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# Advancements in the Mechanical Aspects of Membrane Technology for Oil-Water Filtration: Challenges, Fouling Mitigation, and Achievements

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**Abstract**

Membrane technology has gained prominence in oil-water separation due to its efficiency, sustainability, and ability to address complex filtration challenges. Water scarcity remains a critical global concern, further exacerbated by the discharge of oily wastewater from industries such as textiles, metal finishing, and food processing. Membrane-based filtration systems have emerged as a superior alternative to traditional separation techniques, offering enhanced filtration performance and improved water recovery. However, challenges such as membrane fouling, limited durability, and performance variability under different operational conditions persist. This review provides a comprehensive evaluation of the mechanical aspects of membrane technology in oil-water filtration, focusing on fundamental operational principles, key mechanical parameters affecting performance, advancements in membrane materials, and persistent challenges. Additionally, recent innovations in membrane fouling mitigation strategies are discussed, with an emphasis on their comparative effectiveness. The review also highlights the future research directions necessary to further optimize membrane performance for industrial applications



**Keywords:** Membrane Technology;Filtration efficiency;Oily wastewater;Mechanical parameters;Performance.

## 1. Introduction

Water scarcity continues to challenge sustainable development, with industrial sectors increasingly contributing to this crisis by discharging large volumes of oily wastewater [1]–[3]. Over recent decades, the industrial sector has consistently escalated its water consumption. Concurrently, various industrial operations generate substantial volumes of oily wastewater, posing a threat to human health through contamination of aquatic ecosystems [4]–[6]. Oily wastewater, a common occurrence, originates from diverse industries such as textile manufacturing, metal finishing, oil and gas extraction, and food and beverage processing [7]–[9]. Notably, oil and gas production contributes to the largest stream of oily wastewater globally [10]–[12]. Over time, various treatment methods have been developed to address oily wastewater, including flotation, coagulation, flocculation, gravitational settling, and adsorption [13]–[15]. However, most of these approaches are constrained by the significant use of chemical agents, extensive installation space requirements, and limited efficiency in separating small oil droplets [16]–[18]. These constraints compromise their viability and sustainability. In recent years, gravity-based separators, centrifugation, hydrocyclones, and conventional physical procedures like coagulation and dissolved-air flotation are the most widely used industrial technologies for the treatment of oily wastewater [19]–[21]. According to Jiao et al. [22], gravity separators are inadequate for emulsified oil and were created to remove oil droplets that are 150 µm or larger. Oil droplet sizes below 40 µm render corrugated plate separators inefficient [23]–[26]. Example, hydrocyclone performance decreases with oil droplet size [27]–[30]. According to Joshua et al. [31], the rejection of oil drops from a rejection of 50-80% at 20 µm to between 10 and 30% at 10 µm. Over the past few years, membrane technology has emerged as a promising technique for separating oil and water emulsions, with the aim of water recovery [32]–[34]. Membrane technology-based for oil-water separation techniques are robust and compact in comparison to conventional filtration procedures, and they provide high-quality treated effluent [35]–[37]. Membrane technology can effectively reject or remove a variety of contaminants, including pathogens and suspended impurities, by size exclusion, and adsorption [38]–[41]. Although membrane technology has been widely used for oily wastewater separation, its application is limited due to membrane fouling (pore blockage), which results in poor separation quality of oil and water emulsions [42]–[45]. The major issue with commonly used membrane materials for oil and water separation is pore blockage (membrane fouling), which leads to a drop in permeate flux, reduced separation quality, and decreased efficiency [46]–[48]. This results in an increase in the retentate aqueous solution. Pore clogging during separation causes a rise in transmembrane pressure, a frequently observed problem

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with current membrane materials. Excessive transmembrane pressure also raises the temperature of the feed aqueous solution, further impairing separation efficiency [49]–[53]. Consequently, low membrane wettability, poor permeate quality, reduced permeate flux, and overall poor membrane performance are common issues [54]–[56].

In recent years, biological treatment has gained traction as an environmentally friendly approach, utilizing oil-degrading microorganisms to break down hydrocarbons [57]–[60]. While effective for low-concentration oily wastewater, biological methods require long retention times and controlled operational conditions, making them less practical for high-load industrial discharges [61]–[63]. Membrane technology has emerged as a highly promising alternative due to its ability to efficiently separate oil and water emulsions with high selectivity and minimal chemical usage. Microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) membranes are increasingly applied in industrial wastewater treatment, offering advantages such as high permeate quality, reduced environmental impact, and scalability [64]–[66]. However, challenges such as membrane fouling, energy consumption, and material durability remain key areas of research and innovation.

Despite these advantages, membrane fouling remains a significant hurdle, impacting separation efficiency by blocking membrane pores, reducing permeate flux, and lowering oil rejection rates [67]–[69]. Addressing these challenges requires a deeper understanding of the mechanical factors influencing membrane performance, such as transmembrane pressure (TMP), crossflow velocity (CFV), and temperature. Additionally, research into advanced membrane materials, including ceramic and polymeric composites, has contributed to notable improvements in mechanical stability and filtration efficiency. This review aims to examine the progress made in membrane technology for oil-water filtration by analysing mechanical operational parameters, recent advancements, and persistent challenges. It further provides insights into emerging mitigation strategies for membrane fouling and highlights future research directions to enhance membrane performance.

## 2. BASIC Mechanical OPERATION OF membrane technology

In recent years, membrane technology has emerged as a promising method for separating oil and water, primarily due to its potential to recover water for reuse, a critical consideration given the global water scarcity [70]–[73]. The field of membrane technology has garnered significant attention from researchers due to the pressing water scarcity issues worldwide [74]–[76]. To ensure the efficient separation of oil and water emulsions using membrane technology, it's crucial to understand the basic operation of membrane technology used for oil-water separation process. Generally, membrane technology is characterized by pore sizes and pressure [77]. A range of membrane technologies featuring different operational pressures and membrane pore sizes have been utilized for separating oil and water, as depicted in Table 1.

