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Review article

Mitigating offshore oily wastewater pollution: Sustainable strategies for treatment, disposal, and reuse

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ABSTRACT

Oily wastewater, a major byproduct of petroleum oil and gas production, poses serious environmental risks if not effectively treated. This review analyses the composition of oily wastewater, assesses current treatment methods, and explores strategies to improve efficiency while reducing capital and operational costs. Data corroborated from this work suggests that integrated treatment systems are more effective than single-method approach. Membrane-based technologies such as reverse osmosis (RO), forward osmosis (FO), and membrane distillation (MD) show promise in improving pollutant removal and energy efficiency. However, persistent challenges such as membrane fouling, high capital and operational costs, and membrane stability necessitate further innovation in materials development and hybrid system design. This review highlights the potential of well-designed hybrid systems for offshore oily wastewater treatment. Such systems can significantly enhance contaminant removal while minimising energy consumption and operational costs. Overcoming technical challenges and advancing membrane technologies will be essential for more sustainable and cost-effective oily wastewater treatment.

1. Introduction

The production of oily wastewater is not the result of simple neglect; instead, it is an unavoidable by-product of activities critical to the global economy. Oily wastewater and equipment maintenance are created during crude oil extraction and refining (Abuhasel et al., 2021). Regarding volume, oily wastewater is the predominant consequence of oil and gas production (Putatunda et al., 2019a; Tanudjaja et al., 2019; Liu et al., 2021a). Improper management of oily wastewater discharge into the environment results in water body pollution, adversely impacting aquatic and terrestrial ecosystems. The amount of oily wastewater is immense, with millions of litres generated daily worldwide (Shi et al., 2021). The primary focus in analysing the issues arising from the substantial volume of oily wastewater is its composition. Oily wastewater often consists of a diverse combination of hydrocarbons, some of which have the potential to be poisonous, mutagenic, or carcinogenic (Cantonati et al., 2020; Wu et al., 2017). Contaminants in water bodies may accumulate in the food chain, causing adverse health impacts for animals and humans (Organization, W.H, 2019). Hence, the remediation of oily wastewater is essential for ecosystem conservation rather than only being optional. Historically, conventional approaches to managing this kind of waste often include physical, chemical, and biological methods (Macaulay et al., 2018; Aguirre Hernandez, 2021; Osin et al., 2017; Ossai et al., 2022; Azuazu, 2023). Skimming and flotation typically remove free oil, while coagulation and flocculation help eliminate emulsified oil (Nasiri and Jafari, 2017; Johnson et al., 2017). Biological treatment uses microorganisms to decompose oil contaminants, providing a more environmentally friendly option; however, it is slower than physical and chemical methods (Greenpeace, 2016). Nevertheless, the issue's complexity necessitates a comprehensive review of treatment technologies. Recent advancements in treatment technology are making substantial progress in dealing with the volume of oily wastewater, improving its efficiency and efficacy. Membrane filtration has become very efficient due to its superior ability to separate substances, less reliance on chemicals, and straightforward operation (Akerdi and Bahrami, 2019). The development of nanofiltration (NF) membranes, a notable example, has demonstrated remarkable effectiveness in removing dispersed oil droplets and soluble organic compounds from wastewater streams (Mohammad et al., 2015; Guo et al., 2022). These membranes exemplify how advanced research

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in nanotechnology may lead to significant environmental advantages. Therefore, membrane technologies are now among the best ways to handle generated water. Many strategies for treating oily wastewater include oil-in-water emulsion and separation, chemical treatment, oxidation, chemical precipitation, biological treatment, physical treatment, adsorption, sand filter, stripping, and membrane separation procedures (Medeiros et al., 2022). Various membrane technologies were utilised, including reverse osmosis (RO), NF, and Membrane Distillation (MD). Electrodialysis reversal (EDR), freeze-thaw/evaporation, UV light, chemical amendment, artificial wetlands (Yalcinkaya et al., 2020), and evaporation ponds (Izady et al., 2020) have also been studied. Abousnina and Nghiem (Abousnina and Nghiem, 2014) explored the potential of the forward osmosis (FO) method to remove dissolved organics from oily wastewater.

Inshore facilities provide more flexibility in spatial allocation for wastewater treatment systems, but offshore platforms encounter considerable spatial limitations, complicating system integration. This study examines the characteristics and contemporary treatment techniques of oily wastewater, while also recommending the most appropriate treatment strategy for offshore platforms by using existing seawater and distilled water treatment facilities. It analyses the essential attributes of oily wastewater and assesses several innovative treatment methods, emphasising membrane-based treatments. This analysis provides insights into sustainable treatment approaches and regulatory frameworks while underscoring the importance of global collaboration in tackling this critical environmental issue.

2. Oily wastewater extracting techniques

The extraction and treatment of oily wastewater is crucial for reducing environmental contamination and safely handling industrial waste. Hydrocarbons, suspended particles, and other pollutants typically contaminate oily wastewater. These pollutants result from several phases of the manufacturing process, such as drilling, production, and refining operations. To ensure efficient treatment and disposal, the extraction of oily wastewater necessitates completing several essential processes (Speight, 2019). The manufacturing plant begins by collecting wastewater from a variety of sources. These sources include separators, tanks, and places designated for washing down equipment (Fig. 1). Often, this wastewater combines produced water, which naturally exists in the reservoir alongside oil and gas, with process water, which serves various processes. Following this, a mix of chemical and physical procedures typically accomplishes the separation of oil from water (Speight, 2019). Gravity-based separation technologies, such as API separators, often allow oil to float to the top for skimming (Erfani et al., 2024; Gamwo et al., 2022). In addition, chemical treatments such as coagulation, flocculation, and demulsifiers help break up emulsions and improve the effectiveness of oil separation from water. After separating the oil, the remaining generated water is treated further via media filtering. It is critical to have efficient separation to ensure the sector's sustainability, comply with regulations, and minimise environmental harm (Silvestri, 2021; Olajire, 2020).

