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HYBRID MEMBRANE PHOTOCATALYTIC REACTORS FOR POLLUTED RIVER WATER TREATMENT: A REVIEW ON ADVANCEMENTS AND PILOT-SCALE PROSPECTS

Razlin Abd Rashid[a], Rais Hanizam Madon[a]*, Mohamad Alif Hakimi Hamdan[b], Nur Hanis Hayati Hairom[c], Zuliazura Mohd Salleh[a], Nurasyikin Misdan[a], Noor Khairin Mohd[d]

[a]Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, Malaysia.
[b]MIMOS Berhad, Taman Teknologi MRANTI, Bukit Jalil, 57000 Kuala Lumpur, Malaysia.
[c]Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, Hab Pendidikan Tinggi Pagoh, KM 1, Jalan Panchor, 84600 Muar, Johor, Malaysia.
[d]Process Engineering and Design Unit, Malaysian Palm Oil Board, No. 6, Persiaran Institusi, Bandar Baru Bangi, 43000 Kajang, Selangor, Malaysia.

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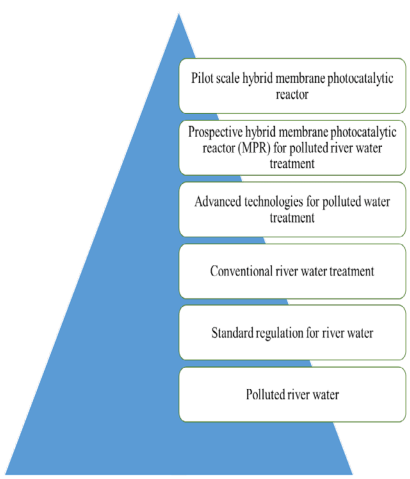
*Corresponding author
raismadon@uthm.edu.my

Graphical abstract



Abstract

The increasing discharge of untreated effluents into rivers, particularly from agricultural and industrial sectors, has led to severe degradation of surface water quality. In response, global and national authorities have established various water quality standards, such as Malaysia's Water Quality Index (WQI) and National Water Quality Standards (NWQS), to ensure cleaner water resources. However, conventional treatment methods such as coagulation, flocculation, and filtration are often inadequate in removing micropollutants and emerging contaminants. This review outlines the current landscape of river water treatment in Malaysia, with a specific focus on emerging hybrid membrane-photocatalytic reactor (MPR) technologies. The integration of membrane separation and photocatalytic degradation in MPR systems offers a synergistic solution to enhance pollutant removal efficiency, reduce membrane fouling, and promote sustainable operation. Recent advancements at the laboratory scale have demonstrated promising pollutant removal efficiencies for both organic and inorganic contaminants. However, scaling to pilot-level remains limited due to catalyst recovery issues and operational complexity. By analyzing regulatory frameworks, treatment performance, and system configurations, this review highlights the potential of hybrid MPRs as a transformative approach for polluted river water remediation. The findings support the development of integrated and high-performance treatment strategies suited for complex aquatic environments.

Keywords: River water, polluted, membrane separation, photocatalysis, pilot scale

1.0 INTRODUCTION

Although rivers are essential for sustaining life, they remain highly vulnerable to pollution caused by unregulated industrialization and agricultural activities. River pollution refers to the contamination of freshwater systems resulting from human activities. Contamination arises from a range of chemical, microbial, and physical sources, including both organic and inorganic pollutants [1]. Additionally, thermal pollution can also contribute to water contamination. This often occurs when industries and power plants use water for cooling, leading to elevated discharge temperatures. Furthermore, rising water temperatures induce oxygen levels to drop significantly, which could further kill fish, disrupt the food chain structure, reduce species diversity, and even stimulate the invasion of new thermophilic species [2]. River pollution is a significant global concern. This necessitates ongoing evaluation and revision of water resource policies at all levels from international frameworks to individual aquifers and wells.

Physical, chemical, and biological assessments are commonly conducted to evaluate water quality and analyse the extent of river pollution. Effective water quality management requires the development of robust plans and supporting infrastructure. The presence of micropollutants in river systems continues to rise due to the high cost and technical difficulty of removing them using conventional treatment methods [3]. Ineffective water management can exacerbate pollution-related risks, potentially resulting in severe public health issues such as disease outbreaks caused by microbial overgrowth [4]. Unfortunately, traditional water treatment methods are often ineffective at eliminating the wide range of micropollutants found in surface water.

Recently, advanced treatment technologies for polluted river water have gained significant attention due to their enhanced performance and efficiency. These technologies offer several benefits, including (i) effective pollutant removal, (ii) improved water purification, and (iii) environmentally sustainable operation. Previous research has largely focused on fundamental studies at the laboratory scale, particularly concerning pollutant removal techniques. However, there remains a significant research gap regarding pilot-scale applications for polluted river water treatment. Therefore, this review explores existing clean water regulations, recent advancements in treatment technologies, and the potential of pilot-scale membrane photocatalytic reactors (MPRs) as a viable solution for polluted river water remediation.

Firstly, this review examines standard water quality regulations, serving as a reference point for researchers and industry stakeholders. It also outlines benchmarks for pollution levels in river water. Conventional river water treatment technologies discussed include coagulation, flocculation, sedimentation, filtration, and disinfection. Their limitations, such as sensitivity to environmental conditions, reliance on biological methods, and generation of secondary waste, are critically discussed. In addition, this review highlights recent advancements in polluted water treatment technologies.

Furthermore, this review discusses the application and future prospects of pilot-scale membrane photocatalytic systems for treating polluted river water, reflecting more recent research developments. The notable efficiency of pilot-scale membrane photocatalytic systems is attributed to factors such as the type of photocatalyst, light intensity, and the type of membrane used. However, several practical issues must be addressed before implementing this system in real-world polluted river environments. This is due to the complex nature of real polluted river water, and the limited discussion in the literature regarding the performance and long-term effectiveness of such advanced systems.

This review aims to provide comprehensive insight into: (i) existing water quality regulations, (ii) types of pollutants in river water, (iii) conventional treatment technologies, (iv) advanced treatment methods, and (v) the application and potential of pilot-scale membrane photocatalytic reactors for polluted river water treatment. The specific objectives of this review are: (i) to examine Malaysian water quality regulations, (ii) to review conventional and advanced treatment methods, and (iii) to explore the implementation prospects of hybrid membrane photocatalytic reactors. In addition, the review highlights the current research gap concerning the use of pilot-scale hybrid MPRs in polluted river water treatment.

2.0 POLLUTED RIVER WATER

Rivers are one of the main sources of water in Malaysia, serving daily needs such as drinking, agriculture, and industrial activities. The demand for clean water has been rising steadily due to rapid urbanization and population growth. However, the discharge of domestic and industrial effluents is a major contributor to river pollution. Polluted river water poses a serious threat to environmental sustainability, as it often stems from the contamination of water bodies by human activities. The introduction of contaminants into natural ecosystems results in the degradation of river water quality [5]. These contaminants may include both organic and inorganic substances, such as dyes, heavy metals, physical waste, ammonium, and nitrate. In addition, elevated water temperatures caused by thermal discharge from power plants also contribute to river pollution. This thermal pollution reduces dissolved oxygen levels, which can be harmful to aquatic life [6].

River pollution is the most critical problem to the sustainability of human communities and environment. This is because humans and other living organisms cannot survive without water. As river pollution increases, it can lead to a water crisis and negatively affect the health of communities and the environment. River pollution causes many negative impacts, including the spread of diseases. Consuming polluted water in daily life can harm human health, potentially causing typhoid, cholera, and hepatitis [7], [8]. Moreover, global ecosystems are highly sensitive to even small environmental changes. Polluted river water can contribute to the degradation of environmental sustainability. Eutrophication is also one of the effects of river pollution. The discharge of chemical waste into water bodies promotes algae growth, which reduces oxygen levels and harms aquatic life. Moreover, food chain disruption can occur when aquatic organisms such as fish and plants consume waste and pollutants, eventually affecting the humans who eat them [9], [10].

According to the latest data, 4% of rivers in Malaysia were classified as polluted, 24% as slightly polluted, and 72% as clean, as shown in Figure 1. Malaysia is a developing country where the number of industries has been increasing rapidly over the years, directly contributing to river pollution. In addition, based on data from the Department of Environment (DOE), among 32 industrial sectors inspected in Malaysia, only a small number had 0% non-compliance [11]. According to the Environmental Quality Report 2023 by the DOE, the percentage of clean rivers has decreased in the past year. The deterioration in water quality observed in 2023 is primarily attributed to increased pollution loads from both point sources and non-point sources. In 2023, the main sources of pollution were reported to be manufacturing industries, agricultural activities, sewage treatment plants, pig farming, and wet markets, including slaughtering activities. These activities have contributed to elevated pollution loads of BOD (444.63 tonnes/day), suspended solids (636.42 tonnes/day), and ammoniacal nitrogen (160.36 tonnes/day). The main contributors to the high levels of BOD, suspended solids, and ammoniacal nitrogen were reported to be sewage treatment plants and pig farming activities.

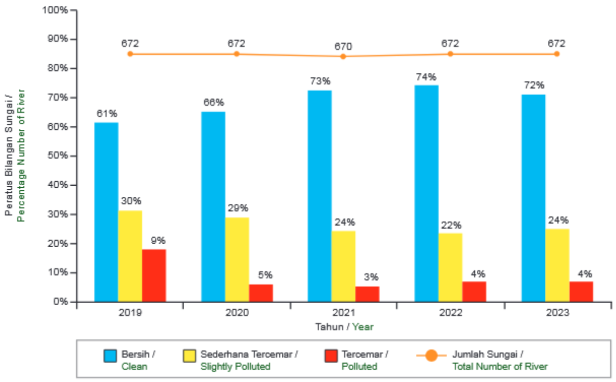


Figure 1 Quality of river water in Malaysia 2023 [18]

Numerous cases of river pollution have been reported as several rivers in Malaysia have been recognized as among the most polluted. In one incident, the water in a river near Ipoh turned white, and dead fish were discovered floating along the surface. Sungai Muda was contaminated with garbage, electronic waste, and municipal waste. Forestry operations in Pahang have also contributed to river pollution. I In 2018, reports indicated that water bodies had turned murky and yellowish, causing significant river pollution that disrupted the water supply. As a result, 449 water treatment facilities in Pahang were temporarily shut down. In 2019, it was reported that Sungai Kim Kim had been contaminated by hazardous waste. The incident began as an isolated case of illegal hazardous waste dumping, but it quickly escalated into a wave of chemical poisoning cases. In one instance, 2,700 residents near Sungai Kim Kim were reported to be gravely ill, prompting the Malaysian Ministry of Education to shut down 111 nearby schools [10], [12], [4].