**Table 1.** A range of membrane technology indicating various operational pressures and membrane pore sizes [78].

| Membrane Type | **Operating** Pressure (bar) | Pore Size (μm) |
|---|---|---|
| **High-Pressure Filtration (HPF)** | 35 - 65 | < 0.001 |
| **Advanced Nanofiltration (ANF)** | 22 - 45 | 0.001 – 0.005 |
| **Enhanced Ultrafiltration (EUF)** | 2 - 12 | 0.005 – 0.02 |
| **Microfiltration Plus (MFP)** | < 2 | > 0.02 |

Furthermore, Illustrated in Figure 1 is an example of an oil and water filtration membrane. The feed consists of oil and water emulsions entering the feed stream of the filtration membrane for separation.

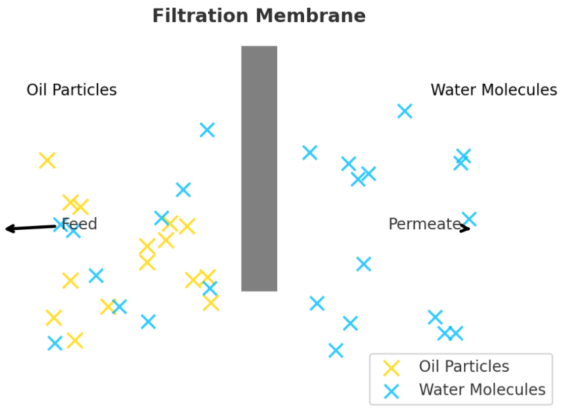


**Figure 1.** Schematic oil and water filtration membrane.

Membrane technology operates like a sieve, with a selective surface designed based on the desired end product. Generally, membrane technologies used for oil-water filtration are either hydrophobic or hydrophilic. Figure 1 illustrates a membrane technology used for oil-water separation that repels oil from passing through. For example, the feed in Figure 1 represents the oil-water emulsions from the feeding tank before filtration. The emulsions enter the feed side, passing through the membrane configuration at a certain velocity and pressure [79]–[82]. Depending on the selectivity of the membrane surface, either water or oil is repelled from passing through to the permeate side [83]. In this case, the water passes through the membrane, as shown in Figure 1, which is aimed at water recovery. The emulsions that are not filtered return to the retentate tank to be filtered again. The model for the analysing the feed is derived from Figure 2 as indicated below.

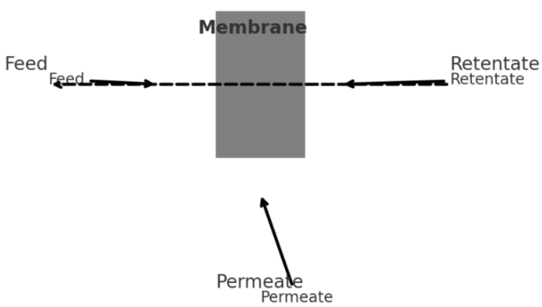


**Figure 2.** Schematic of pressure feed, permeate, and retentate in membrane technology.

Since the operating pressure is the primary driving force for oil-water separation in membrane technology, the forces entering the membrane system were equated to the forces exiting the system, inspired by the conservation of mass equation. Equation (1) was used to estimate the feed into the membrane system, implying that the feed is equal to the sum of the permeate and retentate [84].

$$F_e = P_e + R_e \quad (1)$$

Equation (1), $F_e$ is the feed, $P_e$ is the permeate, and $R_e$ retentate. Feed in Equation (1) is an aqueous solution consist of oil and water emulsions. Emulsions are classified as kinetically stable and thermodynamically unstable. A derivation of the Gibbs free energy in accordance with equation (2) can be used to express the theoretical stability and thermodynamics of an emulsion [85].

$$\Delta G = (\gamma A) - (T\Delta S) \quad (2)$$

Equation (2), $\gamma$ is the surface tension, $A$ is the surface area, $T$ is the emulsion temperature, $\Delta S$ is the entropy of mixing, and finally $\Delta G$ is the Gibbs free energy. The magnitude of $\Delta G$ gives a hint as to an emulsion's thermodynamic stability. If $\Delta G$ is higher than zero in value, afterward the emulsions become relatively unstable and separate [86]. If this $\Delta G$ value is smaller than zero, the emulsions are stable and won't separate. Oil-water and water-oil simple emulsions are typically more prevalent than complex emulsions in the petroleum, mining, and food production industries [59]. Due to the complex oil and water emulsions produced by these industries, techniques had to be developed to assist with the separation of oily wastewater pollution. Membrane technology has long been recognized as an effective method for handling complex oil and water emulsions [5], [87]–[89]. The efficiency of membrane technology is measured by the oil-water quality obtained after separation in the permeate field. Several factors affecting oil-water separation have been reported, including volume flow rate, crossflow velocity, pore size, material selection, and driving pressure. Kumar et al. [90] conducted a study on the performance of a microfiltration membrane technology fabricated using an antifouling-coated composite membrane for oil and water separation. The membrane investigated in their study had porosity of 78% and a pore size of 170 nm. The findings revealed that the membrane achieved a water permeability of 4841 $\mathrm{m^3h^{-1}bar^{-1}}$ under an operational pressure of 27.579 kPa. Oil rejections of 98.80%, 99%, and 92% were attained at oil concentrations of 250 mg/L, 500 mg/L, and 1000 mg/L, respectively. Furthermore, the results demonstrated an enhanced water recovery rate of 85% from the separation of oil-water emulsions, in concluding the findings is was stated that newly fabricated microfiltration membrane shows great potential for the separation of oil and water emulsions.

Mao et al. [91] conducted an experimental investigation on a high-performance ceramic microfiltration membrane technology for separating oil-water emulsions. The microfiltration membrane employed in the study had pore sizes of 210 nm, and its surface exhibited roughness properties. The findings revealed a membrane permeance of 217 $\mathrm{L.m^{-2}.h^{-1}}$/bar and an oil rejection rate of 99.7%. However, further efforts are required to enhance the surface properties of piezoelectric membranes to achieve better filtration performance and reduce membrane fouling. Jiang et al. [92] created a membrane technology with unique surface wettability to explore its effectiveness in filtering oil and water emulsions. The pore size of the membrane utilized in the experimental setup was below 180 µm, and the outcomes demonstrated a separation efficiency exceeding 99%. Furthermore, the findings highlighted the importance of understanding the mechanical operating factors of membrane technology to enhance its performance. Therefore, it is crucial to understand the mechanical parameters that influence the performance of membrane technology.

