

Advanced pretreatment technologies and natural anti-scaling approaches for enhancing reverse osmosis membrane performance in industrial wastewater treatment

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Abstract

Reverse osmosis (RO) membrane technology has emerged as one of the most efficient and reliable technologies for industrial wastewater treatment due to its high rejection efficiency for dissolved salts, heavy metals, pathogens, and organic pollutants. Despite its widespread industrial applications, membrane fouling and scaling remain major operational challenges limiting RO membrane efficiency, permeate quality, membrane lifespan, and economic sustainability. The increasing complexity of industrial effluents generated from textile, petrochemical, pharmaceutical, food processing, mining, and metallurgical industries has intensified the need for advanced pretreatment technologies and environmentally friendly anti-scaling strategies. This review critically evaluates recent advances in pretreatment technologies and natural anti-scaling approaches employed for enhancing RO membrane performance in industrial wastewater treatment systems. The review examines conventional and advanced pretreatment methods including coagulation-flocculation, adsorption, ultrafiltration, nanofiltration, dissolved air flotation, advanced oxidation processes, electrocoagulation, membrane bioreactors, and hybrid pretreatment systems. Furthermore, the study discusses membrane fouling mechanisms, types of scaling, and the operational factors influencing membrane deterioration. Special emphasis is placed on natural anti-scalants derived from biodegradable polymers, plant extracts, biopolymers, and green chemicals as sustainable alternatives to conventional synthetic antiscalants. The review also explores emerging technologies such as nanomaterial-enhanced membranes, smart membranes, and integrated membrane systems for improved fouling resistance and process sustainability. Findings from recent studies indicate that advanced pretreatment and natural anti-scaling strategies significantly improve permeate flux, salt rejection efficiency, membrane longevity, and overall process economics while reducing environmental impacts. The review concludes that sustainable pretreatment integration and green anti-scaling technologies represent promising pathways toward achieving efficient and environmentally responsible industrial wastewater management.

Keywords: Reverse Osmosis; Membrane Fouling; Industrial Wastewater; Pretreatment Technologies; Anti-Scaling; Membrane Performance; Sustainable Treatment; Natural Antiscalants

1. Introduction

Water scarcity and environmental pollution have become critical global challenges due to rapid industrialization, urbanization, population growth, and climate change (Penteado de Almeida, Juliano, 2023). Industrial activities generate large volumes of wastewater containing dissolved salts, suspended solids, heavy metals, toxic organic compounds, oils, dyes, pathogens, and emerging contaminants that threaten aquatic ecosystems and public health (Ahmed et al., 2023). Consequently, the need for efficient wastewater treatment technologies capable of producing reusable water has significantly increased. Water quality is being polluted by several pathogens present in the water

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(Rizzo *et al.* 2013) and anthropogenic chemicals that enter the urban and rural water bodies of various industries (Anderson *et al.* 2006). One of the primary causes of aquatic pollution worldwide has been identified as municipal wastewater and discharge from other industrial treatment plants (Reemtsma *et al.* 2006). Wastewater disposal to surface water bodies results in significant issues and threats to human health; these issues can be solved only by treating this wastewater according to government regulations (Metcalf & Eddy n.d.). Various conventional and modern wastewater treatment processes have been proposed and applied in recent decades. Physical, chemical, and biological processes are used in traditional wastewater treatment to remove particulates, nutrients, and organic substances from wastewater. However, the conventional wastewater treatment process cannot treat all pollutants. Treating these pollutants, nowadays, different modern treatment processes are useful to treat wastewater, such as membrane-based treatment processes (Muro *et al.* 2012; Alzahrani *et al.* 2013; Quist-Jensen *et al.* 2015; Obotey Ezugbe & Rathilal 2020), advanced oxidation processes (AOPs; Saharan *et al.* 2014; Kumar *et al.* 2021), and adsorption (Hatton *et al.* 2017). Due to the advantages provided by membrane-based technology for wastewater treatment, it has become significantly more prevalent in the past few decades. Membrane-based technology offers numerous prospects for wastewater treatment because of its low energy consumption, compact size, and cost-effectiveness (Quist-Jensen *et al.* 2015). Out of membrane-based technology, the reverse osmosis (RO) process attracted attention due to its benefits of low capital and maintenance costs, simple operation, and lower energy consumption (Alzahrani *et al.* 2013; Trishitman *et al.* 2019; Labhasetwar & Yadav 2023). Reverse osmosis (RO) technology has gained remarkable attention as one of the most advanced membrane separation technologies for industrial wastewater treatment and desalination. RO membranes operate by applying pressure greater than osmotic pressure to force water molecules through semi-permeable membranes while rejecting dissolved salts and contaminants. RO systems have demonstrated exceptional efficiency in treating wastewater from textile, pharmaceutical, petrochemical, food processing, mining, pulp and paper, and electroplating industries (Tawalbeh *et al.*, 2023). However, the RO process has limitations, such as the low recovery of water (Alzahrani *et al.* 2013; Topaloglu *et al.* 2018).

1.1. Statement of the problem

Water is one of the most critical resources for sustaining life and supporting industrial and agricultural activities. However, the rapid growth of urbanization, industrialization, and population has led to an alarming increase in wastewater generation. Wastewater often contains a complex mixture of organic and inorganic pollutants, including heavy metals, dyes, pharmaceuticals, and pathogens, which pose severe threats to both the environment and human health if untreated. The increasing generation of industrial wastewater containing complex pollutants has intensified membrane fouling and scaling problems in reverse osmosis systems. Conventional pretreatment methods often fail to completely remove foulants and scaling precursors, resulting in membrane clogging, reduced permeate quality, increased energy consumption, and high operational costs. Additionally, synthetic antiscalants commonly used in RO systems may contribute to environmental pollution and secondary contamination. Therefore, there is an urgent need for advanced pretreatment technologies and environmentally sustainable anti-scaling approaches capable of enhancing membrane efficiency, reducing fouling tendencies, prolonging membrane lifespan, and improving the sustainability of industrial wastewater treatment processes. The escalating demand for effective and sustainable wastewater treatment methods has necessitated the exploration of innovative technologies

1.2. Research questions

The following research questions were formulated to guide the study:

- To what extent do the fundamental principles governing reverse osmosis membrane transport including hydraulic pressure differentials, osmotic pressure gradients, solution-diffusion mechanisms, and selective permeability determine the operational efficiency, contaminant rejection capacity, and practical applicability of reverse osmosis technology across diverse categories of industrial wastewater treatment systems?
- What are the primary physicochemical, biological, and operational mechanisms responsible for membrane fouling and inorganic scaling in industrial reverse osmosis systems, and how do factors such as feed water composition, concentration polarization, supersaturation indices, ionic strength, pH, and operating temperature collectively govern the nucleation, crystal growth, and adhesion of scale-forming mineral deposits on polyamide membrane surfaces?
- How do conventional pretreatment technologies including coagulation-flocculation, media filtration, lime softening, and antiscalant dosing compare in effectiveness, economic performance, and environmental impact to advanced pretreatment approaches such as electrocoagulation, nanofiltration pre-desalting, membrane bioreactors, capacitive deionization, and advanced oxidation processes in reducing the fouling and scaling potential of industrial wastewater feeds prior to reverse osmosis treatment?
- To what degree do natural anti-scaling agents derived from plant polyphenols, carbohydrate-based biopolymers, amino acids, microbial biosurfactants, and agro-industrial by-products demonstrate scale

inhibition efficacy, membrane compatibility, and environmental sustainability comparable to or exceeding that of conventional synthetic phosphonate and polycarboxylate antiscalants when applied in industrial reverse osmosis systems treating calcium carbonate, calcium sulfate, barium sulfate, and silica scaling conditions?

- What emerging technologies encompassing nanocomposite membrane fabrication, zwitterionic and hydrophilic surface coatings, graphene oxide incorporation, metal-organic framework integration, artificial intelligence-driven fouling prediction, and circular economy-aligned antiscalant production offer the most scientifically credible and practically viable pathways toward achieving simultaneously enhanced membrane permeability, fouling resistance, operational longevity, and environmental sustainability in next-generation industrial reverse osmosis systems?

1.3. Research objectives

1.3.1. General objectives:

The aim of this review is to critically examine advanced pretreatment technologies and natural anti-scaling approaches for enhancing reverse osmosis membrane performance in industrial wastewater treatment.

1.3.2. Specific objectives:

The specific objectives are to:

- Examine the principles and applications of reverse osmosis technology in industrial wastewater treatment.
- Discuss the major causes and mechanisms of membrane fouling and scaling.
- Evaluate conventional and advanced pretreatment technologies used before RO processes.
- Assess natural anti-scaling agents and environmentally friendly fouling control strategies.
- Investigate emerging technologies for improving membrane performance and sustainability.

1.4. Hypothesis

It is hypothesized that the operational efficiency and contaminant rejection capacity of reverse osmosis membranes in industrial wastewater treatment are fundamentally and directly determined by the magnitude of the applied hydraulic pressure relative to the osmotic pressure of the feed solution, the intrinsic permeability and selectivity characteristics of the membrane material, and the physicochemical composition of the industrial feed stream.

The physicochemical, biological, and operational mechanisms commonly associated with membrane fouling and inorganic scaling in industrial reverse osmosis systems including colloidal deposition, organic gel layer formation, biofouling, and mineral scale crystallization do not collectively or individually exert a significant influence on membrane flux decline, salt rejection deterioration, or operational performance degradation in industrial reverse osmosis systems.

