with the traditional membrane process or activated sludge process, the main problems during MBR process are severe membrane fouling and high aeration operation costs. The MBR process is commonly used in wastewater treatment plants as a centralized treatment technology. On the contrary, the reused rainwater is usually harvested by the roof or courtyard rainwater storage tanks or reservoirs, and rainwater reuse technology is deemed as a decentralized treatment technology to replenish domestic water. Hence, the former is mainly utilized for municipal wastewater treatment, while it is still in the experimental stage in terms of rainwater reuse currently.

Quality Assessment of Rainwater After Membrane Treatment

Rainwater is an economical and high-quality source, and being taken advantage of can effectively alleviate water shortage. The chemical substance content in rainwater is much lower than that of river water or groundwater normally. Nowadays, rainwater captured by roofs has been utilized as potable and non-potable water sources in many countries. Nevertheless, rainwater has not been widely used as a source of drinking water, domestic washing, or irrigation owing to lack of the capacity to assess water quality quantitatively, such as evaluating the content of microorganisms and chemical substances in the water tank. Therefore, it's crucial to efficiently evaluate the rainwater quality and examine the frequently detected contaminants in rainwater harvesting systems to ensure the quality of rainwater for future quality guidelines. Pollutants and quality parameters of rainwater are summarized in Table 4.

According to the water quality standards required for water quality and effluent, the production and preparation of drinking water and household non-potable water usually need to be achieved through multiple treatment processes, such as coagulation, precipitation, filtration, disinfection, etc., and membrane technology is expected to replace the precipitation, filtration and/or disinfection process to simplify the treatment process, improving technical simplicity and treatment efficiency. Nowadays, researches on rainwater usually focus on roof harvested rainwater and surface runoff rainwater. This part presents the evaluation of rainwater quality in detail and analyzes the quality of rainwater after treatment through membrane technology. The authors will discuss the applicability of membrane technology in rainwater treatment based on the source of rainwater.

Table 4: Pollutants and Quality Parameters of Rainwater



Rainwater source	Catchment materials	Parameters
In a 30 km radius around the City of Guelph in Ontario, Canada.	1L polypropylene Nalgenew bottles.	pH 5.8 ± 0.9–8.2 ± 0.9 Turbidity 0.9 ± 0.5–2.6 ± 3.1 NTU TN 1.5 ± 0.4–2.0 ± 0.6 mg/L TOC 1.8 ± 1.0–2.0 ± 0.5 mg/L Total coliforms >1 CFU/100 ml.
A kindergarten and a primary school in Cu khe village in Hanoi, Vietnam.	Sterilised 1L polyethylene bottles.	pH 7.0–8.1, Turbidity 0.1–1.3 NTU, NO2–N 0–1.398 mg/L, N03–N 0.1–8.6 mg/L, NH3–N 0.03–0.86 mg/L, Coliform 10–12000 CFU/100 ml, *E.coli* <3200 CFU/100 ml
In the Mekong Delta (MD), Vietnam.	Storage basins.	TDS 5.0–113 mg/L, pH 4.3–8.2, Turbidity <10.1 NTU, COD 0.1–23.2 mg/L, Nitrate 0.1–3.9 mg/L, Nitrite 0.004–0.091 mg/L, Total coliforms <102500 CFU/100 ml, *E . coli*< 4650 CFU/100 ml
In Tongji University campus, an urban area of Shanghai, eastern coast of China.	Ceramic tile roofs, pilot-scale.	Turbidity 5.03 ± 1.73 NTU, TOC <22.86 mg/L, TN < 4.23 mg/L, NH4–N <1.85 mg/L, NO3–N <1.56 mg/L, Al<0.01 mg/L, Fe < 0.02 mg/L, Zn No detection, Pb No detection.
In three governorates (Irbid, Jarash, and Ajloun), located in the northwestern part of Jordan, about 65 km north of the capital Amman.	A bucket placed on the roof and samples collected using polyethylene bottles	Turbidity <50 NTU Hardness <130 mg/L TDS <200 mg/L Decreasing over the time.