3. Global volume of oily wastewater

Oily wastewater is the most abundant waste stream in the oil and gas sector. There are about three barrels of greasy effluent for every barrel of oil product (Agency, 2020; Nath et al., 2023). The worldwide average generated water is 300 million barrels per day, for a total of 110 billion barrels per year (Abousnina et al., 2015). The global estimate of oily wastewater on offshore platforms is roughly 90 million bbl/day (Shahbaz et al., 2023). Over 44 million barrels of oily wastewater are released daily from offshore locations. (Abousnina et al., 2015; Scurtu Ciprian Teodor, 2009). The volume of oily wastewater in the oil sector has substantially increased, and this pattern is projected to continue. In some older oil fields, the water cut surpasses 95 % of the total oil well output (Xue et al., 2023; Yeit Haan et al., 2023a). In a study conducted by Clark and Veil (Clark and Veil, 2009), it was discovered that wells in the United States yield >7 barrels of water for every barrel of oil produced. The API surveys determined that the water-to-oil ratio is 7.5 barrels of water per barrel of oil. According to Xue, Liu (Xue et al., 2023), water may constitute up to 98 % of the material obtained from historic crude oil wells. Stripper wells can generate 10–20 barrels of water for every barrel of crude oil produced. On the other hand, Conrad, Yin (Conrad et al., 2020), state that international wells produce a ratio of 3:1 for water to oil. The water output from oil and gas wells exhibits variability. The water-to-oil ratio progressively rises during the lifespan of an oil or gas well. The fluids in these wells have a low initial water content. As the availability of petroleum products decreases, water content rises. Khatib and Verbeek (Khatib and Verbeek, 2003), reported that Shell's working units generated >6 million barrels of water in 2002, a significant increase from the 2.1 million barrels produced in 1990. When the expenses associated with water management exceed a certain level, the well's profitability ceases. Fig. 2 illustrates the enormous quantity of oily wastewater produced in the top 10 producing nations compared to crude oil production. This calculation of oily wastewater was derived from the most conservative estimate, which assumed a ratio of 1 part oil to 3 parts oily wastewater (Samuel et al., 2022a; Administration, U.S.E.I. U.S. Energy Information Administration, International Energy Statistics, 2024).

Three primary practices may be classified as produced water management strategies: disposal, treatment for reuse, and discharge after treatment. Subsurface injection and evaporation ponds are examples of disposal techniques. Oil and gas producers frequently inject water into petroleum formations to maintain reservoir pressure and transport oil to production wells. However, due to the massive amount of oily wastewater, most oily wastewater is still discharged into the desert, as shown in Fig. 3. On the other hand, effective treatment is essential for reuse or

Fig. 1. Production operation system- Oil field – Libya 2024.

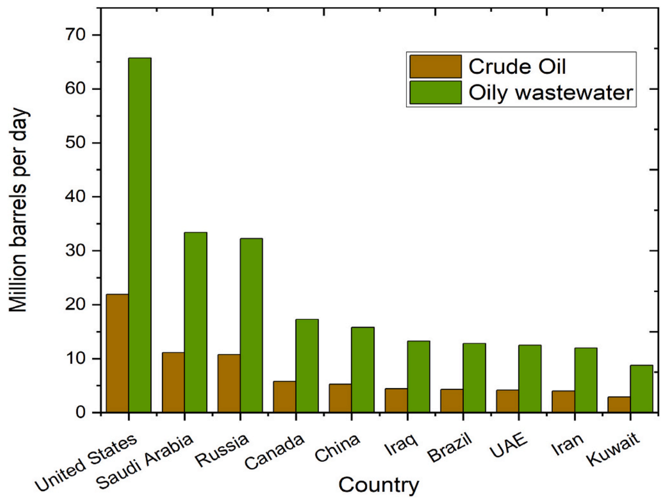

Fig. 2. Illustrates how much oily wastewater the top 10 producers create relative to total oil (Administration, U.S.E.I. U.S. Energy Information Administration, International Energy Statistics, 2024).

safe discharge, which may involve processes such as filtration, bioremediation, distillation, and membrane technologies (Samuel et al., 2022b). Thus, oil and gas companies need to carefully navigate economic costs, regulatory requirements, and environmental considerations when determining the most suitable management approach.

4. Oily wastewater offshore platforms

Offshore oil and gas activities are essential components of the global energy industry, contributing significantly to meeting the world's energy demands. However, these activities generate large volumes of oily wastewater, which, if not properly managed, can pose serious environmental and health risks (International Association of oil and gas producers, 2021). This wastewater is typically rich in hydrocarbons, and heavy metals, and often exhibits high salinity levels, making it a major contaminant in marine environments (Eldos et al., 2022). It originates from various stages of offshore oil extraction, including exploration, drilling, and production, and has a substantial impact on marine ecosystems, potentially leading to long-term damage to aquatic life and biodiversity.

The presence of harmful chemicals and pollutants in oily wastewater, including toxic substances like benzene, toluene, and xylene, as well as metals such as mercury and lead, can severely degrade water quality and disrupt the delicate balance of marine ecosystems (Basile et al., 2023). Moreover, the high salinity of the wastewater can affect the osmotic balance of marine organisms, leading to further ecological disruptions. As global oil demand continues to rise, the volume of oily wastewater produced by offshore platforms is expected to increase, making it more urgent than ever to find effective methods to treat and manage this waste (Environmental Protection Agency, 2019; World Health Organization, 2020). Developing sustainable and efficient treatment technologies to mitigate the environmental impact of oily wastewater from offshore platforms is crucial to ensuring that the growth of the energy sector does not come at the cost of marine health and environmental integrity. Understanding the content and behavior of this wastewater, as well as appropriate management measures, is critical to reducing its impact on the environment and surrounding populations (Villarín and Merel, 2020).

5. Characteristics of oily wastewater

The physical and chemical qualities of oily wastewater may vary greatly depending on the location of the oil or gas field, the geological formation with which the oily wastewater has come into contact, and the kind of crude oil being produced (heavy, medium, or light crude). The characteristics and quantities of oily wastewater may also change throughout a reservoir's life, and water injection (to boost oil production) significantly impacts these qualities and volumes (Agency, 2020; Li et al., 2021). The primary problems with oily wastewater include total dissolved solids (TDS), oil and grease (OG), inorganic, organic