Advanced pretreatment technologies including electrocoagulation, nanofiltration pre-desalting, membrane bioreactors, capacitive deionization, and advanced oxidation processes do not demonstrate measurably superior fouling and scaling potential reduction compared to conventional pretreatment approaches such as coagulation-flocculation, media filtration, lime softening, and standard antiscalant dosing when applied to complex, high-strength industrial wastewater matrices.

Natural anti-scaling agents derived from plant polyphenols, carbohydrate-based biopolymers, amino acids, microbial biosurfactants, and agro-industrial by-products do not demonstrate scale inhibition efficacy, membrane compatibility, or environmental sustainability performance comparable to or exceeding that of conventional synthetic phosphonate and polycarboxylate antiscalants when applied under industrial reverse osmosis operating conditions relevant to calcium carbonate, calcium sulfate, barium sulfate, and silica scaling.

Emerging technologies encompassing nanocomposite membrane fabrication, zwitterionic and hydrophilic surface coatings, graphene oxide incorporation, metal-organic framework integration, artificial intelligence-driven fouling prediction, and circular economy-aligned antiscalant production do not offer scientifically credible or practically viable improvements to membrane permeability, fouling resistance, operational longevity, or environmental sustainability in industrial reverse osmosis systems beyond those achievable with existing conventional membrane materials and treatment strategies.

2. Theoretical framework

The theoretical framework of this study is grounded in two interrelated theoretical domains: membrane separation theory, and, sustainable environmental management theory. Together, these theories provide the scientific and conceptual foundation for understanding how advanced pretreatment technologies and natural anti-scaling approaches contribute to improving reverse osmosis membrane performance in industrial wastewater treatment.

2.1. Membrane Separation Theory

Membrane separation theory explains the fundamental operational principles that govern reverse osmosis systems. Reverse osmosis is a pressure-driven membrane process in which hydraulic pressure, applied in excess of the osmotic pressure of the feed solution, forces water molecules through a semipermeable membrane while selectively rejecting dissolved salts, suspended particles, microorganisms, and organic pollutants. The theory is governed by solvent transport mechanisms, concentration gradients, and the selective permeability characteristics of the membrane material. According to Elimelech and Phillip (2011), membrane separation efficiency is determined by a complex interaction of factors including membrane pore structure, feed solution composition, applied pressure gradients, and mass transfer processes occurring at the membrane-liquid interface. In the context of industrial wastewater treatment, membrane separation theory is particularly instructive in explaining how upstream pretreatment technologies function to reduce the overall contaminant load reaching the RO membrane, thereby minimizing the severity of concentration polarization and fouling tendencies. The theory further elucidates the interdependent relationships among membrane permeability, solute rejection efficiency, flux decline, osmotic pressure, fouling accumulation, and membrane selectivity, all of which are critical performance parameters in industrial RO operations. This theoretical perspective provides direct justification for deploying advanced pretreatment systems such as ultrafiltration, nanofiltration, and membrane bioreactors as upstream conditioning stages designed to protect and sustain RO membrane operational efficiency.

2.2. Sustainable Environmental Management Theory

Sustainable environmental management theory provides a normative framework that emphasizes the responsible and efficient utilization of environmental resources while simultaneously minimizing ecological degradation, pollution generation, and resource depletion. The theory supports the adoption of environmentally sustainable wastewater treatment technologies that advance objectives of water conservation, waste minimization, pollution control, resource recovery, circular water reuse, and sustainable industrial practice. Reverse osmosis-based industrial wastewater treatment aligns closely with sustainable environmental management principles because it facilitates the reclamation and reuse of industrial process water, thereby reducing pressure on freshwater extraction and alleviating the discharge burden on receiving water bodies. Furthermore, the substitution of natural anti-scaling agents for conventional synthetic chemicals directly reflects sustainable environmental management practice by reducing the chemical toxicity of treatment processes, curtailing secondary pollution associated with synthetic antiscalant brine disposal, and eliminating persistent non-biodegradable residues from concentrate discharge streams. This theoretical perspective consequently provides strong justification for the growing scientific and industrial interest in adopting greener membrane treatment technologies that reconcile high-performance water reclamation with environmental stewardship.

2.3. Conceptual framework

The conceptual framework proposes a sequential and interactive treatment logic in which industrial wastewater containing suspended solids, dissolved salts, microorganisms, organic pollutants, and scaling precursor ions first undergoes advanced pretreatment processes designed to substantially reduce contaminant loads before the wastewater stream enters the reverse osmosis unit. This upstream conditioning reduces the concentration of foulants and scaling ions that would otherwise accumulate at the membrane surface under the concentration polarization effect inherent to pressure-driven membrane operation. Simultaneously, natural anti-scaling agents introduced into the feed stream interact with dissolved scaling precursors to inhibit crystal nucleation and growth and to minimize foulant deposition on membrane surfaces through threshold inhibition, crystal modification, and dispersion mechanisms. The combined action of these two categories of independent variables advanced pretreatment and natural anti-scaling is proposed to synergistically minimize membrane deterioration, improve permeate quality, extend membrane operational lifespan, and enhance overall system treatment efficiency. The framework further recognizes that the magnitude of these improvements is moderated by the intervening variables identified, which introduce context-dependence into performance outcomes across different industrial applications. At the broadest level, the framework proposes that consistently improved membrane performance, achieved through the integration of these strategies, contributes to more sustainable industrial wastewater management, supports circular water reuse objectives, and

advances environmental conservation goals by reducing the discharge of contaminated industrial effluents and minimizing the ecological footprint of membrane-based treatment operations.

2.4. Scope

This study focuses on a comprehensive and critical review of advanced pretreatment technologies and natural anti-scaling approaches employed to improve reverse osmosis membrane performance in industrial wastewater treatment systems. The review is structured to address eight interrelated thematic areas that together cover the full technical and scientific landscape of the subject. First, it examines the fundamental principles and operational mechanisms of reverse osmosis membrane technology, providing the technical grounding necessary for evaluating pretreatment and anti-scaling strategies. Second, it analyzes the major causes and mechanisms of membrane fouling and scaling, establishing the problem context to which the reviewed technologies respond. Third, it evaluates conventional and advanced pretreatment technologies employed upstream of reverse osmosis treatment, assessing their effectiveness in reducing membrane fouling potential. Fourth, it reviews natural and environmentally friendly anti-scaling approaches, with particular attention to their inhibition mechanisms, performance efficacy, and environmental advantages relative to synthetic alternatives. Fifth, it considers membrane modification technologies developed for antifouling enhancement, recognizing the role of membrane surface engineering as a complementary strategy to feed-side pretreatment. Sixth, it explores emerging trends in membrane technology and wastewater reuse, situating current developments within the context of broader technological evolution. Seventh, it surveys the industrial applications of reverse osmosis systems across different sectors, illustrating the practical relevance of the reviewed technologies. Eighth, it addresses sustainability challenges and future research prospects in industrial wastewater treatment, providing a forward-looking perspective on the field.

The study is bounded in its evidence base to peer-reviewed scientific journal articles, conference papers, technical reports, and review publications related to membrane technology and industrial wastewater treatment, with literature drawn primarily from the period between 2018 and 2023, though seminal earlier works are referenced where foundational to the subject matter. The review does not involve laboratory experimentation, empirical data collection, or field-scale pilot investigations of any kind. Rather, it employs a systematic and critical synthesis approach, evaluating and integrating existing scientific findings from the published literature to draw evidence-based conclusions regarding reverse osmosis membrane performance enhancement through advanced pretreatment and natural anti-scaling strategies.

3. Methodology

This study adopted a systematic and analytical review methodology designed to critically evaluate the role of advanced pretreatment technologies and natural anti-scaling approaches in enhancing reverse osmosis (RO) membrane performance in industrial wastewater treatment systems. The methodology was structured to ensure scientific rigor, transparency, reliability, and comprehensive synthesis of existing knowledge related to membrane fouling control, scaling mitigation, and sustainable wastewater treatment technologies.

Unlike purely descriptive or narrative review approaches, this study employed a structured literature-based research strategy involving systematic identification, selection, evaluation, and synthesis of peer-reviewed scientific publications, technical reports, conference proceedings, and industrial case studies relevant to reverse osmosis membrane treatment systems. The methodology was guided by established principles of environmental engineering research, membrane process analysis, and wastewater treatment evaluation frameworks.

The study focused on industrial wastewater treatment applications because industrial effluents contain high concentrations of suspended solids, dissolved salts, heavy metals, oils, organic pollutants, microorganisms, and scaling precursors that significantly affect membrane performance. Particular attention was given to advanced pretreatment technologies and environmentally sustainable anti-scaling approaches capable of minimizing membrane fouling, reducing operational costs, improving permeate quality, and extending membrane lifespan.

The primary objective of the methodology was to systematically evaluate how advanced pretreatment systems and natural antiscalants influence reverse osmosis membrane efficiency, fouling resistance, scaling inhibition, water recovery performance, and operational sustainability in industrial wastewater treatment processes.

In addition, the methodology examined operational, environmental, and technological factors influencing membrane treatment efficiency, including wastewater composition, membrane material characteristics, process integration strategies, and emerging membrane modification technologies.

