Environmental Science Advances

ROYAL SOCIETY OF CHEMISTRY

CRITICAL REVIEW

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Cite this: *Environ. Sci.: Adv.*, 2025, 4, 189

Innovative approaches to sustainable wastewater treatment: a comprehensive exploration of conventional and emerging technologies

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Received 14th May 2024
Accepted 21st November 2024

DOI: 10.1039/d4va00136b

rsc.li/esadvances

Access to clean water is under threat due to population growth, climate change, and pollution, emphasizing the need for effective wastewater treatment. Wastewater pollutants pose risks to public health and ecosystems, necessitating proper treatment methods. This paper outlines both conventional and emerging technologies for wastewater treatment. Established techniques, such as activated sludge processing, chlorination, and constructed wetlands, are discussed alongside newer methods, such as advanced oxidation, ultraviolet disinfection, membrane bioreactors, reverse osmosis, artificial intelligence optimization, and nanofiltration, which enhance contaminant removal but may incur high costs and energy demands. Integration of renewable energy sources, such as solar, wind, and biomass, into treatment facilities improves efficiency and reduces emissions. The process efficiency can be possibly enhanced through real-time monitoring and automation, while a sustainable and resource-efficient method involves integrating bio-electrochemical systems with constructed wetlands. There are still challenges in sludge handling, land requirements, and long-term system maintenance. Balancing technological solutions, environmental protection, and economic feasibility is essential for sustainable wastewater management, which can ensure continuous access to clean water in the face of increasing demand for this vital resource.

Environmental significance

This work titled "Innovative Approaches to Sustainable Wastewater Treatment: A Comprehensive Exploration of the Conventional and Emerging Technologies" addresses pressing environmental concerns about wastewater treatment and its implications on sustainability. In the face of escalating threats to clean water access due to population growth, climate change, and pollution, effective wastewater treatment has become imperative to safeguard public health and preserve ecosystems. This comprehensive review provides a critical examination of a wide range of wastewater treatment technologies, spanning from established conventional methods to cutting-edge emerging approaches. By exploring techniques, such as activated sludge processing, chlorination, constructed wetlands, advanced oxidation, ultraviolet disinfection, membrane bioreactors, and reverse osmosis, this study illustrates the diverse landscape of options available for contaminant removal. In particular, this study highlights the integration of renewable energy sources, including solar, wind, and biomass, into treatment facilities as a means to enhance the efficiency and reduce environmental impacts. Furthermore, the discussion on real-time monitoring, automation, and controls underscores the role of digital integration in promoting sustainability, water quality, and cost-effectiveness in wastewater treatment processes. Despite the progress made in technological innovation, this study acknowledges persistent challenges in sludge handling, land requirements, and long-term system maintenance. These challenges underscore the need for a balanced approach to wastewater treatment management, which prioritizes environmental preservation, technological advancement, and economic feasibility. Overall, this study provides valuable insights into the discourse on sustainable wastewater management. By synthesizing technological advancements with environmental preservation strategies and economically viable solutions, it offers a holistic understanding of the challenges and opportunities in wastewater treatment. The findings presented in this study hold significance for environmental scientists, policymakers, and practitioners alike, as we collectively strive towards a more sustainable future.

1. Introduction

Water, crucial for life on Earth, is gaining global recognition as a valuable economic and social resource.[1] Although water constitutes 71% of the Earth's surface, only 2.5% is pure, with merely 1% being easily accessible.[2] Freshwater resources that are vital for sustaining life are at risk of being depleted due to population growth, industrialization, climate change, and its role in energy production.[3] This scarcity poses a pressing environmental challenge, emphasizing the need for sustainable water management practices.[4] Water quality is one of the 17 goals of the Sustainable Development Agenda 2030, highlighting the necessity of addressing this issue.[5]

Wastewater originating from domestic, commercial, agricultural, and run-off sources due to human activities primarily

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consists of 99.9% water content and some solids.[6] The composition of wastewater, influenced by chemical components and flow conditions, is crucial in designing wastewater treatment plants, with seasonal variations impacting the flow conditions.[7,8] The evaluation of wastewater quality involves the analysis of various chemical and material components, such as organic and inorganic substances.[9] Key parameters assessed include BOD (biological oxygen demand), TSSs (total suspended solids), COD (chemical oxygen demand), TSs (total solids), VSs (volatile solids), TN (total nitrogen), TP (total phosphorus), pH, and alkalinity.[10]

Although access to sufficient quantities of high-quality water is fundamental to human survival, the escalating global population is putting immense strain on the planet's already scarce freshwater resources.[1] It is anticipated that by 2050, there will be nine billion people on the planet, leading to elevated pressures on water and food resources.[11] However, current urbanization and population increase faster than the measures taken to enhance the drinking water quality and wastewater treatment.[12] The growing economy and population have increased water use and wastewater discharge, which has significantly increased pollution.[13]

Water pollution has far-reaching impacts on freshwater availability, ecology, and human health, necessitating comprehensive solutions.[14] Human activities, even in modest doses, significantly alter landscapes, vegetation, and water quality processes, affecting the entire drainage basins.[15] Managing materials released into land, water, and air requires proactive techniques due to lengthy removal timelines.[16]

Water scarcity and pollution have become urgent global issues, demanding innovative and sustainable strategies in managing wastewater.[17] While traditional wastewater treatment methods are effective at removing certain contaminants, they often face challenges related to energy consumption, sludge production, and the treatment of new pollutants.[4] As a result, there is a growing motivation to explore and adopt advanced technologies that can overcome these obstacles and promote environmental sustainability.[18]

Wastewater treatment is pivotal in maintaining high water quality standards, safeguarding human health, and preventing waterborne illnesses.[19] By removing pollutants and toxins, treatment plants contribute significantly to public sanitation and safe drinking water.[20,21] Additionally, wastewater treatment is crucial for preserving the ecological balance of aquatic environments.[22] The repercussions extend beyond aquatic ecosystems, potentially harming land ecosystems through the water cycle.[23,24]

Although wastewater treatment technologies are a widely researched topic, there are still research gaps in the utilization of emerging technologies in sustainable wastewater treatment systems. While membrane filtration,[25,26] advanced oxidation processes,[27,28] and biological treatment systems[29] are under investigation for wastewater reclamation, there is limited systematic research on their combined effectiveness in evolving wastewater treatment scenarios, as noted by Singh *et al.*[30] Furthermore, exploring these technologies in decentralized wastewater treatment systems to address sanitation needs in rural and remote communities requires more attention.[31,32] Additionally, Wang Yi, and colleagues have highlighted the lack of comprehensive utilization of artificial intelligence algorithms in wastewater treatment, particularly in conjunction with machine learning for real-time process optimization

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modeling.[33] Addressing these knowledge gaps is crucial for developing innovative and efficient wastewater treatment plants.

This review examines a range of traditional and emerging wastewater treatment technologies, offering a thorough evaluation of their effectiveness, efficiency, and environmental impacts. The goal is to present a comprehensive view of the latest advancements in wastewater treatment, emphasizing the potential of novel approaches in achieving sustainable water management objectives. Through a detailed analysis of the strengths, weaknesses, and opportunities of various technologies, this review aims to educate policymakers, researchers, and industry professionals on the most promising solutions for addressing the complexities of wastewater treatment and resource recovery. Ultimately, the fusion of conventional and emerging technologies, supported by robust policy frameworks and sustainable practices, is crucial to ensure the long-term availability of water resources for future generations. The exploration of integrating new fields such as nanotechnology, artificial intelligence optimization, and biotechnology with traditional methods is crucial in this context. The review further presents an updated and distinctive outlook on sustainable wastewater management, examining factors such as environmental considerations, economic implications, and the challenges posed by emerging contaminants. Furthermore, the incorporation of examples showcasing successful applications of innovative techniques enhances the uniqueness of this work.

2. Research methodology

A systematic literature review methodology is used in this research project. An exhaustive computer-based search of academic databases was conducted to pinpoint studies discussing both traditional and cutting-edge wastewater treatment systems. Studies were selected based on the technology used and inclusion and exclusion criteria and were rigorously assessed for quality. Essential information was extracted from the technology table, including technology type, performance indicators, environmental considerations, and economic viability. Further, the compiled data were analyzed to identify the trends and potential areas for improvement through a critical evaluation against other effective practices. This systematic process aimed to conduct a thorough and evidence-based examination of sustainable wastewater treatment options.

3. Traditional wastewater treatment methods

3.1. Overview of conventional treatment technologies

Conventional techniques for treating wastewater, such as preliminary, primary, secondary, and tertiary treatment, are commonly used to remove pollutants from wastewater.[34] These approaches serve the common goal of mitigating diverse contaminants including heavy metals, inorganic metallic materials, organic matter, residues from disinfection, and microbiological chemicals present in wastewater.[35] Some applications of treated wastewater are shown in Fig. 1.

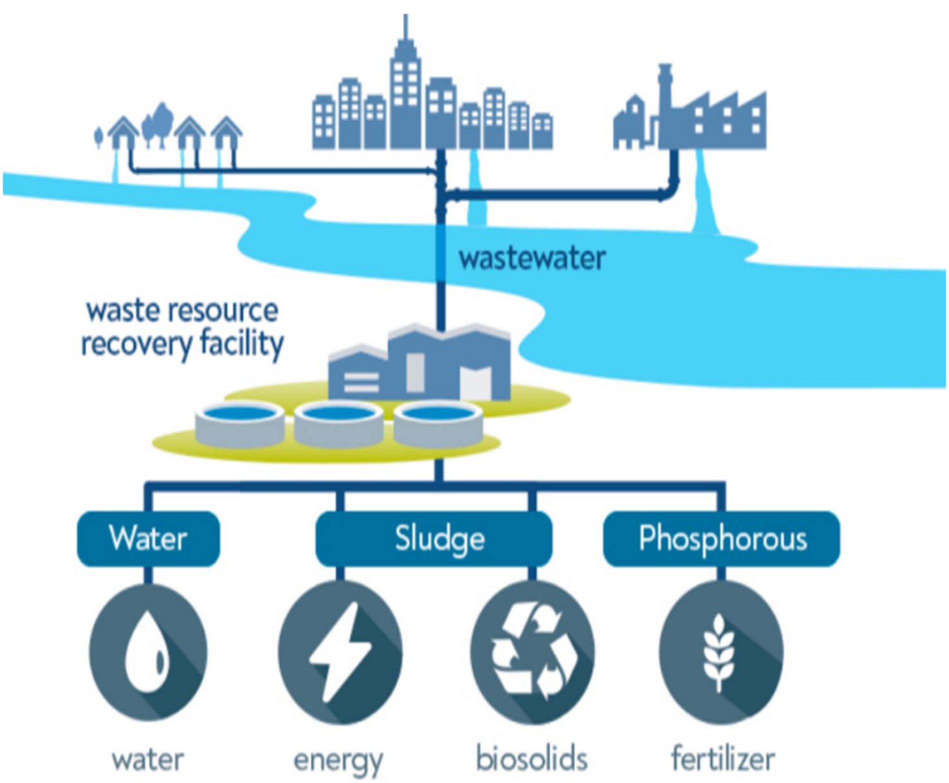

Fig. 1 Stages and applications of wastewater treatment (ref. 36).

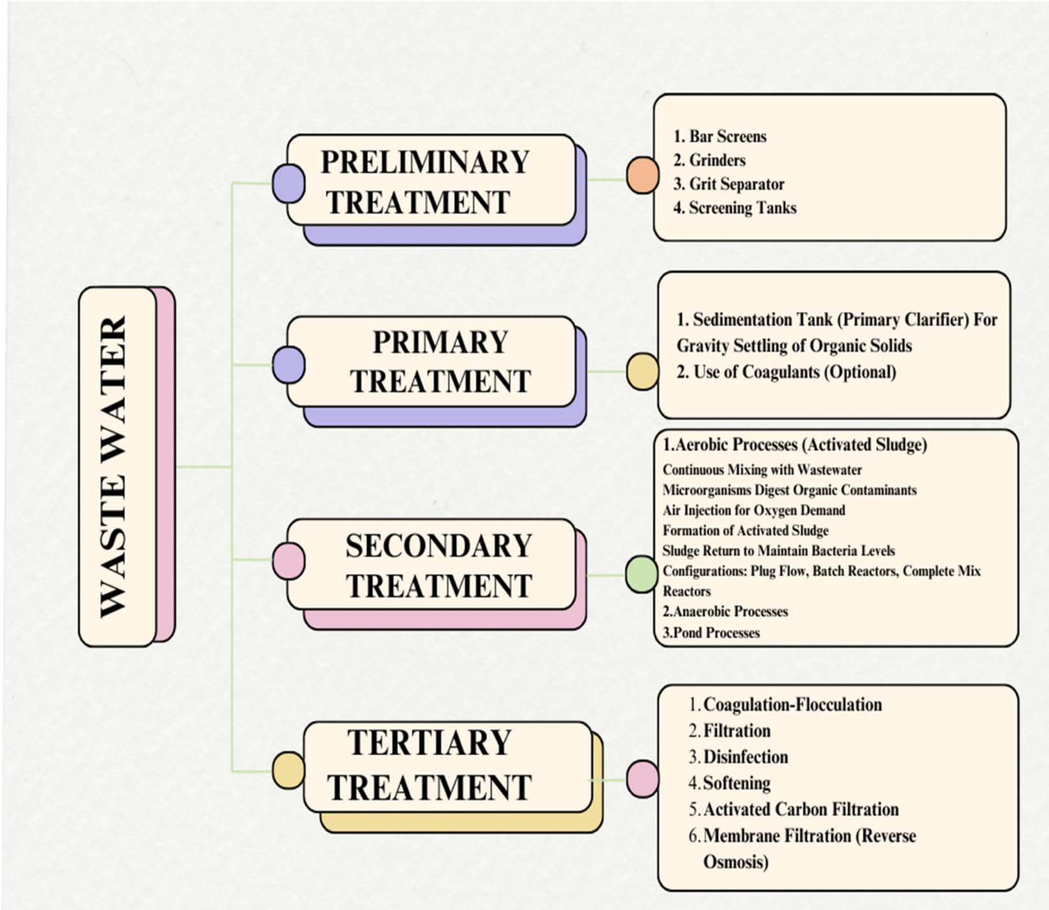

Fig. 2 Overview of wastewater treatment processes.

Following steps are taken to purify water in the conventional wastewater treatment process, as shown in Fig. 2.

