



A comprehensive review of modern wastewater treatment technologies: Efficiency, sustainability integration, and practical challenges

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ABSTRACT

The problem of water scarcity and pollution due to the intensive increase in the population and industrial development is in need of efficient and sustainable wastewater treatment technologies. This review focuses on current practices worldwide including Membrane Bioreactors (MBR), Moving Bed Bioreactors (MBBR), Advanced Oxidation Processes (AOPs), Electrochemical Treatment, Reverse Osmosis (RO), Zero Liquid discharge (ZLD) and Constructed Wetlands Systems (CWs). After the initial database search (Scopus, ScienceDirect) yielded over 150 articles published in 2018– 2024, from which 32 peer-reviewed articles were selected using a rigorous screening process based on their analysis of the effectiveness of treatment, the sustainability of treatment, and costeffectiveness. Quantitative synthesis demonstrates that MBR and RO have high pollutant removal efficiencies (9598% and 9099% respectively) at high costs of operation(0.5 to 1.2 $\frac{USD}{m^3}$). ZLD is also almost 100% efficient but the most costly to operate ($2.539 \frac{USD}{m^3}$). As an alternative, CWs and MBBR are much cheaper and more energy-efficient, with operation costs being 0.1 0.5 USD/m³ lower and treatment efficiencies (70-92) being moderate. Hybridizations of various technologies show the most promising prospects of striking the right balance between optimal operation and being economical. This research concludes that there is no universal solution; the choice of technology has to be determined by certain local environmental factors and financial possibilities. The next generation of research should focus on the optimization of hybrid configurations, capital cost minimization, and use of Artificial Intelligence (AI) and Internet of Things (IoT) to perform smart and real-time monitoring to increase flexibility to climate change. This review provides decision-makers, engineers, and researchers with quantifiable insight to support sustainable wastewater management.



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1. Introduction

Water is among the most fundamental resources for sustainable development and human well-being. However, rapid population growth, urbanization, and industrial development are putting increasing pressure on freshwater resources. At the same time, the discharge of untreated wastewater poses serious risks to public health and the environment. Research by the United Nations Environment Program (UNEP) and other international surveys shows that over 80 percent of the world's wastewater is discharged untreated. This contributes to water-borne diseases, worsens ecosystem degradation, and results in significant long-term economic losses (Liu et al., 2024).

Conventional treatment methods, such as filtration, oxidation ponds, and sedimentation, have been widely used over past decades. Although these methods are relatively easy and inexpensive to use, they consistently exhibit low pollutant removal efficiencies that do not meet the stringent requirements of modern environmental regulations (Jijingi et al., 2024). Therefore, the engineering and scientific societies have turned their attention to designing new wastewater treatment methods and technologies that achieve high water quality, reduce environmental footprints, and maximize the likelihood of safe water reuse. The current research has considered the broad range of these current methods, such as Membrane Bioreactors (MBR), Moving Bed Bioreactors (MBBR), Advanced Oxidation Processes (AOPs),

Electrochemical Treatments, Reverse Osmosis (RO), Zero Liquid Discharge (ZLD), and Constructed Wetland Systems (CWs) (Kim et al., 2024; Nabi et al., 2023; Wang et al., 2022; Zhou et al., 2022). The technologies each have specific benefits in operation but they also have intrinsic limitations in terms of capital cost, energy need, maintenance requirement and the ability to be applied in large scale.

Sustainability has become an essential component of wastewater treatment and is a global requirement. It is directly related to the United Nations Sustainable Development Goals (SDGs). Achieving true integration requires an analytical view of trade-offs. For example, advanced technologies such as RO and AOPs directly address SDG 6 (Clean Water and Sanitation). However, they consume significant energy, potentially undermining SDG 13 (Climate Action) by increasing greenhouse emissions (Wang et al., 2023). Achieving sustainable wastewater treatment depends on balancing thermodynamic efficiency, economic feasibility, and environmental impact.

Despite a growing body of literature, a research gap remains. Many recent reviews focus on the technical performance of specific systems, such as MBR or AOPs. However, they often do not consider overall techno-economic feasibility and real operating constraints. They rarely compare capital and operating costs or assess adaptability to climate change. Most reviews focus on laboratory pollutant removal rates. Critical comparison of costs, operational realities, and sustainability is lacking.

This paper addresses this gap by systematically synthesizing the results of peer-reviewed studies published between 2018 and 2024. In specific, the objectives of this review include the renewed and critical evaluation of the latest and the most developed technologies regarding wastewater treatment; the performance comparison of the technologies; the quantitative assessment of the effectiveness of the technologies in eliminating the pollutants in comparison to their environmental and economic impact; the elucidation of the key operational challenges and limitations of every system; and an overview of opportunities of the future study, namely, the development of hybrid systems and AI. By fulfilling these objectives with convergent analytical framework, this review will serve to make viable recommendations to the engineers, the policymakers and the industry players and ultimately help in the transition to highly resilient, economically viable and sustainable global systems of wastewater management.

2. Research Methodology

2.1 Data sources

The current research employs a systematic analytical review to compare wastewater treatment methods based on efficiency, sustainability, and practical applicability. The study procedure is strictly structured in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure transparency, reproducibility, and scientific rigor. A visual representation of the selection process is presented in the PRISMA flow diagram (Figure 1).

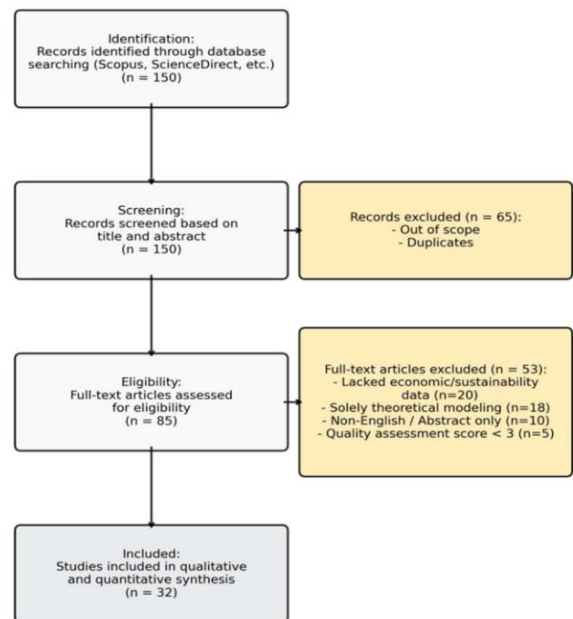


Fig. 1 PRISMA flow diagram of the study selection process.