Physical Analysis

pH

As far as roof rainwater is concerned, regardless of the roof material,the average pH value of rainwater collected from all pilot-scale roofs is within the near-neutral range (pH 6.0–9.0), The pH of pure rainwater may be low due to rainwater acidification caused by atmospheric pollution or spoiled plants. Despins et al. found that the pH of rainwater stored in plastic tanks tended to be slightly acidic, with an average pH of 6.5 at all sites and a minimum pH of 4.8. On the contrary, the average pH of all sites in the concrete rainwater tanks was 7.7, and the maximum pH was 10.2. Under normal circumstances, the natural acidity of rainwater can be neutralized by the alkaline substance from the material of the reservoir, or by adding lime to the plastic container. The pH value of rainwater has no direct effect on drinking and non-drinking water. Therefore, there are few reviews and studies on the pH of membrane technology in the past 20 years. But a low pH value may cause the corrosion of the rainwater collection container, thereby affecting the taste and smell of the effluent after treatment.

Organics

The likelihood of roof rainwater being exposed to pollutants is minimal, resulting in limited organic matter content in rainwater that often complies with potable water standards. The quality of harvested rainwater is predominantly influenced by the surrounding environment. Studies indicate that the removal efficiency of organic matter through the MF process is below 20%. Ding et al. have demonstrated that Dissolved Organic Carbon (DOC) in rainwater isn't effectively eliminated in the GDM process; however, incorporating a Granular Activated Carbon (GAC) layer can improve organic matter removal within the GDM system during the rainwater cycle. Presently, the GDM system is the most extensively researched membrane technology for rainwater treatment, necessitating appropriate enhancement of pretreatment processes for organic matter removal. Regarding the development of membrane technology to treat rainwater, researchers still need to conduct feasibility analysis based on quality criteria and operating conditions.

Heavy Metal

Heavy metals in rainwater are largely derived from human activities, such as the burning of fossil fuels. If surface runoff flows into the receiving water body, it will cause serious ecological risks, so it needs to be effectively treated. The direct leaching of metal components caused by the erosion of the metal plate that collects rainwater is also the reason for the appearance of heavy metals. Lee et al. found that the total aluminum content from the galvanized steel roof was significantly higher than the samples of other roofs in the first flushing tank, and the average concentration of copper in the water samples of the concrete shingle and galvanized steel roof was higher than that of the shingle roof and clay water sample of the tile roof, but neither of them exceeded the recommended level of U.S. Environmental Protection Agency's (USEPA). The content of heavy metals in water and sediments in urban rainwater tanks is usually relatively high and may exceed the level recommended by the guidelines, and the lead content even reaches 35 times the acceptable level of ADWG (2004). It is known that MF and UF technologies have low removal efficiency for heavy metals, while NF has a high removal rate for inorganic salt ions. Therefore, NF and even higher treatment efficiency rainwater technology can be considered as a heavy metal treatment technology.

Biological Analysis

Rainfall on roofs carries microorganisms and contaminants from the air, as well as sedimentary pollutants like bird droppings and fuel emissions. This can lead to high levels of pathogens, including opportunistic ones like Pseudomonas spp., Aeromonas spp., and legionella spp., often found in rainwater tanks used widely in Australia. Concerns over water quality and microbial content, such as elevated E. coli levels and biofilm formation, are growing. Research shows rainwater tank design affects sediment and heavy metal accumulation during rainfall. Metal membrane filters, like 5 mm and 1 mm versions, have proven effective, with >98% removal rates for coliform bacteria and significant particle retention. While complete elimination of microorganisms and pollutants isn't necessary, rainwater quality should be reduced to avoid health risks, often achieved through membrane technology and disinfection. In Ireland, combining membrane systems and disinfection programs ensures safe harvested rainwater, potentially drinkable. These systems remove turbidity and microorganisms but have limited effectiveness against nitrogen and phosphorus, often necessitating additional treatment processes.