## 3. mechanical parameters affecting membrane technology performance

The mechanical parameters that influence the performance of the membrane technology during the oil-water separation process are found to be the flow rate, transmembrane pressure (TMP), crossflow velocity (CFV), feed temperature (T) [93]–[95]. The influence of these mechanical parameters that affects the membrane system is measured by permeate quality during the oil-water separation that influences the permeate rejections [96]. Often the membrane technology operates in one of the two techniques during the oil-water separation process, which is either the constant transmembrane pressure or constant flow rate [97]–[99]. It is important to understand the role of pressure in the membrane technology.

### *3.1. Transmembrane Pressure*

The mechanical pressure in membrane technology, commonly known as transmembrane pressure (TMP) or the driving force, is directly proportional to the permeate flux (J), a measure of membrane performance [100]. As the pressure increases, the permeate flux also increases. However, higher operating mechanical pressure can also increase membrane resistance due to the proportionality law ($J \uparrow \alpha\, R_t \uparrow$)[101]. Darcy's law model is the fundamental model developed to estimate the transmembrane pressure in a membrane system, relating it to the performance of the membrane system, as demonstrated by equation (3) [102].

$$\Delta P = J\mu R_m \quad (3)$$

Equation (3), $J$ represents the permeate flux, $\Delta P$ is the transmembrane pressure, µ is the viscosity of the fluid, and $R_m$ is the membrane resistance. It should be noted that while the equation (3) is adequate for estimating the transmembrane pressure in a membrane system, however, its application is limited due to it does not account for the effects of membrane pores on the surface of the membrane. To address this limitation, the Hagen-Poiseuille model was developed to incorporate the effects of pores, as shown equation (4), where $r$ is the pore radius and $L$ is the pore length [103]. Although equation (4) considers the effects of the pore sizes on the estimation of the transmembrane pressure, its application is limited due to it does not take into account the mechanical resistance of the membrane surface. To improve equations (3) and (4), equation (5) was developed to measure the mechanical resistance in membrane system to improve the performance, where $R_f$ is fouling resistance and $R_{cp}$ is the concentration polarization resistance [104]. It has been noted that equation (3), (4), and (5) has been widely used to estimate the mechanical pressure of the membrane technology, although the equation (5) indicates the improved mechanical pressure estimation it is limited due to it does not consider the effects of osmotic pressure and membrane thickness.

$$\Delta P = \frac{J8\mu L}{r^2} \quad (4)$$

$$\Delta P = J(\mu R_m + \mu R_f + \mu R_{cp}) \quad (5)$$

Tomczak et al. [105] conducted experimental analyses on an ultrafiltration membrane for separating oily wastewaters to recover water. The experiments were conducted across a broad range of temperatures (303 and 323 K), flow rates (2.9 – 0.82 m/s), and transmembrane pressures (0.28 – 0.40 MPa). Remarkably, the findings showed that the filtrate obtained was free of oil, and the content of organic compounds was reduced by over 80%. Sanyal et al. [106] employed ceramic material to produce a membrane for the separation of oil and water aimed at water recovery. In their experimental analysis, the transmembrane pressure was varied from 0.28 to 0.40 MPa. The results revealed an enhanced performance with a 30% increase in permeate flux. Xie et al. [107] constructed an experimental test rig utilizing ceramic material to create a membrane for separating oil and water with the aim of water recovery. Throughout the experimental evaluation, the pressure was maintained constant. The results revealed a porosity of 41%, water permeability of 746 $\mathrm{L.m^{-2}.h^{-1}}$/bar, and a membrane performance in removing waste oil of 88%. Zhao et al. [108] engineered a microfiltration membrane for oil and water recovery employing ceramic material. The membrane, featuring a porosity of 30 – 34% and a pore size of 4.3 µm, underwent testing. The outcomes demonstrated a water permeability of 36.3 $\mathrm{L.m^{-2}.h^{-1}}$/bar. Zhong et al. [109] fabricated the ultrafiltration membrane for oil and water separation using ceramic material. During the experimental testing the permeate flux and oil rejection were monitored at the constant pressure to achieve the improved performance. The results revealed the improved water flux of 303.63 $\mathrm{L.m^{-2}.h^{-1}}$/bar.

### *3.2. Cross-flow velocity*

The cross-flow velocity ($V_{cf}$) in membrane technology is often used to describe the mechanical velocity of the fluid flowing parallel to the membrane surface, which helps to mitigate fouling and concentration polarization [110]. The cross-flow ($V_{cf}$) velocity plays an important role during the oil-water separation process. Four alternative outcomes are identified by the cross-flow velocity ($V_{cf}$): partial permeability, rejection, pinning, and permeation during the oil-water separation process [111]. The critical cross-flow velocity at which a pinned droplet detaches can be estimated from the velocity at this point [112]. It is important to review the mathematical models used to optimize the mechanical cross-flow velocity in membrane technology. To date, there are limited mathematical models developed to evaluate the mechanical velocity in the membrane. However, the common models employed for velocity evaluation are given by equation (6) and (7) [113], [114]. The equation for cross-flow velocity ($V_{cf}$) is presented in (6), where $V_{cf}$ is the cross-flow velocity, $Q_{cf}$ is the cross-flow volumetric flow rate, and $A_{cf}$ is the cross-flow area. In some systems, the cross-flow velocity can also be expressed in terms of the membrane module and configuration. For example in tubular membrane module, it can be approximated by equation (7), where $D_t$ is the diameter of the tubular membrane module. In contrast, the mechanical velocity presented in equation (6) and (7) shows limitations in terms of the estimation of the mechanical velocity because the effects of emulsions viscosity are not considered.