(1) Preliminary treatment (screening): preliminary treatment involves the initial removal of large solids and debris from the wastewater, typically through processes such as screening and grit removal. This stage aims to protect downstream treatment processes and equipment from damage or clogging.

(2) Primary treatment: primary treatment removes suspended solids and organic matter from wastewater *via* processes such as sedimentation and flotation, which allow the solids to settle or float to the surface for removal. Primary treatment also helps to reduce the organic load and turbidity of the wastewater before further treatment.

(3) Secondary treatment (activated sludge process and trickling filters): secondary treatment includes biological treatment techniques such as sequencing batch reactors, trickling filters, and activated sludge processes.[37] By using microbes to decompose organic materials, these methods significantly enhance the removal of pollutants.[38]

Tertiary treatment (chlorination and filtration): some wastewater treatment plants use tertiary treatment to further purify water quality.[39] Filtration, chemical treatment, and advanced biological treatment technologies are used in this step. Using disinfection techniques including ozonation, UV irradiation, and chlorination, remaining germs and bacteria are removed.[40] For hygienic, safe wastewater production, digestion, dewatering, and incineration techniques are important to reduce sludge and improve disposal or reuse.[41]

A cost-effective approach to wastewater treatment includes separating solid waste and sludge, purifying water through aeration and sedimentation, and employing constructed wetlands.[42] These natural systems are highly effective in removing pollutants, and the treated water can be used for irrigation and agricultural purposes, especially in regions prone to drought.[43] For a comparative analysis of traditional wastewater treatment methods, see Table 1.

3.2. Limitations of traditional methods

Primary methods may not achieve complete eradication of contaminants including microbial compounds, heavy metals, inorganic metallic debris, and disinfection byproducts found in wastewater.[34,47] Furthermore, these conventional techniques require substantial space for the establishment of treatment plants and can incur considerable costs.[48] Conventional methods have failed in the separation of emerging contaminants, persistent organic pollutants, and certain recalcitrant substances.[49] Concerns arise over the impacts of conventional

Table 1 Comparison of conventional methods for treating wastewater

Method	Description	Advantages	Disadvantages	Energy consumption and cost	Sludge production	Ref.
Primary treatment	Screening and sedimentation to remove large solids residuals	Simple, low cost, removes large solids	Poor performance for dissolved pollutants, sludge generation	Low	High	44
Secondary treatment	Biological treatment to remove organic matter and suspended solids. Includes activated sludge, trickling filter, and lagoon systems	High removal efficiency for organic matter, nutrient removal	Requires skilled operation, susceptible to shock loads, sludge production	Moderate to high	High	45
Tertiary treatment	Advanced treatment to remove remaining nutrients, pathogens, and suspended solids. Includes filtration, disinfection, and chemical precipitation	High effluent quality, removal of specific pollutants	High cost, energy intensive, complex operation	High	Moderate	46

technologies on the environment like the energy-intensive aeration in activated sludge systems.[50] The adaptability of conventional treatment methods is crucial to handle varying influent compositions, especially potential strain from fluctuations in industrial discharges.[51] The reliance on large-scale infrastructure and substantial land requirements limits their suitability in densely populated urban areas. Dealing with potential large volumes of residual sludge requires proper disposal or resource recovery strategies.[52]

3.3. Need for technology advancements

The evolving range of contaminants in wastewater emphasizes the need for continuous innovation and the integration of advanced treatment methods.[53] Prioritizing research and development in the ongoing discourse on wastewater management is essential to overcome these limitations and ensure treatment systems' resilience in response to emerging environmental concerns.[54] Consequently, there is a growing demand for alternative methods that offer enhanced efficiency, cost-effectiveness, and environmental sustainability.[30] Stringent regulations and hefty fines for violating wastewater discharge limits drive the advancement of cutting-edge treatment methods in the industrial sector.[55]

4. Role of technology in wastewater treatment

Technology is crucial in treating wastewater by offering effective and sustainable approaches to eliminate impurities and contaminants from water sources.[56] Numerous techniques including chemical, physical, and biological processes are utilized in wastewater treatment.[57] One such technique involves the utilization of algae for phytoremediation, whereby algae are cultivated in wastewater to eradicate contaminants and generate biomass for the production of biofuel.[58] Moreover, the utilization of biochar and green nanoparticles derived from agricultural waste exhibits promising potential in eliminating persistent pollutants from water and wastewater.[59] Membrane technology and nanotechnology offer promising prospects in wastewater treatment including carbon nanostructures and nanofilters.[60] Surface-modified carbon nanotubes improve heavy metal adsorption in wastewater treatment, where technology selection depends on parameters such as chemical oxygen demand (COD), total solids (TSs), volatile solids (VSs), and customized solutions to address specific issues.[10,11] Similarly, wastewater that contains metal and cyanide compounds goes through a single oxidation phase that is carefully planned and executed using an alkaline reagent and a chlorine solution.[12]

Anaerobic and aerobic methods, known for their eco-friendliness and cost-effectiveness, particularly the low-energy-consuming anaerobic technologies, have gained popularity for treating organic wastewater.[59] Various alternatives including membrane-based procedures, ion exchange, electrochemical treatment, adsorption, biological treatment, Fenton processes, coagulation, flocculation, and UV-based processes have been strategically employed to address these inherent limitations.[61] While these modern methods present promising solutions for the removal of pollutants from wastewater, it is imperative to acknowledge and systematically address the remaining challenges and limitations associated with their applications.[30]

Novel approaches for wastewater treatment encompass a range of methods, including the generation of ozone through water electrolysis or corona discharge, electrocoagulation, hybrid techniques, nanotechnology, and membrane technology.[62] The primary goal of these technologies is the elimination of toxic contaminants and pollutants in wastewater, such as viruses, bacteria, heavy metals, pharmaceuticals, hormones, synthetic dyes, and flame retardants.[56] This involves employing physical, chemical, and biological methods such as membrane filtration, adsorption, coagulation–flocculation, solvent extraction, ion exchange, photo degradation, catalytic oxidation, electrochemical oxidation, and precipitation, as

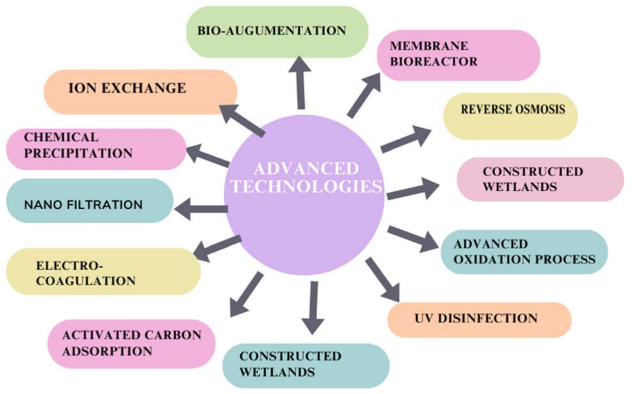

Fig. 3 Advanced wastewater treatment technologies.

shown in Fig. 3.[63] The integration of nanomaterials into these methods has efficiently eliminated various contaminants.[64] However, the significant energy consumption associated with these technologies can lead to substantial costs.[65] The true objective is to develop wastewater treatment plants capable of completely and effectively eliminating emerging contaminants (ECs). Ongoing research is dedicated to enhancing the efficiency, effectiveness, and sustainability of these treatment methods.[25,27,28]

Innovative initiatives have resulted in the development of a wastewater treatment method that combines biological treatment with aerobic microorganisms and ozone sterilization seamlessly.[66] Although these approaches have great potential for treating wastewater and removing pollutants, it is crucial to recognize that the unique approach has different benefits and drawbacks. In summary, technology is a critical driver in advancing sustainable and practical approaches to wastewater treatment.

4.1. Membrane technologies

A membrane is a semi-permeable barrier that controls the transport of substances between two adjacent phases.[67] Due to their intrinsic properties, membranes are playing an important role in the separation of science and new engineering approaches toward industry.[68] Membrane technology is an advanced separation process that utilizes semi-permeable membranes to selectively transport or reject substances between different phases such as liquids or gases.[69] This technology has gained prominence across various industries including water treatment, pharmaceuticals, biotechnology, and environmental protection.[70,71] Operating on the principle of filtration, membrane technology allows for the separation of particles based on size, where the membrane's pore size is smaller than the contaminants to be removed, such as microorganisms or pollutants.[72] This process is often more energy-efficient than the traditional thermal separation methods such as distillation and can operate effectively at lower temperatures, making it suitable for heat-sensitive materials.[73]

There are several types of membrane processes, each tailored to specific applications.[74,75] Microfiltration (MF) is designed to remove larger particles such as suspended solids and bacteria, while ultrafiltration (UF) targets smaller particles including proteins and colloids.[76,77] Nanofiltration (NF) is effective for

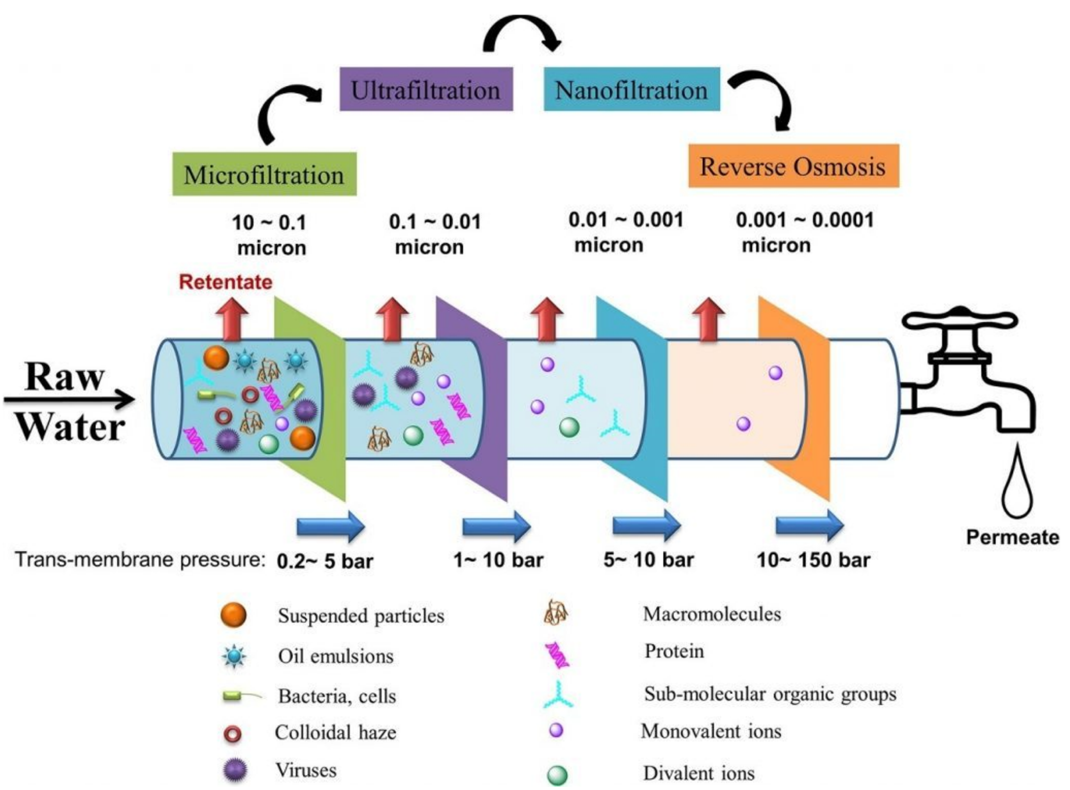

Fig. 4 Illustrating the role of membrane technologies in wastewater treatment (Copyright Nordic membrane 2012–2019).[80]

divalent ions and small organic molecules, and reverse osmosis (RO) can eliminate nearly all contaminants, including monovalent ions and small molecules, requiring high pressure for effective separation.[78] The choice of membrane process depends on the desired purity of the permeate and the characteristics of the feed solution.[79] Fig. 4 illustrates the types of membranes on the basis of pore size for specific removal applications.

In the realm of water and wastewater treatment, membrane technology has emerged as a preferred method for reclaiming water and treating wastewater.[81] Its high separation efficiency allows for the effective removal of contaminants, making treated water suitable for various applications including agricultural and industrial uses.[82,83] Additionally, membrane technology is instrumental in producing drinking water *via* processes such as reverse osmosis, which ensures the removal of harmful substances.[84]

Beyond water treatment, membrane technology plays a crucial role in environmental protection, particularly in reducing pollutants.[85] It is employed in applications such as air pollution control and the treatment of gas-phase organic pollutants.[86] The ability to operate without chemical additives makes membrane technology an environmentally friendly option compared to conventional methods, contributing to sustainable practices.[87] In medical applications, membrane technology is vital for processes such as hemodialysis, where it is used to remove toxins from the blood. Furthermore, artificial lungs utilize membranes to facilitate oxygen transfer without the formation of bubbles, highlighting the technology's importance in healthcare and its potential to improve patient outcomes.[88,89] Despite its numerous advantages, membrane technology faces challenges, particularly related to membrane fouling, which can reduce efficiency and increase operational costs.[89] Ongoing research aims to develop fouling-resistant membranes and improve cleaning techniques to enhance the longevity and performance of membrane systems.[90] Additionally, there is a growing focus on integrating membrane processes with other treatment technologies to create hybrid systems that maximize efficiency and effectiveness in wastewater treatment.[91] Overall, membrane technology is a versatile and efficient method for separation processes, with significant potential for addressing environmental challenges and improving water management practices.[91]

A driving force, such as a semipermeable barrier, controls the rate of component movement through fractional permeation and rejection *via* pores of varying sizes in a typical membrane mechanism.[92] This approach is frequently used in mechanical processes for separating gas or liquid streams. Membranes function as thin barriers for size differential separation, often integrated with chemical and biological treatments or utilized as standalone systems in secondary wastewater treatment.[93,94]

Extensive research has been conducted to investigate the application of membrane technology for wastewater treatment. Studies[95,96] have identified the potential of various membrane technologies, such as RO, MF, UF, and NF, in treating water produced by oil fields and refineries, as well as in removing pollutants from wastewater.

Various advanced wastewater treatment technologies have emerged, encompassing membrane technology,[96] along with adsorption, coagulation, advanced oxidation, and magnetization–biomimetic enzyme condensation.[97] The utilization of nanotechnology, as explored by,[98] has further contributed to enhance the treatment efficiency. Within the chemical industry, prevalent methods include physio-chemical and biological processes, constructed wetlands, and advanced oxidation processes.[99] These diverse technologies present promising solutions for wastewater treatment.