Today, nearly every nation has addressed water pollution through standardized regulations and water laws that restrict the discharge of hazardous chemicals, toxic compounds, odours, and river water discoloration. While countries in Eastern Europe, the Caucasus, and Central Asia (EECCA) have introduced improvements to surface water quality regulations to preserve water resources and promote sustainability, the United States Environmental Protection Agency (EPA) adopted Surface Water Treatment Rules (SWTRs) as a cornerstone of its water legislation [13]. The Environmental Quality Act of 1974 was enacted in Malaysia with the goal of developing standards for pollution prevention, reduction, and control, as well as improving environmental sustainability.

2.1 Standard Regulation For River Water

A healthy river and environment can be identified by the presence of diverse habitats, including surrounding flora and fauna. Generally, three main parameters are used to assess water quality which are physical, chemical, and biological. Physical characteristics are measured by observing direct changes in water conditions. Key physical parameters include turbidity, colour, temperature, taste, and odour. For example, turbidity indicates the level of water cloudiness, masking its true transparency. Suspended matter and compounds can alter water colour, while pollutants such as sulphur, algae, and oily substances contribute to unpleasant odours. In addition, atmospheric conditions can raise the temperature of polluted water, increasing the risk of vaporization and harm to living organisms [10].

Chemical characteristics can be described as the interaction between water bodies and substances such as organic compounds, metals, and dissolved particles, which lead to water quality issues including reduced dissolved oxygen and elevated nitrogen levels. Most dissolved substances are considered undesirable in water due to their carcinogenic and toxic properties [14]. These substances can increase water conductivity and temperature, both of which significantly impact aquatic ecosystems. Today, industrial effluents are the primary cause of reduced dissolved oxygen in river water, leading to instability in natural ecological systems. In addition, the discharge of excessive metals into rivers contributes to ecosystem degradation. This is because most metals are toxic and hazardous, posing a threat to the environment. Pathogens are considered biological contaminants in water bodies. Industrial effluents play a major role in pathogen dissemination, with the potential to cause prolonged contamination [15], [16]. These pathogens can harm both aquatic ecosystems and human health. Cholera is one example of a potentially fatal waterborne disease.

Accelerated urbanization and population growth have adversely impacted the natural environment and contributed to increased pollution. Therefore, to maintain environmental sustainability, effective methods and technologies for controlling and minimizing water pollution are essential. Given the importance of regulating water security and environmental conservation, significant efforts have recently been made to establish national regulations and legislative guidelines. These regulations and regional criteria are crucial for decision-making on pollution control and water quality assessment. For the purpose of determining the Water Quality Index (WQI), each country has established its own regional water quality standards. The Environmental Quality Act (EQA) 1974, administered by Malaysia's Department of Environment (DOE), outlines regulations for the prevention, abatement, control, and improvement of environmental conditions in the country. The Act governs the discharge of waste into the environment, requiring that effluents comply with the standards set by the EQA 1974 [17]. River water quality can be evaluated using the WQI value, as shown in Equation 1.

$$WQI = 0.22(SIDO) + 0.19(SIBOD) + 0.16(SICOD) + 0.15(SIAN) + 0.16(SISS) + 0.12(SipH) \quad (1)$$

According to surface water quality monitoring conducted by the DOE, the main parameters used to assess the Water Quality Index (WQI) are: (i) dissolved oxygen (DO), Subindex DO (SIDO); (ii) biochemical oxygen demand (BOD), Subindex BOD (SIBOD); (iii) chemical oxygen demand (COD), Subindex COD (SICOD); (iv) ammonia nitrogen, Subindex NH_3-N (SIAN); (v) total suspended solids (TSS), Subindex suspended solids (SISS); and (vi) pH, Subindex pH (SIpH). These six parameters are associated with the physical, chemical, and biological properties of water. pH, turbidity, temperature, and total suspended solids (TSS) represent physical characteristics of water, while DO, COD, BOD, and ammonia nitrogen represent chemical concentrations [18]. Faecal coliform microorganisms contribute to changes in the biological characteristics of water. Changes in these three characteristics collectively determine the overall water quality [18]. Thus, the WQI serves as an indicator of whether water is clean and safe for consumption or polluted and hazardous to health. The WQI ranges from 0 to 100, with values between 81 and 100 indicating clean water. This classification system is derived from the assessment of the six key parameters. Table 1 presents the detailed classification of river water quality status based on the Malaysian WQI.

Table 1 Classification of river water quality status based on water quality index [17]

Parameter	Index		
	Clean	Less polluted	Polluted
BOD	91 – 100	80 – 90	0 – 79
NH_3-N	92 – 100	71 – 91	0 – 70
TSS	76 – 100	70 – 75	0 – 69
WQI	81 – 100	60 – 80	0 - 59

Malaysia has also implemented the National Water Quality Standards (NWQS), which specify detailed threshold limits for individual water quality parameters. A total of 74 parameters are listed in the NWQS to ensure comprehensive water quality protection across various uses. While the Water Quality Index (WQI) is an index-based approach that classifies river water into quality classes based on six aggregated parameters—namely pH, dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), and ammoniacal nitrogen (NH_3-N)—the NWQS defines specific allowable limits for each parameter depending on the designated use (e.g., irrigation, drinking, or recreational purposes). The NWQS plays a crucial role in regulatory enforcement and environmental management by providing explicit permissible values for each water quality indicator. Comparing WQI parameters with their corresponding NWQS thresholds enhances understanding of Malaysia's integrated water quality monitoring framework. This comparison is presented in Table 2.

Table 2 Mapping of WQI Parameters to Corresponding NWQS Thresholds (Classes I–V)

WQI Parameter	Mapped to NWQS Threshold?	NWQS Threshold-Based Limit
Ammoniacal Nitrogen (NH_3-N)	Yes	Class I: 0.1 mg/L; II: 0.3 mg/L; III: 0.9 mg/L; IV: 2.7 mg/L; V: >2.7 mg/L
Biochemical Oxygen Demand (BOD)	Yes	Class I: 1 mg/L; II: 3 mg/L; III: 6 mg/L; IV: 12 mg/L; V: >12 mg/L
Chemical Oxygen Demand (COD)	Yes	Class I: 10 mg/L; II: 25 mg/L; III: 50 mg/L; IV: 100 mg/L; V: >100 mg/L
Dissolved Oxygen (DO) (mg/L)	Yes	Class I: 7 mg/L; II: 5–7 mg/L; III: 3–5 mg/L; IV: <3 mg/L; V: <1 mg/L
pH	Yes	Class I: 6.5–8.5; II: 6.0–9.0; III: 5.0–9.0; IV: 5.0–9.0; V: —
Suspended Solids (TSS)	Yes	Class I: 25 mg/L; II: 50 mg/L; III: 150 mg/L; IV: 300 mg/L; V: 300 mg/L

Another key regulation is the Environmental Quality (Industrial Effluent) Regulations 2009, which was established to govern effluent discharge practices in Malaysia. It outlines the regulatory requirements for any premises in Malaysia that discharge industrial waste or effluent into inland waters or soil. The regulation is divided into two standards: Standard A and Standard B. Standard B applies to discharges into any inland waterways, while Standard A applies to discharges into water bodies located within designated catchment zones.

3.0 CONVENTIONAL WATER TREATMENT TECHNOLOGIES

Conventionally, river water treatment involves several main stages which are coagulation, flocculation, sedimentation, filtration, and disinfection, as shown in Figure 2. Common tests used to monitor and control water quality in treatment plants include turbidity, colour, pH, residual chlorine, jar test, residual aluminium, and fluoride [18].

Coagulation and flocculation are combined processes used in water treatment. In the initial stage, raw water undergoes preliminary treatment. The water is first screened to remove large particles or debris such as leaves, sticks, and rubbish. Next, the water proceeds to the aeration process, where it is bubbled with air. This step helps remove trapped gases such as hydrogen sulphide, which can cause unpleasant odours. The main treatment step which is coagulation and flocculation involves the addition of coagulants, such as aluminium and ferric chloride, to separate suspended particles in water through rapid mixing and agitation [20]. Coagulants work by neutralizing the negative charges of non-settleable solids, converting them into smaller colloidal or suspended particles [21], [22]. Flocculation then follows. During flocculation, micro-flocs aggregate into larger, heavier, and visible suspended particles. The turbulence generated by the propeller promotes the agglomeration of micro-flocs. This process typically takes 20 minutes or more to complete, resulting in the formation of larger visible flocs. Afterward, the water containing flocs is transferred to the sedimentation tank. During sedimentation, the larger and heavier flocs settle to the bottom of the tank [4], [23].

Filtration is a physical process that separates colloidal and suspended particles from water by passing it through granular materials. The main mechanisms involved in filtration are straining, settling, and adsorption [24]. After flocs settle to the bottom, the clear water above is filtered to remove any remaining suspended solids. This clear water flows through a filter composed of materials with varying pore sizes, such as gravel, sand, and charcoal. As the floc passes through the filter, the spaces between the filter grains become clogged, reducing pore size and enhancing particle removal. Some dissolved solids and microorganisms such as dust, chemical residues, and bacteria are also removed as they settle on the surface of the filter media grains [20]. In addition, the adsorption of floc onto the surface of the filter grains contributes to particle removal and further reduces the pore spaces between filter media.

Following filtration, the water undergoes disinfection. To eliminate any remaining pathogenic organisms and ensure the water is safe for consumption, chemical disinfectants such as chlorine, chloramine, or chlorine dioxide are added to the filtered water. Moreover, these disinfectants also help eliminate pathogens that may be present in pipelines between the treatment facility and the household tap. Finally, the treated water is delivered to consumers [23].

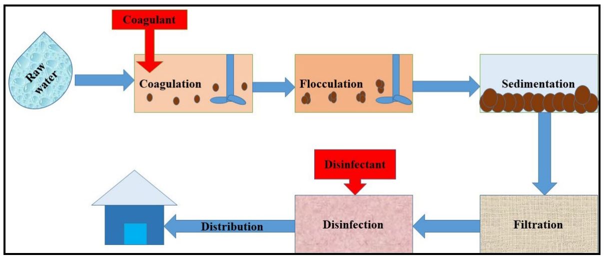


Figure 2 Conventional water treatment process

Coagulation and flocculation are the methods currently applied in water treatment plants. These methods are effective for removing non-soluble compounds and microorganisms, and they are also cost-effective and easy to operate. However, these technologies require chemical coagulants, and high dosages can generate substantial amounts of sludge, necessitating additional treatment. The concentration, chemical properties, pH, and temperature influence the effectiveness of the process [25]. These methods have also been reported to be less effective in removing natural organic compounds and disinfection by-products. Moreover, seasonal changes can complicate the selection of appropriate coagulants. In addition, the extended and varied process sequences make it difficult to monitor and control treatment efficiency [6], [26]. The maintenance and cleaning processes are also reported to be complicated. Furthermore, the use of chlorine as a chemical disinfectant poses health and environmental risks to humans, animals, and aquatic life. Special care is required when handling chlorine during shipping, storage, and application. Water treatment plants must continuously monitor residual disinfectant levels at the point of discharge to ensure the water is safe for residential consumption. Therefore, alternative methods and technologies are needed to improve treatment efficiency and ensure sufficient clean water supply for consumers [27], [28].