$$V_{cf} = \frac{Q_{cf}}{A_{cf}} \quad (6)$$

$$V_{cf} = \frac{4Q_{cf}}{\pi D_t^2} \quad (7)$$

Over the years, it has been reported that cross-flow velocity and transmembrane pressure significantly affect membrane technology performance. Increased cross-flow velocity and decreased transmembrane pressure have been associated with higher shear stress and reduced concentration polarization. According to Hengyang et al. [115] their analysis of oil-water separation in membrane systems showed that stronger turbulence can enhance stationary membrane flux by 41.7% with higher cross-flow velocity and more intense ultrasound. Jinglin et al. [116] studied the application of membrane systems in conjunction with zeolite to treat oily wastewater without altering the oil rejection coefficient. They found that a greater tangential flow velocity (0.01 m/s) quadrupled the flow across the membrane. Despite the feed solution having a high oil concentration (500 mg/L), the membrane's performance remained excellent. In addition, higher quasi-steady-state permeate fluxes ( $165\,L\cdot h^{-1}\cdot m^{-2}$ at a CFV of $4.1\,m\cdot s^{-1}$ compared to $240\,L\cdot h^{-1}\cdot m^{-2}$ at a cross flow velocity of $7.1\,m\cdot s^{-1}$ after a filtration time of 250 min) were achieved by increasing the cross-flow velocity. This increase reduces the likelihood of oil particles accumulating on the membrane surface, thereby lowering the degree of fouling. Jinglin et al. [117] found that at a fixed transmembrane pressure of 1.0 bar, increasing cross-flow velocity from 0.25 to 1.0 $m\cdot s^{-1}$ resulted in increased shear stress at the membrane surface and decreased the average rate of oil particle adsorption from 23% to less than 7%. According to Sura et al. [49], the initial membrane flux was 250 $L\cdot h^{-1}\cdot m^{-2}$under lower transmembrane pressure/cross-flow velocity settings, and 750 $L\cdot h^{-1}\cdot m^{-2}$ under higher transmembrane pressure/cross-flow velocity conditions, about 2.7 times greater. To further improve the membrane performance during oil-water separation it is important to understand the influence of temperature during the filtration process.

### *3.3. Temperature*

Temperature affects various factors that impact membrane performance [118]–[121]. As temperature increases, the viscosity of the feed solution decreases, enhancing permeate flux by reducing resistance to flow through the membrane [122]–[125]. Elevated temperatures can increase the solubility of certain solutes, potentially improving separation efficiency and reducing the likelihood of fouling [126]–[129]. As temperature rises, the permeability of the membrane typically increases due to the expansion of membrane pores and greater molecular activity, resulting in higher flux rates [130]–[132]. Temperature also affects fouling and scaling behavior. Higher temperatures can decrease the viscosity and density of the feed, reducing the chance of foulant accumulation [68].

However, they can also promote the precipitation of salts, leading to scaling. Additionally, the chemical and physical stability of membrane materials can be compromised at higher temperatures, affecting membrane integrity and longevity [133]. Increased temperature can elevate the osmotic pressure of the feed solution, particularly in systems with high solute concentrations, impacting the driving force of processes like reverse osmosis [134]. Understanding these temperature effects is essential for optimizing membrane performance and ensuring efficient and sustainable operation in various applications. Over the years, key temperature-related models have been developed to understand the performance of membrane technology, as indicated by equations (8) to (12) [51]. The viscosity-temperature relationship is given by the Arrhenius model in equation (8), where $\mu(T)$ is the viscosity at temperature T, $\mu_0$ is the reference viscosity at temperature $T_0$, while $E_a$ is the activation energy for viscosity, R is the universal gas constant, T is the temperature in Kelvin, and $T_0$ is the reference temperature in Kelvin.

$$\mu(T) = \mu_0 exp\left(\frac{E_a}{R}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right) \tag{8}$$

In contrast, equation (8) does not consider the effects permeability due to this concerns this model was subjected to improvements where the facts such as permeability of the membrane often increases with temperature were considered, then the permeability-temperature relationship model was given by mathematical equation in (9), where $K(T)$ is the permeability at temperature, $K_0$ is the reference permeability, $E_p$ is the activation energy for permeability, $T$ is the temperature in Kelvin, and $T_0$ is the reference temperature in Kelvin [135]. The flux through the membrane generally increases with temperature due to decreased viscosity and increased permeability, flux-temperature equation is given by equation (10), where $J(T)$ is the permeate flux at temperature, $J_0$ is the reference flux, $E_J$ is the activation energy for flux, $T$ is the temperature in Kelvin, and $T_0$ is the reference temperature in Kelvin [136]. However, equation (10), does not take into account the effects of viscosity, this aspect makes this model to the limited. In comparison, equation (8), (9), and (10) does not consider the effects of mechanical membrane resistance which rises during the oil-water separation, it is important to note that these models need the improvements for industrial application.

$$K(T) = K_0 exp\left(\frac{E_p}{R}\left(\frac{1}{T_0} - \frac{1}{T}\right)\right) \tag{9}$$

$$J(T) = J_0 exp\left(\frac{E_J}{R}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right) \tag{10}$$

Furthermore, mechanical aspect of the temptation influence during oil-water filtration were investigated to improve on the existing mathematical models. The membrane resistance can change with temperature, typically decreasing as temperature increases, the membrane resistance and temperature equation is given by equation (11), where $R_m$ is the membrane resistance at temperature, $R_{m0}$ is the temperature coefficient of resistance, $T$ is the temperature in Kelvin, and $T_0$ is the reference temperature in Kelvin [137]. Additionally, the osmotic pressure and temperature relationship was developed to estimate the osmotic pressure, as indicated by equation (12), where $\pi$ is the osmotic pressure, $C$ is the concentration of the solute, $R$ is the universal gas constant, and $T$ is the temperature in Kelvin [138]. Although these equations help in understanding and predicting the effects of temperature on various aspects of membrane performance.

$$R_m(T) = R_{m0}\big(1 - \alpha(T - T_0)\big) \tag{11}$$

$$\pi = C \times R \times T \tag{12}$$

Table 2 provides a comprehensive overview of the key mechanical parameters influencing membrane technology performance, highlighting their impact, mathematical models, and current research insights.

**Table 2.** Mechanical parameters affecting membrane technology performance

| Mechanical Parameter | Definition | Effect on Performance | Key Mathematical Models | Limitations | Recent Experimental Insights |
|---|---|---|---|---|---|
| Transmembrane Pressure (TMP) | The pressure difference across the membrane that drives filtration. | Higher TMP increases permeate flux but may enhance membrane resistance and fouling. | Darcy's Law, Hagen-Poiseuille Equation, Modified Resistance Model | Does not always account for osmotic pressure and membrane thickness. | TMP variations affect oil rejection efficiency and fouling behavior, requiring optimized pressure levels. |
| Crossflow Velocity (CFV) | The velocity of fluid moving parallel to the membrane surface, reducing fouling and polarization. | Increased CFV improves shear stress, reduces fouling, and enhances membrane flux. | Velocity-Flow Rate Relationship, Tangential Flow Velocity Equations | Existing models do not fully consider emulsion viscosity effects. | Higher CFV enhances membrane performance by reducing oil deposition and increasing flux. |
| Feed Temperature (T) | The temperature of the feed solution, affecting viscosity, permeability, and membrane stability. | Higher temperatures reduce viscosity, improve flux, but may promote scaling and degrade membrane materials. | Arrhenius Viscosity Model, Permeability-Temperature Relationship, Osmotic Pressure Equation | Many models do not incorporate mechanical resistance changes at different temperatures. | Optimal temperature control prevents excessive scaling while maintaining high separation efficiency. |