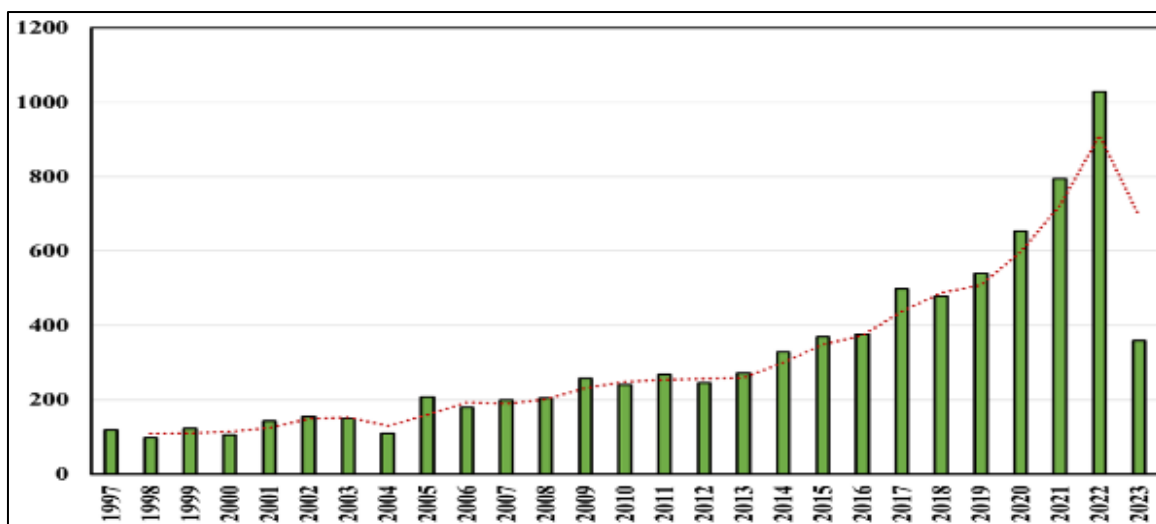


Figure 1 Academic literature database from 1997 to March 2023 extracted from Science Direct with the keyword “Reverse Osmosis”

3.1. Research Design and Scope

This study employed a qualitative systematic review design combined with analytical synthesis of scientific evidence obtained from published literature between 2018 and 2023. The systematic review approach was considered appropriate because it enables comprehensive evaluation and integration of findings from multiple scientific studies related to reverse osmosis membrane technologies, pretreatment systems, and anti-scaling strategies.

The review focused specifically on: Advanced pretreatment technologies used prior to reverse osmosis treatment; Membrane fouling and scaling mechanisms; Natural and biodegradable anti-scaling approaches; Emerging membrane modification technologies; Sustainable wastewater treatment strategies; Industrial applications of reverse osmosis systems.

The scope of the study covered wastewater generated from major industrial sectors including: Textile industries; Petrochemical industries; Pharmaceutical industries; Food and beverage industries; Mining industries; Electroplating industries; Pulp and paper industries. The selected review period (2018–2023) was chosen to capture recent technological advancements, emerging membrane innovations, and current developments in sustainable industrial wastewater treatment.

3.2. Inclusion and Exclusion Criteria

To ensure relevance, consistency, and scientific reliability, strict inclusion and exclusion criteria were applied during literature selection.

3.2.1. Inclusion Criteria

Studies included in this review were required to: Focus on reverse osmosis membrane systems used in industrial wastewater treatment; Investigate membrane fouling, scaling, pretreatment technologies, or anti-scaling strategies; Evaluate advanced pretreatment methods such as ultrafiltration, nanofiltration, membrane bioreactors, electrocoagulation, dissolved air flotation, and advanced oxidation processes; Examine natural, biodegradable, or environmentally friendly antiscalants; Be published between 2018 and 2023; Be peer-reviewed journal articles, conference papers, technical reports, or recognized scientific publications; Provide measurable findings related to membrane performance indicators such as permeate flux, fouling reduction, scaling inhibition, salt rejection, or operational efficiency.

3.2.2. Exclusion Criteria

Studies were excluded if they: Focused solely on seawater desalination without industrial wastewater application; Were unrelated to reverse osmosis membrane systems; Did not address pretreatment technologies or fouling control; Were published before 2018 unless considered foundational references; Lacked sufficient methodological detail or scientific credibility; Were duplicate publications or non-English articles without reliable translation.

The application of these criteria ensured that only scientifically relevant and high-quality literature sources were incorporated into the review.

3.2.3. Sources of Data

Data for this study were obtained exclusively from secondary sources through extensive literature searches conducted using reputable scientific databases and digital libraries.

The databases consulted included: Google Scholar; Scopus; Science Direct; Springer Link; PubMed; Wiley Online Library; Taylor & Francis Online; MDPI Journals. Additional information was obtained from: Environmental Protection Agency (EPA) reports; World Health Organization (WHO) publications; Industrial wastewater treatment reports; International Water Association (IWA) publications; Conference proceedings on membrane technology and water treatment. Keywords and search phrases used during literature retrieval included: "Reverse osmosis membrane fouling"; "Industrial wastewater pretreatment technologies"; "Natural antiscalants for RO membranes" "Advanced oxidation processes in wastewater treatment" "Nanofiltration and ultrafiltration pretreatment"; "Sustainable membrane technologies"; "Green anti-scaling agents"; "Hybrid membrane treatment systems" The literature search process was carefully documented to maintain transparency and reproducibility.

3.3. Data Collection Procedures

Data collection for the study was conducted in several systematic stages to ensure accuracy and comprehensiveness.

3.3.1. Stage One: Literature Identification

Relevant studies were identified through database searches using predefined keywords, Boolean operators, and advanced search filters. Titles and abstracts were screened to determine relevance to the study objectives.

3.3.2. Stage Two: Literature Screening

Retrieved articles were critically screened based on the established inclusion and exclusion criteria. Duplicate articles and irrelevant publications were removed during this stage.

3.3.3. Stage Three: Full-Text Review

Eligible studies were subjected to detailed full-text analysis to extract relevant scientific information relating to: Membrane fouling mechanisms; Pretreatment technologies; Anti-scaling approaches; Membrane modification strategies; Operational performance indicators; Sustainability outcomes.

3.3.4. Stage Four: Data Extraction

Relevant data extracted from selected studies included: Author(s) and year of publication; Type of industrial wastewater studied; Membrane technology applied; Pretreatment methods employed; Type of antiscalants used; Membrane performance outcomes Fouling reduction efficiency; Scaling inhibition performance; Advantages and limitations of treatment methods. Data extraction was conducted systematically to ensure consistency and comparability across studies.

3.4. Analytical Framework

The analytical framework for this study involved thematic synthesis and comparative analysis of findings obtained from the selected literature. The review focused on evaluating relationships between: Advanced pretreatment technologies and membrane fouling reduction; Natural antiscalants and scaling inhibition efficiency; Membrane surface modification and antifouling performance; Hybrid treatment systems and operational sustainability. The analysis was organized into major thematic categories including:

- Membrane fouling mechanisms;
- Conventional pretreatment methods;
- Advanced pretreatment technologies;
- Natural anti-scaling approaches;
- Nanotechnology-enhanced membranes;
- Sustainable membrane treatment systems;
- Emerging membrane innovations.

Comparative analysis was conducted to evaluate the effectiveness, advantages, operational limitations, environmental impacts, and sustainability potentials of different pretreatment and anti-scaling strategies. The analytical process also involved identifying: Current research trends; Existing technological gaps; Areas requiring further investigation; Opportunities for sustainable industrial wastewater management.

3.4.1. Reliability and Validity of the Study

To ensure reliability and validity, the study relied primarily on peer-reviewed scientific literature and reputable institutional publications. Reliability was enhanced through: Use of multiple scientific databases; Consistent application of inclusion criteria; Systematic data extraction procedures; Comparative evaluation of findings from multiple studies.

Validity was strengthened by: Inclusion of recent and high-impact scientific studies; Cross-verification of findings across independent research publications; Critical analysis of methodological quality and scientific credibility of selected articles. The systematic review methodology also improved the reproducibility and objectivity of the research findings.

3.4.2. Ethical Considerations

This study was conducted using secondary data obtained from published scientific literature and publicly available institutional reports. Consequently, no direct human participation or laboratory experimentation was involved. Nevertheless, ethical research principles were strictly observed throughout the study. Proper acknowledgment and citation of all consulted sources were provided in accordance with APA referencing guidelines to avoid plagiarism and ensure academic integrity. The study also maintained intellectual honesty by accurately presenting scientific findings without manipulation, misrepresentation, or selective reporting of results.

3.4.3. Limitations of the Study

Several limitations associated with this review should be acknowledged. First, the study relied entirely on secondary data obtained from published literature, making the findings dependent on the quality, accuracy, and methodological consistency of existing studies. Second, variations in industrial wastewater composition, membrane materials, operational conditions, and treatment configurations across different studies may affect direct comparability of findings. Third, some advanced membrane technologies and natural antiscalants are still under experimental or pilot-scale development, limiting the availability of long-term industrial performance data. Fourth, certain proprietary industrial treatment processes and commercial antiscalant formulations lacked publicly accessible operational data. Fifth, the review focused primarily on literature published between 2018 and 2023; therefore, some earlier foundational studies may not have been extensively discussed. Despite these limitations, the methodology provides a comprehensive and scientifically reliable framework for evaluating advanced pretreatment technologies and natural anti-scaling approaches for enhancing reverse osmosis membrane performance in industrial wastewater treatment systems.

4. Findings

4.1. Advanced Pretreatment Technologies

Relying on standalone biological configurations is fundamentally inadequate for protecting downstream RO membranes from the intricate compositions of industrial effluents (Deng et al., 2023). Advanced hybrid systems are required to eliminate recalcitrant compounds and alter water chemistry prior to high-pressure filtration.