2.2 Research strategy

Targeted keywords used to conduct the comprehensive search included:

- Wastewater treatment technologies, MBR, MBBR, AOPs, Electrochemical treatment, reverse osmosis, ZLD, constructed wetlands, sustainability, efficiency, and hybrid systems.
- To narrow the search to all relevant multidisciplinary studies, the search parameters (Boolean: AND, OR) were applied.

2.3. Inclusion and exclusion criteria

2.3.1 Inclusion criteria

- Studies published between 2018 & 2024.
- Articles that are written and published in English.

Peer-reviewed research articles, systematic reviews, and pilot or full-scale case studies that focus on the selected technologies.

- Research that presents measurable data about the efficiency of treatment, its sustainability factors, or financial viability.

2.3.2 Exclusion criteria

Non-peer-reviewed sources, preprints, conference abstracts, and non-scientific reports were excluded.

The following criteria were unrelated to wastewater treatment and involved only theoretical mathematical modeling, without empirical evidence.

2.4 Screening and selection

The preliminary database search identified more than 150 articles. Duplicates were removed, and the remaining articles were then screened independently using titles and abstracts to establish relevance. The shortlisted articles were then subjected to full-text assessments. After strict adherence to the inclusion and exclusion criteria, 32 studies were selected for qualitative and quantitative analysis.

2.5 Quality assessment and risk of bias

To assess the methodological rigor and reliability of the synthesized data, the 32 selected articles were evaluated using quality and risk-of-bias assessments. Each of the studies was scored based on four key criteria: (1) transparency and scale of the experimental design (lab-scale vs. field application), (2) reliability of the analysis methods used to measure the water quality parameters, (3) all operational measures (e.g., energy consumption, chemical usage) are fully reported, and (4) information about the economy or sustainability. The studies were rated on a scale of 0 to 4. Only those with 3 or higher were included in the final data extraction, as only studies with low risk of bias and high methodological standards were included. This was an extreme step that had to be taken in a manner that would provide a scientifically sound basis for the comparative analysis.

2.6 Data extraction and analysis

SPSS Statistics version 20.0 was used for descriptive statistics, t-tests, and correlation analyses. The SPSS Statistics software version 20.0 was used to analyze the data using descriptive statistics, t-tests, and correlation analysis.

The most significant information from both confirmed studies was found using a standard protocol. This information included:

- Technology type
- Select pollutants (e.g., COD, BOD, heavy metals)
- Percentages of efficiency of treatments.
- Energy consumption (kWh/m³)
- Capital cost estimates and operational cost estimates (*U3*)

Sustainability and environmental indicators.

The overall analysis and the performance of each technology across these multidimensional parameters were then compared in a detailed table.

2.7 Analytical tools

The data were arranged using Microsoft Excel, which provided statistical summaries and the comparative synthesis. Qualitative data were coded into themes to highlight the relationships among technological efficiencies, economic burdens, and sustainability indicators.

2.8 Validation

To enhance reliability, the empirical results were compared with the latest global meta-analysis and overseas technical reports. In cases of anomalies in the performance data, various peer-reviewed sources were compared to establish the most reliable baseline values and standardized meanings.

3. Latest Technologies Used in Wastewater Treatment

3.1 Membrane Bioreactor (MBR) technology

This technology combines biological treatment (such as activated sludge) with solid-liquid separation using membranes (such as microfiltration or ultrafiltration) (Jijingi et al., 2024). This technology is based on the following stages:

- **Biological Treatment:** At this stage, live bacteria are added to the reactor to decompose organic pollutants.
- **Membrane Filtration:** At this stage, physical filtration is performed using special membranes that capture solid particles from the water. The pore sizes of the membranes range from 0.03 to 0.5 microns (Kim et al., 2024).

3.1.1 Advantages of Membrane Bioreactor (MBR) technology

1. **High water quality:** Water treated with MBR technology is considered high-quality and can be reused for various purposes, such as irrigation.
2. **Space saving:** Due to the small size of the MBR facility and the uncomplicated equipment used, it requires a relatively small construction area compared to traditional methods.
3. **Reducing sludge production:** After the water treatment process is complete, the amount of sludge produced is much lower than with other methods.
4. **Tolerance to Harsh Conditions:** Some membranes, such as PVDF, meet specifications for harsh conditions, making them suitable for this technology.

3.1.2 Disadvantages of Membrane Bioreactor (MBR) technology

1. **Membrane breakage:** During prolonged operation, membranes are susceptible to cracking, disrupting the treatment system's operation.
2. **Cost:** Due to the high cost of bio membranes and the quality of the materials used to make them, this technology is more expensive than traditional methods.
3. **Maintenance:** If solids accumulate on the membranes and are not regularly removed, this can lead to membrane damage. To prevent this, regular maintenance must be carefully considered.

3.1.3 Applications of Membrane Bioreactor (MBR) technology

1. Municipal and Industrial Wastewater Treatment.
2. Sterilization of drinking water.
3. Residential and commercial wastewater treatment plants.

The following figure illustrates the mechanism of the membrane bioreactor (MBR)

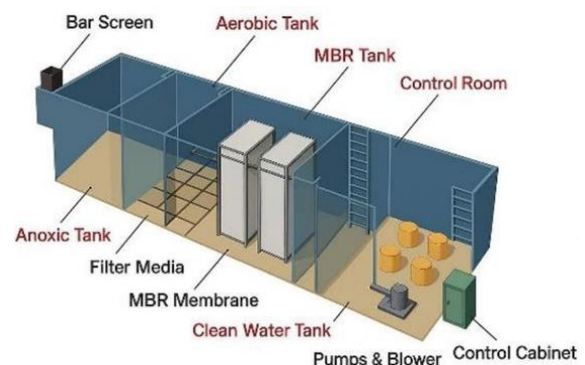


Fig. 2 The MBR technology

3.2 Moving Bed Bioreactor (MBBR) technology

This technology uses a fixed surface immersed in plastic carriers, where microorganisms are added to treat the water.