## 4. performance MATRICS of membrane technology

The effectiveness of membrane technology is largely influenced by the interaction between its internal mechanical properties and key performance factors, including oil rejection, permeate flux, and resistance to fouling [139]–[141]. Inadequate analysis of these parameters and factors can compromise the quality of the filtrate, leading to a decline in membrane performance. Current trends in membrane technology improvements focus on optimizing mechanical parameters such as temperature, pressure, flow dynamics, feed solution properties, and membrane material characteristics to enhance the efficiency and effectiveness of membrane-based processes [141]–[143]. Massoumeh et al. [144] conducted a study on the performance of a microfiltration membrane fabricated using an antifouling-coated composite membrane for oil and water separation. The membrane investigated in their study had porosity of 78% and a pore size of 170 nm. The findings revealed that the membrane achieved a water permeability of 4841 $m^3h^{-1}bar^{-1}$ under an operational pressure of 27.579 kPa. Oil rejections of 98.80%, 99%, and 92% were attained at oil concentrations of 250 mg/L, 500 mg/L, and 1000 mg/L, respectively. In contrast, it has been reported that high pressure reduces the filtrate quality, hance at 1000 mg/L indicated the performance of 92% [145].

Yonghong et al. [66] conducted an experimental investigation on a high-performance ceramic microfiltration membrane for separating oil and water emulsions. The microfiltration membrane employed in the study had pore sizes of 210 nm, and its surface exhibited roughness properties. The findings revealed a membrane permeance of 217 $L.m^{-2}.h^{-1}$/bar and an oil rejection rate of 99.7%. However, further efforts are required to enhance the surface properties of piezoelectric membranes to achieve better filtration performance and reduce membrane fouling. While Guohui et al. [146] created a membrane with unique surface wettability to explore its effectiveness in filtering oil and water emulsions. The pore size of the membrane utilized in the experimental setup was below 180 µm, and the outcomes demonstrated a separation efficiency exceeding 99%. However, during the analysis the effects of variation of applied pressure was not evaluated. Furthermore, the findings indicated that the future of membrane technology depends on developing membranes with these wetting properties that can withstand high transmembrane pressures, achieve higher permeation rates of the desired liquid, resist fouling, and be manufactured scalable at a reasonable cost [147].

Creating a selective wettability membrane with these characteristics will demand innovative solutions and pose various intellectual and research challenges [148]. Such membranes will address the increasing needs for waste and byproduct treatment across a wide range of fields. Xuan et al. [149] devised a novel approach to enhance the efficiency and anti-oil fouling performance of polymeric membranes for oil and water separation. Experimental analyses were conducted to assess membrane effectiveness, revealing superoleophobic surface properties and significant resistance to oil adhesion. The membrane exhibited a water flux of 1000 $L.m^2.h^{-1}$ and a separation efficiency of 97%. However, the surface energy and surface tension of this membrane needs a further investigation since it was reported that it too 18-50 seconds for oil-water permeation to take place, afterwards the cake layer was observed. Jiaqian et al. [150] constructed a multifunctional membrane to investigate the separation of oil and water emulsions through the gravity-driven method. The results indicated a high permeation flux reaching up to 46312 ± 1583 $L.m^2.h^{-1}$ and a separation efficiency exceeding 98%. But extraction efficiency was reported to be decreasing over time. In agreement, Yuan et al. [151] engineered a superwetting membrane for the separation of oil and water emulsions aimed at water recovery. The outcomes demonstrated a flux of up to 2000 $L.m^2.h^{-1}$ and a remarkable separation efficiency of 99.99%. In contrast, Mahya et al. [152] established a novel experimental setup incorporating a microfiltration membrane system to compare the flux recovery ratio of modified and unmodified membranes during the separation of oil and water emulsions for water recovery. The testing phases involved feed concentrations of 300 mg/L and 500 mg/L. Initially, testing was conducted using the unmodified membrane, followed by experimentation on the modified membrane surface. The results revealed a flux recovery ratio of 90.76% for the modified membrane, significantly higher than the 20.41% observed for the bare membrane.

Najib et al. [153] fabricated a low-cost clay membrane which has both thermal and mechanical stability during oil and water separation process. The results revealed the porosity of 29%, water permeation of 290 $L.m^{-2}.h^{-1}$, and rejection performance of 96.9%. While Jinglin et al. [154] developed a self-cleaning and economically viable composite membrane for the separation of oil and water emulsions to enable water recovery. The membrane surface featured an average pore size of 190 nm. The study unveiled a stationary flux of 190 $L.m^{-2}.h^{-1}$/bar and an enhanced rejection performance by 65.7%. Also, the results indicated that at increased pore sizes the flux increases with an accumulation of cake layer. However, this study did not consider the effects of applied pressure, which is one of the important parameters to be considered during the filtration.

Additionally, Yajie et al. [155] conducted experimental tests using a nanofibrous membrane with superoleophilic properties for separating oil and water emulsions to facilitate water recovery. The results demonstrated a stable permeate flux reaching as high as 536 ± 40 $L.m^{-2}.h^{-1}$/bar after 10 hours of continuous filtration of oil and water emulsions. Similarly, the study of Yajie did not also consider the effects of pressure, which also the oil rejection ratio is not indicated. Moreover, Somjyoti et al. [156] constructed a test rig employing a hydrophobic composite membrane to separate oil from water for water recovery. Throughout the testing phase, the membrane permeability was closely monitored to attain optimal separation efficiency. The findings demonstrated a consistent flux ranging from 80 to 100 $L.m^{-2}.h^{-1}$ and excellent water rejection exceeding 99%.