Analysis of Viability and Operation Maintenance

With the advancement of urbanization, the water environment is deteriorating and the ecological environment is destructed, and the problem of urban rainwater accumulation has become increasingly prominent. Till now, the shortage of water resources has caused people to regard rainwater and wastewater as a useable resource instead of as a burden Rainwater reuse is still in a stage of rapid development as a novel research field, especially in water-scarce countries. Rainwater reuse will contribute to strengthening flood resilience and reducing the non-point pollution created by a load of surface pollutants, and at the same time, it weakens the impact of pollutants in rainwater runoff on the ecological environment such as rivers and lakes, revealing remarkable economic, ecological and social effects. However, due to the technical limitation, the true costs and benefits have proven to be difficult to assess. The real implementation of an engineering technology requires comprehensive consideration of the influence of many factors. Here we carry on the brief analysis and discussion.

Viability

The implementation of rainwater recycling projects has a significant impact on urban water sources and the improvement of urban water environments. In developing countries, affordable infrastructure is crucial to meeting daily needs, considering the balance between technology costs and benefits. Rainwater industry holds promising development prospects, attracting private investment and potentially forming new industrial chains for sustainable economic growth. Over time, this progress can greatly contribute to urban development. Economic constraints and lack of funds hinder the monetization of environmental benefits, posing challenges to water recycling initiatives. High input and operating costs limit water resources management in rainwater reuse projects, emphasizing the importance of stable and cost-effective solutions like membrane technology. Decentralized membrane treatment systems offer a sustainable alternative to centralized water supply, although widespread adoption remains a challenge. Residents' acceptance of membrane technology, water quality standards, and technological advancement are key considerations for successful implementation. Despite potential long-term benefits, factors like taste preferences and competing technologies such as desalination may restrict rainwater reuse. Enhancing the reliability, affordability, and safety of membrane technology is essential for its widespread adoption and utilization in rainwater treatment.

Operation Maintenance

The water market characteristics influence the need and viability of rainwater reuse systems, but economic and technical factors hinder their development. Regulatory frameworks and current applications are lacking, leading to ineffective resource allocation and oversight methods. Garcia-Montoya et al. proposed an optimization model for water networks in residential areas, addressing cost and freshwater consumption objectives, yet facing geographical limitations and complex implementation. Despite membrane technology's widespread use in water treatment, issues like low filtration efficiency and fouling persist. The GDM process offers advantages over traditional methods but requires further membrane technology research. Future focus includes developing high-flux membranes to reduce energy consumption and fouling-resistant modules to extend lifespan. Overall, sustainable water resource management requires ongoing exploration and adaptation to diverse factors like technology, society, politics, and geography.

Influence of Membrane Fouling

Membrane technology has advanced in rainwater treatment, but fouling remains a major issue. It's divided into reversible and irreversible types. Reversible fouling can be removed mechanically or chemically, while irreversible fouling requires frequent membrane replacement. Biofouling, a type of bacterial growth, worsens membrane performance, increasing operation costs and shortening membrane lifespan, thus lowering water quality post-treatment. To maintain membrane process economic viability, minimizing fouling is crucial. Researchers propose strategies like pretreating feed water to reduce pollutants and employing membrane monitoring, cleaning, and surface modification. Using Bdellovibrio bacterivorous as pretreatment can notably decrease fouling. MF and UF membranes, aided by aeration and backwashing, are effective for rainwater treatment. The decentralized GDM process is gaining attention for roofing rainwater reuse, showing high particle removal but limited removal of organics and heavy metals. In GDM systems, cake layer formation is the main cause of membrane fouling. A bio-fouling layer containing EPS (polysaccharides and proteins) forms on the membrane surface, with ATP and EPS levels determining membrane permeate flux and filtration performance. Traditional backwash methods may not suffice due to this unique fouling mechanism. Short-periodic backwash attempts have been made to restore membrane permeability, with studies suggesting shorter HRT (e.g., 27 hours) as optimal. However, periodic backwash, effective in pressurized UF, isn't recommended for GDM systems as it increases filter cake resistance, worsening filtration. Adding a GAC layer to GDM filters enhances organic matter removal by concentrating them on the GAC layer, though it negatively impacts membrane flux, exacerbating fouling. Flushing can mitigate flux reduction, offering optimization potential. PAC adsorption as rainwater membrane filtration pretreatment reduces SDI and MFI values, effectively mitigating membrane fouling. Further research is needed to optimize fouling mitigation methods for sustainable operation.