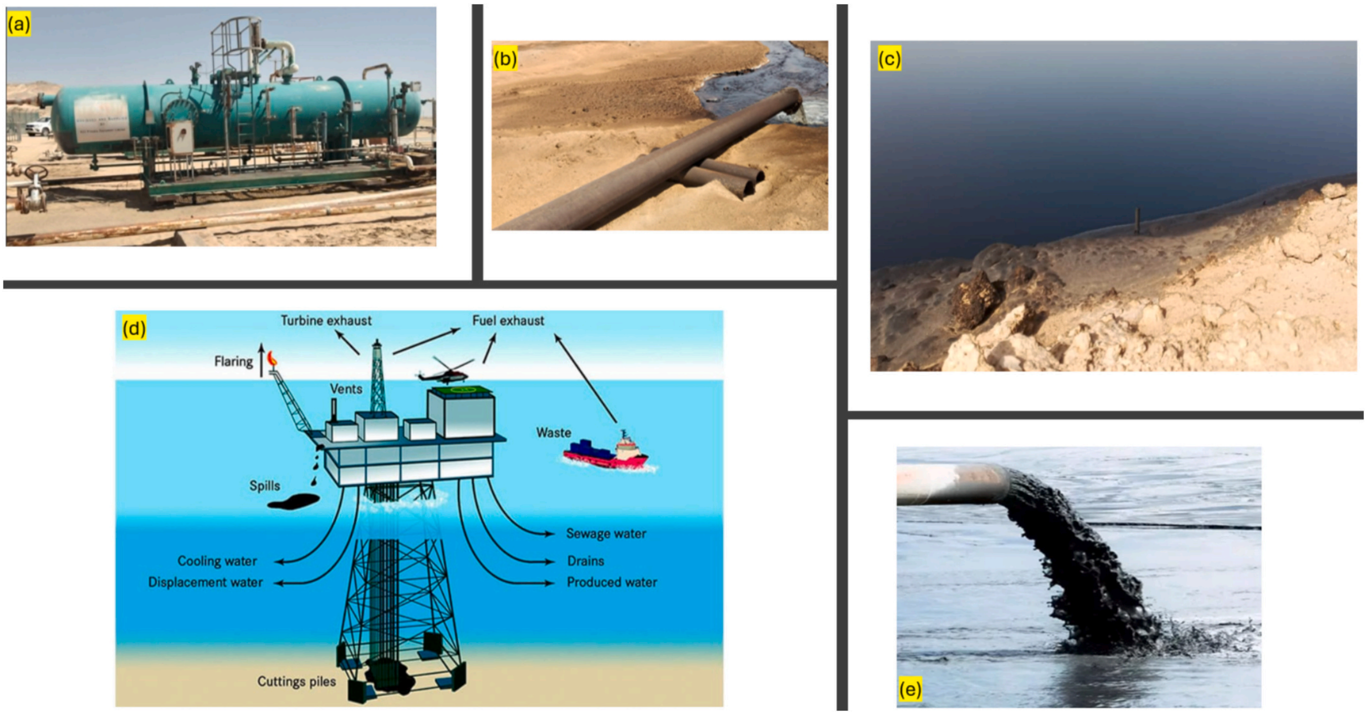

Fig. 3. Oily wastewater extraction process Oil field – Libya 2024 (a) production separator, (b) and (c) discharge point and (c) oily wastewater pits & d) and e) represents the offshore discharge mechanism (Genesis Water Technology, 2023; ECO, 2017).

compounds, and naturally occurring radioactive materials (NORM) (Gamwo et al., 2022; Technologies, 2024). Total oil production can be increased if the characteristics of oily wastewater are well understood. Exploring and better understanding the chemical elements of oily wastewater improves the capacity to choose the best solutions for improved treatment and disposal to optimize oil recovery. One of the most prominent elements of onshore and offshore oily wastewater is OG, caused by several organic compounds, with an average OG level of 40 to 2000 mg/L (Benko and Drewes, 2008). Salinity is also considered an essential feature in onshore oily wastewater; in many circumstances, it is saltier than saltwater (Cline, 1998). The TDS concentration of oily generated water from the western United States ranges from 1000 to 400,000 mg/L (Gazali et al., 2017; Zhao et al., 2024).

Water injection significantly affects the characteristics and amount of oily wastewater (Yu et al., 2017). Thus, knowing relevant factors such as SS and the components of oily wastewater is critical for deciding applications such as scale inhibitors (Putatunda et al., 2019b). Non-indigenous elements may also be found in oily wastewater since they are often employed during exploration and production. Water injection, for example, is usually used to maintain reservoir pressure and improve oil output, a process known as enhanced oil recovery (EOR). This water, often sourced from a separate aquifer, may include SS and bacteria (Oilleader Petroleum, 2024; Nikolova and Gutierrez, 2020). In regions where surface or groundwater is scarce, such as the Middle East, salt water is utilised in EOR, which often causes several issues, the most common of which is scaling caused by the precipitation of heavy salts, particularly various sulphates. Furthermore, produced water (PW) originates from various sources, including injected seawater, surface water, and formation water, which is naturally present in oil reservoirs. During drilling and production, additional chemicals such as coagulants, emulsion breakers, scale inhibitors, corrosion inhibitors, and solvents are used to enhance oil well productivity (Breit et al., 1998). As a result, these chemicals, along with hydrocarbons and other contaminants, may be present in the oily effluent, influencing its composition and treatment requirements.

6. Disposal and treatment of oily wastewater

The discharge of untreated or inadequately treated oily wastewater may result in significant environmental repercussions, especially for aquatic ecosystems and soil integrity (Wilson et al., 2018). Oil films on water impede oxygen transfer, significantly endangering marine organisms, while soil pollution diminishes fertility and obstructs agricultural output (Singh et al., 2020; Lee, 2016). Efficient wastewater management is crucial to alleviate these dangers, necessitating rigors compliance with environmental standards and the use of sophisticated treatment technology. Current management options differ, including the reduction of environmental damage via reinjection wells and the treatment and reuse of oily wastewater for agricultural and ecological purposes. Nonetheless, owing to the substantial quantities of generated water and the restricted capacity of these systems, a considerable volume of wastewater persists in being released into deserts and oceans, underscoring the need for more effective and sustainable solutions (see Fig. 4).

Offshore facilities often discharge greater quantities of oil-contaminated wastewater than onshore operations owing to geographical and operational limitations that hinder the use of advanced treatment technologies, such as biological reactors (Miller et al., 2024). The restricted space, elevated operating expenses, and logistical difficulties inherent to offshore platforms hinder the integration of sophisticated wastewater treatment technologies, resulting in an increased probability of direct discharge into marine ecosystems (Miller et al., 2024; Klemz et al., 2021; Merlin et al., 2021; Linden, 2024). Thus, offshore wastewater substantially adds to marine pollution, impacting biodiversity, changing aquatic ecosystems, and jeopardising fisheries and coastal livelihoods.