Conversely, Shiwei et al. [157] conducted experimental analyses on an ultrafiltration membrane for separating oily wastewaters to recover water. The experiments were conducted across a broad range of temperatures (303 and

323 K), flow rates (2.9 – 0.82 m/s), and transmembrane pressures (0.28 – 0.40 MPa). Remarkably, the findings showed that the filtrate obtained was free of oil, and the content of organic compounds was reduced by over 80%. Shahidul et al. [158] conducted experimental research on a microfiltration composite membrane for separating oil and water emulsions to enable water recovery. Throughout the experimental testing, the oil concentrations were varied from 250 mg/L to 1000 mg/L. The membrane had a porosity of 78% and an average pore size of 170 nm. The results demonstrated excellent performance, with increased oil rejections observed as the oil concentrations rose from 98.80% to 99.20%. In agreement, Jietao et al. [159] explored the application of low-cost membrane technology by utilizing bauxite membranes with straight pores for oil and water separation processes. Throughout the experimental procedure, consideration was given to the effective average oil diameter of approximately 1.90 µm, as well as initial permeation fluxes of $4.31\times 10^3$ and $10.35 \times 10^3\ \mathrm{L.m^{-2}.h^{-1}}$. The findings indicated promising outcomes, with rejection rates reaching nearly 100%. In a similar vein, Miray et al. [160] investigated the efficacy of membrane technology in oil and water separation by examining a range of feed concentrations from 7.5 to 200 ng/mL. The findings highlighted an enhanced oil and water separation performance exceeding 80%. The latest advancements in membrane technology are summarized in Table 3, based on the analysis of the performance metrics discussed in this section.

**Table 3.** Membrane Technology Performance Analysis

| Membrane Technology | Strengths | Limitations | Applications | Future Directions |
|---|---|---|---|---|
| Antifouling-Coated Composite Membrane | High oil rejection (98.80% - 99%), high permeability | Performance declines at high oil concentrations (1000 mg/L) | Oil-water separation, industrial wastewater treatment | Enhancing antifouling properties, improving high-concentration performance |
| Ceramic Microfiltration Membrane | High oil rejection (99.7%), good permeance | Surface roughness affects long-term efficiency | Oil emulsion separation, industrial processes | Refining surface properties for better efficiency |
| Surface Wettability Membrane | High separation efficiency (>99%), unique surface properties | Lack of pressure variation analysis | Advanced filtration of emulsions | Developing membranes with higher transmembrane pressure resistance |
| Superoleophobic Polymeric Membrane | Superoleophobic properties, resistance to oil adhesion | Surface tension needs further study, formation of cake layer | Oil-water separation in harsh environments | Optimizing surface energy and tension for better filtration |
| Gravity-Driven Multifunctional Membrane | High permeation flux (46312 $\mathrm{L.m^2.h^{-1}}$), efficient separation | Efficiency declines over time | Gravity-driven filtration for oil-water emulsions | Enhancing durability and separation stability |
| Superwetting Membrane | High separation efficiency (99.99%), water recovery potential | Scaling challenges for mass production | Water recovery from emulsions | Improving scalability and manufacturing techniques |
| Modified Microfiltration Membrane | Higher flux recovery ratio (90.76%) compared to unmodified membrane | Initial lower performance in unmodified state | Membrane modification for improved performance | Enhancing modification methods for better performance |
| Low-Cost Clay Membrane | Thermal and mechanical stability, cost-effective | Lower porosity (29%), moderate permeation rate | Cost-effective filtration in resource-limited settings | Increasing porosity while maintaining mechanical stability |
| Self-Cleaning Composite Membrane | Self-cleaning properties, economic feasibility | Increased pore sizes lead to cake layer accumulation | Water recovery, industrial wastewater treatment | Improving cleaning efficiency and longevity |
| Nanofibrous Superoleophilic Membrane | Stable permeate flux (536 $\mathrm{L.m^{-2}.h^{-1}}$/bar), durable | Effects of pressure not analyzed, no oil rejection ratio reported | Oil-water emulsion separation, long-term applications | Evaluating pressure effects, refining oil rejection properties |
| Hydrophobic Composite Membrane | Consistent flux (80-100 $\mathrm{L.m^{-2}.h^{-1}}$), high water rejection (>99%) | Flux variations under different conditions not extensively tested | Separation of oil from water in diverse industrial settings | Expanding research on different operational conditions |
| Ultrafiltration Membrane | Effective oil removal, reduces organic compounds (>80%) | Performance varies with temperature and flow rate | Oil removal from wastewater, organic compound reduction | Optimizing operation across wider temperature and pressure ranges |
| Microfiltration Composite Membrane | High oil rejection (98.80%-99.20%) at varying oil concentrations | Limited testing for long-term durability | Filtration of emulsions with variable oil concentrations | Investigating long-term use and durability |
| Bauxite Membrane | Low-cost, high rejection rates (~100%) | Limited study on scaling potential | Low-cost oil-water separation | Developing economically viable scaling options |
| Membrane Technology for Low Feed Concentrations | Enhanced separation performance (>80%) even at low feed concentrations | Efficiency variation with different feed concentrations | Efficient separation for low-concentration feed streams | Enhancing efficiency at varying feed concentrations |

## 5. challenges and ADVANCED STRATEGIES FOR MITIGATING PERFORMANCE DECLINE in membrane technology

The challenge of effectively separating oil-water emulsions has intensified with the development of advanced membranes designed for oil removal. As industries generate increasing volumes of oily wastewater containing emulsified oil, efficient treatment methods are essential to facilitate safe disposal or water reuse [161]–[163]. Membrane technology has emerged as a viable solution due to its ability to remove oil droplets as small as 15 µm while maintaining cost-effectiveness and high separation efficiency [164]–[167]. However, despite its advantages, membrane-based processes face a persistent challenge: membrane fouling.

Membrane fouling occurs when unwanted materials—such as oil residues, suspended particles, and other contaminants—accumulate on the membrane surface or within its pores during the separation process [168]–[170]. This accumulation obstructs membrane pores, leading to a reduction in permeate flux and a decline in the quality of the filtered water. In severe cases, complete pore blockage significantly compromises membrane performance, making oil-water separation less efficient [171]–[174]. Jie et al. [175] highlighted membrane technology as an effective approach for treating oily wastewater, but its practical application is often hindered by fouling caused by oil adsorption onto the membrane surface. Addressing this issue is critical for enhancing membrane longevity and operational efficiency.