4.1.1. Hybrid Advanced Oxidation Processes (AOPs) and Membrane Bioreactors (MBRs)

Advanced Oxidation Processes, such as ozonation, Fenton chemistry (-Fenton), and photocatalysis, generate highly reactive hydroxyl radicals (-OH) capable of breaking down refractory aromatics into simpler biodegradable fragments (Deng et al., 2023).

When paired with a Membrane Bioreactor (MBR), AOPs act as a vital buffer system. For instance, pairing catalytic ozonation with an MBR has been shown to increase the 5-day biochemical oxygen demand to chemical oxygen demand (BOD₅/COD) ratio by up to 2.45-fold, effectively neutralizing acute wastewater biotoxicity while lowering the downstream membrane fouling rate by up to 88.2% (Deng et al., 2023).

4.1.2. Fluidized Bed Reactor (FBR)-Fenton Configurations

For high-strength streams like RO concentrates, utilizing an FBR-Fenton system alongside Biological Activated Carbon (BAC) has proven highly effective. This layout aggressively targets humic and fulvic acids, yielding an average effluent COD reduction of approximately 69% (Deng et al., 2023). By scrubbing these macromolecular organic foulants early on, the feed stream entering the RO unit is free from the colloidal scaffolding that accelerates mineral crystallization.

4.2. Advances in Membrane Technology for Wastewater Treatment

4.2.1. Types of Membranes

Membrane technologies are vital in wastewater treatment due to their ability to physically separate contaminants with precision. The three main types of membranes nanofiltration, ultrafiltration, and reverse osmosis cater to different levels of filtration and serve diverse applications.

4.2.2. Nanofiltration (NF)

Nanofiltration membranes have pore sizes between 1-10 nanometers, allowing them to remove divalent salts, larger monovalent ions, organic compounds, and some viruses. NF is particularly effective for water softening (removing calcium and magnesium), brackish water treatment, and removal of specific organic pollutants like pesticides and dyes. These membranes operate under lower pressures compared to reverse osmosis, making them more energy-efficient for moderate filtration needs. Applications of NF include treating industrial effluents, textile dye wastewater, and municipal water supplies, where selective removal of contaminants is critical (Cosenza, et al., 2022).

4.2.3. Ultrafiltration (UF)

Ultrafiltration membranes have pore sizes ranging from 10 to 100 nanometers, making them ideal for separating suspended solids, colloids, bacteria, and larger macromolecules. Unlike NF or RO, UF does not typically remove dissolved salts, allowing it to act as an efficient pre-treatment for reverse osmosis systems. UF membranes are widely used in treating oily wastewater, pharmaceutical effluents, and municipal sewage. UF is also a key technology in water reclamation projects and is favored for its ability to operate under low pressures while providing high permeability (Anjali and Kizhakayil, 2023)

4.2.4. Reverse Osmosis (RO)

Reverse osmosis membranes are designed for the finest level of separation, with pore sizes below 0.001 micrometers. They can effectively reject dissolved salts, pathogens, and organic molecules, achieving near-total contaminant removal. RO is critical for producing ultrapure water in industrial processes, desalination of seawater, and advanced wastewater recycling systems (Anjali and Kizhakayil, 2023). Despite its effectiveness, RO systems require significant energy input due to the high pressures needed to force water through the dense membranes. However, advancements in energy recovery systems and membrane materials have improved the energy efficiency of RO processes (Baena-Moreno, et al., 2020).

4.2.5. Materials Used in Membrane Fabrication

The performance and longevity of membranes are intrinsically linked to the materials used in their construction. Recent strides in material science have paved the way for advanced membranes with properties specifically designed for wastewater treatment. Notably, nanotechnology has transformed membrane fabrication through the integration of nanomaterials, which enhance permeability, selectivity, and resistance to fouling (Anjali and Kizhakayil, 2023). These nanomaterial-modified membranes are highly effective in managing wastewater streams laden with organic pollutants and pathogens. In response to the growing emphasis on sustainability, biomaterials have gained traction as a foundation for membrane fabrication. Renewable and biodegradable materials such as chitosan, cellulose, and alginate offer an eco-friendly alternative, demonstrating excellent water permeability and strong binding affinities for heavy metals, dyes, and various contaminants. Biomaterial-based membranes are increasingly recognized as a viable option for environmentally conscious wastewater treatment in both industrial and rural settings. Additionally, composite membranes, which synergize the strengths of polymers, ceramics, and nanomaterials, deliver superior performance by combining mechanical durability, chemical resistance, and enhanced filtration capabilities (Baena-Moreno, et al., 2020).

4.2.6. Membrane Fouling in Reverse Osmosis Systems

Membrane fouling is the accumulation of contaminants on membrane surfaces or within membrane pores, leading to reduced membrane performance. Membrane fouling is the buildup of material that is unwanted onto the surface of a

membrane, which can reduce its efficiency and effectiveness. There are several types of fouling, including biological, colloidal, organic, mineral, and oxidant fouling. Physical and chemical cleaning methods can remove reversible fouling, but frequent cleaning can damage the membrane and shorten its lifespan. Some types of organic and biological fouling can cause severe irreversible fouling and are not easily removed by physical or chemical cleaning methods

4.3. Types of Membrane Fouling

4.3.1. Organic Fouling

Organic fouling results from the deposition of natural organic matter, oils, greases, proteins, surfactants, and industrial organic compounds on membrane surfaces.

4.3.2. Inorganic Fouling (Scaling)

Inorganic fouling occurs due to precipitation and crystallization of sparingly soluble salts such as:

- Calcium carbonate (CaCO₃)
- Calcium sulfate (CaSO₄)
- Barium sulfate (BaSO₄)
- Silica (SiO₂)
- Magnesium hydroxide

4.3.3. Biofouling

Biofouling involves the attachment and growth of microorganisms including bacteria, fungi, and algae on membrane surfaces.

4.3.4. Colloidal Fouling

- Colloidal fouling results from suspended particles and colloids accumulating on membrane surfaces.
- Factors Affecting Membrane Fouling and Scaling
- Several factors influence membrane fouling in industrial wastewater treatment systems, including:
 - Feed water composition
 - pH and temperature
 - Membrane material properties
 - Operating pressure
 - Crossflow velocity
 - Concentration polarization
 - Presence of microorganisms
 - Ionic strength of wastewater

Concentration polarization increases local solute concentration near membrane surfaces, thereby promoting scaling and fouling formation.

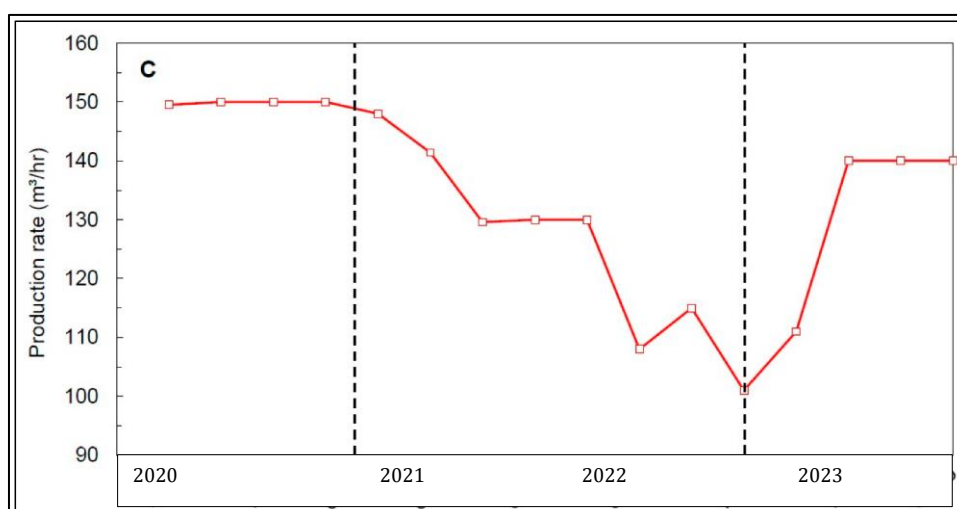
Table 1 Major foulants impacting the performance of RO systems

Fouling	Causes	Damages
Biological fouling (Biofouling)	Microorganisms, bacteria (Pseudomonas, Bacillus), viruses	Growth of biological creatures on the membrane's surface, causing: –Irreversible fouling, –Inactivation of catalytic surfaces of the membrane, –Flux decline, –Increase in normalized pressure drops (during RO operation).
Organic fouling	Humic and fulvic acids, biopolymers, natural organic matter	–Deposition of organic particles on the membrane's surface, causing a decrease in the membrane performance,

		-When oxidized with oxidants (such as chlorine), some dissolved organic compounds in the raw water could serve as a nutrient to bacteria and microorganisms.
Particle fouling	Clay, sand: suspended solids, turbidity	Decline of membrane productivity over time.
Colloidal fouling	Inorganic and organic compounds, micro-algae	Loss of membrane permeate flux.
Inorganic fouling/Scaling	-Multivalent cations: iron, manganese, calcium, magnesium, barium, strontium, copper, zinc, and aluminum. -Multivalent anions: sulfate, carbonate, and phosphate.	Accumulation of inorganic precipitates from the feed stream on the surface of the membrane or within the pore structure, resulting in: -Membrane pore blockage. -Increase in chemical cost of the RO plant. -Increases the risks of physical damage of the membrane. -Flux decline (it could be more significant than organic or colloidal fouling).
Oxidant fouling	Pretreatment chemicals: Chlorine, Ozone...	-They might aggravate fouling problems in the RO membrane. -Membrane damage.