Conversely, onshore wastewater affects coastal areas and freshwater resources, threatening drinking water availability, soil integrity, and agricultural efficiency (Iyiola et al., 2022; ECHIOMA, 2024). In the absence of adequate treatment, oil-contaminated wastewater may infiltrate groundwater aquifers, resulting in prolonged environmental deterioration and public health issues. To address these issues, effective treatment options include multimedia filtration, membrane-based technologies, and sophisticated oxidation techniques are crucial

Fig. 4. Oily wastewater a) outlet from the production separator, b) discharge point, c) water pit, and d) The Google map reveals significant oily wastewater contamination at the HOO-2024.

(Samuel et al., 2022c). These technologies are essential for eliminating oil, grease, and other pollutants from wastewater, so assuring adherence to environmental standards. Multimedia filtering is extensively used in oil re-injection systems to improve water quality before reinjection into reservoirs, therefore minimising formation damage and enhancing oil recovery efficiency (Samuel et al., 2022c; Liu et al., 2024). To attain long-term sustainability, it is essential to use a mix of innovative and integrated treatment methods that reduce environmental impact while enhancing water reuse potential.

6.1. *Re-injection of oily wastewater*

Re-injecting oily wastewater is a widely used method in the petroleum industry to handle and control the disposal of oily wastewater (van den et al., 1996; Burnett, 2004; Abou-Sayed and Guo, 2002). Fig. 5 depicts the water injection system at the HOO oil field in Libya, which is designed to reinject oily wastewater into the reservoir. The conventional approach to the ecologically accountable disposal of oily wastewater is economically and technologically feasible and has been established. Before re-injection, it is essential to use multi-media filtration to remove all solid particles from the oily wastewater altogether, as shown in Fig. 5 (b). This procedure facilitates the elimination of substantial particles, averting obstructions in injection wells (van den et al., 1996; Burnett, 2004; Abou-Sayed and Guo, 2002). Oil droplets in wastewater are typically classified by size: free oil (>150 μm), dispersed oil (20–150 μm), and emulsified oil (<20 μm). Multi-media filtration (MMF) systems, composed of layers such as anthracite coal, sand, and garnet, effectively remove larger oil droplets and suspended solids. This system's layered nature allows for segregating larger particles in the top portion of the bed while efficiently removing small particles in the bottom area. According to studies, the most efficient multi-media filters can remove substantial solid particles and oil droplets (Water, n.d.). However, they are less efficient at capturing emulsified and dissolved oils, necessitating advanced treatments like ultrafiltration or membrane technologies for comprehensive purification (Medeiros et al., 2022; Professionals, 2025). Failure to remove these large, solid particles could pollute the injection well, create blockages along the wellbore, and damage the formation.

6.2. *Re-use of oily wastewater for environmental and agricultural purposes*

Oily wastewater degrades habitats and disrupts food chains, threatening aquatic life. It also raises concerns for human health because it contaminates drinking water sources (Edition, 2011). Consequently, managing this wastewater is critical; conventional end-of-pipe treatments can be costly and ineffective in the long run. Agriculture is an industry with a prodigious demand for water. It is the world's largest consumer of fresh water, accounting for approximately 70 % of total freshwater withdrawals (Fao and Food and agriculture organization of the United Nations, 2018; Organization, W.H, 2002). Thus, reusing treated oily wastewater in agriculture presents a tempting prospect. If the water has sufficient nitrogen, phosphorous, and potassium, which are all crucial for plant development, it may be used for irrigation, fertigation, and fertiliser supply. The development of efficient and cost-effective treatment technologies lays the groundwork for the possibility of reusing oily wastewater. Advances in this field have led to the emergence of methods capable of removing contaminants to levels that meet the stringent guidelines for water reuse. Membrane technologies such as ultrafiltration and nanofiltration have been up-and-coming, demonstrating a high degree of contaminant removal (Ge et al., 2017). Furthermore, using microorganisms in biological treatments to biodegrade oils has shown significant success, praising its sustainability and reduced energy consumption (Naughton et al., 2017). Several case studies underscore the feasibility of reusing treated oily wastewater in environmental and agricultural contexts. For instance, Australian research explored the use of treated wastewater from coal seam gas operations for irrigation, concluding that appropriate treatment could secure the water for crop irrigation, potentially alleviating the strain on freshwater resources (Queensland Government, 2019). According to

Fig. 5. Water injection system of oily wastewater HOO-Libya(a,b, c and d); Water injection system (e) (Engineering, 2016).

extensive research, Singapore has emerged as one of the world's leaders in wastewater recycling, with 100 % of its wastewater treated and reused primarily for agricultural irrigation (Queensland Government, 2019; Bauer and Wagner, 2022). Despite its potential advantages, reusing oily wastewater has its challenges. Concerns exist regarding the long-term impacts on soil quality, the accumulation of heavy metals, and changes in microbial populations, which could have unforeseen ecological consequences. Furthermore, public perception and acceptance play a critical role; using reclaimed water, particularly that with an oily origin, may encounter resistance. Reusing oily wastewater for environmental and agricultural purposes is a sustainable solution to water scarcity and pollution. Technological innovation, research, and regulatory oversight can mitigate environmental impacts and increase agricultural water.

7. Oily wastewater treatment technologies

The management of oily wastewater encompasses many techniques classified by their mechanisms: gravity separation, chemical treatment, physical approaches, membrane separation, and hybrid systems. Each assumes a pivotal function contingent upon the kind of oil, emulsion stability, and discharge specifications.

7.1. Gravitational separation

An emulsion may be a heterogeneous combination in which tiny droplets of one liquid are scattered uniformly across another. Within an oil-in-water emulsion, the minute droplets consist of oil and are evenly distributed throughout the water. As seen in oil spills, emulsions may occur naturally or can be produced via industrial processes (Sousa et al., 2022; Shah Buddin et al., 2022). Water and oil are immiscible due to their contrasting polarities, which means they cannot mix naturally. As a result, emulsions formed by water and oil are frequently unstable and separate over time. However, the presence of emulsifiers may stabilise these emulsions, making the separation process more difficult (Rezvankhah et al., 2020). Gravitational separation is an essential technique to separate substances based on their density difference, such as oil and water (Fig. 6). Over time, lower-density oil will naturally ascend to the surface. Although this approach is energy-efficient, it might improve speed and effectiveness since emulsified oil droplets may be too minuscule to be separated alone by gravity (Asif et al., 2022; Yen Tan et al., 2021). In rare cases, the effectiveness of gravity separation may be compromised by the presence of certain emulsifiers or when the oil droplets have a comparable density to the water.