The occurrence of membrane fouling in oily wastewater treatment requires ongoing maintenance and contributes to increased operational costs. Several factors influence fouling behaviour in oil-water emulsions, including the deformability of oil droplets, their tendency to coalesce within the bulk solution and on the membrane surface, membrane wetting by oil films, pore blockage, and the intrusion of oil into the membrane structure [176]–[178]. These complexities create unique challenges that must be addressed to improve membrane performance. To mitigate membrane fouling, researchers are exploring innovative strategies, including surface modifications to enhance antifouling properties, the development of hydrophilic and superoleophobic membranes, and advancements in cleaning techniques to prolong membrane lifespan. Understanding and overcoming these challenges are essential to optimizing membrane-based oil-water separation technologies, ensuring their long-term viability for industrial and environmental applications.

Figure 3 shows an example of the fouling phenomenon in the membrane technology used for oil and water separation. In Figure 3, where is the $\mathbf{d_p}$ is pore diameter and **d** is the foulant diameter, when the foulant's diameter is roughly equal to the pore diameter, membrane pores plug. Also, the foulant reduces the filtration area by reducing the pore cross-sectional area, which affects the filtration quality during the oil/water separation process [179]. Finally, when the foulant diameter is greater than the pore diameter, complete pore blockages occur, the cake layer is formed, and there will be minimal or no oil/water separation by the membrane system [180]. Membrane fouling is a greater challenge faced by the oil and water separation technology reported in the literature study [181], [182]. Fouling mitigation is expensive, typically involves delays in the treatment of oily wastewater, and lowers the effectiveness of membrane filtration, which lowers the quality of the oil-water separation [40], [183].

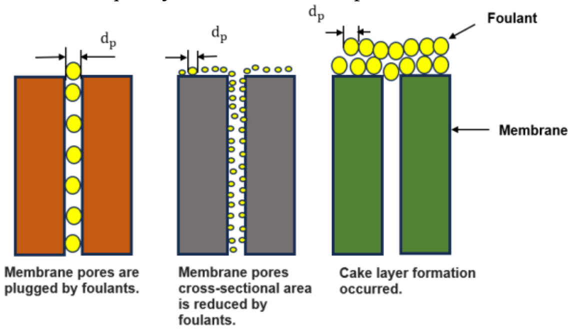


**Figure 3.** Example illustrating membrane fouling.

To combat membrane fouling, researchers and engineers have developed various mitigation strategies, each employing unique mechanisms with specific advantages and limitations. These strategies aim to minimize fouling buildup, enhance membrane cleaning efficiency, and prolong membrane lifespan [14], [184]–[186]. Among the most widely explored approaches are surface modifications, chemical cleaning, physical backwashing, and the incorporation of antifouling coatings [187]–[189].

Surface modification techniques, such as grafting hydrophilic or superoleophobic coatings onto membranes, have shown promising results in reducing oil adhesion and fouling. By altering membrane surface properties, these modifications enhance resistance to oil adsorption and biofouling, leading to improved separation performance [190]–[192]. Additionally, periodic backwashing—where pressurized water or air is used to dislodge accumulated contaminants—helps restore membrane permeability and extends operational efficiency [193], [194].

Furthermore, the integration of advanced cleaning protocols, including chemical cleaning agents and enzymatic treatments, has been employed to dissolve and remove foulants more effectively. Emerging technologies, such as electrically assisted cleaning and the use of novel nanomaterials, are also being explored to further optimize fouling control.

A comparative analysis of these mitigation strategies is presented in Table 4, highlighting their effectiveness, operational feasibility, and potential drawbacks. Understanding and implementing effective fouling control methods is crucial for improving the reliability of membrane technology in oil-water separation applications.

Advancements in membrane materials have played a crucial role in improving oil-water separation efficiency, addressing challenges such as membrane fouling, mechanical stability, and permeability [209], [210]. Researchers have developed various membrane materials, each offering unique advantages and limitations under different operational conditions. Polymeric membranes remain widely used due to their cost-effectiveness and ease of fabrication [211], [212]. However, they are prone to fouling and may require surface modifications to enhance their performance. Ceramic membranes, on the other hand, exhibit superior thermal and chemical resistance, making them ideal for high-temperature and harsh industrial environments [213]–[215].

Despite their high efficiency, their brittleness and elevated production costs pose limitations. Composite membranes combine the benefits of polymeric and ceramic materials, offering enhanced mechanical strength and tenable properties [216]–[218]. These membranes demonstrate high rejection efficiencies and improved durability. Similarly, nanofibrous membranes provide high surface area and permeability, making them suitable for advanced filtration applications [219]–[221]. However, large-scale application remains a challenge.

Superhydrophilic and superoleophobic membranes have emerged as promising solutions for mitigating fouling and enhancing oil-water separation [222]–[224]. Superhydrophilic membranes exhibit excellent antifouling properties, reducing the accumulation of oil residues on the membrane surface. Meanwhile, superoleophobic membranes, characterized by their ability to repel oil while allowing water to pass through, offer self-cleaning properties and high separation efficiency [225], [226]. Despite their advantages, these innovative membranes require further research to address scalability and cost-effectiveness for widespread industrial use. A comparative analysis of different membrane materials under various operational conditions is provided in Table 5: Performance Metrics of Different Membrane Materials and Figure 4: Oil Rejection Efficiency of Membranes. This comparison highlights key performance parameters, including pressure and temperature ranges, flow rates, oil rejection efficiencies, fouling resistance, advantages, and limitations. Understanding these aspects is critical for selecting the most suitable membrane material for specific oil-water separation applications, ensuring both efficiency and long-term sustainability.