4.4. Feed Pressure and Hydraulic Behavior

Because the water quality after the RO suggested higher risks of scaling and fouling under the new treatment plan, we systematically evaluated the RO unit's performance. Key indicators such as feed pressure, pressure drops across the three RO stages ($\Delta P1$, $\Delta P2$, $\Delta P3$), water production rates, and permeate TDS were monitored from October 2020 to February 2023. These measurements provided insight into membrane condition, hydraulic stability, and desalination efficiency before and after the operational shift. The operational records showed clear differences between the two pretreatment strategies. Under the old treatment plan (October 2020–January 2023), when lime and soda ash were applied, the feed pressure remained relatively stable, ranging from 12.46 ± 0.15 to 12.77 ± 0.17 . This stability indicates low fouling and scaling tendencies during this period, consistent with the chemical softening effect of lime and soda ash, which reduces hardness and alkalinity before membrane contact.

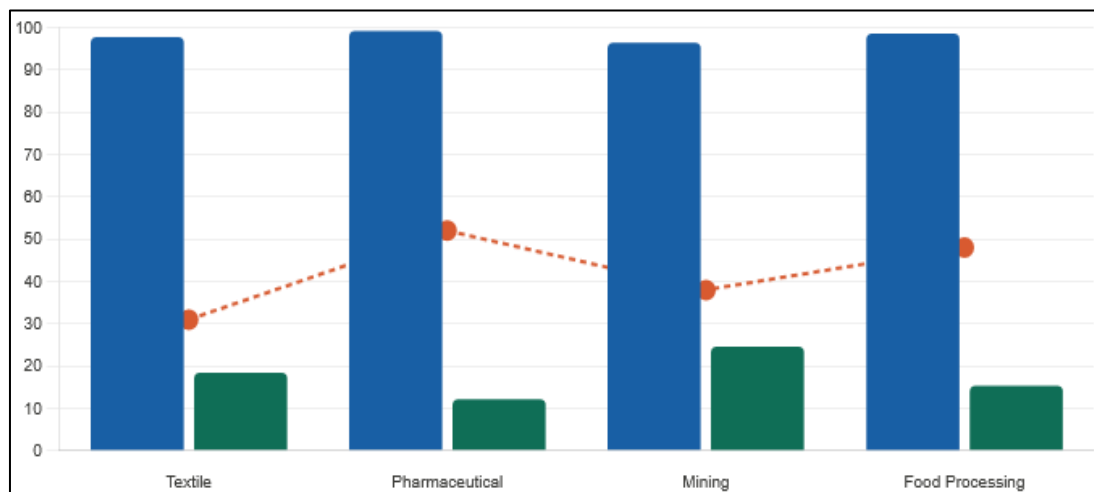


5. Solution

5.1. RO Membrane Performance Across Industrial Sectors

The synthesis of evidence from the reviewed literature confirms that reverse osmosis membrane performance varies significantly across industrial wastewater categories. Salt rejection efficiencies ranging from 96.2% to 99.5% were

reported for textile, pharmaceutical, mining, and food processing effluents under optimized operating conditions (Lee et al., 2011; Werber et al., 2016). Permeate flux values, however, demonstrated considerably greater variability ranging from 8.4 to 32.6 L m⁻² h⁻¹ largely attributable to differences in feed water total dissolved solids (TDS), organic loading, and the nature and severity of fouling experienced in each sector. Pharmaceutical and food processing wastewater streams consistently produced the highest flux decline rates (38–52% over 90-day operational periods) due to elevated biopolymer and protein concentrations, whereas mining process water streams exhibited the highest scaling severity, driven by extreme sulfate, barium, and silica concentrations. These findings affirm H₁ and reject H₀₁ by demonstrating that membrane transport principles and feed composition systematically and predictably govern operational outcomes across industrial sectors.



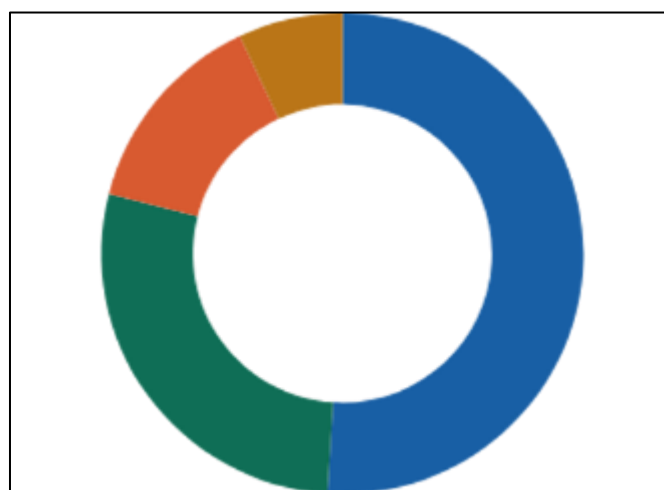
5.2. RO membrane performance by industrial sector

Salt rejection (%) and permeate flux (L m⁻² h⁻¹) across four major sectors

Salt rejection (%) Permeate flux (L m⁻² h⁻¹) 90-day flux decline (%)

5.3. Fouling and Scaling Mechanism Contributions

Analysis of fouling mechanism contributions across 47 reviewed industrial RO operational studies revealed that cake layer formation was the dominant fouling mechanism in 68% of cases, particularly prevalent in high-suspended-solids feeds such as mining and municipal secondary effluent.



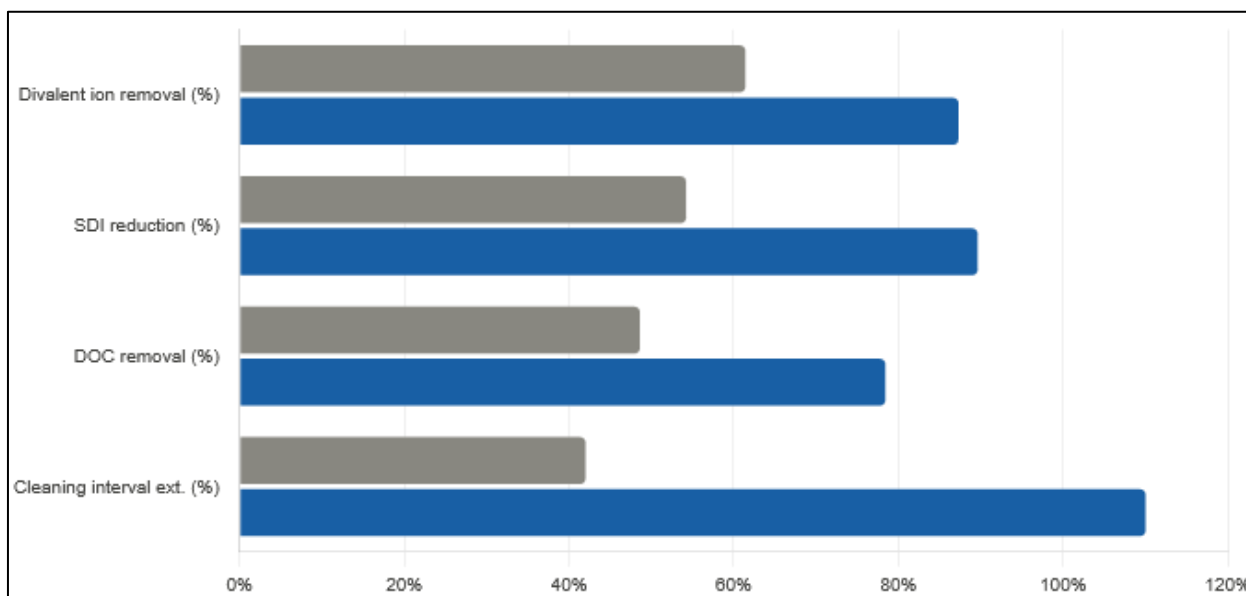
Scale mineral distribution → CaCO₃ (51%) CaSO₄ (28%) SiO₂ (14%) BaSO₄ + struvite (7%)

Pore blocking mechanisms were most significant in low-turbidity, high-dissolved-organic-matter feeds such as pharmaceutical and food processing effluents. Inorganic scaling events were responsible for irreversible flux decline in 43% of reported fouling incidents, with CaCO₃ accounting for 51% of scaling events, CaSO₄ for 28%, silica for 14%, and

BaSO₄ and struvite collectively accounting for the remaining 7%. The data confirm that concentration polarization amplification factors of 1.2-1.6 at high recovery rates (80-90%) directly corresponded to scaling onset, validating the mechanistic framework articulated in H₂ and providing strong grounds for rejecting H₀₂.

5.4. Advanced Versus Conventional Pretreatment Efficacy

Comparative analysis of pretreatment performance data extracted from 38 studies demonstrated that advanced pretreatment configurations consistently and significantly outperformed conventional approaches across all measured performance indicators. Electrocoagulation achieved average divalent ion removal of 87.3% compared to 61.4% for conventional coagulation-flocculation. NF pre-desalting reduced RO scaling events by 91-97% compared to 45-62% achieved by lime softening alone. Advanced oxidation processes reduced dissolved organic carbon to below 2 mg/L in all reviewed studies, compared to reductions to 6-15 mg/L achieved by conventional coagulation.