Challenges for Future Research

Rainwater, an abundant resource, holds significant potential in addressing water scarcity and enhancing urban ecology. However, challenges such as seasonal variability, collection/storage difficulties, technological limitations, and resident reluctance hinder its full utilization. Financial constraints and resident acceptance also impede membrane technology's application in rainwater treatment. Membrane fouling remains a primary obstacle, affecting filtration efficiency and increasing costs. Chemical cleaning helps mitigate fouling, but biofouling persists despite pretreatment. Rainwater characteristics and intensity further influence membrane treatment efficacy. Selection of membrane technology should align with rainwater composition. Despite advancements, research on membrane workload remains insufficient, hampering practical application. Improvement in membrane technology, including reduced costs and enhanced performance, is ongoing. However, traditional single membrane treatment technology still cannot meet people's needs in some cases. Methods to deal with the challenges of membrane technology in rainwater reuse are as follows:

- Strengthen the research on the modeling process of economic benefit analysis or system feasibility analysis to improve scientific and technical operation level of membrane technology.
- Research and develop new anti-fouling membrane materials or components to extend the service life of membrane components, or strengthen research on pretreatment and chemical cleaning to improve operational stability.
- Optimize the membrane process to improve the efficiency of rainwater treatment and solve the problem that the single membrane technology cannot achieve satisfactory treatment results.
- Develop pressure-driven membranes with higher membrane rejection or permeation flux to improve energy utilization and reduce process energy consumption.
- Strengthen the publicity of membrane technology on rainwater reuse and increase the acceptance of residents. The research on membrane surface modification is gradually deepening, and the development and utilization of new materials and synthesis processes will open up new methods for the improvement of membrane performance.

Future research in this field is expected to produce fruitful discoveries and broad prospects.

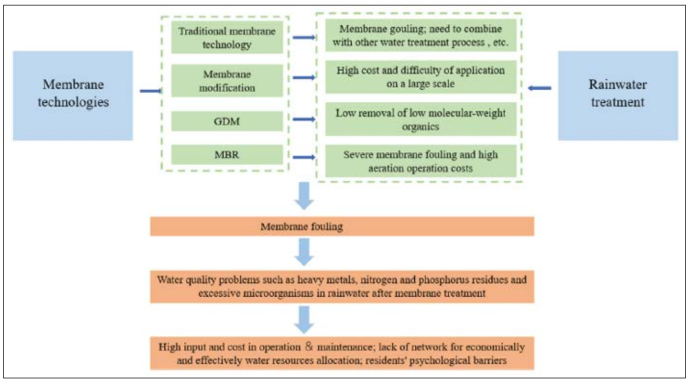


Figure 1: Main Obstacles of Membrane Technologies in the Field of Rainwater Treatment

Conclusion

With the development of rainwater reuse and membrane technology, membrane technology has been gradually applied to rainwater treatment. It is of vital importance to recognize rainwater reuse as a key resource for securing adequate future water supplies and membrane technology will still be in a key position in the future development trend. In this study, we have determined the application status and development direction of membrane technology in rainwater reuse, which is convenient for future technological improvement. Researchers should be fully aware of the need to solve membrane fouling and its high-energy drive requirements. The development of new membrane materials and the improvement of membrane surface properties are still the main research areas in the future. The technical field must be fully considered its cost and benefit analysis, and select the most suitable and reliable technology for further implementation. Researchers should actively explore and exploit applicable membrane treatment components to enhance future treatment efficacy in the field of water treatment [1-59].

Acknowledgment

This research was jointly supported by National Natural Science Foundation of China (No. 51608150), the Open Project of State Key Laboratory of Urban Water Resource and Environment, Harbin Institute of Technology (No. ES201810-02), the Natural Science Foundation of Heilongjiang Province (YQ2020E020); Special support from the China Postdoctoral Fund (2018T110303); and special support from the Heilongjiang Postdoctoral Found (LBH-TZ14).