Gray water, textile effluents, paper mill wastewater, pharmaceutical wastewater, and hospital effluents are a few industrial wastewater streams treated efficiently by membrane technologies.[100] These advanced treatment methods can also remove a wide range of contaminants and clean the water for potential discharge.[101]

The gray water, which is slightly polluted wastewater from sinks, showers, and washing machines, can be effectively treated using a combination of membrane bioreactors (MBRs) and plastic tube ultrasonic welding machine of reverse osmosis (RO).[102] After treatment, the water is separated from biomass through a membrane filtration process in MBR.[103] Subsequently, the purified water undergoes further treatment to remove salts and organic matter using RO.[104] This hybrid setup ensures that the water meets strict quality standards suitable for various reuse options such as toilet flushing, irrigation, and other non-potable uses.[105]

Membrane technology combinations are also employed to treat textile industry effluents containing high color, COD, and toxicity.[106] The textile industry is a large contributor to water pollution because of the dyes and dangerous chemicals that are dumped into local rivers during production. These contaminants are not easily removed by conventional treatment methods resulting in the exploration of alternative materials such nanofibers. Nanofiltration (NF) and reverse osmosis (RO) processes are utilized to remove dyes, salts, and organic compounds from the textile effluent.[107] The implementation of pretreatment procedures such as coagulation or adsorption can help decrease the membrane fouling potential and enhance the overall treatment efficiency.[108] The high surface area and easy adsorption nature of nanofibers are considered excellent for treating textile wastewater.[109] A study has shown the potential of this approach, where electrospun nanofibers made from thermoresponsive polymers have localized adsorption sites for hydrophobic organic compounds and removed over 90% dyes from distinct populations by selecting sub-optimal dye concentrations.[110] Although this technique is versatile, and it allows the production of nanofibers with diameters from 300 to 500 nm, which can be prepared using different polymers such as polyacrylonitrile (PAN) or even incorporating TiO_2 in their structure for better dye degradation under UV light, they are frequently linked to electrostatic issues during fiber extension leading unwanted branches on very uniform fibers interfering mainly at interfacial region dye interaction causing adsorption promotion.[110] The dual responsivity exhibited by these polymers allows for receptor adaptations to the surrounding conditions, such as temperature or pH.[111] The dye removal process can be further accentuated through tuning polymer properties. A copolymer of *N*-isopropylacrylamide and dimethylaminoethyl methacrylate efficiently removes acidic as well as basic dyes from waste water, which is highly applicable for textile effluent treatment.[112] The application of nanofibers for textile wastewater is encouraging in that it enhances the efficiency level of dye removal and aids water resource sustainability.[113] By introducing nanofiber technology within the current treatment systems, textile manufacturers reduce their environmental footprint substantially while enabling them to comply with strict regulations on wastewater discharge.[114] Moreover, the possible reuse of nanopowders for dye adsorption is economically important because this helps it in providing a low-cost solution, which can be useful for wastewater management among textile industries.[115]

Another study presents the development and application of novel smart composite materials for the simultaneous removal of organic impurities and toxic heavy metals from industrial wastewater.[116] These materials demonstrate high removal efficiencies, reusability, and significant reduction in chemical oxygen demand (COD) levels, making them promising candidates for industrial water remediation and reuse. The smart composite materials are fabricated using a combination of synthetic and natural polymers such as pullulan, which exhibit a temperature-responsive behavior. The materials can efficiently extract organic contaminants such as phenols, anhydrides, textile dyes, pesticides, herbicides, and antibiotics, as well as inorganic heavy metals, from wastewater. The removal efficiency exceeds 90% at optimal concentrations. The high reproducibility in synthesis, properties, and elimination spectrum of these smart composite materials sets them apart as innovative solutions for industrial wastewater treatment. The established 4-cycle reusability and substantial reduction in COD levels further highlight their potential for practical applications in water reuse.

Regarding wastewater from the paper industry, it is characterized by high concentrations of organic matter, suspended solids, and nutrients, which can be effectively treated using a combination of membrane filtration and biological processes.[117,118] Ultrafiltration (UF) is responsible for the removal of suspended solids and colloidal matter, while reverse osmosis acts as a post-treatment process to remove dissolved salts and organic compounds.[119,120] The treated water can then be reused in various processes within the paper mill to eliminate freshwater usage and reduce the environmental footprint.[121]

Advanced treatment methods are necessary for the removal of contaminants found in pharmaceutical and hospital wastewaters, which include organic micro pollutants, antibiotics and pathogens.[27] These methods typically involve membrane technologies (such as UF or RO), advanced oxidation processes (AOPs), and/or activated carbon adsorption.[122] The treated water can then be discharged or reused in compliance with specific requirements and regulations.[123]

Additionally, some scientists[124,125] have highlighted the advantages of membrane bioreactors, which integrate activated sludge treatment with membrane filtration for biomass retention. This approach proves beneficial in the treatment of industrial, domestic, and food processing waste. Collectively, these studies emphasize the promising role of membrane technology in enhancing the efficiency and sustainability of wastewater treatment processes.

4.1.1. Reverse osmosis. Wastewater treatment utilizes RO technologies to eliminate impurities and contaminants.[126] RO membranes play a crucial role in this process, but their efficiency can be compromised by the elevated salinity and organic content found in wastewater.[127] To enhance RO performance, nanofiltration membranes are a viable option, reducing wastewater flow and operational costs.[128] An alternative method involves employing forward osmosis (FO), a technique with promising applications in water and wastewater treatment. Ongoing research is focused on optimizing FO membranes and draw agents to enhance the overall process.[129]

However, to treat high salinity or streams that are prone to fouling, the FO process is proving to be an innovative water technology with a lot of potential applications.[130] Among its many benefits are its low hydraulic pressure requirements, efficient rejection of solutes and contaminants, and improved fouling resistance in comparison to membrane technologies that are pressure-driven.[35,36]

In addition to these technologies, phytoremediation, a plant-based approach, offers an eco-friendly and cost-effective means of treating RO wastewater, converting it into useable water.[131] Reverse osmosis wastewater (ROWW) contains high levels of salts, heavy metals, and pollutants, making it unsuitable for use.[132] Nevertheless, a solution that is both environmentally friendly and economic involves employing phytoremediation—a plant-based method capable of converting ROWW into useable water.[133]

Diverse phytoremediation techniques such as phytodegradation, phytoextraction, phytoremediation, and phytovolatilization can be efficiently utilized to improve the quality of ROWW. Recent research efforts have been dedicated to utilize plants to purify ROWW, revealing promising results in the advancement of water quality.[134]

FO is suggested as a method for providing fertilizing solutions to plants, using brackish groundwater as the input solution and calcium ammonium chloride as the extraction solution.[135] NF is employed for draw solution regeneration, but high salinity groundwater requires additional post-treatment to reduce nutrient concentrations before applying the fertilizing solution to crops.[136] Pilot-scale assessments of FDFO-NF (Fertilizer drawn forward osmosis-nanofiltration) using coal mining saline groundwater as the draw solution aimed to produce irrigation water meeting standards. Among tested solutions, ammonium sulfate exhibited the highest water recovery rate, KH_2PO_4 showed the highest water flux recovery, and ammonium phosphate monobasic had the lowest final nutrient concentration.[11]

Mohammed *et al.* explored a novel approach to enhance polyamide (PA) membranes for desalination and water treatment by modifying the support layer with Y-type zeolites. The resulting PA membranes, formed *via* interfacial polymerization of piperazine

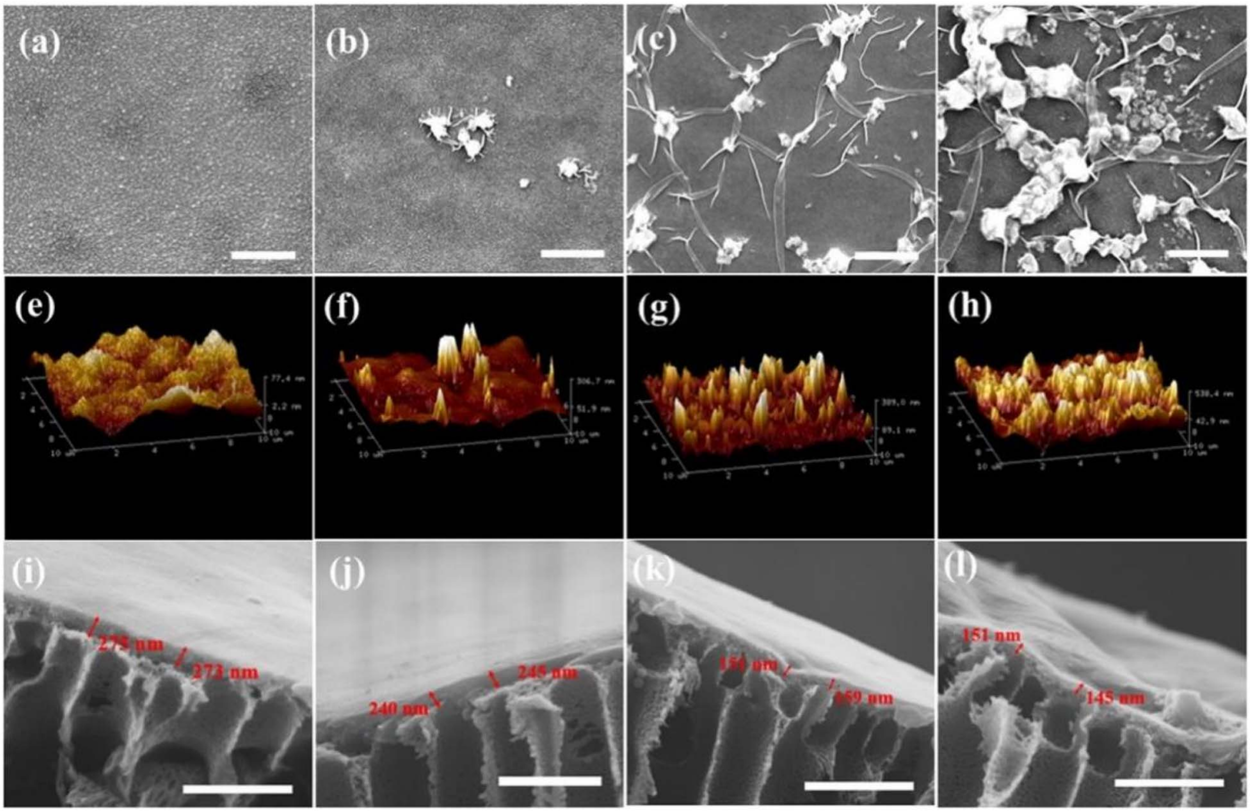

Fig. 5 SEM photographs of all membranes: (a) M-0, (b) M-50, (c) M-100, and (d) M-150. AFM images: (e) M-0, (f) M-50, (g) M-100, and (h) M-150. Cross-sectional photographs of (i) M-0, (j) M-50, (k) M-100, and (l) M-150. (Copyright, Nature 2023), ref. 137.

(PIP) and 1,3,5-benzenetricarbonyl trichloride (TMC), achieved a water transport rate of 22.5 ± 2.2 L m^{-2} h^{-1} bar^{-1} and high salt rejection rates (over 99% for $MgCl_2$, $MgSO_4$, and Na_2SO_4). This work demonstrates the effectiveness of zeolite modification in improving nanofiltration performance. The SEM and AFM characterization of membranes and pure water permeance and rejection results are presented in Fig. 5 and 6 respectively.[137]

Another study presents a novel nanocomposite membrane for simultaneous oil/water separation and desalination of oily, saline wastewater. The synthetic process and work mechanisms

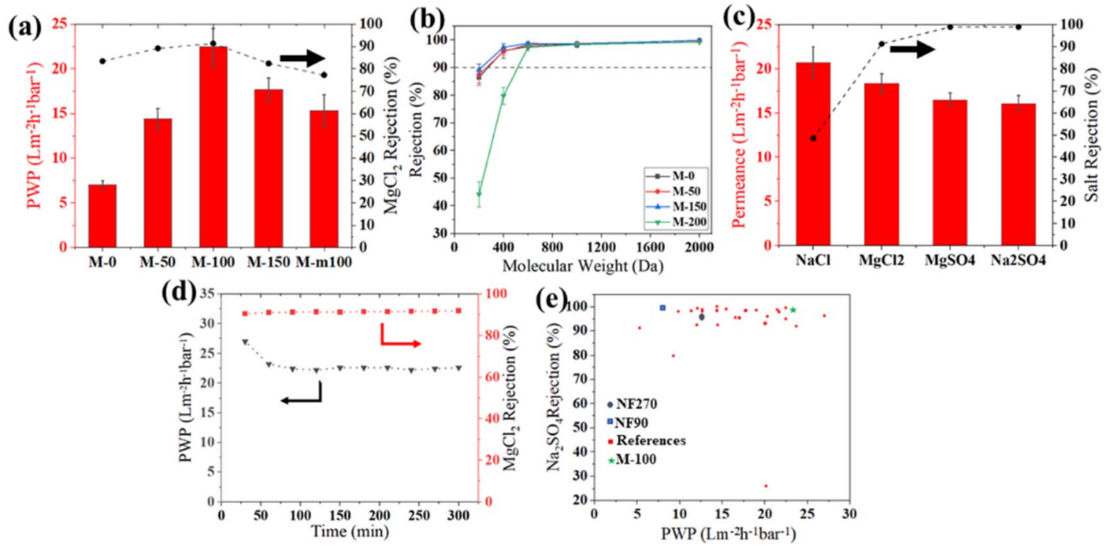

Fig. 6 (a) TFC membrane permeance and rejection for pure water with $MgCl_2$ (1000 ppm), (b) PEG rejection performance, (c) salt solution permeance and rejection towards NaCl, $MgCl_2$, $MgSO_4$, and Na_2SO_4 with M-100, (d) long-term performance of M-100 and (e) comparison with recently published PIP/TMC membranes tested with 1000 ppm Na_2SO_4 feed solution (Copyright, Nature 2023) ref. 137.