This technology is efficient and easy to operate (Zhou et al., 2022). A scientific study using this technology yielded good results in terms of water treatment rates, showing that it removed 98.5% of the biological biochemical demand and 86% of the nitrogen (Wang et al., 2022). Equipment used in MBBR technology:

- Plastic panels: These panels have a large surface area that supports biofilm growth.
- Filter tank: The plastic panels are placed inside the tank, providing the nutrients the biofilm bacteria need.
- Broadcast system: This system ensures that the bacteria can metabolize.
- Separation system: This system separates the plastic carriers from the treated water.
- MBBR mechanism:
 1. Bacteria generation: Wastewater is fed into the tank containing the plastic panels.
 2. Feeding: Bacteria grow on the plastic panels, forming biofilms.
 3. Decomposition: Microorganisms treat wastewater by Consuming the Oxygen Demand (BOD) and Apparent Oxygen Demand (COD).
 4. Separation: The plastic panels on which bacteria have grown are removed from the tank, resulting in high-quality treated water.

MBBR technology is characterized by its small reactor size, simple components, and ease of operation and maintenance. It is also widely used in a variety of wastewater types, enabling its widespread use. The following figure illustrates this technology.

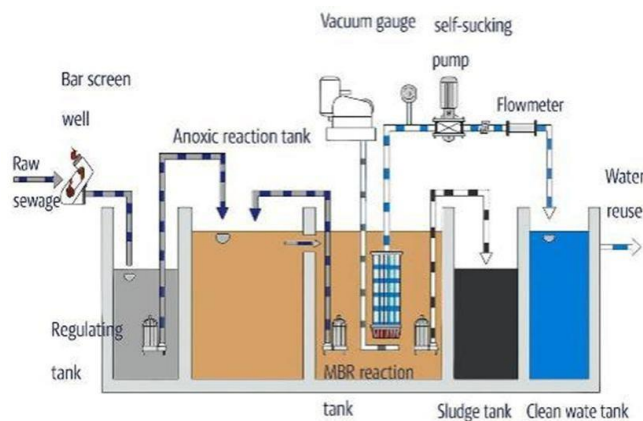


Fig. 3 The MBR technology

3.3 Advanced Oxidation Technologies (AOPs)

The use of UV light to remove micropollutants such as pharmaceutical residues and heavy metals by generating active hydroxyl radicals. It is highly effective but requires significant energy consumption and precise control systems (Nabi et al., 2023). This method is widely used to remove microplastics, pharmaceuticals, pesticides, and some inorganic materials (Wang et al., 2023). The most important types of oxides used in this method are ozone oxidation (O_3), ultraviolet oxidation (UV), hydrogen peroxide oxidation (H_2O_2), and oxidation

using a combination of these methods (such as O_3/UV or H_2O_2/UV), in addition to other methods such as sonochemical oxidation (Turan, 2025).

3.4 Moving Bed Bioreactor (MBBR) technology

3.4.1 Electrocoagulation / Electrooxidation

This technology relies primarily on the synchronization of the formation of sintered materials during the electro-sintering process and of oxidized materials during the electrooxidation process. It is used to remove organic pollutants from water (Parsons, 2005). This technique can be summarized as follows (Hübner et al., 2024):

- Electrocoagulation:

1. One of the metal electrodes in the electrolytic cell dissolves when an electric current is applied, producing metal hydroxides that react with the contaminants.
2. As a result of the reaction of mineral hydroxides with contaminants in water, a floc is formed. These materials float to the surface, making them easier to remove.
3. Low-density contaminants do not react with hydroxides, but as a result of this process, gas bubbles of hydrogen and oxygen form, carrying these contaminants to the water's surface, enabling them to be picked up and removed.

- Electrooxidation:

1. This process uses electrodes that produce oxides when exposed to an electric current.
2. These oxides break down the contaminants and completely remove them.
3. Electrochemical oxidation can be a slow process, but it can completely remove contaminants.
4. It can be used to remove persistent organic contaminants (such as pesticides) or to enhance the removal of other contaminants by reacting with the generated oxidants. Figure 4 illustrates this technique.

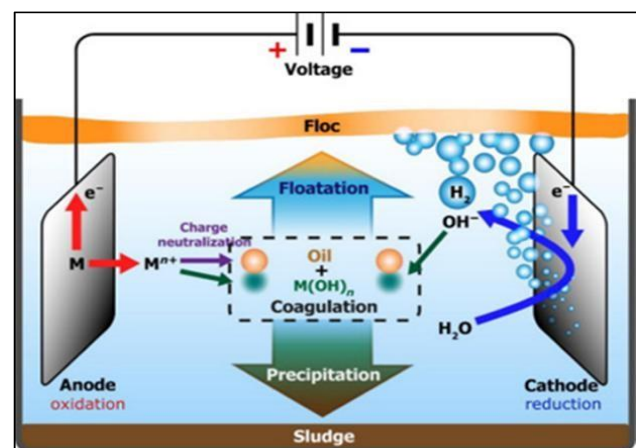


Fig. 4. The Electrochemical processing technology

3.5 Reverse Osmosis

This method is widely used in seawater desalination, as it removes salts and minerals from water by applying pressure that forces them through a membrane that acts as a filter. This

filter captures the molecules and removes them from the water (Hübner et al., 2024).

This method is highly effective in purifying water, making it potable. However, this technology requires significant energy to generate the pressure necessary to push the water toward the

filters. It also removes beneficial minerals from the water, which reduces the quality of the resulting water (Voigt & Jaeger, 2024).

The following figure shows the device used in this technology and its mechanism of action.