Centrifugation is a highly efficient and sophisticated mechanical separation method used to improve the process. Centrifugal force accelerates the separation of phases by causing the denser water to migrate outward, facilitating the collection of the less dense oil in the centre for more straightforward extraction. This approach has shown its effectiveness for various emulsion types and has the advantage of handling large quantities quickly (Levitin, 2020). Coalescence is a technique where minuscule oil droplets merge to form larger ones, facilitating their subsequent separation. The efficiency of this process depends on factors such as droplet size, interfacial tension, and fluid dynamics. Recent studies have investigated the coalescence kinetics of oil droplets under various conditions. For instance, in a recent study, Tu et al., (Tu et al., 2024) examined the coalescence behavior of sesame oil droplets under high internal phase conditions, providing insights into efficient oil extraction techniques. Another study developed a mathematical model to predict the evolution of water droplet size distribution in inline electrostatic coalescers, which are devices used to enhance coalescence efficiency in oil-water separation processes (Kooti et al., 2023). These studies contribute to a better understanding of the factors influencing coalescence efficiency and the development of more effective separation technologies. Filters or coalescing plates may aid in this process by providing surfaces for oil droplets to collide and merge (Gavrielatos, 2021). Coalescers are available in various materials and designs customised to meet industrial needs. One example of a material that has attracted interest is polymer membranes, capable of selectively separating oil from emulsions (Speight, 2019; Gavrielatos, 2021). The Coalescence technique is essential for enhancing the efficiency of oil-water separation operations in sectors including oil and gas production, petrochemicals, and wastewater treatment facilities. Coalescence technologies have a role in minimising the environmental consequences of releasing oily wastewater and raising the quality of treated water for reuse or discharge by increasing the size and separability of oil droplets (Speight, 2019).

7.2. Chemical treatment

There are many different approaches to handling oil-in-water emulsions, but one of the more frequent ones is chemical demulsification. Chemical demulsification is a method used to break down emulsions, which are stable mixtures of liquids that don't mix into distinct

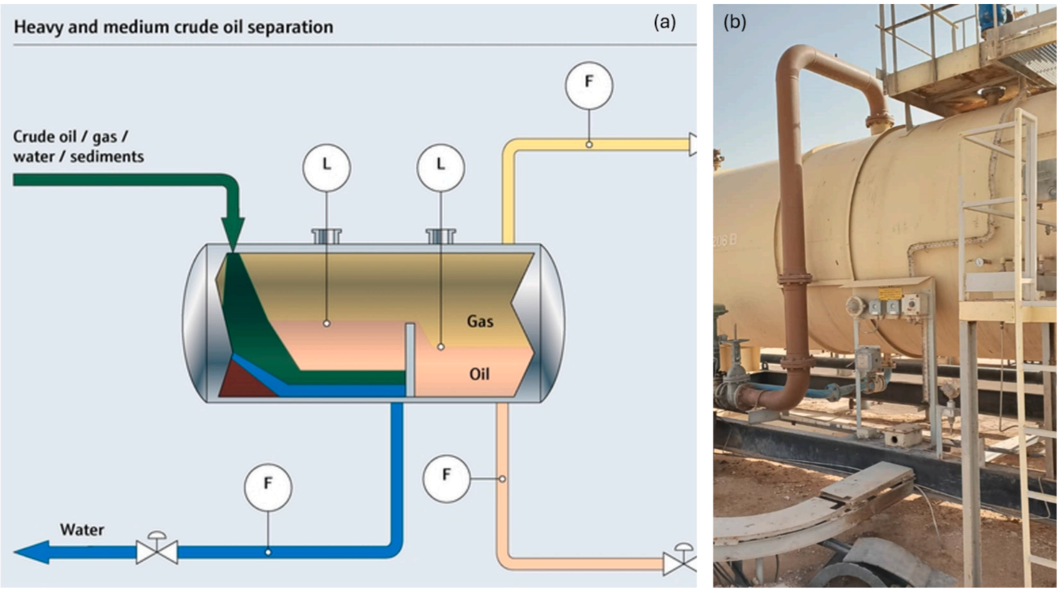

Fig. 6. Shows the gravitational separation system.

phases and can be categorised into oil-in-water (O/W) and water-in-oil (W/O) varieties. Using certain chemicals, referred to as demulsifying, decreases the emulsion's stability, enabling the oil and water to separate from one another. The protective coating that surrounds oil droplets is broken down by demulsifies, which speeds up the coalescence process (Tian et al., 2022; Martin et al., 2019). The use of chemicals, even though they are effective, presents environmental issues owing to the possibility of residual contamination and the subsequent treatment that is necessary for the water (Yonguep et al., 2022; Jenkins, 2019).

Electrochemical separation methods use electrical energy to aid in chemical separation and purification in various applications. These approaches are based on electrochemistry, in which the application of an electrical potential induces or influences chemical processes. Electrochemical separation techniques apply an electrical charge to destabilise the emulsion, including electrocoagulation and electroflotation. Electrodes introduced into the emulsion form coagulants that neutralise the charges on the oil droplets, causing them to clump together and separate from the water. This method has been successful in treating industrial wastewater and has the added advantage of disinfecting the water in the process (Yu et al., 2022). A more recent focus in emulsion separation is the development of environmentally friendly and sustainable technologies. One such innovation is the use of ultrasonic separation methods, where ultrasonic waves cause vibration in the droplets, leading to their accumulation and subsequent separation (Kumar et al., 2024; Atehortúa et al., 2019). This method has shown promise due to its low energy consumption and minimal environmental impact.

7.2.1. *Oxidation*

Oxidation processes denote chemical reactions involving the transfer of electrons between substances, resulting in the breakdown of pollutants in wastewater. These oxidising agents possess sufficient strength to decompose even the most intricate and detrimental compounds in oily wastewater (Abuhasel et al., 2021). Pandis, Kalogirou (Pandis et al., 2022), assert that aerobic oxidation procedures (AOPs) include a series of chemical treatments designed to eliminate organic and inorganic contaminants from water and wastewater via oxidation facilitated by interactions with hydroxyl radicals (OH). This term broadly refers to several technologies, including ozone (O_3), hydrogen peroxide (H_2O_2), ultraviolet (UV) light, and Fenton's reagent.