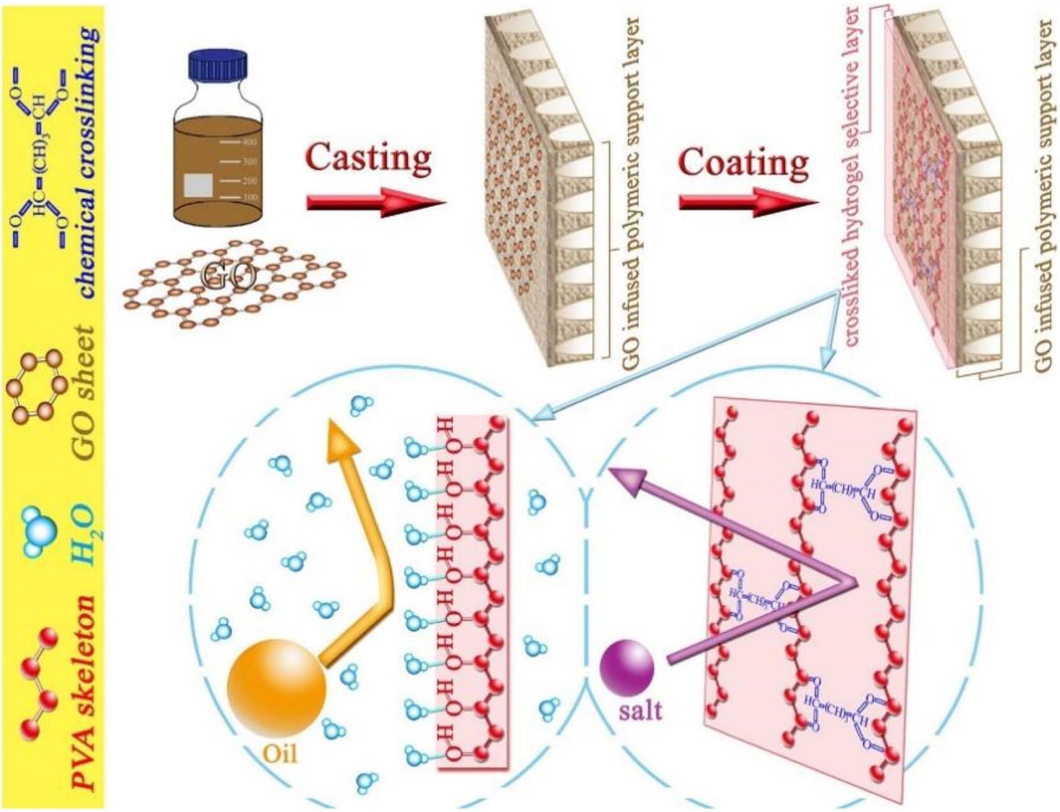

Fig. 7 Illustration of the synthetic process and work mechanisms of the Hydrogel/GO FO membrane (Copyright Nature 2015) ref. 138.

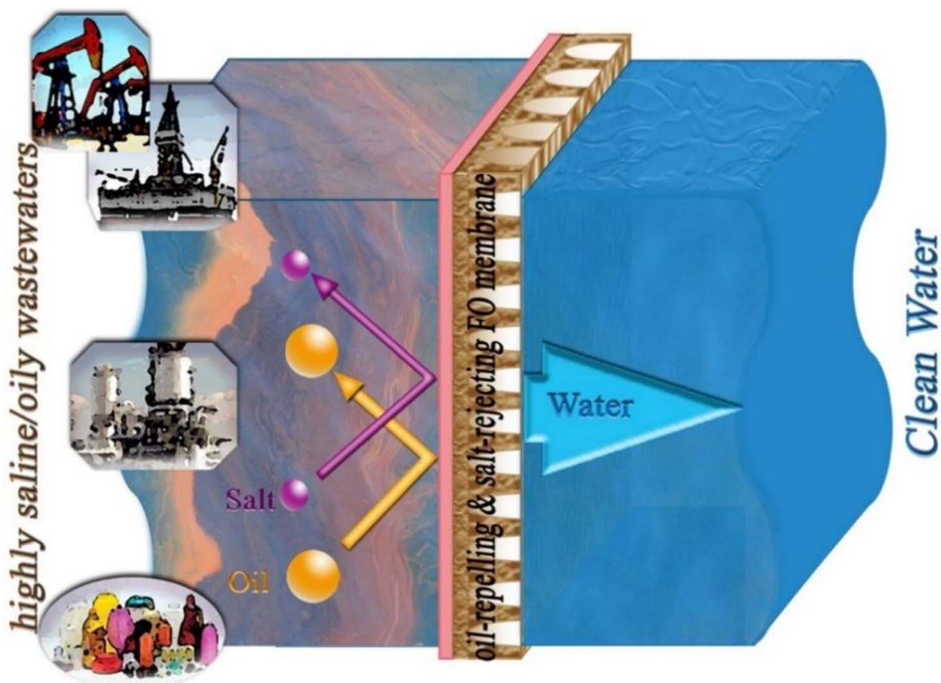

Fig. 8 Schematic of simultaneous oil/water separation and desalination by hydrogel/GO FO membrane (Copyright Nature 2015) ref. 138.

of the hydrogel/GO FO membrane are shown in Fig. 7. The membrane features an oil-repelling, salt-rejecting hydrogel selective layer on a graphene oxide-infused polymeric support. Compared to commercial membranes, this design achieves over three times higher water flux with >99% removal of oils and multivalent ions, making it highly effective for treating challenging wastewaters. The schematic diagram of simultaneous oil/water separation and desalination by the prepared membrane is given in Fig. 8.[138]

4.1.2. Nanofiltration. Nanofiltration (NF) emerges as a promising, efficient and cost-effective methodology in wastewater treatment, presenting advanced approaches to eliminate both organic and inorganic molecules from water.[139] In diverse applications, NF membranes are employed to selectively eliminate ions and organic compounds, doing water softening, color removal, disinfection of by-products, seasonal fouling, and heavy metal removal.[140] Specifically, polyether sulfone (PES) nanofiltration membranes stand out for their capacity to effectively remove toxic metal ions from water, owing to their robust thermal, chemical, and mechanical properties.[141]

For industrial applications such as bio-refinery and petrochemical processes, solvent-resistant nanofiltration (SRNF) membranes have been developed.[139] These membranes exhibit stability and excel in efficiently separating organic compounds even under extreme conditions.[142]

Laurell *et al.* developed loose nanofiltration (LNF) membranes to effectively remove natural organic matter (NOM) from Finnish surface water (Fig. 9). One LNF membrane achieved over 95% NOM rejection with a 40% hardness rejection rate. While operational costs could increase by 53–69%, environmental impacts may decrease by over 18%. Improved removal of low-molecular-weight compounds could further reduce chlorine usage and costs.[143]

Ghanbari *et al.* developed $Ti_3C_2T_x$ MXene@metal–organic framework nanosheets for thin-film polymer membranes (Fig. 10), achieving high salt rejection rates (98.6% for Na_2SO_4) and a threefold increase in permeation rate (17.1 L m^{-2} h^{-1} bar^{-1}). The membranes also rejected over 95% of heavy metal ions and showed a 95.3% flux recovery rate, with long-term performance maintaining 91.5% of the initial permeation rate.[144]

Another study presents a composite membrane of polyaniline (PANI) and $Ti_3C_2T_x$ (MXene) that significantly reduces fouling (Fig. 11). The MXene-PANI/PES membrane achieves

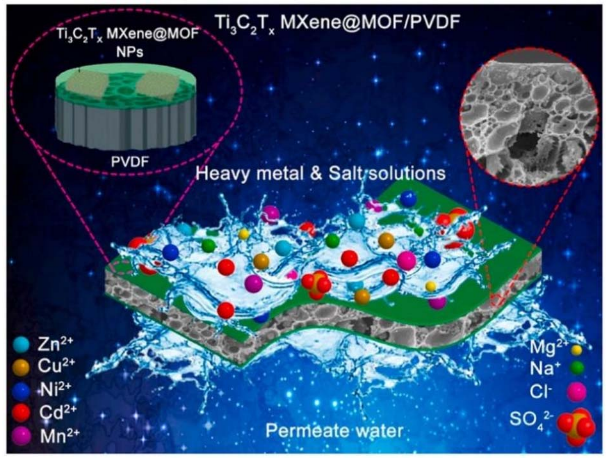

Fig. 10 Schematic of the preparation of MXene/MOF-PVDF nanocomposite membrane (Copyright Elsevier 2023) ref. 144.

a 200.9% increase in pure water flux, over 99% retention of bovine serum albumin, and high dye rejection rates. With a conductivity of 0.5 S m^{-1}, applying a negative voltage results in a 93.7% flux recovery rate, showcasing its potential as an efficient anti-fouling conductive membrane.[145]

Zhao *et al.* develops a nanofiltration membrane featuring fast permeation (105 L m^{-2} h^{-1} bar^{-1}), high Na_2SO_4 rejection (99.4%), and Cl^-/SO_4^{2-} selectivity (130). Utilizing graphitic carbon nitride (g-C_3N_4) to control interfacial polymerization, the membrane's nanoscale-ordered hollow structure enhances performance, making it superior for water purification and desalination applications.[146] The obtained results are presented in Fig. 12.

Zeng *et al.* develops a polyether sulfone (PES) membrane with MXene@TiO_2 heterojunctions (MXTM) for oily wastewater treatment (Fig. 13). The membrane achieves a high water flux of 3045 L m^{-2} h^{-1} bar^{-1} and over 99.8% oil/water separation efficiency. It also exhibits exceptional hydrophilicity and self-cleaning properties, maintaining a flux recovery rate of >98%

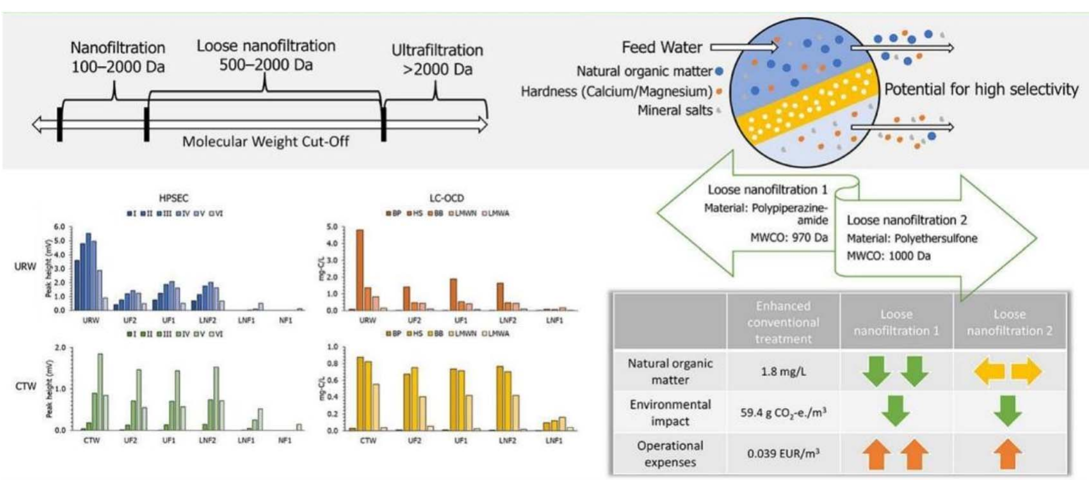

Fig. 9 Illustration of nanofiltration membranes for surface water treatment by Laurell *et al.* (Copyright 2024) ref. 143.

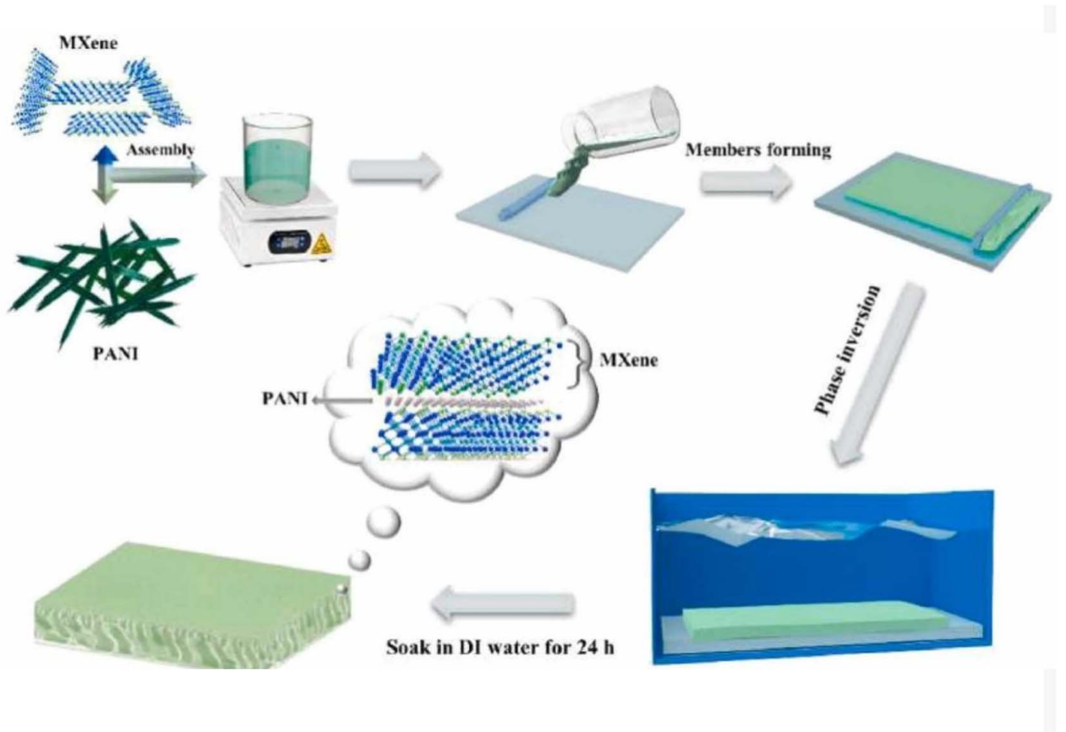

Fig. 11 Synthesis of polyaniline (PANI) and $Ti_3C_2T_x$ (MXene) composites (Copyright Elsevier 2023) ref. 145.

over 10 cycles using visible light for photodegradation. This innovative membrane highlights the potential of MXene-based materials for effective oily wastewater treatment.[147]

4.1.3. Ultrafiltration technologies. Ultrafiltration (UF) technologies for wastewater treatment have a number of benefits.[148] UF can efficiently remove natural organic matter (NOM) from raw water, which is commonly found in all types of water sources used for freshwater production.[41] UF is also an affordable method of treating surface water which makes it appropriate for treating wastewater and sea water.[42]

The water treatment ultrafiltration membrane assembly comprises multiple systems, for effective purification: a plate surface type system, a capillary tube type system, a tubular system, and a uniform dispersion detection system.[83] Physical methods are used for fire extinguishing and sterilization. In the tubular system, bacteria are effectively eliminated by heating the water flow with enough stirring.[149] In the plate surface-type system, the direction of the water flow is controlled, and all-around UV irradiation sterilization is applied, ensuring a high degree of water sterility.[150] The physical operations involved have a short operation time, are generally harmless to humans, and do not significantly increase costs.[151] Several operating modes in the tubular system, including aeration, stirring, and impacting, contribute to attaining these effects.[152] The technique enables thorough stirring prior to filtration, improving the distribution of inclusions in the water for improved filtering effects.[43] UF membranes can also be used in industries such as textile, dairy, beverages, microelectronics, petrochemicals, cosmetics, and pharmaceuticals because of their versatility and capacity to separate and purify different substances.[44]

In summary, UF technologies offer benefits such as efficient natural organic matter (NOM) removal, cost-effectiveness, and versatility for various industries.[153] However, membrane fouling and the scalability of membrane enhancement solutions are important considerations in the application of UF for wastewater treatment.[151,154] Moreover, while membrane enhancement solutions show promise, their scalability and economic feasibility remain uncertain.[152,155] Although chemical cleaning techniques can effectively reduce membrane fouling, they also run the risk of damaging membranes.[45]

Yang explores the combined use of powdered activated carbon (PAC) and ozone (O_3) pretreatment for ultrafiltration (UF) performance. The 100PAC-5O_3 process significantly reduced reversible and irreversible fouling resistance by 82.89% and 58.17%, respectively, and outperformed O_3-PAC in degrading natural organic matter (Fig. 14) The findings highlight PAC-O_3's potential for enhancing surface water treatment and controlling membrane fouling[156] (Fig. 14).