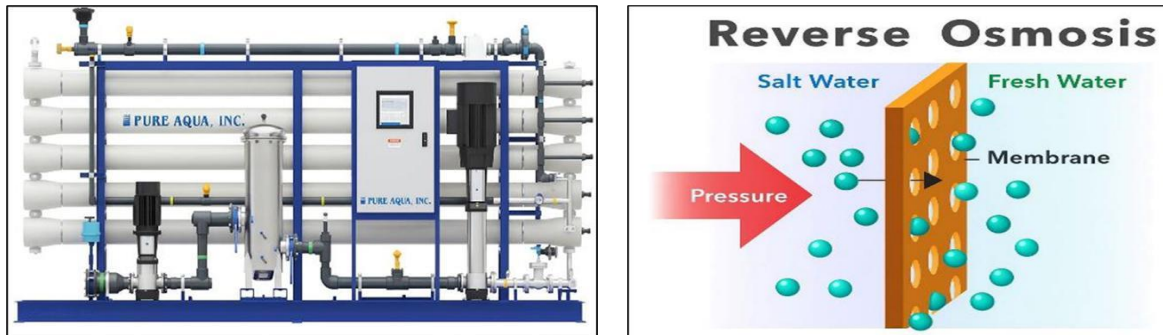


Fig 5. The mechanism of reverse osmosis technology

3.6 Zero liquid discharger technology

This technology is considered one of the most advanced in the globe and it removes up to 100 percent of industrial wastewater. It is mainly based on a series of operations that start with evaporation, salt removal and removal of organic matter. The technologies are obtained through various approaches, and they are RO, mechanical evaporation, and final crystallization (Kaswan & Kaur, 2023).

1) The technology could be outlined in the following stages:

- a) **Primary Treatment Stage:** It entails removal of suspended organic and solid matter and is normally achieved through application of special filters.
- b) **Concentration Stage:** This stage makes use of reverse osmosis. Thermal evaporation is also possible to extract the existing salts.
- c) **Crystallization Stage:** In this phase, crystallization and re-solidification of the extracted salts are done so that they can be extracted or recycled.

2) This approach is also characterized by the following:

- a) Lessening the amount of wastewater discharged to the environment.
- b) There is the opportunity to use recycled water and this would save a lot of waste on water resources.
- c) Reconstruction of reconstructed salts potential.

3) Irrespective of these benefits, this technology has serious challenges such as:

- a) High capital and installation costs.
- b) High energy consumption, particularly during evaporation processes.
- c) Requires advanced monitoring systems and skilled operation.

The following figure shows a ZLD treatment facility.



Fig 6. ZLD technology

3.7 Constructed Wetland System (CWS)

This technology is considered a natural or semi-natural approach that relies on biological, physical, and chemical processes to treat wastewater.

It takes place in an environment similar to natural wetlands. The water treatment system is designed using a specific engineering method that allows wastewater to pass through porous media, such as gravel or sand, where aquatic plants are grown. These plants and the surrounding environment remove pollutants from the water (Saravanan et al., 2022).

1) This system consists of a set of simple components, namely (Cirik & Gocer, 2020):

1. An artificial treatment basin, which is lower than the original soil surface and insulated with special materials.
2. Gravel, sand, or special soil is placed in the basins to act as a filtering medium.
3. Aquatic plants, such as reeds or papyrus, are grown in the basin.

4. A water distribution system consisting of a set of channels that deliver contaminated water to be treated into the treatment system.

5. A drainage system regulates the water level within the basins and drains the treated water.

The types of this system vary according to the water flow mechanism.

2) The most important of these types are (El-Fadel & Hashisho, 2014):

1. Horizontal Bottom Flow (HF) System: In this method, water is pumped horizontally, below the system (i.e., below the soil surface). This prevents unpleasant odors from escaping the water and reduces insect infestation.

2. Vertical Flow (VF) System: Water is pumped to the top of the basin and flows vertically. This method is used when the water to be treated is rich in ammonia.

3. Free Surface System (FWS): The treated water enters the basin, forming a swamp or an open body of water. Despite this method's simple design, it leads to the spread of insects and unpleasant odors.

3) The treatment stages in this system are summarized as follows:

a) Filtering solids as they pass through the gravel basin.

1. Adsorption of heavy metals and organic matter to the surface of the medium.

2. Biological decomposition of organic matter and nutrients by bacteria.

3. Absorption of minerals such as phosphorus and nitrogen through plant roots.

4). This technology has several advantages, including:

1. It is considered low-cost compared to previous technologies.

2. It does not rely on external energy sources, making it environmentally friendly.

3. It helps preserve vegetation and enhances the aesthetic appeal.

4. It does not require periodic maintenance, which increases the economic feasibility of this method.

Figure 7 shows the previous treatment plant.