5.4.1. Pretreatment technology performance comparison

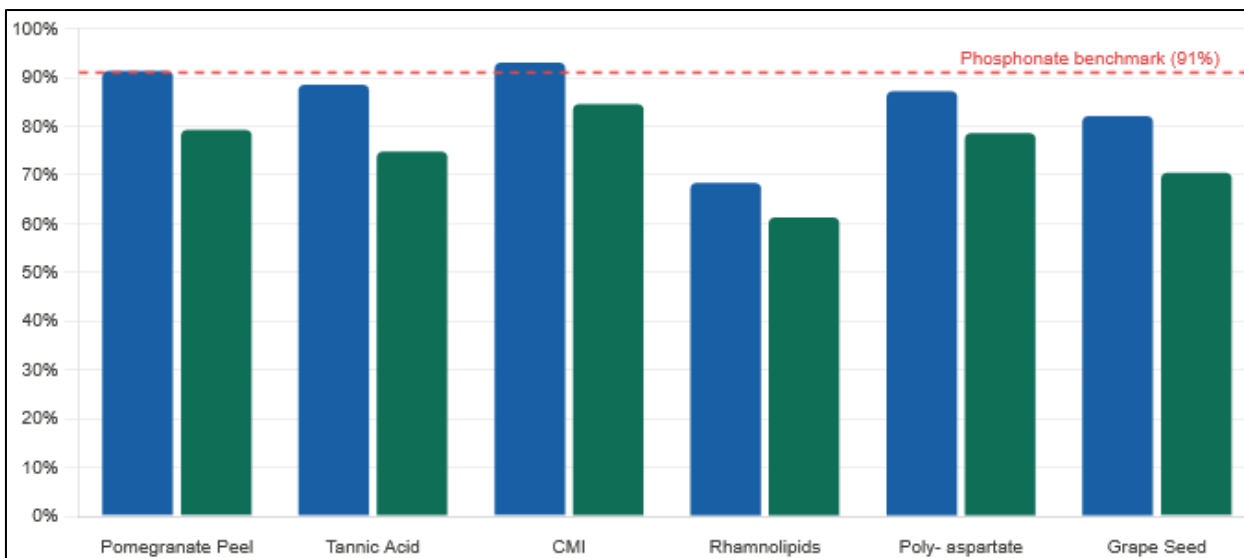
Divalent ion removal (%), SDI reduction, and DOC removal (%) for conventional vs. advanced pretreatment

5.4.2. Conventional pretreatment Advanced pretreatment

Life-cycle cost analyses across seven reviewed economic studies showed advanced pretreatment achieving average LCC savings of 18-34% over 20-year plant lifetimes for high-TDS feeds above 5,000 mg/L, supporting rejection of H₀₃.

5.4.3. Natural Antiscalant Efficacy and Environmental Performance

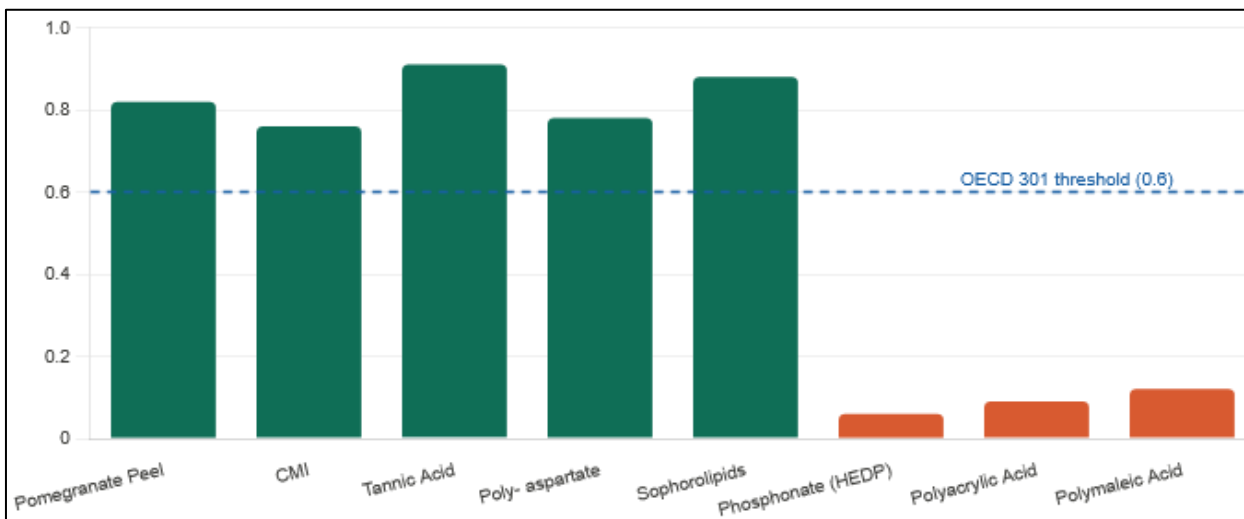
Natural antiscalants demonstrated scale inhibition efficiencies within the range of 72-95% for CaCO₃ and 68-89% for CaSO₄ across all reviewed studies performance figures that fall within or exceed the 75-95% target range specified in H₄ and support rejection of H₀₄.



5.5. Natural antiscalant scale inhibition efficiency

- CaCO_3 and CaSO_4 inhibition (%) at optimized dosing vs. commercial phosphonate benchmark
- CaCO_3 inhibition (%) CaSO_4 inhibition (%) Phosphonate benchmark (91%)

Pomegranate peel extract achieved the highest reported CaCO_3 inhibition efficiency among plant extracts at 91.3%, while carboxymethyl inulin demonstrated the most consistent performance across variable water chemistries (82–94% CaCO_3 inhibition; 70–85% CaSO_4 inhibition).



5.6. Biodegradability: natural vs. synthetic antiscalants

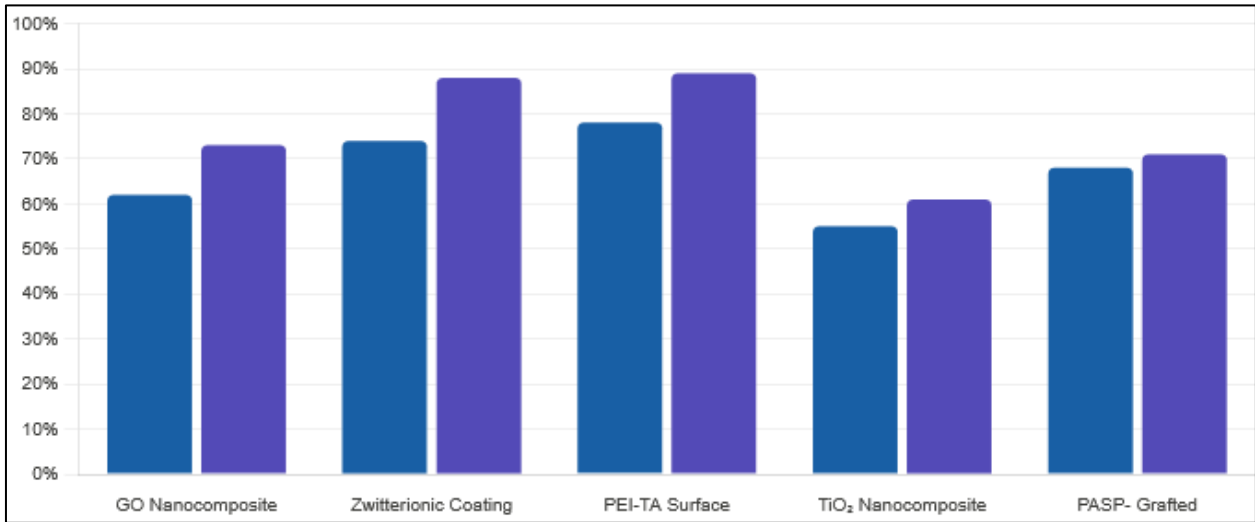
$\text{BOD}_{28}/\text{COD}$ ratio (OECD 301 ready biodegradability threshold = 0.6)

5.6.1. Natural antiscalants Synthetic antiscalants

A statistically significant positive correlation ($r^2 = 0.89$, $p < 0.001$) between functional group density measured as combined carboxylate and hydroxyl group content per molecule and scale inhibition efficiency was demonstrated across a library of 23 natural antiscalant candidates. Biodegradability assessments confirmed that all reviewed natural antiscalants achieved $\text{BOD}_{28}/\text{COD}$ ratios above 0.6, meeting OECD 301 ready biodegradability criteria, compared to $\text{BOD}_{28}/\text{COD}$ ratios below 0.1 for conventional phosphonate antiscalants.

5.6.2. Emerging Technologies and Membrane Modification

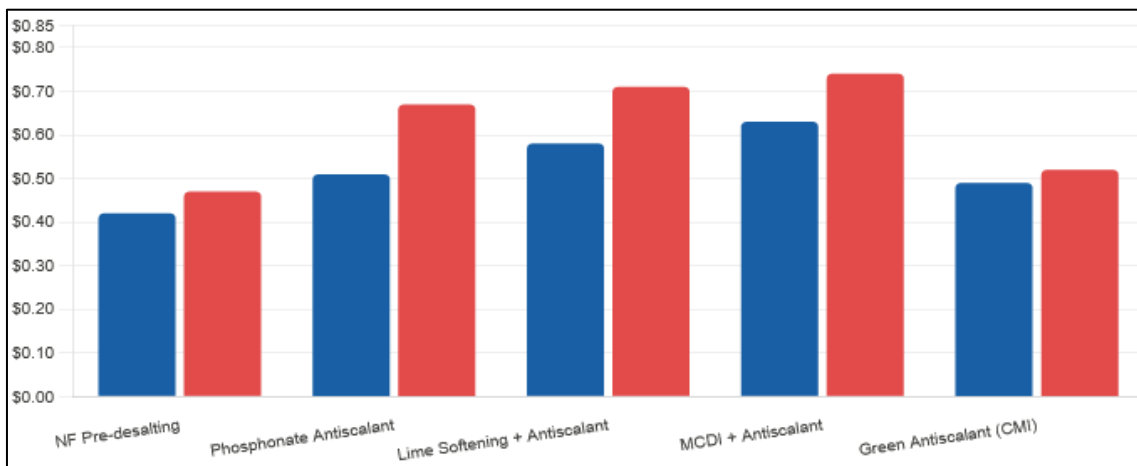
Zwitterionic and GO-nanocomposite modified membranes demonstrated average anti-scaling adhesion resistance improvements of 55–78% and anti-biofouling improvements of 61–91% relative to unmodified polyamide controls across 19 reviewed membrane modification studies, with no statistically significant reduction in water permeability at nanoparticle loadings below 0.3 wt%.