4.0 ADVANCED TECHNOLOGIES FOR POLLUTED WATER TREATMENT

Today, advanced technologies offer effective alternatives to conventional methods for river water treatment and quality control. They provide higher treatment efficiency, effective removal of macro- and micropollutants, production of high-quality clean water, simplified operation, and improved environmental sustainability. This study primarily focuses on electrocoagulation, photocatalytic degradation, and membrane separation technologies, given their growing adoption at both pilot and industrial scales. Additionally, it highlights other notable technologies, including ozonation, activated carbon adsorption, constructed wetlands, advanced oxidation processes (AOPs), ion exchange, and biological treatments. A comparative analysis of these technologies is included to provide a broader understanding of their effectiveness and limitations across different polluted river water treatment contexts.

4.1 Electrocoagulation

Electrocoagulation (EC) is an alternative water treatment technique that employs an electrochemical process. It involves the in situ generation of coagulants by applying an electric current across metallic electrodes to remove water pollutants. This technique offers high treatment efficiency, industrial-scale handling capacity, and environmental friendliness [29], [30]. The performance of electrocoagulation is summarized in Table 3. The electrochemical reactions occurring at the metal electrodes in the EC reactor are summarized as follows:

At anode:

$$M(s) \rightarrow M^{n+}(aq) + ne^- \quad (2)$$

$$2H_2O\,(l) \rightarrow 4H^+(aq) + O_2(g) + 4e^- \quad (3)$$

At cathode:

$$Mn^{n+}(aq) + ne^- \rightarrow M\,(s) \quad (4)$$

$$2H_2O\,(l) + 2e^- \rightarrow H_2(g) + 2OH^- \quad (5)$$

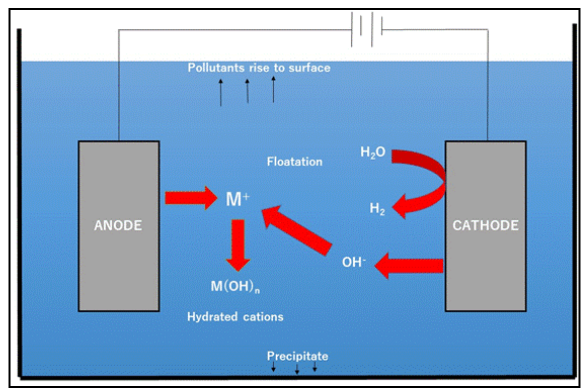


Figure 3 Illustration of electrocoagulation

As illustrated in Figure 3, metal cations (Mn^+), such as Al^{3+} and Fe^{2+}, destabilize colloidal particles and react with hydroxide ions (OH^-) in water to form coagulant agents that aid in contaminant removal [31]. These coagulants form amorphous metal hydroxide precipitates, while hydrogen gas bubbles lift pollutants to the surface of the EC reactor, where they are collected and removed [32],[33]. Several key parameters influence the performance of EC, including: (i) supplied current, (ii) reaction time, (iii) electrode configuration, and (iv) initial pH of the water. The applied current directly affects the concentration of metal ions, coagulant generation, and the density of hydrogen bubbles in the EC process [33]. Higher current levels result in smaller hydrogen bubbles, increasing the surface area available for particle attachment and thereby enhancing separation efficiency. Notably, a COD reduction in oil waste emulsion was achieved in under 22 minutes using a current density of 25 mA/cm² [35]. Additionally, water electrolysis at the cathode contributes to pH changes throughout the EC process. For example, when the initial water pH is acidic, it tends to increase during the process until reaching a neutral level [36], [37], [38].

Despite its potential, several limitations hinder the application of EC at pilot scale. One major issue is the impermanence of electrodes. Their short lifespan necessitates frequent cleaning, maintenance, and replacement to ensure optimal performance. Another limitation is the need to control multiple influencing factors to achieve consistent results. These include electrode material and design, electrode spacing, polarity, current density, water conductivity, and particle size. Additionally, the method requires frequent fine-tuning, making it both time-consuming and costly.

Table 3 Polluted water treatment via electrocoagulation

Electrocoagulation process	Water matrices	Condition of process	Pollutant removed	Pollutant removal efficiency (%)	Ref.
Combined electrocoagulation with the mixing process	River water contaminated by textile	Applied current: 15 A Period of treatment: 60 minutes Configuration of electrode: Aluminum (Al) plate electrode, 4 cathodes, 2 anodes Initial pH: 8 Additional propeller for the mixing process	TSS TDS BOD COD Final pH	98% 74% 57% 49% Neutral	[32]
Electrocoagulation	River water	Applied current: 9V Period of treatment: 120 minutes Configuration of electrode: Cathode: Aluminum, Anode: Aluminum with 2 cm inter-electrode distance Initial pH: >7	Final pH Electrical conductivity COD Organic matter (UV_{254})	7.8 – 7.9 460 μScm^{-1} 78% 95%	[34]
Combined electrocoagulation and chemical coagulation	Brewery wastewater	Applied current: 5W Period of treatment: 20 minutes Configuration of electrode: Cathode: Aluminum, Anode: Aluminum Initial pH: >5 Additional alum (Aluminium sulfate) as the chemical coagulant	COD Reactive phosphorous (RP) Total phosphorous (TP) TSS	26% 74% 76% 85%	[39]
Electrocoagulation	Pulp and paper wastewater	Applied current: 5.55mA/cm^2 Period of treatment: 33.7 minutes Configuration of electrode: Iron cathode/anode with 20mm inter-electrode distance Initial pH: 6.38	COD Colour TSS TOC Final pH	61.2% 98.6% 100% 41% 8.2	[40]

4.2 Photocatalytic

Recently, photocatalysis has gained widespread attention among researchers, particularly for its application in water treatment and purification due to its environmentally friendly nature. This method facilitates the degradation of both organic and inorganic pollutants in water, especially where conventional oxidation processes are ineffective. This process can convert organic pollutants into harmless end products. Additionally, it produces minimal by-products, requires only a small amount of catalyst, and is considered less hazardous [41]. By using semiconductor metal oxides as photocatalysts and exposing them to light, this approach promotes electron mobility within the metal oxide structure. This results in the formation of hydroxyl radicals, which subsequently break down organic contaminants into inorganic compounds such as water and carbon dioxide, as illustrated in Figure 4 [42], [43] as shown in Figure 4.

Generally, the photocatalytic process begins when the photocatalyst absorbs light energy, typically from UV radiation. When the photon energy (hv) equals or exceeds the band gap energy (Eg), an electron in the valence band (VB) is excited to the conduction band (CB), leaving behind a hole (h^+vb) in the VB. This stage is referred to as the 'photoexcitation' state. The excited electron (e^-cb) carries a negative charge [42], [44].

$$\text{Photocatalyst} + hv \rightarrow \text{Photocatalyst}(e^-_{cb} + h^+_{vb}) \quad (6)$$

Meanwhile, the generated hole (h^+_{vb}) is positively charged and possesses high oxidative potential, enabling the direct oxidation of organic pollutants.

$$h^+_{vb} + \text{Pollutant} \rightarrow \text{Oxidation of Pollutant} \quad (7)$$

Hydroxide ions (OH^-) in the aqueous solution serve as hole-scavengers, preventing the recombination of photoelectrons (e^-_{cb}) and holes (h^+_{vb}) [44], [45], [46]. The reaction between the hole (h^+_{vb}) and hydroxide ions (OH^-), or the decomposition of water, generates highly reactive hydroxyl radicals (•OH). These radicals are highly unstable and initiate the degradation of organic pollutants.

$$h^+_{vb} + H_2O \rightarrow H^+ + \cdot OH \quad (8)$$

$$h^+_{vb} + OH^- \rightarrow \cdot OH \quad (9)$$

The molecular oxygen is reduced into superoxide anion by the electron (e^-_{cb}).

$$e^-_{cb} + O_2 \rightarrow \cdot O^{2-} \quad (10)$$

The oxygen radical forms organic peroxides in the presence of organic scavengers or hydrogen peroxides.

$$\cdot O^{2-} + \text{Pollutant} \rightarrow \text{Pollutant-OO}\cdot \quad (11)$$
$$\cdot O^{2-} + HO_2\cdot + H^+ \rightarrow H_2O_2 + O_2 \quad (12)$$

The excess of H_2O_2 reacts with hydroxyl radicals and h^+_{vb} to produce $HO_2\cdot$.

$$H_2O_2 + \cdot OH \rightarrow HO_2\cdot + H_2O \quad (13)$$
$$H_2O_2 + h^+_{vb} \rightarrow H^+ + HO_2\cdot \quad (14)$$

e^-_{cb} also contributes to the production of hydroxyl radicals and leads to the primary mineralization of organic matter [46], [47].

$$H_2O_2 + e^-_{cb} \rightarrow \cdot OH + OH^- \quad (15)$$
$$H_2O_2 + \cdot O^{2-} \rightarrow \cdot OH + OH^- + O_2 \quad (16)$$
$$\cdot OH + \text{Pollutant} \rightarrow CO_2 + \text{degraded Pollutant} + H_2O \quad (17)$$

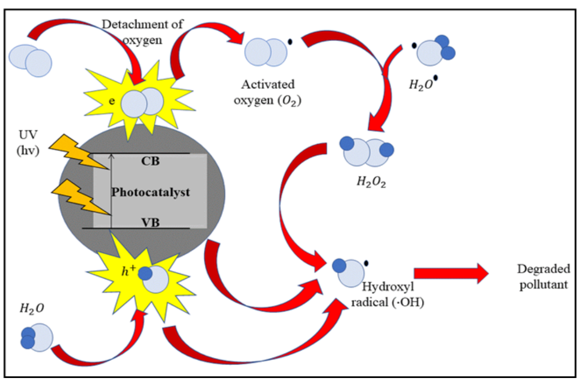


Figure 4 Illustration of photocatalytic degradation of pollutants

The type of photocatalyst is a critical factor that influences the efficiency of the photocatalytic process. According to Khan et al. [49], key attributes of an effective photocatalyst include an appropriate band gap, suitable morphology, large surface area, reusability, and structural stability. An ideal photocatalyst should exhibit the following qualities: (a) high photocatalytic activity; (b) long-term thermal stability; (c) mechanical strength and resistance to attrition; (d) broad-spectrum non-selectivity; and (e) chemical and physical stability under diverse conditions [50], [43]. Semiconductor metal oxides are widely used as photocatalysts due to their compatibility with photocatalytic systems. In such systems, light absorption initiates charge separation, generating positive holes that drive the oxidation of organic pollutants [51]. Common examples of semiconductor metal oxides include titanium dioxide (TiO_2), zinc oxide (ZnO), iron (III) oxide (Fe_2O_3), cerium oxide (CeO_2), cadmium sulphide (CdS), and zinc sulphide (ZnS). Due to their high efficiency, cost-effectiveness, and low toxicity, these materials are frequently used as photocatalysts [52].