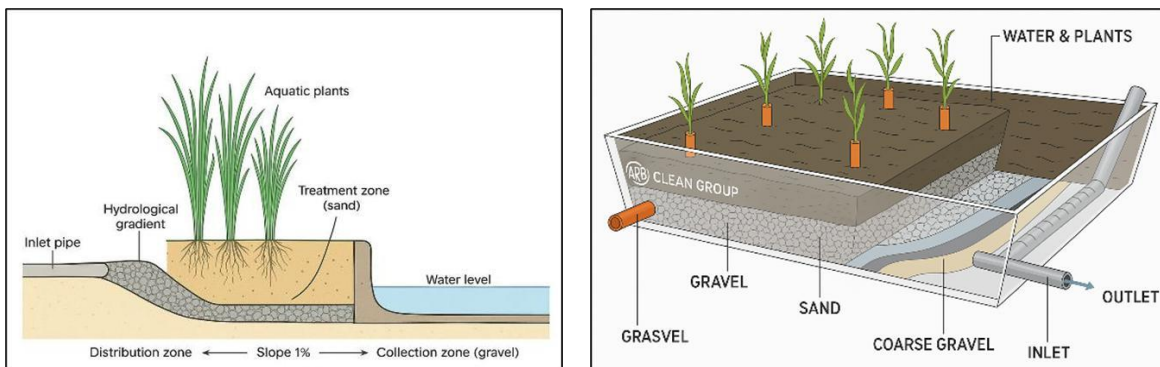


Fig. 7 The CWs technology

4. Synthesized Results and Comparative Performance Analysis

4.1 Membrane Bioreactor (MBR) technology

Past studies show that MBR technology is an extremely efficient way to treat industrial and domestic wastewater, though with different operating parameters. In the case of industrial use, e.g., wood-based panel wastewater, MBR systems (with 0.2-micron membranes) with a hydraulic retention time (HRT) of 20 hours and a solid retention time (SRT) of 20 days attained high pollutant removals: 98 % of Chemical Oxygen Demand (COD), 99 % of turbidity, and 70 % of phenols, with a constant membrane pressure of less than 0.6 bar (Cirik and Goc MBR systems performed well with a lower HRT of 6 hours to treat domestic wastewater with high removal rates (COD, Biological Oxygen Demand, phosphorus, and total nitrogen). (El-Fadel & Hashisho, 2014). Nevertheless, although MBR is highly efficient even in very polluted conditions, such as landfill leachate, with 98% BOD and 96% ammonium removal, the low operation cost is a limitation to its practical use (Coppini et al., 2018).

4.2 Moving Bed Biofilm Reactor (MBBR) technology

MBBR has emerged as a highly versatile biological treatment process, especially for treating industrial effluents with complex organic matter loads. Research on the wastewater in the textile industry, which is often endowed with the recalcitrant dyes and heavy metals, has shown that the MBBR technology could achieve a COD removal rate between 92 and 98.5 %, and dye/color removal of up to 87 % and 95 % BOD removal (Yang et al., 2020; Uddin et al., 2024). Moreover, this technology has a strong ability to isolate heavy metals, eliminating 85% of Zn, Pb, Cr, and Fe (Uddin et al., 2024). MSBBR is also effective in domestic wastewater, achieving 95.6% COD removal and more than 80% total nitrogen removal (Uddin et al., 2024).

4.3 Advanced Oxidation and Biological Treatment processes

Treatment technologies should be assessed for their environmental impact, expressed as a carbon footprint, which can be determined through Life-Cycle Assessment (LCA). Recent reviews emphasize that secondary greenhouse gas

emissions can be greatly reduced by optimizing advanced treatment systems. An example of this is the study by Kaswan and Kaur (2023), which showed that the overall carbon footprint (CO₂ equivalent emissions) can be reduced to as low as 51.7% by optimizing operational parameters in textile wastewater treatment. Equally, high-tech applications in highly polluted, dye-rich industrial wastewater have been shown to achieve LCA-based CO₂ emission reductions of up to 96.6% compared with traditional, energy-intensive procedures (Zhang et al., 2021; Maatooq & Abdulwahd, 2026). Moreover, optimized biological-chemical setups have achieved impressive results in treating pharmaceutical wastewater, achieving a maximum 100% removal of Biological Oxygen Demand (BOD) (Lee et al., 2022).

4.4 Electrochemical Treatment technology

Electrochemical processes have proven particularly effective for treating highly toxic, recalcitrant industrial contaminants. The treatment of textile effluents containing highly toxic dyes achieved high removal efficiencies, with 97% reductions in COD, Total Organic Carbon (TOC), and Total Suspended Solids (TSS) (Gopal et al., 2026).

4.5 Reverse Osmosis (RO) technology

RO remains a powerful physical separation technology primarily used in desalination and tertiary treatment. Its ability to treat seawater has been demonstrated, and these researchers were able to treat water with high levels of salt to generate high-quality effluent that could be effectively used in agriculture and other more general human use, but post-treatment was still necessary to make it potable (Kurihara et al. 2001).

4.6 Zero Liquid Discharge (ZLD) technology

ZLD technology based on resource recovery and circular-economy principles in the management of wastewater in industries. A large-scale application in India involving 1,200 cubic meters of industrial effluents showed a 97% improvement in the field's water quality. The system also recovered 1.5 tons of salts per day, representing a significant improvement in operational efficiency and the economic sustainability of the facility (Chen et al., 2022).

Constructed wetland systems (CWS) are small artificial wetlands created to simulate natural wetlands as found in certain regions of Florida and elsewhere (Chen et al., 2022).

4.7 Constructed Wetland Systems (CWS)

Constructed Wetland Systems (CWS) are decentralized, natural, and low-energy treatment of sewage. One of the most

important studies in South Africa (Curia et al., 2011; Wahyuningtyas et al., 2026) revealed that CWS reduced phosphorus by 82% and nitrates by 70 percent, making the industrial effluent safe to reuse. CWS is globally distributed in a statistically significant manner to show its flexibility in socio-economic terms:

- *Europe & Germany*: Widely adopted in rural areas and small villages for domestic wastewater; also utilized in Germany as a sustainable complement to complex mechanical treatments.
- *Middle East (Jordan and Egypt)*: Heavily supported by international organizations to address rural sanitation deficits through decentralized domestic wastewater treatment projects.
- *India*: Extensively implemented in remote locations and educational institutions to ensure public health and safety.

4.8 Cross-Technology Comparative Synthesis

It has demonstrated a perceived trade-off between the technologies under consideration as compared to efficiency in the treatment, cost of operation, and environmental impact (carbon footprint), as shown in a meta-analytical literature review of the survey:

1. *Removal efficiency vs. cost*: Membrane and physical separation technologies (MBR, RO, ZLD) and Electrochemical processes have the highest removal rates (usually over 95% for COD/BOD/TOC) and can recover resources (salts). They are, however, distinguished by an extreme in energy consumption, strain of operation, and high cost of maintenance (membrane fouling).
2. *Biological adaptability*: MBBR is a balanced system that is not prone to toxic shock (e.g., heavy metals, dyes), and it achieves more than 90 percent organic removal efficiency; hence, it is far more viable for complex industrial effluents at a lower operating cost than MBR.
3. *Environmental sustainability (LCA)*: CWS has the lowest carbon footprint in its business, thanks to its natural biofiltration. Conversely, energy-intensive systems (like standard aeration or MBR) have high indirect CO₂ emissions unless optimized through advanced configurations (as seen in the LCA reductions discussed in section 4.3).