Liu investigates Fe(II)/PAA (Per Acetic Acid) as a pretreatment for ultrafiltration of secondary wastewater. Fe(II)/200 μM PAA reduced fouling resistance by 90.2% and effectively removed >85% of organic micropollutants and improved phosphorus removal. The process also enhanced nitrogen removal by producing biodegradable byproducts. Fe(II)/PAA shows strong potential for improving water quality in secondary effluent treatment (Fig. 15).[157]

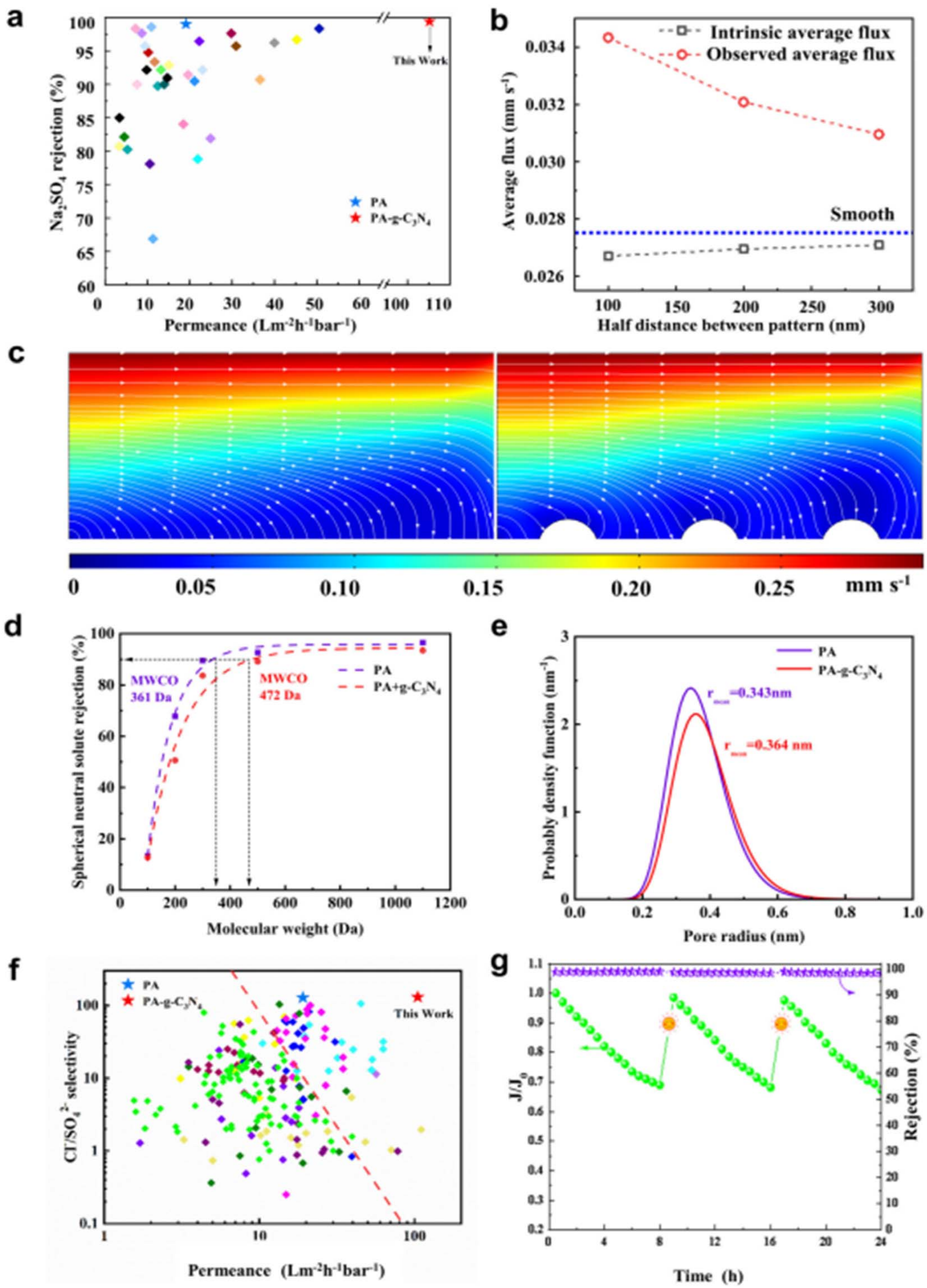

Fig. 12 Separation results for NF membranes. (a) Performance comparison of PA-g-C_3N_4 and NF membranes, (b) average flux of various half distances among patterns, (c) comparison among flow streamlines of smooth and nanoscale-ordered structures, (d) MWCOs of the PA and the PA-g-C_3N_4 membrane, (e) mean pore size of the PA and the PA-g-C_3N_4 membrane, (f) trade-off between Cl^-/SO_4^{2-} selectivity and water permeability of different NF membranes, (g) flux decline and rejection of the PA-g-C_3N_4 membrane with methylene blue as the feed solute; cleaning was done with visible light. (Copyright Nature 2023) ref. 146.

Ma *et al.* developed a PEI (polyethylenimine)-modified PES (Poly Ethylene Sulfone) ultrafiltration membrane with a 110 kDa cut-off to enhance the removal of humic acid and copper presented in Fig. 16. Despite reduced flux, the membrane achieved high removal efficiencies due to smaller pores and adsorption. Aluminum coagulants outperformed iron, with better performance at higher dosages. The modified membrane maintained excellent removal after storage and cleaning cycles. This

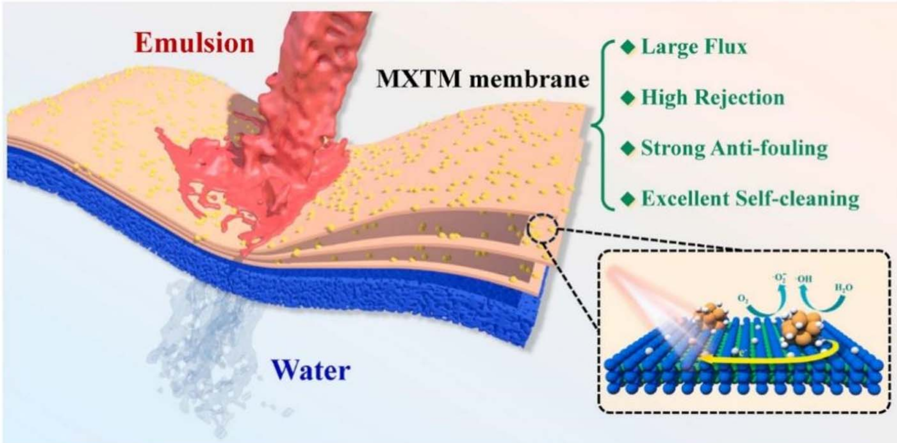

Fig. 13 Polyether sulfone (PES) membrane with MXene@TiO_2 heterojunctions (MXTM) for oily wastewater treatment (Copyright Elsevier 2024) ref. 147.

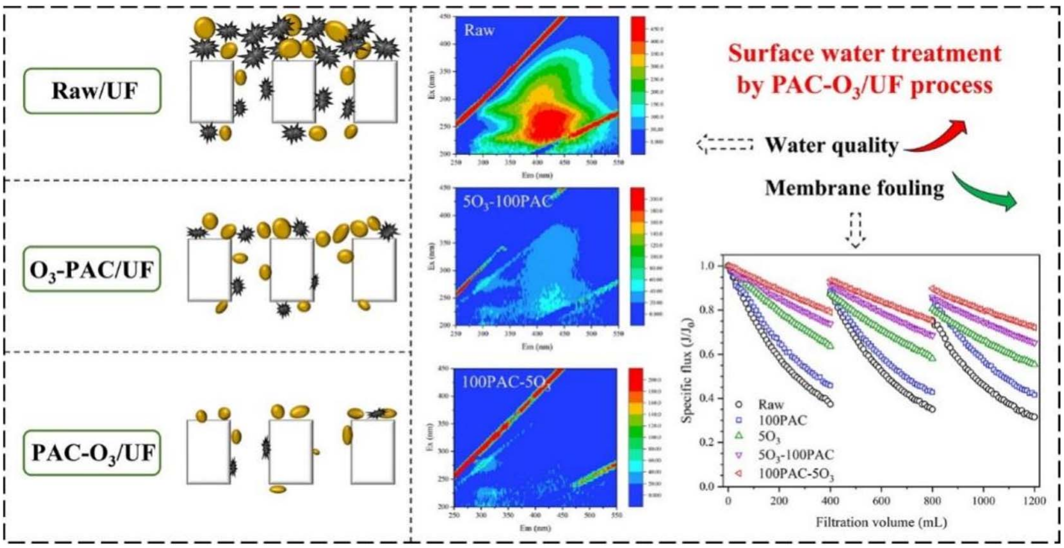

Fig. 14 Comparison of Raw/UF, O_3-PAC/UF and PAC-O_3/UF's potential for enhancing surface water treatment and controlling membrane fouling (Copyright Elsevier 2023) ref. 156.

approach shows strong potential for improving water treatment processes.[158]

Diallo *et al.* evaluated three ceramic ultrafiltration membranes (0.02, 0.05, 0.1 μm) for recovering secondary effluent (Fig. 17). The 0.02 μm membrane (UF1) outperformed the others, achieving 75% COD, 72% BOD5, and 96% TSS removal under optimal conditions (1 bar, 1 m s^{-1}). UF1 also retained over 90% of microorganisms, removed 100% of helminth eggs, and reduced TKN by 14% and TP by 50%. The results demonstrate UF1's strong potential for improving water reuse from secondary effluents.[39]

Ultrafiltration (UF) systems effectively remove particles and organics from water without affecting pH, while conventional water treatment plants (WTPs) can lower pH due to coagulants. Raw water usually has a near-neutral pH of 6.70 to 7.51. UF offers superior contaminant removal and stable pH compared to traditional methods[159]

4.2. Advanced oxidation processes (AOPs)

The utilization of strong oxidizing agents, to rapidly and effectively degrade organic and inorganic contaminants in wastewater, is what makes advanced oxidation processes (AOPs) an eco-friendly and efficient wastewater treatment technology[160]. These processes are for the treatment of pollutants that are resistive to traditional treatment technologies.[161] The advantages of AOPs include their ability to treat a wide range of pollutants, potential for complete mineralization, and ability to degrade persistent pollutants.[162] However, AOPs also have some drawbacks such as high energy requirements, the need for catalysts or chemicals, and the potential formation of harmful byproducts.[163,164] AOPs can effectively mineralize or degrade contaminants into non-toxic end products, making them suitable for various wastewater effluents.[165]

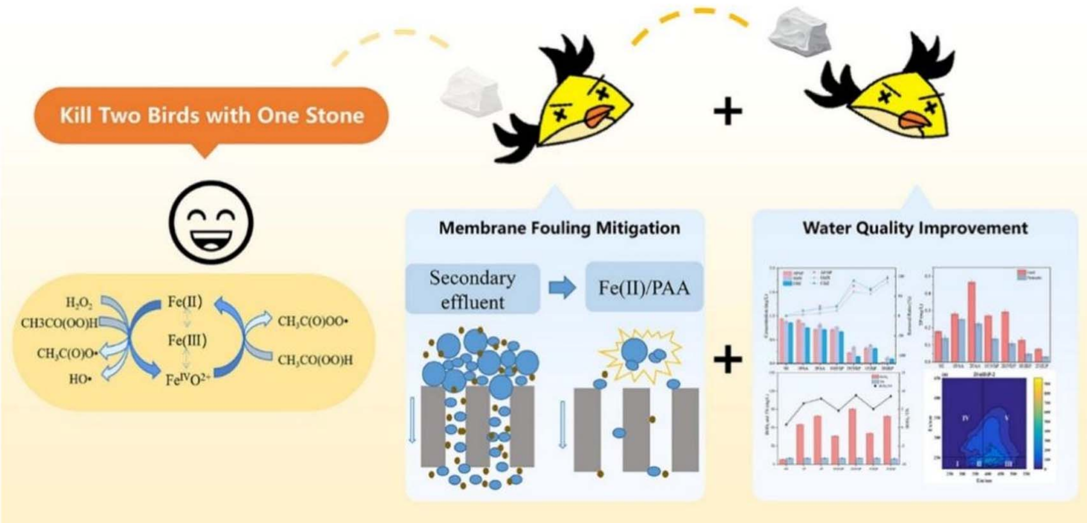

Fig. 15 Representation of Fe(II)/PAA ultrafiltration setup for wastewater treatment (Copyright Elsevier 2023) ref. 157.