TiO_2, ZnO, and CeO_2 are semiconductor photocatalysts with wide band gaps, which enhance photocatalytic performance under UV light [41]. According to Chen et al. [52], ZnO demonstrates superior photocatalytic degradation efficiency and greater cost-effectiveness for commercial applications. Previous studies have confirmed that ZnO exhibits higher photocatalytic degradation efficiency for various organic compounds and pollutants. Table 4 summarizes previous studies on the performance of ZnO as a photocatalyst in degrading organic pollutants. These findings demonstrate ZnO's strong potential for treating environmental pollutants.

Furthermore, the efficiency of photocatalytic degradation is significantly influenced by operational parameters. Variables such as pH, pollutant concentration, temperature, and airflow rate affect substrate adsorption and dissociation, surface charge of the catalyst, and the potential for valence band oxidation [43]. A Despite its strong potential in degrading organic pollutants, this method still has certain limitations. The advantages and limitations of the photocatalytic system are summarized in Table 5.

Table 4 Polluted water treatment via photocatalytic degradation

Water matrix/ Target pollutant	Photocatalyst	Light source	Efficiency	Ref.
Medical wastewater-Flumequine	Immobilized TiO_2	UV light irradiation	Degradation (2.5h): 90%	[53]
Sulphur containing compound	Flower-like ZnO flakes	UV light irradiation	Desulfurization (60 mins): 30%	[54]
Sulphur containing compound	ZnO-KCC-1	UV light irradiation	Desulfurization (60mins): 70%	[55]
Palm oil mill secondary effluent (POMSE)	ZnO-PEG	UV light irradiation	Reduce (3h): Colour- 84% Turbidity-94% COD-94% BOD-99mg/L	[56]
Textile wastewater-Dye wastewater	Nano-TiO_2	UV light irradiation	Reduce (5h): Salinity-96% Conductivity-96% TSS-99% TDS-99% BOD-95% COD-91% TN-62%	[57]
Textile wastewater-Azo Dye C.I Basic Red 46	Immobilized-TiO_2	Solar UV irradiation	Decolourization: 99%	[58]
Medical wastewater-	TiO_2	UV irradiation	Reduce (240 min): Trimethoprim-70% Enrofloxacin-80% Amoxicillin-100% Sulfadiazine-100% Azithromycin-100%	[59]

Table 5 Advantages and challenges of photocatalytic method

Advantages	Challenges
•No additive consumption	•Separation of the catalyst from the treated water will be hard at the pilot scale
•Simplicity	• High cost due to UV irradiation
•Lower sensitivity to pH	• Low quantum yield
•The highest reduction of organic pollutants	

4.3 Membrane Technology

Membrane technology offers several advantages for separating suspended and dissolved materials in wastewater and saltwater. It is considered adaptable, flexible, and compatible with integrated systems across various applications. Additionally, membrane systems are relatively simple in both concept and operation. Moreover, membrane technology can reduce chemical usage, energy consumption, and residual waste generation [60]. In water purification, membrane technology provides an advanced method for removing suspended and dissolved particles, including microorganisms (such as bacteria and protozoa) and certain metals (such as iron and manganese) [4]. There are generally four main types of membrane filtration: microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO), as illustrated in Figure 5 [61]. The use of membrane technology is associated with lower energy consumption, operational simplicity, reduced environmental impact, and enhanced sustainability [62].

Microfiltration typically refers to filtration processes with pore sizes smaller than 1 micron. Typical depth filters used in microfiltration have pore sizes of approximately 0.5, 0.2, and 0.1 microns. Microfilters are commonly composed of membrane-based materials. Crossflow microfiltration is typically implemented using spiral-wound membrane systems [63]. Feed water is directed across the membrane surface at pressures ranging from 10 to 50 psi, typically at a relatively high flow rate. Only a small portion of the feed water (approximately 5–10%) permeates through the membrane. The remaining water is either recycled or directed to subsequent membrane modules. Additionally, a small quantity of concentrate is discharged from the system. Surface fouling on the microfiltration membrane is reduced through the crossflow mechanism [64]. Although a wide range of materials has been used for microfiltration, polyether sulfone (PES) and polyvinylidene fluoride (PVDF) are among the most commonly applied [65].

Ultrafiltration (UF) is a membrane-based separation process that operates with pore sizes ranging from 0.1 to 0.001 microns. Typically, UF removes bacteria, viruses, high molecular weight compounds, colloidal materials, and both organic and inorganic molecules. Water treatment systems utilizing UF technology typically involve simpler operational phases compared to conventional methods. In addition, UF technology provides high-quality clean water, cost-effective operation, system upgradability, and compact design that reduces spatial requirements [66].

Nanofiltration (NF) is quite like reverse osmosis (RO) in both principle and function. The key distinction lies in the extent to which monovalent ions, such as chlorides, are removed. Reverse osmosis can remove monovalent ions at rates of approximately 98–99% under a pressure of 200 psi. In contrast, nanofiltration membranes typically remove monovalent ions in the range of 50–90%, depending on the membrane material and manufacturing process used [67]. As a result, a wide variety of nanofiltration membranes is available to suit different treatment needs. Each membrane type is optimized for specific applications and may not be suitable for other uses.

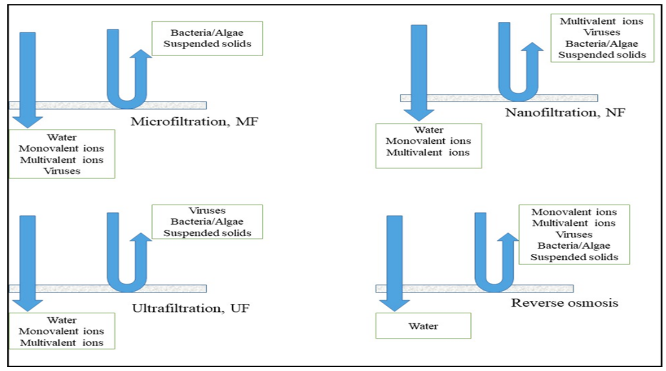


Figure 5 Comparison between MF, UF, NF and RO

In Malaysia, three water treatment plants reportedly utilize membrane technology, located in Pulau Pinang, Selangor, and Kelantan. Most of these facilities employ industrial-scale ultrafiltration (UF) membrane technology [23]. However, UF technology remains ineffective in removing low molecular weight organic compounds and ions, such as sodium, calcium, magnesium, and chloride. In addition, UF is unable to remove odour from water and is typically suitable only for short-term application. Therefore, pre-treatment is necessary to mitigate membrane fouling and extend membrane lifespan. An alternative or hybrid approach is needed to enhance treatment efficiency and increase the production of high-quality clean water.

4.4 Comparative Overview of Other Advanced Technologies

While electrocoagulation, photocatalysis, and membrane separation have been extensively discussed in previous subsections, a range of other advanced water treatment technologies have also shown significant potential for remediating polluted river water as shown in Table 6. These alternatives differ in operational mechanisms, pollutant removal efficiencies, scalability, and environmental impacts. This section provides a comparative overview of key technologies including ozonation, activated carbon adsorption, constructed wetlands, advanced oxidation processes (AOPs), ion exchange, biological treatments, and electrodialysis by highlighting their strengths, limitations, and potential roles in integrated treatment systems.

Ozonation utilizes ozone gas (O_3) as a powerful oxidizing agent to break down organic and inorganic pollutants. It is particularly effective in removing color, odor, and pathogens, making it suitable for tertiary water treatment applications. However, ozonation involves high operational costs and requires careful handling due to ozone's unstable and toxic nature. Additionally, it lacks residual disinfection capability and is sensitive to temperature and pH conditions [70].

Activated carbon, in both powdered (PAC) and granular (GAC) forms, is widely used for the removal of organic compounds, taste, odor, and micropollutants. Its high surface area enables effective adsorption, however, performance declines as the carbon becomes saturated, requiring regeneration or replacement. Moreover, activated carbon is generally ineffective against many inorganic pollutants [71], [72].

Constructed wetlands (CWs) are engineered systems that replicate natural wetlands to remove contaminants through sedimentation, filtration, microbial activity, and plant uptake. They are cost-effective, environmentally friendly, and require minimal operational input. However, they require large land areas, exhibit slow treatment rates, and may be unsuitable for high-volume industrial applications [73].

Advanced oxidation processes (AOPs), such as Fenton reactions, UV/H_2O_2, and O_3/H_2O_2 systems, generate hydroxyl radicals (•OH) that aggressively oxidize a broad spectrum of pollutants. They are highly effective for non-biodegradable contaminants but are limited by high energy and chemical consumption, as well as complex reactor designs [68], [69].

Ion exchange processes selectively remove targeted ions such as heavy metals and hardness-inducing cations from water. These systems are highly effective for specific applications but require chemical regeneration and careful monitoring to avoid resin fouling and secondary waste generation [74].

Conventional biological systems such as activated sludge and trickling filters are effective for biodegradable organic matter. However, they are less effective in treating toxic, persistent, or non-biodegradable pollutants. Their effectiveness depends on the stability of microbial communities, adequate aeration, and sufficient hydraulic retention time [75].

Electrodialysis (ED) uses an applied electrical potential to selectively separate ions through ion-exchange membranes. It is effective for desalination and brackish water treatment; however, high capital costs and membrane fouling limit its broader application in polluted river water treatment [76], [77]

Table 6 Summary of Alternative Water Treatment Technologies

Technology	Advantages	Limitations	Application	Ref.
Ozonation	High oxidation capacity; effective disinfection	High operational cost; ozone instability; no residual effect	Odor and color removal; pathogen inactivation	[70]
Activated Carbon Adsorption	Effective for organic pollutants; simple system design	Requires regeneration; performance declines with saturation	Taste and odor control; pesticide removal	[71], [72]
Constructed Wetlands (CWs)	Eco-friendly; low energy and operational input	Land-intensive; slow treatment rate	Rural or low-load wastewater treatment	[73]
AOPs	Generates strong radicals; degrades persistent organics	High energy and chemical demand; complex setup	Treatment of non-biodegradable pollutants	[68], [69]
Ion Exchange	Targeted removal of specific ions (e.g., metals)	Chemical regeneration required; resin fouling possible	Water softening; heavy metal removal	[74]
Biological Treatments	Cost-effective for biodegradable organics	Ineffective for toxins and persistent pollutants; requires stable microbial communities	Municipal wastewater treatment	[75]
Electrodialysis (ED)	Effective ion separation; useful for salinity reduction	High capital cost; membrane fouling concerns	Desalination; brackish water treatment	[76], [77]

5.0 PROSPECTIVE HYBRID MEMBRANE PHOTOCATALYTIC REACTOR (MPR) FOR POLLUTED RIVER WATER TREATMENT

Following the comparative evaluation of several advanced water treatment technologies in previous section which includes ozonation, AOPs, adsorption, biological methods, and ion exchange, this section presents the prospective potential of the hybrid membrane photocatalytic reactor (MPR) as an integrated and scalable alternative.