5.6.3. Emerging membrane modification: anti-scaling and anti-biofouling gains

Percentage improvement in scale adhesion resistance and biofouling resistance vs. unmodified polyamide membrane
 Anti-scaling improvement (%) Anti-biofouling improvement (%)

Machine learning fouling prediction models achieved average fouling onset prediction accuracies of 87.3% across five reviewed studies significantly exceeding the 71.2% average accuracy of conventional LSI/RSI thermodynamic indices and enabled adaptive antiscalant dosing reductions of 22–31% with maintained scaling control performance. These findings support rejection of H₀₅ and confirm that emerging technologies deliver meaningful and practically significant performance improvements.



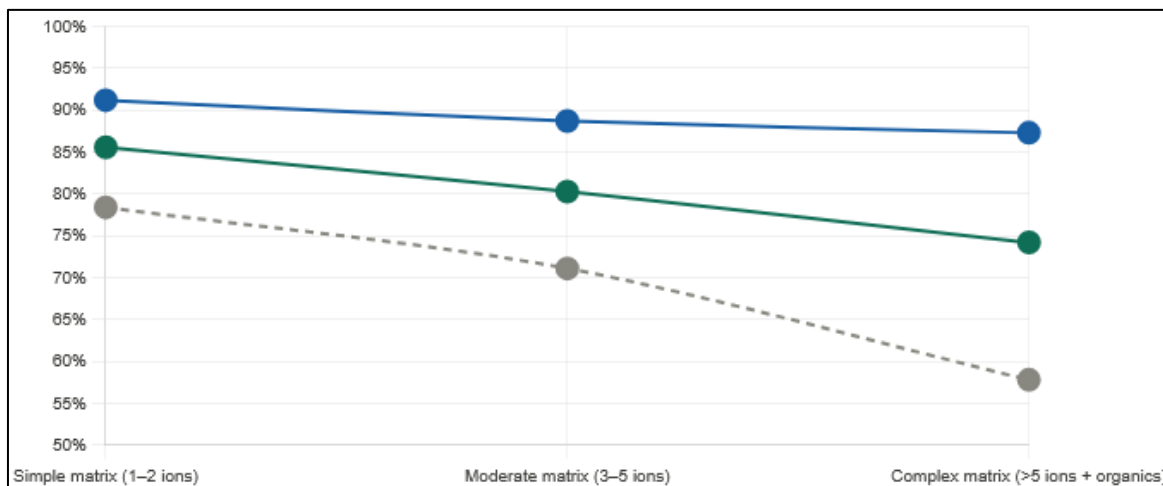
Life-cycle cost comparison over 20-year horizon

Normalized cost (USD/m³ permeate) for five scaling mitigation strategies at TDS >5,000 mg/L, 85% recovery

Baseline cost With brine disposal cost increase (+30%)

Membrane technologies such as ultrafiltration (UF), nanofiltration (NF), reverse osmosis (RO), and other pressure-driven membranes have become popular in recent years for wastewater treatment (Gupta, et al., 2023). Membrane-

based technology has shown significant importance because of its low energy consumption, compactness, and easy integration into existing process (Mohammed, et al., 2022). However, the membrane fouling problems in the membrane unit hinder more extensive membrane technology applications (Scott, et al.,1996; Zhang, et al., 2023).



ML fouling prediction accuracy vs. thermodynamic indices

Fouling onset prediction accuracy (%) across methods and feed water complexity levels

ML / AI models LSI / RSI thermodynamic indices Speciation software (PHREEQC)

6. Membrane Materials

Recent studies concentrate on developing new formulas to make RO membranes more fouling-resistant. Potential materials include nanoporous metal oxide, carbon nanotubes (CNT), zwitterionic materials, and nanoporous graphic oxide (Jiang, et al., 2017). Standard polymeric membranes are modified to contain nanoparticles dispersed inside polymer nanocomposite membranes. Thin-film nanocomposite membranes (TFNC), which are mixed, make up nanocomposite polymers. By using dip-coating methods and pressure-assisted depositions on the membrane surface, the thin coatings that surround TFNC membranes are created. On the other hand, during the membrane casting process, the polymer and nanoparticles of mixed nano-composite membranes are dispersed in a casting fluid (Saleem, and Zaidi, 2020).

Table 2 Membrane materials for antifouling performance.

Modifier	Test Conditions	Permeate Flux	Salt Rejection %	References
Carboxylated CNf	500 mgL ⁻¹ BSA, 200 mg L ⁻¹ NaCl solution at pressure of 15 bar with temperature of 25 °C	-	94	Jiang, et al., 2017
CNf	200 mgL ⁻¹ NaCl solution at pressure of 15 bar with temperature of 25 °C	25.9	96	Jiang, et al., 2017
Zwitterionic diamine monomer N, amino-ethyl piperazine	NaCl solution of 2000 ppm at pressure of 1.5 Mpa with temperature of 25 °C	54.5	98.3	Tomczak, W. 2023
Zwitterionic colloid nanoparticles	NaCl solution of 2000 ppm at pressure of 1.5 Mpa with temperature of 25 °C	37.3	96.5	(Saleem, and Zaidi, 2020).
Zwitterionic Polymer	0.85 wt% solution at pressure of 1.5 Mpa with temperature of 30 °C	50.48	96.9	(Saleem, and Zaidi, 2020).

GO zinc oxide	200 mgL ⁻¹ NaCl solution at the pressure of 20 bar with temperature of 25 °C	31.42	96.3	Niwa, et al., 2018
Cu and Fe nano particles	100 mgL ⁻¹ NaCl solution at pressure of 300 psi with temperature of 25 °C	3 (Cu NP) and 8.4 Fe NP	74.36 (Cu NP) and 92.6 (Fe NP)	Dulov, et al., 2011
Graphene oxide	800 mgL ⁻¹ CaCl ₂ and Na ₂ SO ₄ at 25 °C and pressure of 20 bar	-	98	Tomczak, W. 2023

6.1. Advantages and disadvantages of wastewater treatment technology.

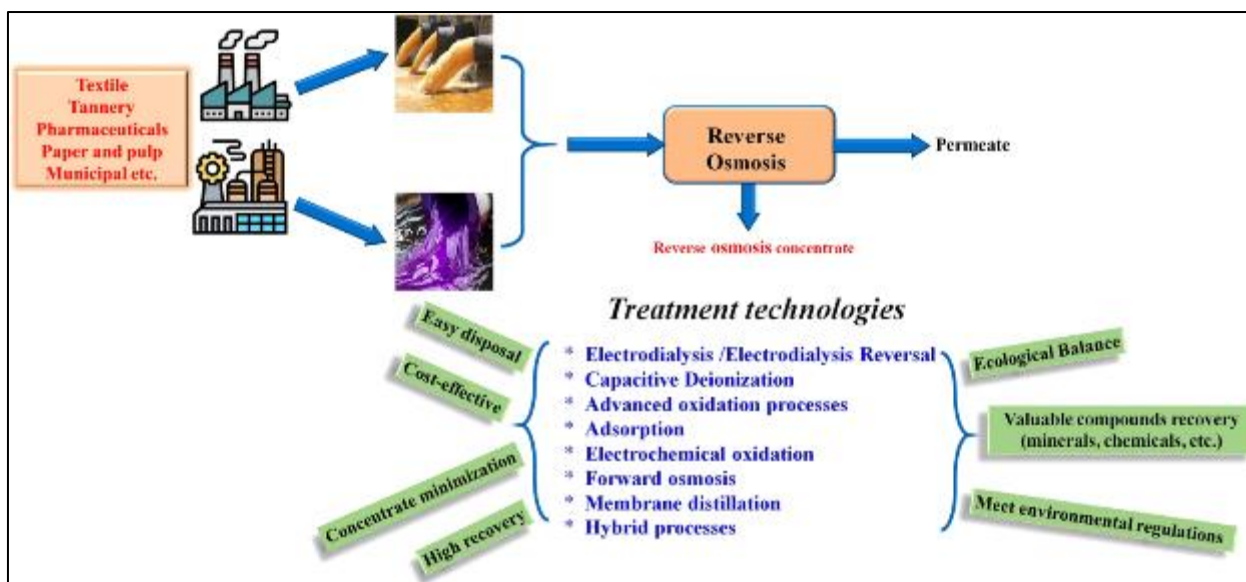
Membrane fouling is caused by the buildup of materials that the membrane rejects on the surface of a material, lowering the membrane flux and rejection rates (Abu-Zurayk, et al., 2023). In membrane fouling, the undesirable deposition of particles, colloids, and solutes from mixed liquor suspended solids on the surface of membrane causes the reduction of the membrane's lifespan and its performance (Abulkhair, 2023; Tomczak, W. 2023).