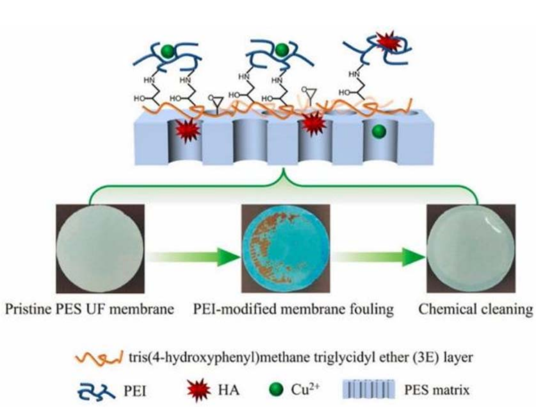

Fig. 16 PEI-modified PES ultrafiltration membrane (Copyright Elsevier 2023) ref. 158.

Pharmaceutical compounds (PCs) in water systems pose significant ecological risks, and conventional treatment methods often fail to remove them.[166] Integrated adsorption/advanced oxidation process (AOP) systems effectively remove pollutants from wastewater by combining adsorption and AOP, benefiting from simple design, mild conditions, and low costs. The process involves two stages: first, a solid adsorbent captures pollutants, reducing their concentration.[167] Next, AOP treatment generates reactive oxidizing species that break down remaining pollutants into less harmful byproducts such as carbon dioxide and water.[168] The effectiveness of these systems depends on factors such as the type of adsorbent, the characteristics of the contaminants, and the AOP technique used.[169] Overall, integrated adsorption/AOP systems enhance

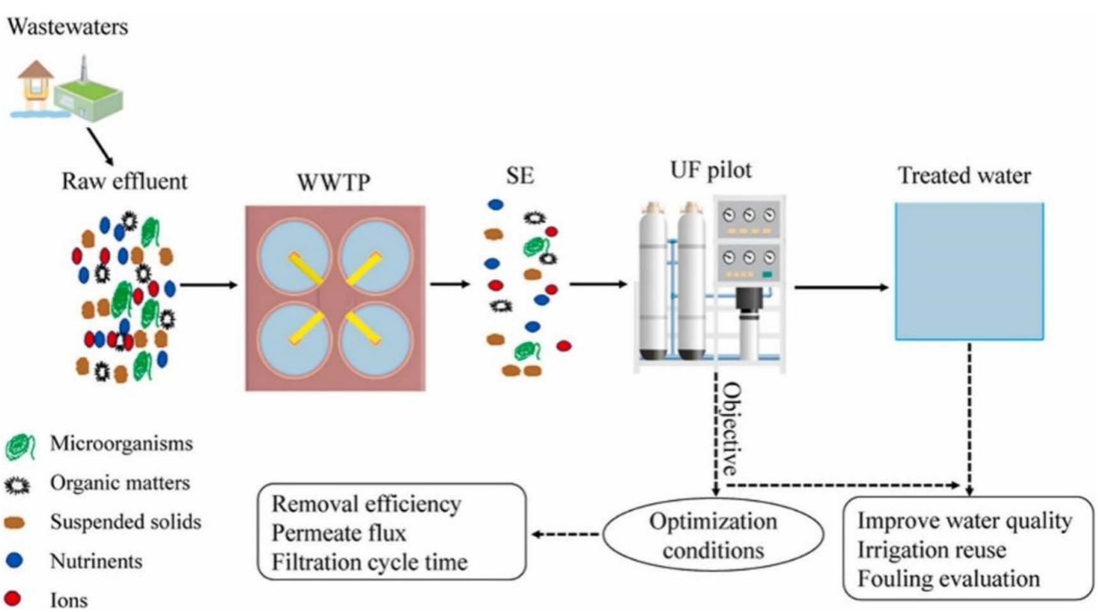

Fig. 17 Ceramic ultrafiltration membranes (0.02, 0.05, 0.1 μm) for recovering secondary effluent (Copyright Elsevier 2024) ref. 39.

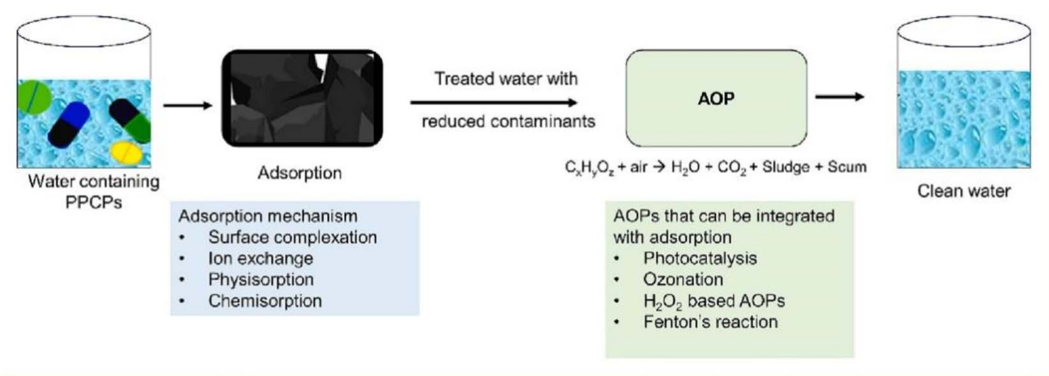

Fig. 18 General mechanism of integrated adsorption/AOP systems (Copyright Elsevier 2023) ref. 170.

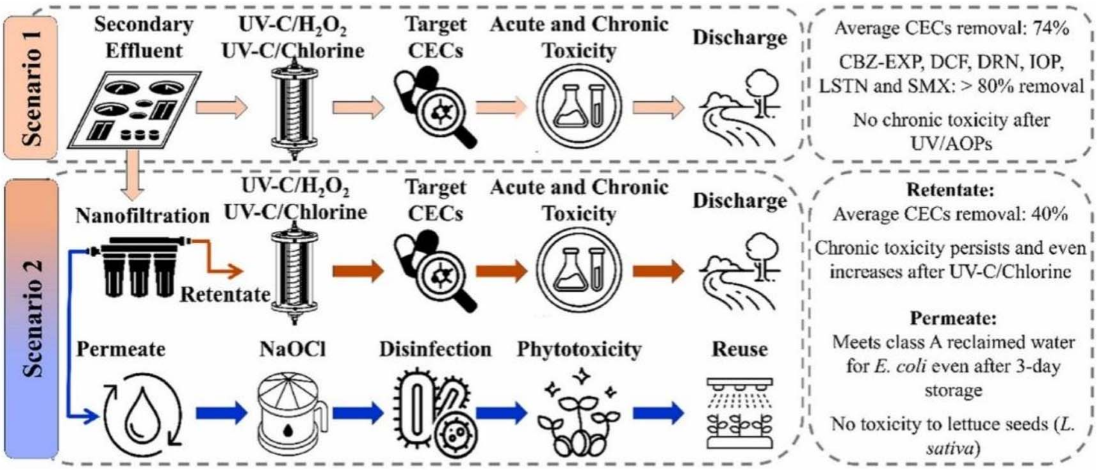

Fig. 19 Schematic of the treatment scenarios in Silva *et al.*'s work (Copy right Elsevier 2024) ref. 172.

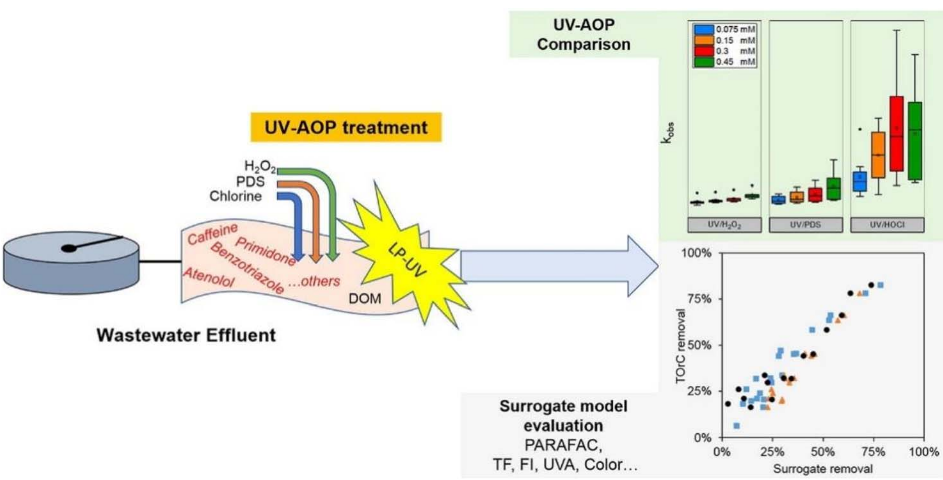

Fig. 20 Wastewater effluent treatment using three UV-based advanced oxidation processes (AOPs) (Copyright Elsevier 2019) ref. 173.

wastewater treatment efficiency and improve the removal of organic contaminants and pathogen (Fig. 18).[170]

Yang *et al.*[171] developed graphitic carbon nitride (g-C_3N_4)-based catalysts that are promising for advanced oxidation processes (AOPs) in water treatment, particularly in Fenton-based processes, catalytic ozonation, and persulfate activation. Recent research highlights their catalytic performance, mechanisms, and the influence of water chemistry factors such

Fig. 21 Layout of the full-scale system for purifying STP discharge (Copyright Elsevier 2021) ref. 190.

as pH and organic matter. While much focus has been on photocatalysis, there is increasing interest in their broader applications, offering both challenges and opportunities for future developments.

Silva *et al.* evaluated advanced oxidation processes (AOPs), UV-C/H_2O_2 and UV-C/chlorine, for removing 14 contaminants of emerging concerns (CECs) from municipal secondary effluent (MSE) and its nanofiltration retentate (NFR) (Fig. 19). Their results indicated that UV-C effectively removed CECs in MSE but was less effective in NFR. The addition of 10 mg L^{-1} of H_2O_2 or Cl_2 enhanced performance, with UV-C/H_2O_2 being more effective than UV-C/chlorine. Both AOPs eliminated chronic toxicity in MSE towards *Chlorella vulgaris*, but toxicity persisted in NFR, especially with UV-C/chlorine due to toxic by-products. The nanofiltration permeate (NFP) had low CECs and microbial content, and a single chlorine addition effectively controlled *E. coli* regrowth for three days, indicating potential for safe crop irrigation reuse. Overall, the findings highlight the effectiveness and limitations of UV-C/H_2O_2 and UV-C/chlorine in wastewater treatment.[172]

Miklos *et al.* examined the removal of 17 trace organic chemicals (TOrCs) from municipal wastewater using three UV-based advanced oxidation processes (AOPs): UV/H_2O_2, UV/PDS, and UV/chlorine. UV/chlorine showed the highest effectiveness, followed by UV/H_2O_2 and UV/PDS, with the latter two exhibiting greater selectivity (Fig. 20). While UV/chlorine was effective, it may generate more oxidation by-products. The study identified UV absorbance (UVA), total fluorescence (TF), and fluorescence peak as useful optical surrogates for predicting TOrC removal. The findings of this study highlight the strengths and limitations of these UV-AOPs in wastewater treatment.[173]

4.2.1. UV disinfection and chemical oxidation methods. UV-based advanced oxidation processes (UV-AOPs) are effective for treating municipal secondary effluents, with UV/H_2O_2, UV/chlorine, and UV/persulphate studied for converting dissolved effluent organic matter (dEfOM).[174] UV/chlorine exhibits potential due to its significant reduction of acute toxicity.[175] Compared to UV/H_2O_2, UV/chlorine is more energy-efficient, effective for disinfection and oxidation, and less impacted by water matrix components.[176] In real water treatment, UV/chlorine and UV/persulfate AOPs demonstrate better efficacy and lower energy requirements than UV/H_2O_2, highlighting the need for further research on the molecular-level transformation of dEfOM in UV-AOPs to enhance municipal wastewater treatment.[177,178]

4.3. Biological treatment methods

Water treatment processes that use microorganisms to remove pollutants from wastewater are known as biological treatments.[179] Biological treatment methods include sludge or biofilm processes.[180] Sludge processes have a number of disadvantages such as high rates of sludge production but biofilm processes are more widely used.[181] A variety of microbial species, such as Candidatus Accumulibacter Phosphatis (CAP), *Spirogyra*, *Aspergillus luchuensis*, and *Candida*, are used in biological wastewater treatment to remove contaminants.[182] These biological treatment technologies are not only efficient and economic, but they also allow for the reclamation of water, which makes them a promising option for wastewater treatment in the future.[183–185]

Advanced wastewater treatment technologies based on biological processes encompass the sequencing batch reactor (SBR), moving bed biofilm reactor (MBBR), and membrane bioreactor (MBR). The SBR, functioning at the laboratory scale, proves effective in eliminating contaminants such as benzophenone-*n* (BPs) from commercial products, particularly when extending the hydraulic retention time (HRT) and during the reaction stage.[186] MBBR employs biofilms for pollutant removal

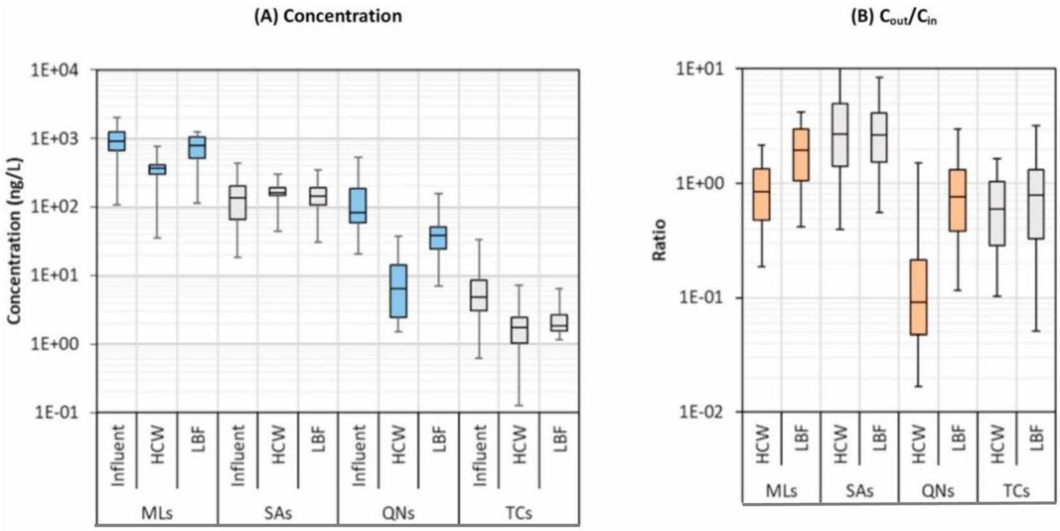

Fig. 22 Total concentrations of four antibiotic categories (A) and their C_{out}/C_{in} (outlet concentration/inlet concentration) ratios (B) in the hybrid constructed wetland (HCW) and layered biological filter (LBF) (Copyright Elsevier 2021) ref. 190.