References

1. M Sgroi, FGA Vagliasindi, P Roccaro (2018) Feasibility, sustainability and circular economy concepts in water reuse. Current Opinion in Environmental Science & Health 2: 20-25.
2. M García-Montoya, A Bocanegra-Martínez, F N apoles-Rivera, M Serna-Gonzalez, JM Ponce-Ortega, et al. (2015) Simultaneous design of water reusing and rainwater harvesting systems in a residential complex. Comput Chem Eng 76: 104-116.
3. R.I McDonald, P Green, D Balk, BM Fekete, C Revenga, et al. (2011) Urban growth, climate change, and freshwater availability. Proc Natl Acad Sci U S A 108: 6312-6317.
4. AK Haritash, CP Kaushik, A Kaushik, A Kansal, AK Yadav (2008) Suitability assessment of groundwater for drinking, irrigation and industrial use in some North Indian villages. Environ Monit Assess 145: 397-406.
5. Y Luo, W Guo, HH Ngo, LD Nghiem, FI Hai, et al. (2014) A review on the occurrence of micropollutants in the aquatic environment and their fate and removal during wastewater treatment. Sci Total Environ 473-474.
6. Q Yang, L Wang, H Ma, K Yu, JD Martin (2016) Hydrochemical characterization and pollution sources identification of groundwater in Salawusu aquifer system of Ordos Basin, China. Environ Pollut 216: 340-349.
7. MA Alim, A Rahman, Z Tao, B Samali, MM Khan, et al. (2020) Suitability of roof harvested rainwater for potential potable water production: a scoping review. J Clean Prod 248: 119226.
8. C Christian Amos, A Rahman, J Mwangi Gathenya (2016) Economic analysis and feasibility of rainwater harvesting systems in urban and peri-urban environments: a review of the global situation with a special focus on Australia and Kenya. Water 8: 149.
9. A Goonetilleke, A Liu, S Managi, C Wilson, T Gardner, et al. (2017) Stormwater reuse, a viable option: fact or fiction?. Econ Anal Pol 56: 14-17.
10. Z Li, F Boyle, A Reynolds (2010) Rainwater harvesting and greywater treatment systems for domestic application in Ireland. Desalination 260: 1-8.
11. CC Amos, A Rahman, F Karim, JM Gathenya (2018) A scoping review of roof harvested rainwater usage in urban agriculture: Australia and Kenya in focus. J Clean Prod 202: 174-190.
12. C Despins, K Farahbakhsh, C Leidl (2009) Assessment of rainwater quality from rainwater harvesting systems in Ontario, Canada. J Water Supply Res Technol 58: 117-134.
13. M Lee, M Kim, Y Kim, M Han (2017) Consideration of rainwater quality parameters for drinking purposes: a case study in rural Vietnam. J Environ Manag 200: 400-406.
14. JY Lee, G Bak, M Han (2012) Quality of roof-harvested rainwater–comparison of different roofing materials. Environ Pollut 162: 422-429.
15. J Mao, B Xia, Y Zhou, F Bi, X Zhang, et al. (2021) Effect of roof materials and weather patterns on the quality of harvested rainwater in Shanghai, China. J Clean Prod 279: 123419.