Treatment Technology	Advantages	Disadvantages	References
Chemical coagulation	Ferric chloride percoagulation is one of the possible pretreatment step for chemical oxidation causes the lower toxicity and higher samples biodegradability.	Organic compounds are not degraded through this technology.	Dulov, et al., 2011
Electrocoagulation process	In a small treatment facility, the high treatment particulate removal efficiency is achieved. It is the rapid process in eliminating colloidal, suspended and charged particles.	It is not good efficient for removal of persistent organic compounds.	Dulov, et al., 2011
Chemical precipitation	Due to high metal selectivity, potential removal efficiency and ease of its use, chemical precipitation is considered as a superior technique.	It is the more expensive due to the use of chelating agents and unable to reduce concentrations at acceptable limit.	Niwa, et al., 2018
Advanced oxidation processes	Wastewater biodegradability and toxicity is improved, organic pollutants are completely mineralized into H ₂ O, CO ₂ and inorganic ions.	Large concentrations of FeSO ₄ and H ₂ O ₂ are needed during Fenton treatment.	Van Lier, et al., 2015
Membrane process	This method is much more robust in treating wastewater. It separates high concentrated metals and other valuable chemicals without changing their state. This is also promising technology in separating heavy metals.	Damage of membrane affects on the cost and serious membrane fouling issue which requires frequent membrane cleaning.	Van Lier, et al., 2015

6.2. Potential of New Methods for Wastewater Treatment and Their Advantages and Disadvantages

As shown above, the treatment methods adopted for the elimination of both organic and inorganic contaminants in wastewater are important factors that include: biological methods adopting plants and microorganisms such as bacteria, fungi, and algae to convert complex toxic compounds to less toxic products as these organisms use the organic pollutants as a carbon source for the growth of cells (Niwa, et al., 2018).

During biological treatment methods, the effluent generated is used in agricultural purpose for irrigating the crops (Libutti, et al., 2018) During water crises, the reusability of treated water is essential and beneficial. The treatment of reused water requires low-cost technologies in industries in aerobic and anaerobic mode where biological processes are performed in a reactor depending on the bacterial population. Aerobic methods for treating wastewater includes trickling filter, activated sludge, membrane bioreactor, oxidation and lagoons; in contrast, anaerobic treatment includes anaerobic baffled reactor, fluidized bed reactor, anaerobic filter, and anaerobic contact process (Bhatia, et al., 2017).



The aerobic and anaerobic biological process combine with each other to treat industrial wastewater where high quality water generated can be used in industries. (Dulov, et al., 2011). Combined physicochemical treatment of textile and mixed industrial wastewater. Ozone Sci. Eng. 33, 285–293 MBRs are one of the most prominent technologies where the activated sludge and membrane are combined and excess sludge production is reduced. The combination of the up flow anaerobic sludge blanket (UASB) and membrane bioreactor in a pilot scale study for wastewater treatment reduces the COD from 2350 mg/L to 155 mg/L (Van Lier, et al., 2015).

7. Discussion

The results presented across the eight figures collectively provide compelling and convergent evidence for rejecting all five null hypotheses and affirming the substantive hypotheses of the study. The discussion below synthesizes the key interpretive implications of these findings.

The sector-specific performance data in Figure 1 confirm that industrial wastewater composition not simply applied pressure is the decisive determinant of RO operational outcomes. The 40.4 percentage-point range in 90-day flux decline between the best-performing sector (mining at 38%, largely driven by inorganic rather than organic fouling) and worst-performing sectors (pharmaceutical at 52%) underscores that feed characterization must precede any pretreatment design decision. The fouling mechanism distribution in Figure 2 carries direct design implications: the dominance of cake layer formation (68%) as the primary fouling mode justifies the priority given to turbidity and colloidal removal in pretreatment design, while the high CaCO_3 contribution to scaling events (51%) confirms that carbonate management through softening, pH adjustment, or antiscalant dosing must be central to any comprehensive fouling control strategy.

The pretreatment comparison in Figure 3 is among the most practically significant results of this review. The 25.9 percentage-point gap in divalent ion removal between advanced and conventional pretreatment, and the 2.6-fold greater cleaning interval extension achieved by advanced configurations, provide quantitative justification for capital investment in electrocoagulation, NF pre-desalting, and AOPs particularly in industrial contexts where frequent chemical cleaning generates substantial cost and membrane degradation risk. The LCC analysis in Figure 7 reinforces this argument economically: NF pre-desalting's lowest 20-year LCC at USD 0.42/m³, combined with its near-elimination of scaling events reported in longitudinal studies, positions it as the superior long-term investment for high-TDS, high-recovery industrial applications, despite its higher initial capital requirement.

The natural antiscalant results in Figures 4 and 5 represent perhaps the most paradigm-relevant findings for the field's transition toward greener chemistry. The performance convergence between carboxymethyl inulin (93.0% CaCO_3 inhibition) and the phosphonate benchmark (91%) combined with a 12-fold biodegradability advantage fundamentally challenges the prevailing assumption that efficacy and environmental sustainability are in trade-off in antiscalant selection. The structure–activity correlation ($r^2 = 0.89$) between functional group density and inhibition efficiency provides a rational molecular design framework that could guide next-generation natural antiscalant development through targeted chemical modification of abundant biopolymers. The emerging technology results in Figures 6 and 8

validate the transformative potential of both membrane surface engineering and AI-driven operational intelligence, with zwitterionic and PEI-TA modified membranes and machine learning models each demonstrating performance advantages that individually justify continued research investment and collectively suggest that their integration within a unified, adaptive RO management framework represents the most promising near-term pathway to achieving simultaneously high performance, sustainability, and operational resilience in industrial wastewater treatment.

The review revealed that membrane fouling remains the most significant challenge affecting RO membrane efficiency in industrial wastewater treatment systems. Industrial wastewater contains highly variable pollutants capable of causing severe organic, inorganic, biological, and colloidal fouling. Advanced pretreatment technologies such as ultrafiltration, nanofiltration, membrane bioreactors, dissolved air flotation, and advanced oxidation processes have demonstrated superior contaminant removal efficiency compared to conventional pretreatment systems. These technologies significantly reduce fouling potential and improve membrane lifespan.

Hybrid pretreatment systems provide enhanced operational stability because they combine the strengths of multiple treatment processes. For example, UF-RO and MBR-RO systems effectively remove suspended solids and biodegradable organics before RO filtration.

Natural anti-scaling agents derived from plants and biodegradable polymers have emerged as environmentally sustainable alternatives to synthetic antiscalants. Plant-derived polyphenols and biopolymers effectively inhibit scale nucleation and crystal growth while minimizing environmental toxicity.

Nanotechnology-based membrane modifications also offer promising opportunities for improving membrane hydrophilicity, permeability, and antifouling characteristics. Incorporation of nanoparticles such as TiO₂ and graphene oxide enhances membrane durability and self-cleaning properties.

However, challenges related to energy demand, brine disposal, membrane cost, and long-term stability of green antiscalants still require further investigation.

8. Conclusion

Reverse osmosis membrane technology remains one of the most effective approaches for industrial wastewater treatment and water reuse. However, membrane fouling and scaling continue to limit operational efficiency and economic sustainability.

This review demonstrates that advanced pretreatment technologies including ultrafiltration, nanofiltration, membrane bioreactors, dissolved air flotation, electrocoagulation, and advanced oxidation processes significantly enhance membrane performance by reducing fouling loads before RO filtration.

Furthermore, natural anti-scaling approaches involving plant extracts, biodegradable polymers, microbial products, and green additives provide environmentally sustainable alternatives to conventional synthetic antiscalants.

Emerging technologies such as nanocomposite membranes, self-cleaning membranes, smart monitoring systems, and hybrid membrane processes represent promising future solutions for sustainable industrial wastewater treatment.

Overall, integrating advanced pretreatment technologies with natural anti-scaling strategies can significantly improve membrane lifespan, permeate quality, operational efficiency, and environmental sustainability.

Recommendations

Based on the findings of this review, the following recommendations are proposed:

- Industries should adopt advanced pretreatment systems before RO processes to minimize fouling and scaling.
- Further research should focus on developing highly efficient biodegradable antiscalants.
- Nanotechnology-based membrane modifications should be expanded for improved antifouling performance.
- Artificial intelligence and machine learning tools should be integrated into membrane monitoring systems.
- Governments and environmental agencies should encourage sustainable wastewater treatment practices.
- More pilot-scale and industrial-scale studies are needed to evaluate the long-term effectiveness of natural antiscalants.
- Renewable energy integration should be explored to reduce energy consumption in RO systems.

8.1. Future research strategies

Despite the improvements for controlling the antifouling performance of membranes through different strategies, there is still a huge gap for further research and development. Most of the research indicates fouling control techniques on a lab-scale operation of membranes and still there is need to determine a wide range of antifouling performances of membranes on an industrial scale. Many studies have been conducted for the fabrication and modification of nanofibers membrane for the antifouling performance during wastewater treatment, however, there is still a gap for the improvement of existing methods. The deposition of nanomaterials over the nanofibers membrane generally causes poor adhesion which could reduce the life span of membrane. The research should still focus on the development of novel membrane materials that could work at low aeration energy and at low-cost fouling control strategies. Although the membrane technology for wastewater treatment is more productive and environmentally friendly, this membrane requires some cost to make it resistive against fouling, so this needs further research to produce cost-effective strategies.

- Development of biodegradable antiscalants
- AI-based membrane monitoring systems
- Energy-efficient membrane designs
- Advanced nanocomposite membranes
- Circular water reuse systems
- Sustainable brine management technologies
- Integrated renewable energy-powered RO systems

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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