The hybrid membrane photocatalytic reactor (MPR) represents an advanced alternative to conventional water treatment methods. It combines photocatalytic degradation with membrane filtration technology to enhance pollutant removal efficiency [42], [78], [79], [55]. Unlike other treatment approaches such as ozonation, AOPs, constructed wetlands, or adsorption, hybrid MPR integrates simultaneous degradation and separation in a single unit, improving overall efficiency and minimizing post-treatment requirements. Photocatalytic degradation in the hybrid MPR plays a crucial role in reducing membrane fouling and mitigating flux decline, thus extending membrane lifespan [80]. Hybrid MPR systems have demonstrated significant improvements over conventional treatment systems and hold substantial potential for industrial-scale wastewater treatment. According to The Lens which is a server for global patent and scholarly knowledge as public resources, the demand for the application of MPR is relatively higher and more active over the year. This trend indicates growing academic and industrial interest in MPR technology, with ongoing studies exploring its performance and scalability.

This is due to the numerous advantages offered by MPR compared to other treatment systems, including: (i) reduced energy consumption and smaller installation footprint, (ii) simpler system configuration and improved process control, (iii) effective confinement of the photocatalyst within the reaction environment, (iv) enabling continuous operation with simultaneous separation of catalyst and product, (v) controlled and adjustable retention time of molecules within the reactor, (vi) enhanced potential for photocatalyst reuse [78], [81], [79].

The concept of developing the MPR system emerged from growing interest and extensive research into photocatalysis for environmental applications, particularly for the oxidation and reduction of organic pollutants in water and air. The strong potential of photocatalysis for pollutant removal has positioned it as a green and sustainable approach, offering several advantages: (i) ability to operate under ambient temperature and pressure; (ii) use of greener and safer photocatalysts; (iii) applicability to a wide range of substrates, including liquid, solid, and gaseous phases; (iv) utilization of renewable solar energy; (v) compatibility with other chemical or physical systems. Despite these advantages, the separation and recovery of heterogeneous photocatalysts remain a major challenge for large-scale photocatalytic applications. Therefore, integrating membrane technology with photocatalysis is considered a promising strategy to address this challenge [81]. Membrane separation is a physical process that not only enables selective separation, but also effectively confines the photocatalyst within the reaction environment, allowing continuous operation with simultaneous separation of catalyst and treated product.

Although other technologies offer various advantages, the MPR system provides an integrated platform that extends membrane lifespan, allows photocatalyst reuse, and supports scalability, making it a competitive option among the advanced treatment methods discussed. To achieve optimal performance in MPR systems, several key factors must be considered during implementation. One of the most critical factors is the selection of a suitable photocatalyst. According to Khan et al. [49], an effective photocatalyst should possess a suitable band gap, appropriate morphology, high surface area, reusability, and chemical stability to enhance photocatalytic efficiency, thereby minimizing membrane fouling and flux decline. In addition, the photocatalyst should exhibit: (a) high catalytic activity, (b) resistance to poisoning and long-term stability at elevated temperatures, (c) mechanical durability and resistance to attrition, (d) non-selectivity toward a wide range of pollutants, and (e) stability under diverse physical and chemical conditions [82].

Another critical consideration is the selection of membrane type and material. There are four types of membranes that are typically applied in hybrid MPR such as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis. Each membrane type has distinct properties and is composed of different materials, influencing its performance in MPR applications. It is essential to choose a membrane that effectively retains the photocatalyst within the reaction environment to prevent its loss through permeate. When treating organic pollutants, the membrane should also prevent the passage of substrates and intermediate products into the permeate stream. Additionally, the membrane must be resistant to UV irradiation and oxidative attack by hydroxyl radicals to ensure long-term stability in MPR operations [83]. Therefore, the successful implementation of hybrid MPR systems depends primarily on two key factors: the choice of photocatalyst and the selection of membrane material.

Table 7 Polluted water treatment via hybrid MPR

Water matrix	Photocatalyst	Membrane	Process condition	Efficiency	Ref.
Pharmaceutical diclofenac (DCF)	TiO_2 (0.75g/L)	UF	UV irradiation pH7 Aeration (30min)	Reduce (5h): DCF: >56% TOC: 52%	[84]
Textile wastewater	ZnO-PEG (0.10g/L)	UF	UV irradiation pH 11 Inlet pressure: 6 bar Temp. 25^{o}C	Reduce (3h): Colour - 100% Turbidity – 100% COD – 97% Final normalized flux: 41%	[85]
Palm oil mill secondary effluent (POMSE)	ZnO-CC (0.05g/L)	NF	UV irradiation pH 9 Inlet pressure: 6 bar Temp. 25^{o}C	Reduce: Colour- 99% COD-98% BOD-96% Turbidity- 99%	[93]
Dye-oil emulsion	Dopamine-modified TiO_2 nanowire (5mg)	Intercalated graphene-oxide-based photocatalytic membrane	Visible light irradiation	Reduce (120min): Organic pollutant- >98%	[86]
p-nitrophenol wastewater	Fe(III)-ZnS/g-C_3N_4 photo-Fenton (1.0g/L) Addition of H_2O_2 (170mg/L)	MF	Solar light irradiation Aeration- 0.5m^3/h pH 5	Reduce (4h): Organic pollutant- 91%	[87]
Dye-Congo red dyes	ZnO-PVP-St (0.3g/L)	NF	UV light irradiation pH 7	Reduce: Colour: 100%	[80]
Industrial dye wastewater	ZnO-PVP-St (0.1g/L)	NF	UV light irradiation pH 11	Reduce: Colour: 100% COD: 92% Turbidity: 100% TSS: 100%	[42]

Table 7 highlights the strong potential of hybrid membrane photocatalytic reactors (MPR) for advanced water purification applications. This approach represents a significant advancement over standalone photocatalytic methods. Previous studies have demonstrated the high efficiency of photocatalysis in degrading organic pollutants. When integrated with membrane systems, the photocatalyst can be effectively separated from the treated effluent. Moreover, the photocatalytic component reduces membrane fouling and flux decline, thereby extending membrane lifespan. The photocatalytic process facilitates the breakdown of organic pollutants, while the membrane component aids in the separation of catalysts, bacteria, suspended solids, and other contaminants. Recent studies have shown that ZnO nanoparticles exhibit superior performance as photocatalysts in hybrid MPR systems. Compared to TiO_2, ZnO is more stable, cost-effective, and photosensitive, with a higher rate of H_2O_2 generation and greater impact on reducing membrane flux decline [78], [85]. The wurtzite structure of ZnO provides a high exciton binding energy, enhancing UV light utilization at ambient temperature and resulting in improved degradation efficiency. Therefore, hybrid MPR systems are widely regarded as highly promising for wastewater and polluted river water treatment. This hybrid technology also holds strong potential for implementation in Malaysia, particularly for treating polluted river systems.

In summary, the hybrid membrane photocatalytic reactor (MPR) represents a highly efficient, scalable, and environmentally friendly solution with strong potential for widespread adoption in polluted river water treatment.

6.0 PILOT SCALE HYBRID MEMBRANE PHOTOCATALYTIC REACTOR

Hybrid membrane photocatalytic reactors (MPRs) have recently gained wide attention due to their high performance and efficiency in water treatment. Various configurations of advanced hybrid MPR systems have been applied for the removal of a wide range of organic pollutants. Although technologies such as ozonation, constructed wetlands, and AOPs have been implemented in localized settings, their limitations in residual control, land requirements, and operational complexity highlights the need for a more integrated and scalable solution like MPR.

Previous studies have demonstrated that hybrid MPR systems perform effectively in treating industrial effluents such as those from textile, palm oil mill, and pharmaceutical industries. However, most of these studies were conducted at the laboratory or small scale, where operating conditions are easier to manage and control. Transitioning to the pilot scale provides critical insights into the real-world viability and operational robustness of the technology, which are essential precursors to full-scale industrial implementation.

A pilot-scale plant is a scaled-down version of a full-scale facility, used to assess process behaviour and system performance prior to industrial deployment [88]. It enables the evaluation of key parameters such as input requirements, processing times, flow dynamics, and system stability. In certain cases, pilot-scale facilities can support niche production volumes while reducing financial risk. Pilot-scale systems also facilitate the collection of operational data needed to optimize the efficiency of large-scale manufacturing processes [89], [90].

Compared to the previously discussed technologies, the pilot-scale MPR uniquely enables simultaneous pre-treatment, degradation, and filtration, while consuming less energy and requiring minimal chemical additives. This makes it particularly suitable for treating polluted river water with highly variable composition and flow conditions. Table 8 presents performance data from previous studies on pilot-scale hybrid MPR systems. The data supports the system's potential to maintain high pollutant removal efficiency at realistic operating volumes, while simultaneously enhancing clean water output and membrane durability through integrated photocatalyst recovery. Pilot-scale hybrid MPR has been widely recognized as having strong potential for polluted river water treatment. This is attributed to its ability to treat larger volumes of polluted wate typically beyond 10 litres per cycle which resulting in increased clean water output. Furthermore, integrating photocatalysis as a pre-treatment enhances the long-term stability of the separation system, thereby improving the overall durability and efficiency of hybrid MPR operations. The use of an appropriate membrane enables effective separation while retaining the photocatalyst within the reaction zone. Operating in continuous mode further supports catalyst reuse, contributing to cost-effectiveness and sustainability [59].

Table 8 Polluted water treatment via pilot scale hybrid MPR

Water matrix	Photocatalyst	Membrane type	Process condition	Efficiency	Ref.
Micro-pollutant water (Diclofenac – DCF)	TiO_2 (0.5g/L)	UF hollow fiber	UV irradiation pH 6 Stirrer Total effective PMR unit volume: 25L	Reduce (8h): DCF: 99.5% Mineralization: 69%	[91]
Organic pollutant	TiO_2 (0.3g/L)	MF hollow fiber	UV irradiation Temp.: 15-20^{o}C Reactor volume: 500L air flow rate: 100L/min	Reduce: Humic acid: 61.4% (22h) RhB: 83.5% (20.5h) MB: 30% (19h)	[92]

Therefore, pilot-scale hybrid MPR systems offer a practical and scalable solution for treating polluted river water, with proven performance in real-world settings, strong membrane-photocatalyst synergy, and high potential for industrial implementation.