16. S Angrill, A Petit-Boix, T Morales-Pinzon, A Josa, J Rieradevall, et al. (2017) Urban rainwater runoff quantity and quality - a potential endogenous resource in cities?. J Environ Manag 189: 14-21.
17. W Gwenzi, N Dunjana, C Pisa, T Tauro, G Nyamadzawo (2015) Water quality and public health risks associated with roof rainwater harvesting systems for potable supply: review and perspectives. Sustainability of Water Quality and Ecology 6: 107-118.
18. Q Zhang, X Wang, P Hou, W Wan, R Li, et al. (2014) Quality and seasonal variation of rainwater harvested from concrete, asphalt, ceramic tile and green roofs in Chongqing, China. J Environ Manag 132: 178-187.
19. GD Gikas, VA Tsihrintzis (2012) Assessment of water quality of first-flush roof runoff and harvested rainwater. J Hydrol 466-467.
20. GJ Wilbers, Z Sebesvari, A Rechenburg, FG Renaud (2013) Effects of local and spatial conditions on the quality of harvested rainwater in the Mekong Delta, Vietnam. Environ Pollut 182: 225-232.
21. M Abu-Zreig, F Ababneh, F Abdullah (2019) Assessment of rooftop rainwater harvesting in northern Jordan. Phys Chem Earth 114: 102794.
22. W Ahmed, H Brandes, P Gyawali, JP Sidhu, S Toze (2014) Opportunistic pathogens in roof-captured rainwater samples, determined using quantitative PCR. Water Res 53: 361-369.
23. N Sultana, S Akib, M Aqeel Ashraf, M Roseli Zainal Abidin (2015) Quality assessment of harvested rainwater from green roofs under tropical climate. Desalination and Water Treatment 57: 75-82.
24. B Reyneke, M Waso, S Khan, W Khan (2020) Rainwater treatment technologies: research needs, recent advances and effective monitoring strategies. Current Opinion in Environmental Science & Health 16: 28-33.
25. RF Moreira Neto, ML Calijuri, IdC Carvalho, AdF Santiago (2012) Rainwater treatment in airports using slow sand filtration followed by chlorination: efficiency and costs. Resources Conserv Recycl 65: 124-129.
26. M Peter-Varbanets, C Zurbrügg, C Swartz, W Pronk (2009) Decentralized systems for potable water and the potential of membrane technology. Water Res 43: 245-265.
27. W Wang, Y Zhang, M Esparra-Alvarado, X Wang, H Yang, et al. (2014) Effects of pH and temperature on forward osmosis membrane flux using rainwater as the makeup for cooling water dilution. Desalination 351: 70-76.
28. PCS Roth, D Curtis, Vuong X Diem (2009) Customization and Multistage Nanofiltration Applications for Potable Water, Treatment, and Reuse. Nanotechnology Applications for Clean Water 2014: 107-114.
29. J-M Laîne, C Campos, I Baudin, M-L Janex (2003) Understanding membrane fouling: a review of over a decade of research. Water Supply 3: 155-164.
30. E Obotey Ezugbe, S Rathilal (2020) Membrane technologies in wastewater treatment: a review. Membranes 10: 89.
31. S Hube, M Eskafi, KF Hrafnkelsdottir, B Bjarnadottir, MA Bjarnadottir, et al. (2020) Direct membrane filtration for wastewater treatment and resource recovery: a review. Sci Total Environ 710: 136375.