**Table 4.** Comparative Analysis of Membrane Fouling Mitigation Strategies

| **Strategy** | **Mechanism** | **Effectiveness** | **Limitations** | **Impact on Performance** | **Flux Recovery** | **Membrane Lifespan** | **References** |
|---|---|---|---|---|---|---|---|
| **Surface Modification** | Alters surface properties to reduce adhesion | High (95% oil rejection) | Limited long-term stability | Reduces fouling, but coating degradation may occur | 50–100 L/m²·h | Moderate | [195]–[198] |
| **Backwashing** | Reverses filtration flow to dislodge foulants | Moderate (85% flux restoration) | Ineffective for irreversible fouling | Restores flux but may not remove all foulants | 70–85% | Moderate to Low | [175], [188], [199] |
| **Chemical Cleaning** | Dissolves foulants using acids/alkalis | High (80–95% flux recovery) | Can degrade membrane material | Effective but reduces membrane lifespan | 80–95% | Low | [200]–[202] |
| **Electrochemical Methods** | Uses electrical forces to remove foulants | High (98% oil rejection) | High energy consumption | Enhances rejection but energy-intensive | 100–120 L/m²·h | Moderate to High | [203]–[205] |
| **Biological Cleaning** | Uses enzymes or microbes to break down fouling | Moderate to High (75–90% flux recovery) | High cost, optimization needed | Environmentally friendly, but slow process | 75–90% | High | [206]–[208] |

**Table 5.** Performance Metrics of Different Membrane Materials

| Membrane Material | Pressure Range (MPa) | Temperature Range (°C) | Flow Rate ($L.m^{-2}.h^{-1}$) | Oil Rejection Efficiency (%) | Fouling Resistance | Key Advantages | Limitations |
|---|---|---|---|---|---|---|---|
| Polymeric Membrane | 0.1 - 0.5 | 5 - 80 | 500 - 2000 | 85 - 98 | Moderate | Cost-effective, easy fabrication, flexible applications | Prone to fouling, lower mechanical stability |
| Ceramic Membrane | 0.2 - 1.0 | 10 - 300 | 1000 - 5000 | 95 - 99.9 | High | High thermal stability, excellent chemical resistance | Higher cost, brittle under extreme conditions |
| Composite Membrane | 0.1 - 0.8 | 5 - 120 | 800 - 4000 | 90 - 99.5 | High | Enhanced mechanical strength, tenable properties | Complex fabrication, potential cost challenges |
| Nanofibrous Membrane | 0.05 - 0.5 | 5 - 90 | 600 - 3500 | 88 - 98.5 | Moderate to High | High surface area, improved permeability | Limited large-scale applications |
| Superhydrophilic Membrane | 0.1 - 0.6 | 5 - 100 | 700 - 3800 | 90 - 99 | Very High | Superior antifouling properties, high durability | May require advanced fabrication techniques |
| Superoleophobic Membrane | 0.1 - 0.7 | 5 - 110 | 750 - 4200 | 92 - 99.8 | Very High | Excellent oil repellence, self-cleaning ability | Limited commercial availability |

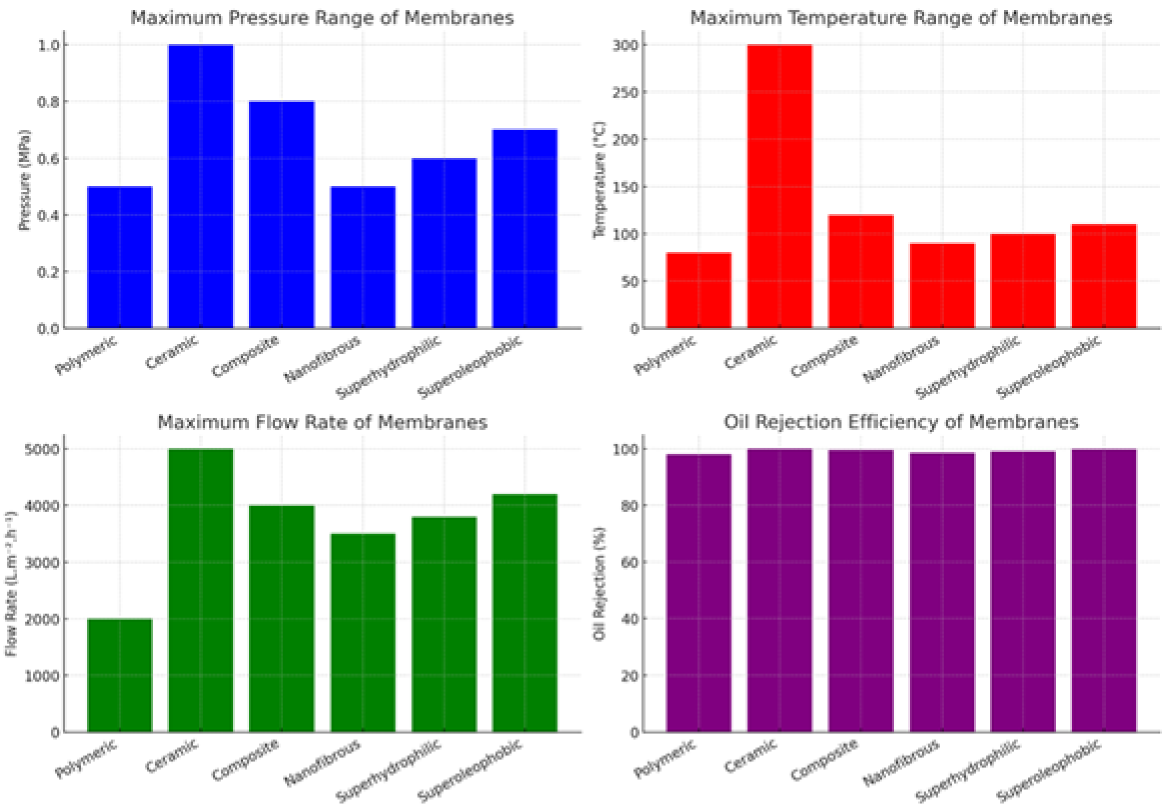


**Figure 4.** Oil Rejection Efficiency of Membranes

### Future direction

Advancements in membrane technology have significantly improved oil-water separation efficiency, enhancing permeate flux, selectivity, and membrane lifespan. Recent progress has focused on refining membrane materials, optimizing operational parameters, and mitigating challenges such as fouling and scaling. As a result, membrane technology has become an increasingly viable solution for complex oil-water separation processes. However, critical challenges remain, particularly in managing membrane fouling, scaling, and ensuring durability under varying operational conditions. Future research should prioritize optimizing key mechanical parameters, including transmembrane pressure, temperature, and cross-flow velocity, to enhance filtration efficiency while reducing energy consumption. The influence of osmotic pressure and membrane thickness on filtration performance has received limited attention, underscoring the need for the development of more advanced mathematical models. These models should accurately predict membrane behaviour under diverse operating conditions, providing a framework for optimizing industrial-scale filtration processes. Additionally, the lack of mathematical models evaluating mechanical velocity in oil-water filtration membranes presents a gap in understanding flow dynamics, which must be addressed to improve system efficiency.

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