7.2.1.1. Ozone treatment. Ozone is a potent oxidizer that effectively eradicates various organic contaminants. It is very efficient in addressing non-biodegradable materials often present in oily wastewater. Ozone diminishes the toxicity of these chemicals by breaking them down into smaller molecules, facilitating their removal from water (Derco et al., 2021; Wei et al., 2017).

7.2.1.2. Hydrogen peroxide and UV light. The amalgamation of hydrogen peroxide with ultraviolet (UV) light constitutes a very efficacious method for wastewater treatment. Ultraviolet radiation promotes the breakdown of hydrogen peroxide, producing hydroxyl radicals extremely reactive entities that may degrade a wide range of contaminants often present in oily wastewater (Sharma et al., 2023; Ghernaout and Elboughdiri, 2020).

7.2.1.3. Fenton's reaction. Fenton's reagent, a combination of hydrogen peroxide (H_2O_2) and iron salts (usually Fe^{2+}), produces highly reactive hydroxyl radicals (•OH) in acidic environments, often at pH 3. These radicals may decompose a diverse array of intricate organic contaminants (Całus-Makowska et al., 2025). This method is particularly efficacious for addressing oily wastewater with elevated levels of resistant organics, since the radicals catalyse oxidation processes that facilitate the breakdown of pollutants into simpler, less deleterious molecules. Optimal reaction temperatures typically vary between 20 °C to 40 °C, depending upon the nature of the wastewater (Liu et al., 2021b; Zhang et al., 2019; He and Zhou, 2017).

7.2.2. *Chemical precipitation*

Chemical precipitation is a widely used method for removing pollutants from wastewater. Chemical precipitation converts dissolved substances into precipitates, which are insoluble forms that may be readily extracted from the liquid phase (Spellman and Drinan, 2014). This approach may mitigate many contaminants, including hazardous metals, phosphates, and sulphates, which provide considerable environmental hazards. Precipitation is achieved by altering the pH of the water or by adding certain chemicals that react with dissolved pollutants. However, it is crucial to recognise that this approach is ineffective in eliminating dissolved elements. This method often employs lime softening. Research was conducted to investigate the treatment of oily wastewater characterised by a hardness of 2000 mg/L, a sulphur content of 500 mg/L, total dissolved solids (TDS) of 10,000 mg/L, and oil droplets at 200 mg/L. The study effectively used a hot lime press to diminish sludge production and alkali consumption by 50 % (Danai-Evgenia, 2018; Wan, 2017). The polynuclear polymers composed of mixed metals (Fe, Mg, and Al) effectively coagulate, inhibit scaling, and extract oil from oily wastewater containing up to 400 mg/L of suspended particles (You et al., 2018). Additionally, previous research has used calcite, spill sorb, and lime to assess the effectiveness of heavy metal removal from oily wastewater (Maretto, 2015). Lime demonstrated exceptional efficacy in eliminating heavy metals, with a clearance rate above 95 %.

7.3. *Biological treatment*

Oily wastewater may be efficiently treated by biological methods, either aerobic or anaerobic, to remove aromatic compounds (Yu et al., 2017; Adetunji and Olaniran, 2021; Mokif et al., 2022; Bhattacharyya et al., 2022). These treatments use microorganisms, including bacteria, fungus, and protozoa, to biodegrade or convert organic contaminants into less toxic molecules, such as carbon dioxide and water (Mbachu et al., 2020). These bacteria use pollutants as energy or nutrients, therefore purifying the wastewater while they metabolise the organic matter. Aerobic biological processes, including activated sludge, trickling filters, and rotating biological contactors, need oxygen for the sustenance of microorganisms that degrade oily pollutants (Aragaw, 2021; Lu et al., 2019). Anaerobic biological therapy transpires in oxygen-deprived settings, where bacteria flourish and generate biogas as a by-product for energy recovery (Balakumar et al., n.d.). Facultative biological treatment technologies operate under both aerobic and anaerobic conditions, exemplified by pond systems including an aerobic upper layer and anaerobic lower levels (Osborne et al., 2009; Milledge et al., 2019). Bioremediation methods use indigenous or foreign microorganisms to decompose oily contaminants, emphasising ex-situ and in-situ approaches. Ex-situ procedures include the excavation or removal of contaminated materials, while in-situ approaches address waste treatment at the site of contamination. Bioaugmentation, a subset of bioremediation, involves the introduction of cultivated microorganisms to enhance the native microbial community's capacity to address certain pollutants (Muter, 2023; Chettri et al., 2024). The biological treatment of oily wastewater has ecological and economic advantages, including lower energy consumption compared to physical and chemical treatments, and high removal efficiency for various contaminants (Medeiros et al., 2022; Varjani and Upasani, 2021; Varjani and Upasani, 2017). Nevertheless, it encounters constraints like temperature, pH, and nutrition availability affecting microbial activity and treatment effectiveness, as well as the presence of hazardous chemicals that impede biological processes. Meticulous system design and regulation of operational parameters are essential for maintaining consistent performance.

7.4. Physical treatment methods

7.4.1. Adsorption

Adsorption is a surface phenomenon in which solute molecules, such as oil, collect on the surface of a solid or liquid instead of dispersing in the surrounding medium. This process may occur via two mechanisms: physisorption, characterised by weak van der Waals interactions, and chemisorption, which entails the creation of covalent or ionic bonds (Williamson et al., 2024; Sobolčiak et al., 2021; Yeit Haan et al., 2023b). Adsorption is mostly used for the treatment of oily wastewater owing to its efficacy and the simplicity of collecting adsorbed oil, which may be recycled for financial benefit (Abuhasel et al., 2021; Yeit Haan et al., 2023a). A diverse selection of materials has been used as adsorbents, selected for their elevated surface area, porous architecture, and surface chemistry, all enhancing their efficacy in oil removal. Optimal adsorbents have elevated adsorption capability, durability, accessibility, and economic viability (Akhtar et al., 2024). Typical examples include activated carbon, zeolites, clays, and charcoal, however newer investigations have examined sophisticated materials like graphene, carbon nanotubes, and diverse nanocomposites (Odoom et al., 2024).