7.0 CONCLUSION

Rapid urbanization and industrial growth have intensified surface water pollution, particularly in river systems receiving diverse effluents from agricultural and manufacturing sectors. Despite existing regulations and conventional treatment methods such as coagulation and sedimentation, these approaches remain inadequate for removing micro-contaminants, persistent organic pollutants, and heavy metals.

Recent advancements in water treatment technologies—including ozonation, activated carbon adsorption, constructed wetlands, advanced oxidation processes (AOPs), and ion exchange—have been discussed in this study. While each method offers specific benefits, their individual limitations underscore the need for more integrated and scalable treatment solutions.

In this context, the hybrid membrane photocatalytic reactor (MPR) emerges as a promising next-generation technology, offering dual functionality through the simultaneous degradation and physical separation of pollutants. Although its effectiveness has been established at the laboratory and small scale, pilot-scale implementation is crucial for evaluating real-world feasibility and industrial relevance.

This review has not only examined the core water treatment technologies but also highlighted their comparative advantages and limitations. The evidence suggests that hybrid MPRs—particularly in pilot-scale configurations—are well aligned with Malaysia's water treatment challenges and the broader goals of environmental sustainability.

Therefore, continued research and development of pilot-scale hybrid MPR systems should be prioritized, especially for river water treatment applications. This effort will accelerate progress toward Sustainable Development Goal 6 (Clean Water and Sanitation), ensuring equitable access to safe water sources while promoting long-term environmental resilience.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

References

[1] Lee Goi, C. 2020. The river water quality before and during the Movement Control Order (MCO) in Malaysia. *Case Studies in Chemical and Environmental Engineering*. 2: 100027. DOI: https://doi. org/10.1016/j.cscee.2020.100027

[2] Picos-Corrales, L. A., Sarmiento-Sánchez, J. I., Ruelas-Leyva, J. P., Crini, G., Hermosillo-Ochoa, E., & Gutierrez-Montes, J. A. 2020. Environment-Friendly Approach toward the Treatment of Raw Agricultural Wastewater and River Water via Flocculation Using Chitosan and Bean Straw Flour as Bioflocculants. *ACS Omega*. 5(8): 3943-3951. DOI: https: //doi.org/10.1021/acsomega.9b03419

[3] Qian, J., Qu, K., Tian, B., & Zhang, Y. 2021. Water treatment of polluted rivers in cities based on biological filter technology. *Environmental Technology and Innovation*. 23: 101544. DOI: https:// doi.org/10.1016/j.eti.2021.101544

[4] Omran, A. 2011. Factors influencing water treatment management performance in Malaysia: a case study in Pulau Pinang. *Annals of the Faculty of Engineering Hunedoara*. 9(1): 53. DOI: https://annals.fih. upt.ro/pdf-full/2011/ANNALS-2011-1-06.pdf

[5] Wang, H., Wang, J., Bo, G., Wu, S., & Luo, L. 2020. Degradation of pollutants in polluted river water using Ti/IrO2-Ta2O5 coating electrode and evaluation of electrode characteristics. *Journal of Cleaner Production*. 273: 123019. DOI: https://doi.org/10.1016 /j.jclepro.2020.123019

[6] Hairom, N. H. H., Soon, C. F., Mohamed, R. M. S. R., Morsin, M., Zainal, N., Nayan, N., Zulkifli, C. Z., & Harun, N. H. 2021. A review of nanotechnological applications to detect and control surface water pollution. *Environmental Technology and Innovation*. 24: 102032. DOI: https://doi.org/10.1016/j.eti.2021.102032

[7] Huang, Y. F., Ang, S. Y., Lee, K. M., & Lee, T. S. 2015. Quality of Water Resources in Malaysia. *Research and Practices in Water Quality*. London: IntechOpen Limited. DOI: https://doi.org/10.5772/58969D.

[8] Suprihatin, S., Cahyaputri, B., Romli, M., & Yani, M. 2017. Use of biofilter as pre-treatment of polluted river water for drinking water supply. *Environmental Engineering Research*. 22(2): 203-209. DOI: https://doi.org/10.4491/eer.2016.110

[9] Sururi, M. R., Notodarmojo, S., Roosmini, D., Putra, P. S., Maulana, Y. E., & Dirgawati, M. 2020. An investigation of a conventional water treatment plant in reducing dissolved organic matter and trihalomethane formation potential from a tropical river water source. *Journal of Engineering and Technological Sciences*. 52(2): 271-288. DOI: https://doi.org/10.5614/j.eng.technol.sci.2020.52.2.10

[10] Yap, C. K., Peng, S. H. T., & Leow, C. S. 2019. Contamination in Pasir Gudang Area, Peninsular Malaysia: What can we learn from Kim Kim River chemical waste contamination? *Journal of Humanities and Education Development*. 1(2): 82-87. DOI: https://doi.org/10.22161 /jhed.1.2.4

[11] Mokhtar, Z. 2023. Review of Malaysia's environmental waterway compliances with industrial effluent discharge. *International Journal of Business, Economics and Law*. 30(1): 151–156. https://ijbel.com/ wp-content/uploads/2023/12/IJBEL30.ISU1_326. pdf

[12] Qannaf, A., Zaid, A., & Ghazali, S., 2019. Preliminary Investigation of Water Treatment Using Moringa Oleifera Seeds Powder as Natural Coagulant: A Case Study of Belat River, Malaysia. *The International Journal of Engineering and Science*. 8(2): 79-85. DOI: https://doi.org/ 10.9790 /1813-0802017985

[13] EAP Task Force, O. for economic cooperation and development (OECD). 2008. Surface Water Quality Regulation in EECCA Countries: Directions for Reform 1-13. https://www.oecd.org/env/outreach /41832129.pdf. (Accessed 22 February 2024).

[14] Ahmed, M. F., & Mokhtar, M. Bin. 2020. Treated water quality based on conventional method in Langat River Basin, Malaysia. *Environmental Earth Sciences.* 79(18): 12665. DOI: https://doi.org/ 10.1007/s12665-020-09160-7

[15] Peavy, H. S., Rowe, D. R., & Tchobanoglous, G. 1985. *Environmental engineering*. New York: McGraw-Hill. DOI: https://iou.ac/wp-content/ uploads/2021/03/CE-341-LECTURE-1-PDF.pdf. (Accessed 22 February 2024).

[16] Weiner, R.F., Matthews, R.A. 2003. *Environmental Engineering: Fourth Edition*. Amsterdam: Elsevier Inc. DOI: https://doi.org /10.1016/B978-0-7506-7294-8.X5000-3

[17] Department of Environment Malaysia. 2009. Environmental Quality (Industrial Effluent) Regulations 2009 (P.U. (A) 434). https://www.doe.gov.my/wpcontent/uploads/2021/08/Environment al_Quality_Industrial_Effluent_Regulations_2009_-_P.U.A_434-2009. pdf. (Accessed 23 February 2024).

[18] Department of Environment. 2016. National Water Quality Standard of Malaysia. https://www.doe.gov.my/portalv1/wp-content/uploads /2019/05/Standard-Kualiti-AirKebangsaan.pdf. (Accessed 14 June 2024).

[19] Maharjan, A.K., Kamei, T., Amatya, I.M., Mori, K., Kazama, F., Toyama, T. 2020. Ammonium-nitrogen (NH4+-N) removal from groundwater by a dropping nitrification reactor: Characterization of NH4+-N transformation and bacterial community in the reactor. *Water*. 12(2): 599. DOI: ttps://doi.org/10.3390/w12020599

[20] Teh C. Y., Budiman P.M, Shak K. P. Y., and Wu T. Y. 2016 Recent advancement of coagulation–flocculation and its application in wastewater treatment. *Industrial & Engineering Chemistry Research*, 55(16): 4363–4389. DOI: https://doi.org/10.1021/acs.iecr.5b04703

[21] Litu, L., Ciobanu, G., Cîmpeanu, S. M., Kotova, O., Ciocinta, R., Bucur, D., & Harja, M. 2019. Comparative study between flocculation-coagulation processes in raw/wastewater treatment. *The AgroLife Scientific Journal*, 8(1): 139-145. DOI: https://doi.org/10.1556 /446.2021.00029

[22] Hussain, S., Awad, J., Sarkar, B., Chow, C.W.K., Duan, J., van Leeuwen, J. 2019. Coagulation of dissolved organic matter in surface water by novel titanium (III) chloride: Mechanistic surface chemical and

spectroscopic characterisation. *Sep. Purif. Technol*. 213: 213-223. DOI: https://doi.org/10.1016/j.seppur.2018.12.038

[23] Pakharuddin, N. H., Fazly, M. N., Ahmad Sukari, S. H., Tho, K., & Zamri, W. F. H. 2021. Water treatment process using conventional and advanced methods: A comparative study of Malaysia and selected countries. *IOP Conference Series: Earth and Environmental Science*, 880(1): DOI: https://doi.org/10.1088/1755-1315/880/1/012017

[24] Cescon A, Jiang J-Q. 2020. Filtration Process and Alternative Filter Media Material in Water Treatment. *Water*. 12(12): 3377. DOI: https://doi.org/10.3390/w12123377

[25] Iwuozor, K. O. 2019. Prospects and challenges of using coagulation-flocculation method in the treatment of effluents. *Advanced Journal of Chemistry-Section A*. 2(2): 105-127. DOI: https://doi.org/10.29088/SAMI/AJCA.2019.2.105127

[26] Chekli, L., Galloux, J., Zhao, Y.X., Gao, B.Y., Shon, H.K. 2015. Coagulation performance and floc characteristics of polytitanium tetrachloride (PTC) compared with titanium tetrachloride (TiCl4) and iron salts in humic acid-kaolin synthetic water treatment. *Sep. Purif. Technol.* 142: 155-161. DOI: http://dx.doi.org/10.1016/j.seppur.2014.12.043S

[27] Amran, A. H., Zaidi, N. S., Muda, K., & Loan, L. W. 2018. Effectiveness of natural coagulant in coagulation process: a review. *International Journal of Engineering & Technology.* 7(3.9): 34-37. DOI: https://doi.org/10.14419/ijet.v7i3.9.15269

[28] Hofman-Caris, R., Hofman, J. 2017. Limitations of Conventional Drinking Water Technologies in Pollutant Removal. In: Gil, A., Galeano, L., Vicente, M. (eds) Applications of Advanced Oxidation Processes (AOPs) in Drinking Water Treatment. *The Handbook of Environmental Chemistry*. Switzerland: Springer-Verlag. DOI: https://doi.org/10.1007/698_2017_83