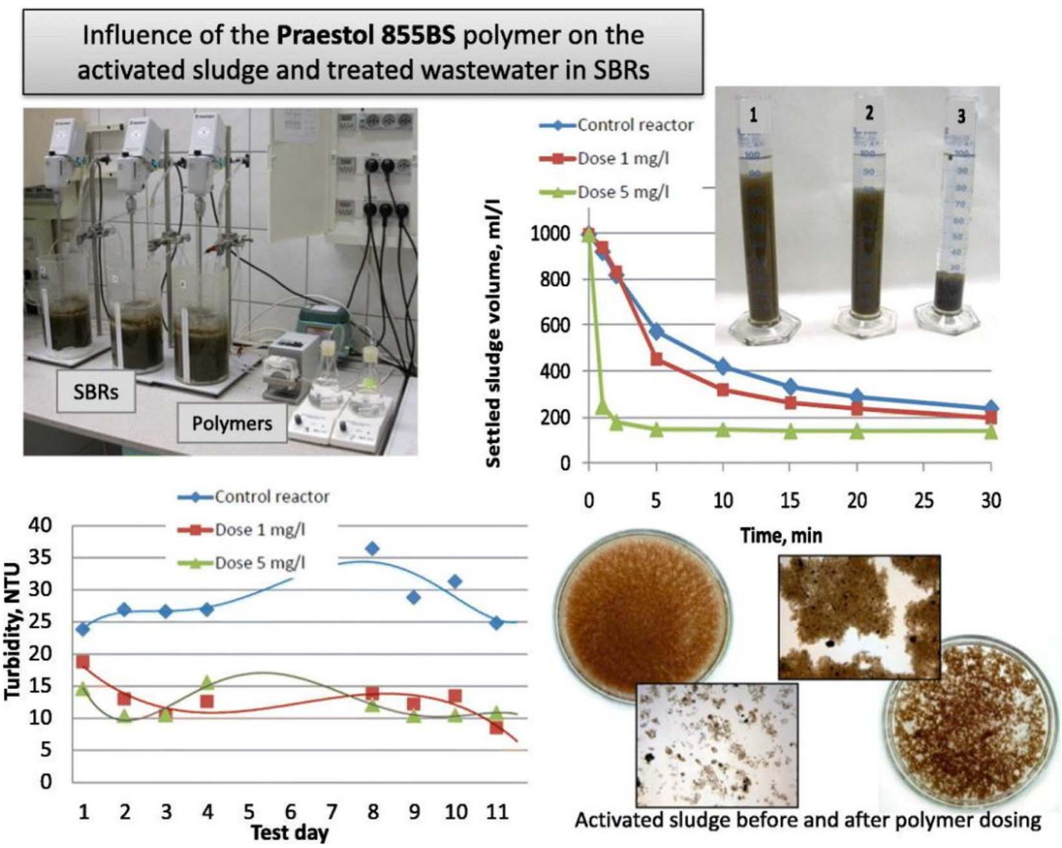

Fig. 23 Influence of Praestol 855BS polymer on the activated sludge and treated wastewater in SBRs (Copyright Elsevier 2023) ref. 191.

and has demonstrated successful performance in treating dairy wastewater, showcasing proficiency in organic matter and nutrient removal.[187,188] MBR combines membrane filtration and biological treatment to produce high-quality effluent. It has been used to treat gray water and has demonstrated significant removal efficiency for pollutants such as total suspended solids (TSS) and COD.[189]

Dan A *et al.* assesses the removal of antibiotics from sewage treatment plant (STP) (Fig. 21) effluent using a hybrid constructed wetland (HCW) and a layered biological filter (LBF) at

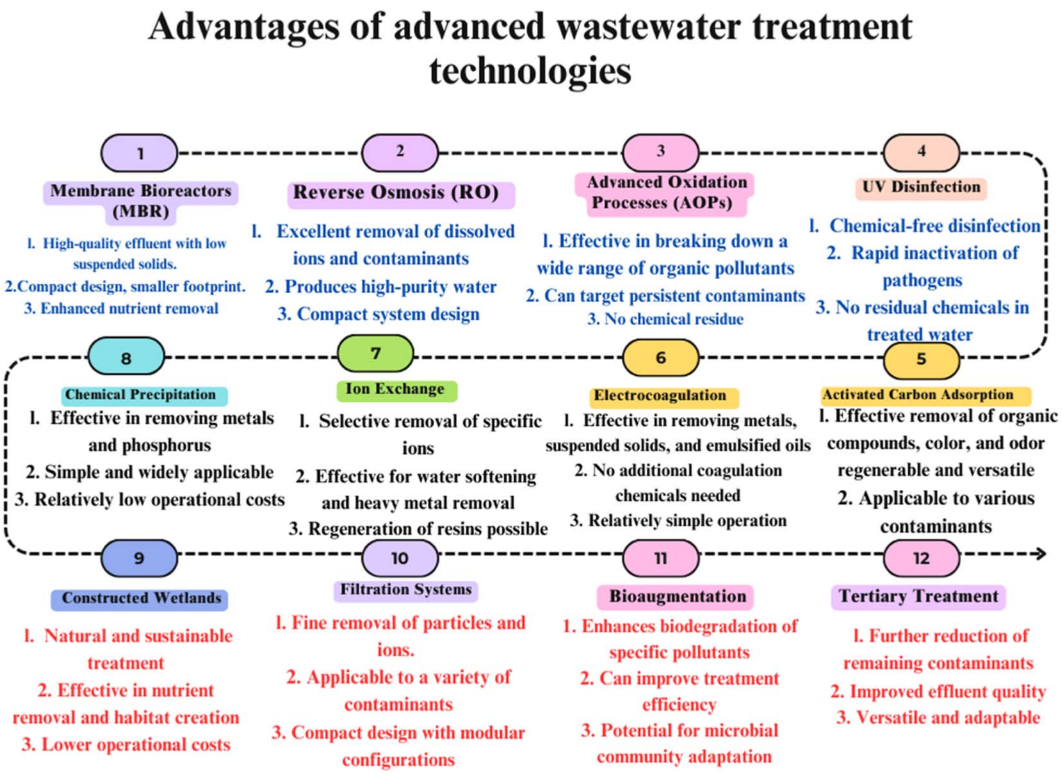

Fig. 24 Advantages of advanced wastewater treatment technologies.

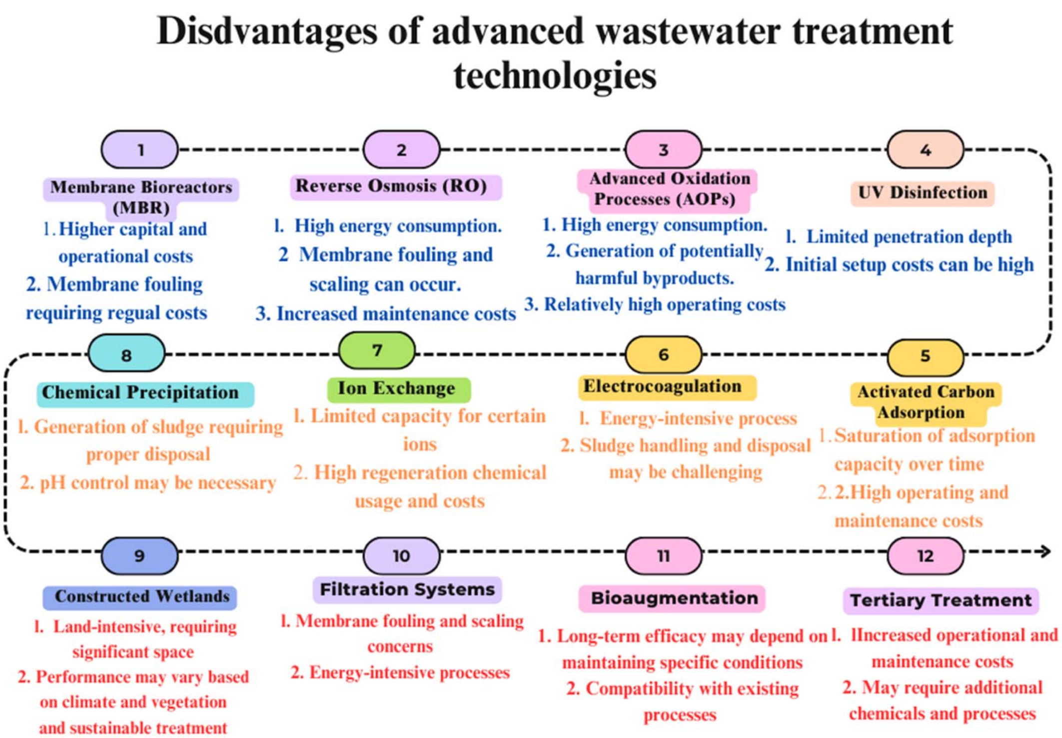

Fig. 25 Disadvantages of advanced wastewater treatment technologies.

different hydraulic loading rates (HLRs). Quinolones achieved the highest removal efficiency in HCW (70–95%), followed by macrolides (58–77%) and tetracyclines (59–67%). LBF showed lower efficiencies, especially for macrolides (13–25%) and sulfonamides (<0%). Optimal HLRs were 1.0 m per day for quinolones and 2.0 m per day for tetracyclines and macrolides

Table 2 Technological innovation in wastewater treatment

Technology	Applications	Advantages	Challenges	Environmental impact	Economic feasibility	Integration potential with conventional systems	Ref.
Advanced oxidation processes (AOPs)	Removal of recalcitrant pollutants, disinfection	Effective for various pollutants, complete mineralization	High energy consumption, generation of by-products	Can generate reactive oxygen species	Moderate to high	Can be integrated as a tertiary treatment step	198 and 199
Membrane-based technologies	Microfiltration, ultrafiltration, nanofiltration, reverse osmosis	High removal efficiency, energy recovery	Membrane fouling, high operational cost	Lower sludge production, energy efficient	Moderate to high	Can be integrated at different treatment stages	25, 200 and 201
Biological nutrient removal (BNR)	Removal of nitrogen and phosphorus	Cost-effective, energy efficient	Sensitivity to operational conditions, sludge production	Reduces nutrient pollution	Low to moderate	Can be integrated into activated sludge systems	202 and 203
Constructed wetlands	Treatment of municipal and industrial wastewater	Low operational cost, ecological benefits	Land requirement, slow treatment rate	Nutrient removal, habitat creation	Low to moderate	Can be used as a tertiary treatment step	204
Hybrid systems	Combination of different technologies	Enhanced treatment efficiency, resource recovery	Complexity, higher investment cost	Reduced environmental impact, energy recovery	Moderate to high	Can be customized for specific wastewater characteristics	205

in HCW, and 6.4 m per day for LBF. Removal mechanisms included adsorption, microbial degradation, and photolysis for quinolones in HCW, while tetracyclines were mainly removed by adsorption. Plant uptake significantly aided macrolide removal in HCW. Overall, HCW outperformed LBF for most antibiotics, although LBF tolerated higher loads.[190]

Antibiotic concentrations in sewage treatment plant effluent are ranked as follows: macrolides (108–2040 ng L^{-1}) > sulfonamides (18.3–433 ng L^{-1}) > quinolones (1.52–536 ng L^{-1}) > tetracyclines (0.13–33.3 ng L^{-1}). Average removal efficiencies are: quinolones in hybrid constructed wetlands (HCW) (70–95%) > macrolides in HCW (58–77%) > tetracyclines in both systems (59–67%) > quinolones in layered biological filters (LBF) (28–64%) > macrolides in LBF (13–25%) > sulfonamides in both systems (<0%). These differences in removal performance between HCW and LBF indicate distinct removal mechanisms in each system (Fig. 22).

Piaskowski *et al.* investigated the impact of two cationic polyelectrolytes on activated sludge properties and treated wastewater quality in lab-scale sequencing batch reactors (SBRs) (Fig. 23). Dosing the polyelectrolytes improved the sludge volume index (SVI) by 42 to 80% compared to the control but overdosing increased SVI by 10–14% and produced difficult-to-thicken flocs. The polyelectrolytes, Praestol 855BS and Superfloc C-18530, did not significantly change the chemical characteristics of the treated wastewater but reduced turbidity by 54–64%. A simulation of a technological failure showed that Praestol formed stable flocs, while Superfloc led to a temporary decline in wastewater quality due to lower floc cohesion.[191]

Based upon the above discussions, the advantages and disadvantages of advanced technologies of wastewater treatment are presented in Fig. 24 and 25.

Wastewater treatment uses diverse methods for pollutant removal, ensuring water resource sustainability through physical, chemical, and biological processes. Rigorously constructed systems uphold stringent water quality standards, safeguarding human health and ecological balance.[60] Through a balanced integration of technological advancements, environmental conservation measures, and economic viability considerations, sustainable management of wastewater treatment can be achieved.