The benefits of adsorption are many. It accepts many contaminants without generating detrimental by-products, in contrast to specific chemical treatments. Furthermore, several adsorbents may be reactivated and used again, hence reducing operating expenses and environmental repercussions. The straightforwardness and scalability of adsorption systems render them appropriate for diverse industrial wastewater volumes (Rashid et al., 2021). Nonetheless, the approach has several drawbacks. Adsorbents may reach saturation over time, necessitating replacement or regeneration, often via heat or chemical processes. These activities may deteriorate the material and diminish its effectiveness after several cycles (Akhtar et al., 2024; Baskar et al., 2022). Moreover, the existence of competing chemicals in wastewater might hinder adsorption performance, sometimes requiring pretreatment. The elevated cost and restricted availability of sophisticated adsorbents, especially in resource-constrained environments, continue to hinder broad application (Odho et al., 2025; Steigerwald, 2023; Ibrahim et al., 2016).

7.4.2. Sand filtration

A sand filter (SF) is a filtration device that employs layers of granular material, mostly fine sand supported by gravel, to purify water as it passes through. The technique eliminates pollutants by physical trapping and adsorption, wherein contaminants adhere to the sand's surface (Verma et al., 2017; Hoslett et al., 2018; Yeszhan et al., 2025). Upon entry of oily wastewater, oil droplets are segregated by mechanisms such as coalescence, flocculation, and gravity settling (Putatunda et al., 2019b). Due to its lower density compared to water, oil ascends to the surface and may be removed by skimming. Research indicates that sand filters may eliminate up to 90 % of oil and suspended particles, often lowering concentrations to comply with environmental regulations (Ogunbiyi et al., 2023). One of the primary advantages of sand filters is their affordability they need less maintenance, and the materials used are inexpensive and readily accessible. Their resilience makes them suitable for regions with inadequate infrastructure. Nonetheless, sand filters possess constraints. They exhibit less efficacy when addressing elevated oil concentrations or emulsified oils, necessitating pretreatment via oil-water separators or dissolved air flotation devices (Rocha e Silva et al., 2018). Furthermore, the management of trash generated by trapped oil and the periodic replacement of sand might pose environmental and logistical difficulties (Chalaris et al., 2023).

7.4.3. Air stripping

Stripping is a mass transfer method often used to remove volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs) from wastewater (Kumar et al., 2022; Dewidar and Sorial, 2021). The efficacy is mostly contingent upon the volatility of the targeted pollutants. Recent innovations have markedly improved stripping techniques for oily wastewater treatment, including air-stripping towers, steam stripping, and membrane stripping. In air-stripping systems, polluted water runs counter to an air stream, facilitating the transfer of volatile chemicals into the gaseous phase (Karkhaneh et al., 2024). Conversely, steam stripping employs steam to enhance the volatilisation of organic contaminants from wastewater (Abdullahi et al., 2014). Membrane stripping use hydrophobic membranes to remove volatile chemicals, providing a more energy-efficient method by reducing the need for substantial quantities of air or steam (Iyiola et al., 2022; Samuel et al., 2022c).

The efficacy of these systems is assessed based on their adherence to discharge regulations, adaptability in addressing diverse pollutants, and overall cost-efficiency. Studies have shown that properly engineered stripping systems may efficiently eliminate a significant quantity of VOCs and SVOCs from oily wastewater (Liang et al., 2020; Li et al., 2018). Nevertheless, issues include the management of substantial wastewater quantities, regulation of released stripping contaminants, and optimisation of energy use persist. Consequently, the integration of stripping with adjunct treatment technologies is often essential to satisfy strict water quality standards.

7.5. Membrane separation methods

Oily wastewater comprises a complex mixture of grease, free-floating, dispersed, and emulsified oil. Improper handling can pose a significant risk to the environment (Joshi and Bhatia, 2022). Traditional treatments such as gravity separation, skimming, flotation, and filtration often prove ineffective when applied to stable oil-in-water emulsions. Because existing technologies are limited, more advanced treatment strategies are required. Membrane technology stands out due to its capacity to target and separate certain pollutants on a molecular scale. The membrane technology is based on a semipermeable barrier that selectively allows molecules or ions to pass through. This effectively separates specific molecules, or ions, from the flowing stream. The operational ways to classify membranes include microfiltration (MF), UF, NF, and RO. The pore size of the membranes and the pressure required to achieve separation distinguish these methods from each other (Nasir et al., 2021). Membrane technology has advanced, especially for oil-containing effluent. Polymer-based membranes like PVDF and PTFE are hydrophobic, making them ideal for oil-and-water separation (Wang et al., 2019). Additionally, membrane bioreactors (MBRs) combine MF with biological treatments. This degrades organic pollutants and filters toxins (Ahmed et al., 2021). Various industries have thoroughly documented membrane technology for oily wastewater treatment. Oil refineries use RO to recycle wastewater and UF membranes for pre-treatment before desalination (Ai et al., 2022). Food processors may benefit from MBRs to extract oils and lipids from their effluents (Mahat et al., 2021).

7.5.1. Reverse osmosis (RO) and Nanofiltration (NF)

RO membranes can remove heavy metals and dissolved organic molecules from viscous wastewater. The energy needed to operate RO membrane (applied pressure) is a drawback (Hailemariam et al., 2020). While NF membranes need less energy than RO membranes, their bigger pores make them less successful in removing low-molecular-weight components. NF may remove mild phenols (C1-C3) and BTEX (Maroufi and Hajilary, 2023). The main problem of NF and RO is membrane pollution (Peydayesh, 2022; Mastropietro et al., 2021). Additionally, the limited lifespan of the membrane material is regarded as a further disadvantage.

7.5.2. Ultrafiltration (UF), Microfiltration (MF) and Electrodialysis (ED)

UF due to its excellent oil removal, lack of chemical additives, small installation space, and low energy consumption, UF is a popular technology for treating oily wastewater (Arefi-Oskoui et al., 2020). UF membranes met SS and dissolved component removal criteria in one investigation compared to MF membranes. Hydrocarbons were rejected at 96 %, heavy metals such as Cu and Zn at 95 %, and BTEX at 54 % (Siagian et al., 2021; Pauzan et al., 2021). The combination UF-ozone system also produced results equivalent to commercially available methods like Macro Porous Polymer Extraction (MPPE), which eliminated BTEX at 99 % (Aryanti et al., 2019). Oil particles in generated water may be removed using MF-UF membranes (Jebur and Wickramasinghe, 2021). Pretreatment with crossflow UF and biological treatment may remove 99 % of oil particles from oil emulsions (Ahmad et al., 2020a; Othman et al., 2021). Electrodialysis (ED) allows cations and anions to flow across charged membranes between two electrodes (Severin and Hayes, 2019). According to Xu et al. (Hoslett et al., 2018), ED's primary drawbacks are its high energy input and ineffective removal of dissolved compounds, including aromatic hydrocarbons.