5. Comparison Between Previous Technologies

The Table 1 compares previous methods in terms of a set of limitations. It also includes the efficiency of each method, potential challenges, and sustainability. This table was obtained after reviewing numerous research studies and examining their results.

Table 1. Comprehensive comparison of the latest water treatment methods

	MBR	MBBR	AOPs	RO	EC	ZLD	CW _s
Target pollutants	COD, BOD, TSS, NH ₄	BOD, TSS, NH ₄	Complex organic pollutants	Heavy metals and salts	COD and organic matter	Heavy metals and salts	organic pollutants
Treatment Rate	High	Moderate to High	High	Very high	High	Very high	Medium

Waste Produced	Concentrated biological sludge	Low Volume Sludge	Secondary oxides	Brine	Mineral deposits with sludge	Brine	-
Energy Consumption	Higher	Low	High	Very high	Medium	Very high	Very low
Maintenance	Medium	Medium	Medium	High	Medium	High	Very low
Space Required	Small	Small	Medium	Small	Medium	High	Very high
Operating Cost	High	Medium	High	Very high	Medium	Very high	Very low
Efficiency	High	Good	Very high	High	High	High	Medium
Sustainability	ME	High	Medium	Low	Medium	Very high	Medium
Challenges	High cost, regular maintenance	Not effective on all pollutants	Hazardous products	High cost	Precise control, high energy consumption	High cost	Not effective on all pollutants

Since the economic obstacle is the most important when choosing or adopting one of the previous technologies, we have created a comparison table showing the economic feasibility versus efficiency.

This Table 2 was arrived at after reviewing previous studies and the results were as follows: **Table 2.** Comprehensive economic feasibility and efficiency

Efficiency %	OpEX (USD/m ³)	Cap EX (USD/m ³)	Technology
98-95	0.8-0.5	1.5-2.0	MBR
92-85	0.3-0.5	1.0-1.4	MBBR
99-90	1.0-0.6	2.0-2.8	AOPs
96-90	0.4-0.7	1.8-2.5	EC
99-90	1.2-0.8	2.5-3.5	RO
100-98	3.9-2.5	6.5-4	ZLD
70	0.3-0.1	0.5-0.1	CWs

6. Supportive Applications For Wastewater Treatment Technologies

The above methods are considered among the most modern global technologies in wastewater treatment. Scientists have not only developed these technologies but also developed complementary, supportive, and auxiliary applications,

enhancing their efficiency and improving the quality of their work. The following applications are highlighted;

6.1 Hybrid Wastewater Treatment Systems

This method is widely used because it combines several separate methods, maximizing the benefits of each. It balances the drawbacks of each method and outweighs the advantages.

A previous study (Norra & Radjenovic, 2021; Jam et al., 2025) presented experimental results using a combination of biological, chemical, and physical processes. MBR and AOPs were combined with reverse osmosis (RO) technology. The study indicated that this combination achieves a balance between efficiency and stable operation. Through field testing and numerical simulations, this hybrid method was shown to remove more than 99% of COD, significantly reduce sludge production, and achieve substantial energy savings compared to conventional single-stage systems. This method also demonstrated high flexibility in handling various types of wastewaters, both domestic and industrial. However, the study demonstrated that the overall cost of this technology is considered economically expensive. This study concluded that this supportive method is a promising approach to addressing the sanitation problem in densely populated and industrial communities. The following figure shows an illustrative diagram of the hybrid system.

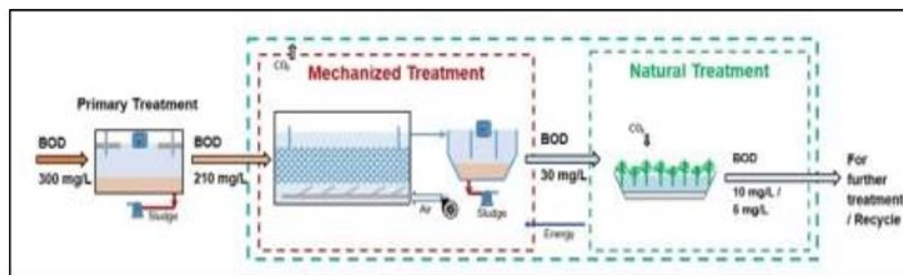


Fig 8. The monitoring mechanism for the water treatment plant using the SCADA system

Below are examples of practical hybrid systems that have been tested: Combining biodegradation with advanced oxidation:

- This combination enabled a high removal of organic matter, particulate matter, and contaminants.
- Combining electrochemical and membrane treatment: Improved turbidity removal and reduced membrane damage.
- Reverse osmosis and activated carbon: This method removed odors from water and improved its quality.

6.2 Monitoring Treatment Plants Using Advanced Control

Since treatment plants require continuous monitoring by workers, human errors have increased significantly, affecting their operations. With the development of artificial intelligence and the Internet of Things (IoT), researchers have incorporated these technologies into plant monitoring, significantly reducing human error.

A scientific study presented results on the potential use of AI and IoT technologies in the management and operation of

treatment plants (Xue et al., 2023). Special sensors were used to instantly measure key water parameters such as COD, BOD, ammonia, and pH. These readings are sent to specialized algorithms that adjust the quantities of chemicals to be added. This method also provides notifications of imminent malfunctions, allowing technicians to address them before they occur, thereby maintaining plant efficiency and reducing maintenance costs and downtime.

This study reported implementations in Spain and Germany, and where energy consumption was reduced by 25%. Downtime was also reduced by 40%.

Although introducing such technologies into treatment plants is important, they are considered costly and require specialized expertise to implement. The world may witness greater flexibility with the use of advanced control in this area.