Combining traditional methods such as activated sludge with cutting-edge technologies such as membrane bioreactors (MBRs) and electrochemical treatment offers a comprehensive approach to wastewater management.[192] Hybrid systems show promise in effectively reducing contaminant levels, particularly chemical oxygen demand (COD), while enabling the recovery of valuable resources from wastewater.[105] Nanotechnology emerges as a key focus for wastewater treatment, with nanomaterials demonstrating exceptional adsorption and degradation capabilities against various pollutants such as heavy metals and organic compounds.[193] Research efforts should prioritize the development and evaluation of emerging nanomaterials in real-world environmental conditions to ensure performance and safety.[194] These responsive composite materials can augment pollutant removal when integrated with traditional treatment methods, paving the way for them to evolve into

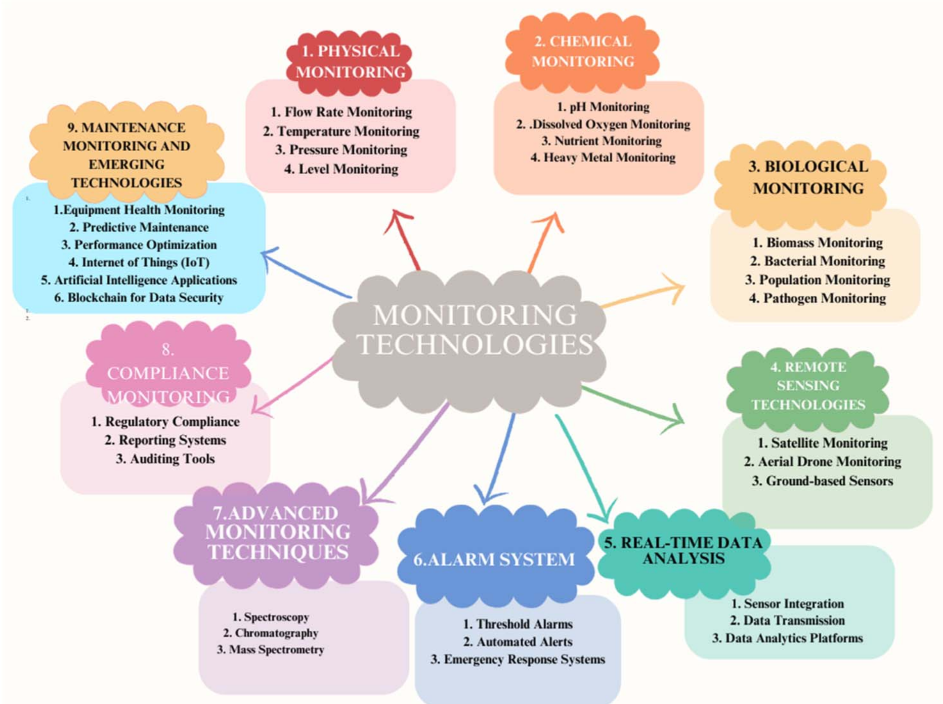

Fig. 26 Monitoring technologies for wastewater treatment plants.

smart pollution control tools. Furthermore, leveraging principles of circular economy in wastewater treatment can enhance resource recovery and waste minimization, including the extraction of nutrients, biogas, and other valuable compounds from wastewater for industrial reuse.[195] By shifting towards a waste-to-resource paradigm, researchers can drive more sustainable practices in wastewater management.[196] Collaboration among academia, industry, and policymakers is vital to promptly translating these novel approaches into viable solutions that address global water challenges.[197]

Summary of the technological innovations in wastewater treatment and their potential to integrate with conventional technologies are presented in Table 2. This table presents the AOP, membrane-based technologies in MBRs, wetlands, biological nutrient removal (BNR), constructed wetland operational conditions in relation to their range of application(s), advantages/challenges, and perceived environmental benefits/economic feasibility/potential integration capacity.

4.4. Monitoring technologies of wastewater treatment systems

Wastewater treatment process benefits from real-time monitoring, automation, and control technologies. A summary of these are presented in Fig. 26. These systems improve the sustainability and efficiency of water management. Real-time monitoring of wastewater is a social responsibility to improve water quality and addresses economic concerns. The transition to renewable energy helps to tackle climate change, yet the intermittent nature of these sources presents challenges for grid operators, requiring improved flexibility and integration.

Automation and control systems lower operating costs and improve the state of the aquatic environment.[206] Integrated control ensures sustainability.[207] The utilization of Internet of Things (IoT), digital sensors, and actuators in the monitoring and control of water systems provides advantages such as remote access, accurate performance evaluation, and a decrease in the overall system cost.[208] Table 3 presents the key findings about monitoring technologies in wastewater treatment systems. Together, these technologies make the system automated, dependable, and integrated.[214] In summary, integrating automation and control technologies with real-time monitoring is essential for improving the efficacy and efficiency of wastewater treatment systems.[215–218]

4.5. Integration of renewable energy sources

Incorporating renewable energy sources into advanced wastewater treatment brings numerous benefits including energy conservation, reduced environmental impact, and resource recovery. Renewable sources such as solar, wind, and biomass can effectively support wastewater treatment facilities' energy demands and promote sustainability.[67,68] For example, solar energy can be used for both electricity generation and heating, while wind energy supports tasks such as evaporation and concentration.

Environmental and economic benefits of integrating solar and biogas technologies into urban wastewater treatment facilities are substantial, as shown in Table 4. This trend aligns with a broader movement towards renewable energy, including solar, wind, geothermal, and hydroelectric power, to decrease fossil fuel dependence.[207] Transitioning to renewable energy

Table 3 Key discoveries about monitoring technologies in wastewater treatment systems

Key findings	Advantages	Challenges	Ref.
Real-time monitoring and automation	Enhances system efficiency, lowers operational costs, and improves water quality. Facilitates remote access and accurate performance evaluation	Requires initial investment in technology and infrastructure. Potential for technical issues or system failures that can disrupt monitoring	209
Utilization of advanced sensors	Provides continuous data on critical parameters (*e.g.*, pH, turbidity, dissolved oxygen), enabling proactive decision-making and timely interventions	Sensor calibration and maintenance can be challenging. Environmental factors may affect sensor accuracy and reliability	210
Benefits of integrated monitoring systems	Allows for continuous oversight of treatment processes, leading to proactive maintenance and compliance with regulations. Reduces risks and improves operational efficiency	Integration with existing systems may be complex and require specialized knowledge. Data management and analysis can be resource-intensive	211
Impact on sustainability and social responsibility	Contributes to sustainability by promoting the use of renewable energy sources and addressing economic and environmental concerns. Enhances social responsibility in water management practices	Transitioning to renewable energy sources may face infrastructure and regulatory hurdles. Public acceptance and understanding of new technologies can be challenging	212
Cost-effectiveness and flexibility	Lowers operational costs and improves facility flexibility, allowing better management of renewable energy sources	Initial costs for automation technology can be high. Flexibility may require ongoing adjustments and updates to the system as conditions change	213

helps to reduce greenhouse gas emissions and address climate change, though the intermittent nature of these sources presents challenges for grid operators, requiring improved flexibility and integration.[208]

Waste-to-energy technologies, such as those that process organic waste such as food waste, wastewater sludge, and animal manure, present significant potential for generating renewable energy and fuel.[209,214] Integrating these renewable resources into wastewater treatment facilities not only enhances energy efficiency and environmental sustainability but also creates pathways for resource recovery, advancing the sector toward a low-carbon future.

Table 4 provides a detailed analysis of various wastewater treatment technologies, covering performance indicators, environmental benefits, economic feasibility, and areas for improvement. Conventional activated sludge systems, for example, achieve high biochemical oxygen demand (BOD) reduction (over 90%) and total suspended solid (TSS) removal (over 85%) but are energy-intensive, with moderate initial and high operational costs. Membrane bioreactors (MBRs) achieve even higher removal rates (BOD > 95%, TSS > 99%, pathogen removal > 99%) and require less land; however, they are associated with high capital costs and require improvements to reduce membrane fouling and enhance cost-effectiveness. Constructed wetlands provide BOD removal rates above 80%, with varying levels of nutrient removal, offering natural filtration and biodiversity benefits, though they are land intensive.

Other technologies such as artificial intelligence (AI) optimization, detailed in Table 4 allow for real-time monitoring and predictive maintenance, improving efficiency and reducing chemical use. Biogas production from sludge offers renewable energy by converting organic-rich sludge into methane, achieving methane yields of up to 70% of the theoretical maximum while reducing greenhouse gas emissions. Electrocoagulation, an emerging technology, removes over 90% of both BOD and TSS, although it is energy-intensive and produces sludge that requires effective management.

Advanced oxidation processes (AOP) achieve chemical oxygen demand (COD) reductions exceeding 90%, effectively treating recalcitrant pollutants; however, they produce hazardous by-products and have high operational costs. Nanotechnology, while promising for specific pollutant removal, is currently limited by high costs and potential environmental risks, keeping it largely experimental on a large scale.

A complementary view on the cost, efficiency, and scalability of these technologies is provided in Table 5. Conventional activated sludge systems, though effective for BOD, COD, and suspended solids removal, have moderate to high costs but are scalable for small to large applications. MBRs offer high efficiency for contaminant removal but are limited by membrane replacement costs. Constructed wetlands, while having low energy and maintenance costs, are suitable for various scales but require significant land, which limits their use in urban areas. AI-driven optimization provides cost savings by enhancing operational efficiency across treatment methods.

Table 4 Analysis of different wastewater treatment technologies for performance, environmental considerations, economic feasibility, trends and areas of improvement

Technology	Performance indicators	Environmental considerations	Economic feasibility	Trends	Areas for improvement	Ref.
Conventional activated sludge	BOD removal > 90%, TSS removal > 85%	High energy consumption, potential for nutrient runoff	Moderate initial costs, high operational costs	Widely used, but facing scrutiny due to energy use	Explore energy-efficient alternatives and nutrient recovery	219
Membrane bioreactors (MBR)	BOD removal > 95%, TSS removal > 99%, pathogen removal > 99%	Reduced land footprint, lower sludge production, high energy use	High capital costs, lower operational costs due to reduced sludge handling	Increasing adoption in urban areas for space efficiency	Reduce membrane fouling and improve cost-effectiveness	219–222
Constructed wetlands	BOD removal > 80%, nutrient removal varies	Natural filtration, biodiversity enhancement	Low capital and operational costs, land-intensive	Growing interest in sustainable and natural treatment methods	Optimize design for varying climates and pollutant loads	223–227
Artificial intelligence optimization	Real-time monitoring and predictive maintenance	Improved efficiency, reduced chemical usage	Potential for cost savings through optimized operations	Rapid growth in AI applications for wastewater management	Ensure data security and integration with existing systems	33 and 228
Biogas production from sludge	Methane yield > 70% of theoretical maximum	Reduces greenhouse gas emissions, renewable energy source	Initial investment in digesters, potential for energy revenue	Rising interest in circular economy and energy recovery	Enhance biogas yield and integrate with other processes	229–231
Electrocoagulation	BOD removal > 90%, TSS removal > 90%	Generates sludge, energy-intensive	Moderate capital costs, lower operational costs	Emerging technology with potential for industrial applications	Develop energy-efficient systems and better sludge management	222 and 232–234
Advanced oxidation processes (AOP)	Chemical oxygen demand (COD) reduction > 90%	Produces hazardous by-products, requires careful management	High operational costs, effective for specific contaminants	Increasing use for treating recalcitrant pollutants	Minimize by-product formation and improve cost-effectiveness	29, 235 and 236
Nanotechnology	Enhanced removal efficiencies for specific pollutants	Potential environmental risks from nanoparticles	High research and development costs, but promising long-term savings	Innovative applications in pollutant removal	Research environmental impacts and scalability	237 and 238

Table 5 Analysis of different wastewater treatment technologies for cost, efficiency, and scalability

Technology	Cost	Efficiency	Scalability	Ref.
Conventional activated sludge	Capital and operating costs is moderate to high	Highly efficient for BOD, COD, and suspended solid removal but may not be so effective for nutrient removal	Widely applicable for small to large scales	239–241
Membrane bioreactors (MBR)	Membrane replacement – high capital and operating costs	Highly efficient in removing BOD, COD, suspended solids as well as nutrients and has ability of high quality effluent. Production	Costly but scalable for medium to large scales	242–244
Constructed wetlands	Lower energy and maintenance cost compared to the conventional system, low to moderate capital cost, high land requirement	Having ability to remove organic matter, nutrients (N, P), suspended solids and trace metals. Long term operation has removal efficiency up to 91%	Suitable for small to large scales, but requires large land	245–248
Artificial intelligence optimization	Lower life-cycle cost, moderate to high capital cost for implementation and maintenance	Provides real time monitoring and optimization of existing treatment processes	Application on different treatment technologies, highly scalable	249–251
Biogas production from sludge	May have moderate capital cost and utilizes biogas for energy savings	Conversion of organic rich sludge to high biogas and nutrient rich digestate with high efficiency. It reduces greenhouse gases and energy consumption	Ideal for organic waste, which is high, and therefore scalable to various scales	252–255
Electrocoagulation	High or moderate cost of operating due to energy consumed	Good at removing suspended solids, heavy metals and a few organic pollutants. It can, however, be energy intensive	Used as a pretreatment or polishing step, suitable for small to medium scales	256 and 257
Advanced oxidation processes (AOP)	Chemical consumption and energy that necessitates high capital and operating costs	Utilized for the highly effective removal of recalcitrant organic compounds and pathogens	Some of the least expensive catalytic synthesis routes are scalable, but due to high costs of the catalysts they are only used in a polishing step	198 and 258–260
Nanotechnology	A high capital and operating costs as well as potential environmental risks	The potential with which it could remove a broad range of pollutants such as heavy metals and organic compounds is promising. For large scale application it is still in the experimental phase	Due to high costs and experimental nature, has limited scalability	237 and 261–263

Biogas production is ideal for facilities with high-organic waste and is scalable across treatment scales, while electrocoagulation is effective for certain pollutants but better suited for small- and medium-scale applications due to its energy demands. Both AOPs and nanotechnology show potential for removing hard-to-treat pollutants, though their scalability is restricted by high costs and complex implementation requirements.

5. Conclusion

The issue of water scarcity poses a critical challenge to humanity, stemming from factors such as population expansion and the impact of climate change. The treatment of wastewater emerges as a pivotal measure for safeguarding both human health and the broader environment. Nevertheless, endeavors to enhance the water quality and treatment encounter difficulties in keeping pace with the swift growth of our communities. Human activities including alterations to landscapes and the introduction of pollutants have intricate consequences on water resources, thereby exacerbating the predicament of water scarcity. Applications, advantages and limitations of some wastewater treatment technologies along with their environmental impact, economic feasibility as well as the integration potential were discussed in the paper. Each technology has its own merits and demerits, but an appropriate selection depends on the kind of wastewater composition. Applying bio-electrochemical systems (BESs) in constructed wetlands can contribute to sustainable, resource-efficient and environmentally friendly wastewater treatment. The two-value process is complementary, and the ideal pollutant removal/energy generation balance can be achieved by combining natural processes with technological solutions. The effective management of wastewater treatment necessitates a delicate balance between technological innovation, environmental preservation, and economic feasibility. Addressing these multifaceted challenges comprehensively is imperative to mitigate the adverse impacts of water scarcity and safeguard the well-being of both the environment and communities.

Data availability

As this is a review article, no new experimental data were generated or analysed in this study. All data supporting the findings are derived from the cited literature, which is publicly available in the referenced sources. Any figures or illustrations presented in the article were created by the authors and are available upon request.

Conflicts of interest

The authors declare no conflict of interest.

Acknowledgements

We are thankful to Rawalpindi Women University, Rawalpindi, Pakistan and Singapore Membrane Technology Centre, Nanyang Environment and Water Research Institute, Nanyang Technological University, 1 Cleantech Loop, 637141, Singapore for facilitating research.

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