32. AD Ortega Sandoval, V Barbosa Bri~ao, VM Cartana Fernandes, A Hemkemeier, MT Friedrich (2019) Stormwater management by microfiltration and ultrafiltration treatment. Journal of Water Process Engineering 30: 100453.
33. N García-Vaquero Marín, J Cho, RJ Casta~neda, E Lee, JA Lopez-Ramírez (2013) Sustainable improvement of drinking water quality by nanofiltration powered by renewable energy. Water Supply 13: 309-318.
34. W Pronk, A Ding, E Morgenroth, N Derlon, P Desmond, et al. (2019) Gravity-driven membrane filtration for water and wastewater treatment: a review. Water Res 149: 553-565.
35. SF Anis, R Hashaikeh, N Hilal (2019) Microfiltration membrane processes: a review of research trends over the past decade. Journal of Water Process Engineering 32: 100941.
36. K Glucina, JM Laîne, L Durand-Bourlier (1998) Assessment of filtration mode for the ultrafiltration membrane process. Desalination 118: 205-211.
37. SF Anis, R Hashaikeh, N Hilal (2019) Microfiltration membrane processes: a review of research trends over the past decade. Journal of Water Process Engineering 32: 100941.
38. S Chen, H Sun, Q Chen (2020) Performance of an innovative gravity-driven microfiltration technology for roof rainwater treatment. Environmental Engineering Research 26: 200450.
39. PH Dobrowsky, M Lombard, WJ Cloete, M Saayman, TE Cloete, et al. (2015) Efficiency of microfiltration systems for the removal of bacterial and viral contaminants from surface and rainwater. water air & Soil Pollution 226: 33.
40. W Feng, A Deletic, Z Wang, X Zhang, T Gengenbach, et al. (2019) Electrochemical oxidation disinfects urban stormwater: major disinfection mechanisms and longevity tests. Sci Total Environ 646: 1440-1447.
41. HA Oosterom, DM Koenhen, M Bos (2000) Production of demineralized water out of rainwater: environmentally saving, energy efficient and cost effective. Desalination 131: 345-352.
42. M Farago, S Brudler, B Godskesen, M Rygaard (2019) An eco-efficiency evaluation of community-scale rainwater and stormwater harvesting in Aarhus, Denmark. J Clean Prod 219: 601-612.
43. AD Ortega Sandoval, V Barbosa Bri~ao, VM Cartana Fernandes, A Hemkemeier, MT Friedrich (2019) Stormwater management by microfiltration and ultrafiltration treatment. Journal of Water Process Engineering 30: 100453.
44. SC Mamah, PS Goh, AF Ismail, ND Suzaimi, LT Yogarathinam, et al. (2021) Recent development in modification of polysulfone membrane for water treatment application. Journal of Water Process Engineering 40: 101835.
45. L MZ Kennedy, E Febrina, S Van Hoof, J Shippers (2003) Effects of coagulation on filtration mechanisms in dead-end ultrafiltration. Water Sci Technol Water Supply 3: 109-116.
46. S Al Aani, TN Mustafa, N Hilal (2020) Ultrafiltration membranes for wastewater and water process engineering: a comprehensive statistical review over the past decade. Journal of Water Process Engineering 35: 101241.
47. Y Ren, Y Ma, G Min, W Zhang, L Lv, et al. (2021) A mini review of multifunctional ultrafiltration membranes for wastewater decontamination: additional functions of adsorption and catalytic oxidation. Sci Total Environ 762: 143083.
48. AW Mohammad, YH Teow, WL Ang, YT Chung, DL Oatley-Radcliffe, et al. (2015) Nanofiltration membranes review: recent advances and future prospects. Desalination 356: 226-254.
49. VV Goncharuk, AA Kavitskaya, MD Skil'skaya (2011) Nanofiltration in drinking water supply. J Water Chem Technol 33: 37-54.
50. B K€ose-Mutlu (2020) Natural organic matter and sulphate elimination from rainwater with nanofiltration technology and process optimisation using response surface methodology. Water Sci Technol 83: 580-594.
51. Y Yu, X Chen, Y Wang, J Mao, Z Ding, et al. (2021) Producing and storing self-sustaining drinking water from rainwater for emergency response on isolated island. Sci Total Environ 768: 144513.
52. M Paul, SD Jons (2016) Chemistry and fabrication of polymeric nanofiltration membranes: a review. Polymer 103: 417-456.
53. C Muro, F Riera, M del Carmen Díaz (2012) Membrane separation process in wastewater treatment of food industry, Food Industrial Processes – Methods and Equipment 2012: 253-280.
54. Lefebvre (2018) Beyond NEWater: an insight into Singapore's water reuse prospects. Current Opinion in Environmental Science & Health 2: 26-31.
55. AG Pervov, NA Matveev (2014) Stormwater treatment for removal of synthetic surfactants and petroleum products by reverse osmosis including subsequent concentrate utilization. Petrol Chem 54: 686-697.
56. S Jiang, Y Li, BP Ladewig (2017) A review of reverse osmosis membrane fouling and control strategies. Sci Total Environ 595: 567-583.
57. RLM Jeffrey, R McCutcheon, Menachem Elimelech (2005) A novel ammonia–carbon dioxide forward (direct) osmosis desalination process. Desalination 174: 1-11.
58. W Xu, Q Chen, Q Ge (2017) Recent advances in forward osmosis (FO) membrane: chemical modifications on membranes for FO processes. Desalination 419: 101-116.
59. Y Chun, D Mulcahy, L Zou, IS Kim (2017) A short review of membrane fouling in forward osmosis processes. Membranes 7: 30.