6.3 Evaluation of Membrane Treatment Technology

Considering that MBR technology is one of the most widely used technologies, researchers have worked to improve the efficiency of this technology through the following (Mahmood et al., 2013):

1. Evaluating the environmental impact of membrane technologies used in treatment.
2. Collecting data on membrane manufacturing materials and measuring the energy consumed during the manufacturing, installation, and operation phases.
3. Studying the environmental impacts of this technology, including gaseous emissions, chemical pollution, and toxicity.
4. Analyzing the results and proposing solutions. This stage identifies weaknesses in the materials used and proposes recommendations to reduce energy consumption and the resulting harmful emissions. Life-Cycle Assessment (LCA) of membranes is a comprehensive study of all phases of this technology's operation.

6.4 Decentralized Wastewater Treatment Systems

This method is used in large population centers, whereby small, separate treatment plants are constructed (Arumugam et al., 2023).

This method is widely used in developing countries such as South Africa, as it reduces the cost of transporting wastewater and waste by up to 70%. This method cannot be considered separate or independent from previous technologies. Rather, it relies on distributing small stations to cover the entire area with high population density. This is closely linked to studying each community's needs individually, as the type of small station to be constructed depends on the type of water to be treated. Since developing countries have overlapping wastewater and industrial wastewater, this method has been used to manage treatment processes.

6.5 Reusing of Treated Wastewater for Agricultural Purposes

To conserve water resources, governments worldwide are moving toward using treated wastewater for agricultural purposes because of its high phosphorus and nitrogen content. This method has become widely used in arid regions suffering from severe water scarcity.

A reference study (Simmons et al., 2010) showed that using treated water from the MBBR method in the irrigation system for wheat-grown land increased production by up to 12% and reduced the need for nitrogen fertilizers by 30%. However, this method requires close monitoring to prevent the soil from becoming salinized and contaminated.

6.6 Adapting to Climate Change

Due to the changing global climate and the significant fluctuations we are witnessing, severe impacts on the operation of water treatment plants have been observed. Therefore, plants must be highly flexible to help overcome these changes. These include:

1. Using reserve storage basins.
2. Using clean energy sources such as solar energy.
3. Establishing a weather forecasting system. A scientific study conducted in Vietnam (Trinh et al., 2013) reported that modifying the operation of processing systems increased their resilience by 43% during flood seasons and reduced breakdowns and maintenance costs.

7. Comparative Summary of Wastewater Treatment Technologies

The reviewed studies demonstrated that the aforementioned water treatment technologies have varying effectiveness depending on the type of water being treated. From the above, we can highlight the following results:

1. The MBR technology is highly efficient at removing organic pollutants and suspended solids, producing usable water. However, this method requires relatively high energy and periodic maintenance due to continuous membrane damage.
2. The MBBR technology is more flexible than the previous method and consumes less energy, but its impact on various pollutants is limited.
3. The oxidation technology is more effective in removing colors and odors from wastewater, resulting in pure water with good specifications. However, it is considered expensive in terms of energy and materials used for treatment.
4. Reverse osmosis technology is widely used in seawater treatment due to its high capacity to remove salts and heavy metals. However, it requires a lot of energy and produces harmful waste.
- 5- As for the electrochemical treatment technology, it was quite effective at removing organic materials and heavy metals, but it requires periodic maintenance of the circuit electrodes.

8. Discussion

Rather than simply restating the high pollutant removals in the results, the operational trade-offs and how such technologies work should also be considered. The high-quality effluent produced by Membrane Bioreactor (MBR) and Reverse Osmosis (RO) technologies (Jijngi et al., 2024; Kurihara et al., 2001; Turan, 2025) is compromised by severe membrane fouling and high energy consumption. This creates a significant bottleneck to its practical implementation, especially in low-income areas, where initial capital and maintenance requirements typically dominate technical performance.

On the other hand, nature-based and suspended-growth treatment systems, including Moving Bed Bioreactor (MBBR) and Constructed Wetland Systems (CWs), represent a paradigm shift toward low-energy, decentralized treatment (Curia et al., 2011; Yang et al., 2020). Even though, as the literature frequently says, they are less effective at removing highly contaminated industrial wastewater than membrane systems, their true power lies in their ecological sustainability, low operating costs, and strong alignment with sustainability and climate change adaptation principles.

Advanced Oxidation Processes (AOPs) and Electrochemical Treatments have been highly effective in degrading persistent and complex organic contaminants, such as dyes and pharmaceuticals, that are not readily degraded by conventional biological treatment (Huebner et al., 2024; Norra & Radjenovic, 2021). Nevertheless, a critical synthesis of the reviewed literature provides significant differences in reported efficiencies. For example, some laboratory experiments have demonstrated near-full mineralization, but others have reported incomplete mineralization or the production of toxic byproducts when such technologies are implemented on complex, real-life industrial effluents. Thus, the statement that no single system can address all treatment issues is not only a general observation but also a reflection of inherent contradictions: the success of a technology depends heavily on location-specific factors and the extent of its use. This demonstrates the increased need for hybrid systems (e.g., MBR with AOPs or RO) to balance high efficiency with reduced operational load and to counteract the shortcomings of a single process (Kim et al., 2024; Uddin et al., 2024).

Lastly, a critical review of the methodological constraints of this review is required to assess the current status of wastewater treatment technologies. Although this study was written according to PRISMA, several structural biases need to be noted. First, the use of large English-language databases is biased by language and database selection; since only major English-language databases were searched, it is possible that valuable regional studies have been missed, especially those in non-English-speaking developing countries where decentralized systems are widely applied. Second, there is a risk of publication bias due to the exclusion of gray literature (government field reports, NGO sanitation assessments, and industrial white papers). Research results reported in academic journals are generally those that show positive or statistically significant removal efficiencies, which may bias perceptions of the operational success of some technologies and underreport system failures in real-world conditions. Moreover, even in the original literature, many of the reviewed articles are based on laboratory-scale experiments that are not extensively validated in the field, and few use rigorous Lifecycle Assessment (LCA) or carbon footprint analysis, making it extremely difficult to provide a real and consistent comparison of long-term sustainability.