[29] Shahedi, A., Darban, A. K., Taghipour, F., & Jamshidi-Zanjani, A. 2020. A review on industrial wastewater treatment via electrocoagulation processes. *Current opinion in electrochemistry*, 22: 154-169. DOI: https://doi.org/10.1016/j.coelec.2020.05.009

[30] Hashim, K. S., AlKhaddar, R., Shaw, A., Kot, P., Al-Jumeily, D., Alwash, R., & Aljefery, M. H. 2020. Electrocoagulation as an Eco-Friendly River Water Treatment Method. *In Lecture Notes in Civil Engineering (Vol. 39)*. Singapore: Springer. DOI: https://doi.org/10.1007/978-981-13-8181-2_17

[31] Moussa, D. T., El-Naas, M. H., Nasser, M., & Al-Marri, M. J. 2017. A comprehensive review of electrocoagulation for water treatment: Potentials and challenges. *Journal of Environmental Management*. 186: 24-41. DOI: https://doi.org/10.1016/j.jenvman.2016.10.032

[32] Nugroho, F. A., Aryanti, P. T. P., Nurhayati, S., & Muna, H. M. 2019. A combined electrocoagulation and mixing process for contaminated river water treatment. *AIP Conference Proceedings*, 2097: DOI: https://doi.org/10.1063/1.5098192

[33] Jing, G., Ren, S., Pooley, S., Sun, W., Kowalczuk, P. B., & Gao, Z. 2021. Electrocoagulation for industrial wastewater treatment: an updated review. *Environmental Science: Water Research & Technology*, 7(7): 1177-1196. DOI: https://doi.org/10.1039 /D1EW00158B

[34] Kumari, S., & Kumar, R. N. 2021. River water treatment using electrocoagulation for removal of acetaminophen and natural organic matter. *Chemosphere*, 273: 128571. DOI: https://doi.org/10.1016/j.chemosphere.2020.128571

[35] Tahreen, A., Jami, M. S., & Ali, F. 2020. Role of electrocoagulation in wastewater treatment: A developmental review. *Journal of Water Process Engineering*. 37: 101440. DOI: https://doi.org/10.1016/j.jwpe.2020.101440

[36] Tir, M. and N. Moulai-Mostefa. 2008. Optimization of oil removal from oily wastewater by electrocoagulation using response surface method. *Journal of Hazardous Materials*. 158(1): 107-115. DOI: https://doi.org/10.1016/j.jhazmat.2008.01.051

[37] Dalvand, A., M. Gholami, A. Joneidi, and N.M. Mahmoodi. 2011. Dye Removal, Energy Consumption and Operating Cost of Electrocoagulation of Textile Wastewater as a Clean Process. *CLEAN - Soil, Air, Water*. 39(7): 665-672. DOI: https://doi.org/10.1002/clen.201000233

[38] Janpoor, F., A. Torabian, and V. Khatibikamal. 2011. Treatment of laundry wastewater by electrocoagulation. *Journal of Chemical Technology & Biotechnology*. 86(8): 1113-1120. DOI: https://doi.org/10.1002/jctb.2625

[39] Swain, K., Abbassi, B., & Kinsley, C. 2020. Combined electrocoagulation and chemical coagulation in treating brewery wastewater. *Water*. 12(3): 726. DOI: https://doi.org/10.3390/w12030726

[40] Jaafarzadeh, N., Omidinasab, M., & Ghanbari, F. 2016. Combined electrocoagulation and UV-based sulfate radical oxidation processes for treatment of pulp and paper wastewater. *Process Safety and Environmental Protection*. 102: 462-472. DOI: https://doi.org/10.1016/j.psep.2016.04.019

[41] Saravanan, R., Sacari, E., Gracia, F., Khan, M. M., Mosquera, E., & Gupta, V. K. 2016. Conducting PANI stimulated ZnO system for visible light photocatalytic degradation of coloured dyes. *Journal of Molecular Liquids*. 221: 1029-1033. DOI: https://doi.org/10.1016/j.molliq.2016.06.074

[42] Hairom, N. H. H., Mohammad, A. W., Ng, L. Y., & Kadhum, A. A. H. 2015. Utilization of self-synthesized ZnO nanoparticles in MPR for industrial dye wastewater treatment using NF and UF membrane. *Desalination and Water Treatment*. 54(4-5): 944-955. DOI: https://doi.org/10.1080/19443994.2014.917988

[43] Iervolino, G., Zammit, I., Vaiano, V. & Rizzo L. 2020. Limitations and Prospects for Wastewater Treatment by UV and Visible-Light-Active Heterogeneous Photocatalysis: A Critical Review. *Topics in Current Chemistry*. 378:7. DOI: https://doi.org/10.1007/s41061-019-0272-1

[44] Fan, J., Li, T., & Heng, H. 2016. Hydrothermal growth of ZnO nanoflowers and their photocatalyst application. *Bulletin of Materials Science*. 39(1): 19-26. DOI: https://doi.org/10.1007/s12034-015-1145-z

[45] Wang, Y., Li, X., Wang, N., Quan, X., & Chen, Y. 2008. Controllable synthesis of ZnO nanoflowers and their morphology-dependent photocatalytic activities. *Separation and Purification Technology*. 62(3): 727-732. DOI: https://doi.org/10.1016 /j.seppur.2008.03.035

[46] Li, X., Wang, J., Yang, J., Lang, J., Wei, M., Meng, X., Sui, Y. 2013. Enhanced photocatalytic activity of ZnO microflower arrays synthesized by one-step etching approach. *Journal of Molecular Catalysis A: Chemical*, 378: 1-6. DOI: https://doi.org/10.1016/j.molcata.2013.05.013

[47] Chen, C., Mei, W., Wang, C., Yang, Z., Chen, X., Chen, X., & Liu, T. 2020. Synthesis of a flower-like SnO/ZnO nanostructure with high catalytic activity and stability under natural sunlight. *Journal of Alloys and Compounds*. 826: 154122. DOI: https://doi.org/10.1016/j.jallcom.2020.154122

[48] Alhaddad, M., & Shawky, A. 2020. Superior photooxidative desulfurization of thiophene by reduced graphene oxide-supported MoS2 nanoflakes under visible light. *Fuel Processing Technology*. 205: 106453. DOI: https://doi.org/10.1016/j.fuproc.2020. 106453

[49] Khan, M. M., Adil, S. F., & Al-Mayouf, A. 2015. Metal oxides as photocatalysts. *Journal of Saudi Chemical Society*. 19(5): 462-464. DOI: https://doi.org/10.1016/j.jscs.2015.04.003

[50] Hamdan, M. A. H., Hairom, N. H. H., Jalil, A. A., Ahmad, M. K., Madon, R. H., Dzinun, H., Hamzah, S., Kamal, A. S. M., & Jusoh, N. W. C. 2020. Catalytic conversion of synthetic sulfur-pollutants in petroleum fractions under different photocatalyst loadings and initial concentration. *International Journal of Emerging Trends in Engineering Research*. 8(11.2 Special Issue): 132-138. DOI: https://doi.org/10.30534/ijeter/2020/1881.22020

[51] Kang, X., Liu, S., Dai, Z., He, Y., Song, X., & Tan, Z. 2019. Titanium Dioxide: From Engineering to Applications. *Catalysts.* 9. DOI: https://doi.org/10.3390/catal9020191

[52] Chen, X., Wu, Z., Liu, D., & Gao, Z. 2017. Preparation of ZnO Photocatalyst for the Efficient and Rapid Photocatalytic Degradation of Azo Dyes. *Nanoscale Research Letters*, 12(1): 4-13. DOI: https://doi.org/10.1186/s11671-017-1904-4

[53] Kane, A., Assadi, A. A., Jery, A. El, Badawi, A. K., Kenfoud, H., Baaloudj, O., & Assadi, A. A. 2022. Advanced Photocatalytic Treatment of Wastewater Using Immobilized Titanium Dioxide as a Photocatalyst in a Pilot-Scale Reactor: Process Intensification. *Materials.* 15(13): 4547. DOI: https://doi.org/10.3390/ma15134547

[54] Nadzim, U. K. H. M., Hairom, N. H. H., Hamdan, M. A. H., Ahmad, M. K., Jalil, A. A., Jusoh, N. W. C., & Hamzah, S. 2022. Effects of different zinc oxide morphologies on photocatalytic desulfurization of thiophene. *Journal of Alloys and Compounds*. 913: 165145. DOI: https://doi.org/10.1016/j.jallcom.2022.165145

[55] Hamdan, M. A. H., Hairom, N. H. H., Zaiton, N., Harun, Z., Soon, C. F., Hubadillah, S. K., Jamalludin, M. R., Che Jusoh, N. W., & Abdul Jalil, A.

2021. Photocatalytic Degradation of Synthetic Sulfur Pollutants in Petroleum Fractions under Different pH and Photocatalyst. *Emerging Advances in Integrated Technology*. 2(1): 30-38. DOI: https://publisher.uthm.edu.my/ojs/index.php/emait/article/view/8705

[56] Zarifah, N., Hanis, N., Hairom, H., Abu, D., Sidik, B., Liyana, A., Wahab, A. 2018. Palm oil mill secondary effluent (POMSE) treatment via photocatalysis process in presence of ZnO-PEG nanoparticles. *Journal of Water Process Engineering*. 26: 10-16. DOI: https://doi.org/10.1016/j.jwpe. 2018.08.009

[57] Bahadur, N., & Bhargava, N. 2019. Novel pilot scale photocatalytic treatment of textile & dyeing industry wastewater to achieve process water quality and enabling zero liquid discharge. *Journal of Water Process Engineering*. 32: 100934. DOI: https://doi.org /10.1016 /j.jwpe.2019.100934

[58] Berkani, M., Kheireddine, M., Mohammed, B., & Yassine, B. 2020. Photocatalytic Degradation of Industrial Dye in Semi - Pilot Scale Prototype Solar Photoreactor: Optimization and Modeling Using ANN and RSM Based on Box – Wilson Approach. *Top Catal.* 63: 964–975. DOI: https://doi.org/10.1007/s11244-020-01320-0

[59] Moles, S., Mosteo, R., Gómez, J., Szpunar, J., Gozzo, S., Castillo, J. R., & Ormad, M. P. 2020. Towards the removal of antibiotics detected in wastewater in the POCTEFA territory: occurrence and TiO2 photocatalytic pilot-scale plant performance. *Water*. 12(5): 1453. DOI: https://doi.org/10.3390/w12051453

[60] Obotey Ezugbe E, Rathilal S. 2020. Membrane Technologies in Wastewater Treatment: A Review. *Membranes,* 10(5): 89. DOI: https://doi.org/10.3390/membranes10050089.

[61] Palit, S. 2014. Frontiers of Nanofiltration, Ultrafiltration and the Future of Global Water Shortage - A Deep and Visionary Comprehension. *International Letters of Chemistry, Physics and Astronomy*. 38: 120-131. DOI: http://doi.org/10.18052/ www. scipress.com/ILCPA.38.120

[62] Gürses A., Güneş K., Şahin E. 2021. *Green Chemistry and Water Remediation: Research and applications*. Amsterdam: Elsevier. 135-187. DOI: https://doi.org/10.1016/ B978-0-12-817742-.00005-0.

[63] Zularisam A. W., Ismail A. F., & Sakinah, M. 2010. Application and Challenges of Membrane in Surface Water Treatment. *Journal of Applied Sciences*. 10(5): 380-390. DOI: https://doi.org/10.3923/ jas.2010.380.390.

[64] Hakami, M. & Alkhudhiri, A. & Al-Batty, S., Zacharof, M.-P., Maddy, J. & Hilal, N. 2020. Ceramic Microfiltration Membranes in Wastewater Treatment: Filtration Behavior, Fouling and Prevention. *Membranes*. 10: DOI: https://doi.org/10.3390/membranes10090248

[65] Juang, Y., Nurhayati, E., Huang, C., Pan, J.R., Huang, S. 2013. A hybrid electrochemical advanced oxidation/microfiltration system using BDD/Ti anode for acid yellow 36 dye wastewater treatment. *Separation and Purification Technology*. 120: 289–295. DOI: https://doi.org/10.1016/j.seppur.2013.09.042

[66] Chew, C. M., Aroua, M. K., Hussain, M. A., & Ismail, W. M. Z. W. 2016. Evaluation of ultrafiltration and conventional water treatment systems for sustainable development: An industrial scale case study. *Journal of Cleaner Production*. 112: 3152-3163. DOI: https://doi.org /10.1016/j.jclepro.2015.10.037

[67] Abid, M.F., Zablouk, M.A., Abid-Alameer, A.M., 2012. Experimental study of dye removal from industrial wastewater by membrane technologies of reverse osmosis and nanofiltration. *Iran. J. Environ. Health Sci. Eng.* 9(1): 1726. DOI: https://doi.org/10.1186/1735-2746-9-17

[68] Mahmoodi, M., & Pishbin, E. 2025. Ozone-based advanced oxidation processes in water treatment: Recent advances, challenges, and perspective. *Environmental Science and Pollution Research International*. 32(7): 3531–3570. DOI: https://doi.org/10.1007/ s11356- 024-35835-w

[69] Rekhate, C. V., & Srivastava, J. K. 2020. Recent advances in ozone-based advanced oxidation processes for treatment of wastewater—A review. *Chemical Engineering Journal Advances*. 3: 100031. DOI: https://doi.org/10.1016/j.ceja.2020.100031

[70] Lim, S., Shi, J. L., von Gunten, U., & McCurry, D. L. 2022. Ozonation of organic compounds in water and wastewater: A critical review. *Water Research*. 213: 118053. DOI: https://doi.org/10.1016 /j.watres.2022.118053

[71] Srivastava, A., Gupta, B., Majumder, A., Gupta, A. K., & Nimbhorkar, S. K. 2021. A comprehensive review on the synthesis, performance, modifications, and regeneration of activated carbon for the adsorptive removal of various water pollutants. *Journal of Environmental Chemical Engineering*, 9(5): 106177. DOI: https://doi.org/10.1016/j.jece.2021.106177

[72] Azam, K., Shezad, N., Shafiq, I., Akhter, P., Akhtar, F., Jamil, F., Shafique, S., Park, Y.-K., & Hussain, M. 2022. A review on activated carbon modifications for the treatment of wastewater containing anionic dyes. *Chemosphere*, 306, 135566. DOI: https://doi.org/ 10.1016/j.chemosphere.2022.135566

[73] Wu, H., Wang, R., Yan, P., & others. 2023. Constructed wetlands for pollution control. *Nature Reviews Earth & Environment*, 4: 218–234. DOI: https://doi.org/10.1038/s43017-023-00395-z

[74] Benalla, S., Addar, F. Z., Tahaikt, M., Elmidaoui, A., & Taky, M. 2022. Heavy metals removal by ion-exchange resin: Experimentation and optimization by custom designs. *Desalination and Water Treatment*. 262: 347–358. DOI: https://doi.org/10.5004/dwt.2022.28607

[75] Qian, J., Qu, K., Tian, B., & Zhang, Y. 2021. Water treatment of polluted rivers in cities based on biological filter technology. *Environmental Technology & Innovation*. 23: 101544. DOI: https://doi.org/10.1016/j.eti.2021.101544

[76] Gurreri, L., Tamburini, A., Cipollina, A., & Micale, G. 2020. Electrodialysis applications in wastewater treatment for environmental protection and resources recovery: A systematic review on progress and perspectives. *Membranes.* 10(7): 146. DOI: https://doi.org/10.3390/membranes10070146

[77] Al-Amshawee, S., Yunus, M. Y. B. M., Azoddein, A. A. M., Hassell, D. G., Dakhil, I. H., & Hasan, H. A. 2020. Electrodialysis desalination for water and wastewater: A review. *Chemical Engineering Journal*. 380: 122231. DOI: https://doi.org/10.1016/j.cej.2019.122231

[78] Sidik, D. A. B., Hairom, N. H. H., & Mohammad, A. W. 2019. Performance and fouling assessment of different membrane types in a hybrid photocatalytic membrane reactor (PMR) for palm oil mill secondary effluent (POMSE) treatment. *Process Safety and Environmental Protection*, 130: 265–274. DOI: https://doi.org/ 10.1016/j.psep.2019.08.018

[79] Desa, A. L., Hairom, N. H. H., Sidik, D. A. B., Zainuri, N. Z., Ng, L. Y., Mohammad, A. W., & Jalil, A. A. 2020. Performance of tight ultrafiltration membrane in textile wastewater treatment via MPR system: Effect of pressure on membrane fouling. *IOP Conference Series: Materials Science and Engineering*. 736(2): 022033. DOI: https://doi.org/10.1088/1757-899X/736/2/022033

[80] Hairom, N. H. H., Mohammad, A. W., & Kadhum, A. A. H. 2014. Effect of various zinc oxide nanoparticles in membrane photocatalytic reactor for Congo red dye treatment. *Separation and Purification Technology*. 137: 74-81. DOI: https://doi.org/10.1016/j.seppur.2014. 09.027

[81] Molinari, R., Lavorato, C., Argurio, P., Szymański, K., Darowna, D., & Mozia, S. 2019. Overview of photocatalytic membrane reactors in organic synthesis, energy storage and environmental applications. *Catalysts*. 9(3): 1-39. DOI: https://doi.org/10.3390/catal9030239

[82] Moradi, Z., Jahromi, S. Z., & Ghaedi, M. 2021. Design of active photocatalysts and visible light photocatalysis. *Interface Science and Technology*. 32: 357-399. DOI: https://doi.org/10.1016/B978-0-12-818806-4.00012-7

[83] Shon, H. K., Phuntsho, S., Chaudhary, D. S., Vigneswaran, S., & Cho, J. 2013. Nanofiltration for water and wastewater treatment – A mini review. *Drinking Water Engineering and Science*. 6(1): 47–53. DOI: https://doi.org/10.5194/dwes-6-47-2013

[84] Plakas, K. V., Sarasidis, V. C., Patsios, S. I., Lambropoulou, D. A., & Karabelas, A. J. 2016. Novel pilot scale continuous photocatalytic membrane reactor for removal of organic micropollutants from water. *Chemical Engineering Journal*. 284: 905–915. DOI: https://doi. org/10.1016 /j.cej.2016.06.075

[85] Desa, A. L., Hairom, N. H. H., Ng, L. Y., Ng, C. Y., Ahmad, M. K., & Mohammad, A. W. 2019. Industrial textile wastewater treatment via membrane photocatalytic reactor (MPR) in the presence of ZnO- PEG nanoparticles and tight ultrafiltration. *Journal of Water Process Engineering*. 31: 100872. DOI: https://doi.org/10.1016/j.jwpe.2019. 100872

[86] Yu, Z. 2019. High-performance composite photocatalytic membrane based on titanium dioxide nanowire/graphene oxide for water treatment. *Journal of Applied Polymer Science.* 137(12): DOI: https://doi.org/10.1002/app.48488

[87] Wang, Q., Wang, P., Xu, P., Hu, L., Wang, X., Qu, J., & Zhang, G. 2021. Submerged membrane photocatalytic reactor for advanced treatment of p-nitrophenol wastewater through visible-light-driven

photo-Fenton reactions. *Separation and Purification Technology*. 256: 117783. DOI: https://doi.org/10.1016/j.seppur.2020.117783

[88] Fernández-Ponce, M. T., Parjikolaei, B. R., Nasri Lari, H., Casas, L., Mantell, C., & Martínez de la Ossa, E. J. 2016. Pilot-plant scale extraction of phenolic compounds from mango leaves using different green techniques: Kinetic and scale up study. *Chemical Engineering Journal*, 299: 420–430. DOI: https://doi.org/10.1016/j.cej.2016.04.046

[89] Malato, S., Blanco, J., Vidal, A., & Richter, C. 2002. Photocatalysis with solar energy at a pilot-plant scale: An overview. *Applied Catalysis B: Environmental*. 37(1): 1–15. DOI: https://doi.org/10.1016/S0926-3373(01)00315-0

[90] Tedesco, M., Cipollina, A., Tamburini, A., & Micale, G. 2017. Towards 1kW power production in a reverse electrodialysis pilot plant with saline waters and concentrated brines. *Journal of Membrane Science*. 522: 226–236. DOI: https://doi.org/10.1016/j.memsci.2016.09.015

[91] Sarasidis, V. C., Plakas, K. V., Patsios, S. I., & Karabelas, A. J. 2014. Investigation of diclofenac degradation in a continuous photocatalytic membrane reactor: Influence of operating parameters. *Chemical Engineering Journal*. 239: 299–311. DOI: https://doi.org/10.1016/j.cej.2013.11.026

[92] Ryu, J., Choi, W., & Choo, K. 2005. A pilot-scale photocatalyst-membrane hybrid reactor: Performance and characterization. *Water Science and Technology*. 52(10–11): 491–497. DOI: https://doi.org/10.2166/wst.2005.0672

[93] Abu, D., Sidik, B., Hanis, N., Hairom, H., Ahmad, M. K., Madon, R. H., & Mohammad, A. W. 2020. Treatment of POMSE using a photocatalytic membrane system in pilot scale. *Process Safety and Environmental Protection*, 141: 372–381. DOI: https://doi.org/10.1016/j.psep.2020.06.038