9. Conclusions

A fundamental trade-off in contemporary wastewater treatment, as this review points out, is that highly efficient systems require substantial energy and capital, whereas low-cost, sustainable systems tend to have lower capacity to treat highly recalcitrant industrial effluents. To achieve long-term sustainability, it is therefore necessary not to focus on

individual technologies but on context-specific hybrid solutions.

Nevertheless, the transfer of these technological improvements to a global application is at present crippled by certain hypodogmatic constraints of the extant literature. Instead of generic propositions, future studies should fill the following identified gaps directly:

Scale-up gap: The existing literature is heavily characterized by controlled, laboratory-scale experiments with limited long-term validation.

Recommendation: Future studies should focus on longitudinal, field-scale implementation to rigorously test system resilience, membrane fouling rates, and maintenance requirements under changing, real-world environmental conditions.

Sustainability Assessment Gap: There are few studies that systematically quantify the indirect environmental effects of energy-intensive, high-efficiency treatments.

Recommendation: The support should include Life-Cycle Assessment (LCA) and carbon footprint tracking as regular reporting measures that researchers should use to make an honest assessment of a technology's long-term ecological sustainability.

Operational cost gap: The high cost and maintenance requirements of high-technology systems make them impractical in resource-constrained environments.

Recommendation: Future engineering work must integrate treatment plants with renewable energy sources and build predictive monitoring processes based on AI to optimize energy use and automate processes.

Complex effluent gap: When dealing with complex, mixed-pollutant streams, individual technologies struggle to balance high removal rates with economic feasibility.

Recommendation: To address the shortcomings of individual systems, experimental work should be conducted to develop custom hybrid configurations (e.g., combining biological pretreatment, such as MBBR, with Advanced Oxidation) that target a narrow spectrum of industrial wastewater profiles.

Finally, it is necessary to fill these methodological gaps and adopt rigorous, globally viable, and field-tested hybrid strategies to help take wastewater management beyond hypothetical efficiency to actual application.

10. Future Challenges

1. Due to industrial advancements and the production of new industrial products, new pollutants are being generated, such as nanomaterials and microplastics, which are difficult to treat using traditional methods.
2. The high operating costs of plants such as ZLD and RO.
3. The need for expensive technologies to monitor plant operations, such as AI and IoT, as well as specialized technical personnel.
4. Developing countries lack many of the resources necessary to operate treatment plants, limiting their deployment.
5. Climate change imposes severe constraints on the operation of treatment plants.

11. Recommendations

1. A comprehensive evaluation of each method should be conducted separately.

Comparison should not be limited to pollutant removal efficiency; broader comparative factors should be incorporated to more clearly highlight each method's capabilities.

1. The superiority of one method over another does not mean that it can be used regardless of other factors. Rather, the actual operating environment and local conditions of the location of one of the previous treatment plants must be taken into account.

2. Hybrid systems that combine multiple technologies can be used to treat stubborn pollutants, thereby maximizing the benefits of each method.

3. Expand testing and make it more comprehensive than laboratory studies; rather, it should include real-world and field experiments.

4. Develop work tools and equipment, such as purification membranes and electrodes, to reduce wear and tear.

5. The need to link water treatment systems with smart monitoring technologies to reduce human error.

6. Adopting tools for analyzing and studying the environment and location before selecting the technology type to achieve the desired maximum benefit.

7. Enhancing cooperation between universities and institutions to evaluate the operation of plants and provide scientific studies to determine the efficiency of the plant.

8. Governments should enact legislation requiring owners of large plants to install sterilization mechanisms before obtaining the necessary plant licenses.

9. Supporting the use of renewable energy, such as solar and wind, in treatment plants to reduce energy waste and air pollution.

10. Implementing public awareness campaigns on the need to focus on decentralized treatment, especially in remote areas.

The study's limitation

Despite providing a comprehensive overview of modern wastewater treatment technologies, this review is subject to several limitations. First, the analysis was restricted to peer-reviewed articles from selected scientific databases, potentially excluding relevant grey literature and regional reports. Second, the direct comparability of the reported efficiencies might be influenced by differences in experimental conditions, performance indicators, and sustainability assessment methodologies across the reviewed studies. Moreover, numerous studies are based on laboratory- or pilot-scale systems, and there is still limited data on the full-scale operation, which restricts the analysis of long-term performance and economic feasibility. Also, sustainability integration was measured using metrics that were not comparable across studies. The areas where future research should focus are the harmonized evaluation frameworks, long-term field applications, and region-specific assessments, especially in developing countries.

Practical or theoretical implications

The review offers theoretical and practical implications to the discipline of wastewater treatment engineering. In theoretical terms, the analysis examines and critically evaluates recent developments in wastewater treatment technologies by combining efficiency figures, sustainability concepts, and operational issues in a single analytical framework. The review helps fill the gap between the concepts of process engineering and sustainable development by connecting the technical performance indicators with the dimensions of sustainability. Moreover, it points to discrepancies in research evaluation criteria and the need for uniform assessment practices.

In practice, these review findings can provide decision-support information to engineers, policymakers, and infrastructure planners. A comparative analysis of treatment technologies in terms of efficiency, energy demand, environmental impact, and operational complexity would help stakeholders choose solutions suited to a particular context. Also, the discussion of real-life implementation issues offers guidance on enhancing scalability, economic viability, and long-term operational stability, especially in developing regions with limited resources and infrastructure.

Statements and Declarations

Data availability

The data supporting the findings of this study are available upon request from the corresponding author. conflict of interest The authors declare no conflicts of interest regarding this manuscript.

Conflicts of interest

The author of this paper declared no conflict of interest regarding the authorship or publication of this paper.

Author contribution

Study conception and design: H.Y.E., N.Q.S. Literature search: H.Y.E., N.Q.S. Data acquisition: H.Y.E., N.Q.S. Data analysis and interpretation: H.Y.E., N.Q.S. Manuscript preparation: H.Y.E., N.Q.S. Manuscript editing and review: H.Y.E., N.Q.S. All authors read and approved the final version of the manuscript.

AI disclosure

The authors declare that no generative AI or AI-assisted technologies were used in the preparation of this manuscript

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