7.5.3. *Forward osmosis (FO)*

FO is an osmotic-driven membrane process that utilizes a semi-permeable membrane to separate water from dissolved solutes (see Fig. 7). The process is driven by the osmotic pressure difference between a concentrated draw solution and a dilute feed solution, allowing water to naturally diffuse through the membrane while retaining contaminants (Ibraheem et al., 2023; Xu et al., 2022; Blandin et al., 2020). This mechanism is particularly advantageous for treating high-salinity and complex wastewater streams, such as oily wastewater, due to its low energy requirements and reduced fouling propensity compared to pressure-driven processes (Abuhasel et al., 2021). Recent studies have demonstrated the efficacy of FO in removing dissolved organics from oily wastewater, especially in offshore settings where seawater can serve as an abundant draw solution (Liu et al., 2021a). For instance, Abousnina and Nghiem (Abousnina and Nghiem, 2014) evaluated the performance of HTI-Cartridge and HTI-Pouch FO membranes in both RO and FO modes. Their findings indicated that membrane rejection of acetate was highly pH-dependent, with nearly complete rejection at neutral pH levels. Given that produced water from light crude oil typically has a pH ranging from 6 to 7.7, FO presents a promising method for acetate removal without the need for pH adjustment. Furthermore, Han, Zhang (Han et al., 2019), state that FO holds significant promise for treating marine oily wastewater due to its high contaminant rejection efficiency, low energy requirements, and compatibility with high-salinity environments, making it a suitable option for sustainable offshore applications.

Advancements in membrane materials have further enhanced FO performance. The development of thin-film composite (TFC) membranes with antifouling properties, such as those embedded with zwitterionic materials, has shown improved resistance to organic fouling commonly encountered in oily wastewater treatment (Lee et al., 2019). These modifications contribute to sustained water flux and extended membrane lifespan. Hybrid systems integrating FO with other membrane processes have also been explored to address the limitations of standalone FO systems. For example, combining FO with Membrane Distillation (MD) has been investigated for achieving zero liquid discharge (ZLD) in wastewater treatment. In such configurations, FO serves as a pre-concentration step, reducing the load on subsequent MD processes and enhancing overall system efficiency (Ang et al., 2020; Blandin et al., 2016; Al-Obaidi et al., 2024; Yusuf et al., 2020). Despite these advancements, challenges such as membrane fouling and draw solution regeneration persist. Ongoing research focuses on developing more robust membranes and efficient draw solutes to overcome these hurdles, aiming to make FO a more viable and sustainable option for oily wastewater treatment in offshore and other industrial applications.

7.5.4. *Membrane distillation (MD)*

MD a microporous hydrophobic membrane separates water vapor from liquid streams using vapor pressure difference as driving force (Biniaz et al., 2019; Seraj et al., 2022). MD process equipment is smaller and cooler than conventional thermal processes. This method lowers environmental heat loss due to low process temperatures and equipment surface area (Yan et al., 2021). We tried 30 °C for the MD system feed solution, which we usually store at 60–90 °C. Solar, geothermal, and MD systems may reduce economic effects (Orfi et al., 2017). Remote places have cheaper solar-powered MD systems than RO systems (Kashyout et al., 2021). MD removes water ions and non-volatile organic compounds safely and more effectively than RO. Unlike RO, MD is heat-driven yet works from 0 to a few hundred kPa. Renewable energy-powered multi-stage MD devices are proposed (Lee et al., 2017). Typical PTFE, PP, and PVDF MD membranes are chemically resistant polymers and are less prone for fouling (Aijaz et al., 2023). Despite the indisputable nature of the semi-permeable barrier, it is crucial to address membrane fouling to prevent negative consequences. The membrane's surface can absorb oil and other hydrophobic substances, thereby reducing its permeability and selectivity. Consequently, regularly cleaning or replacing the membrane is necessary to maintain cleanliness (Huang et al., 2017). Addressing membrane systems' energy requirements and capital and operational expenditures is also essential.

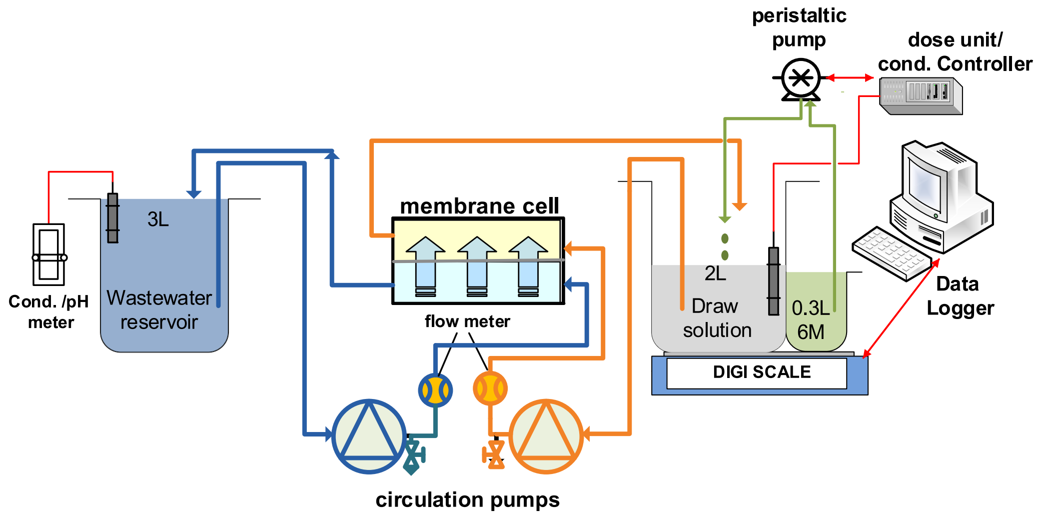

Fig. 7. Schematic diagram of the Forward Osmosis (FO) process for oily wastewater treatment (Abousnina and Nghiem, 2014).

7.6. Hybrid systems as an appropriate alternative

Membrane technology refers to using thin barriers, known as membranes, to separate and purify substances based on their size, shape, or charge. A novel approach to addressing water issues involves integrating membrane processes with other technologies, such as advanced oxidation processes (Kim et al., 2022), activated carbon adsorption, or ion exchange (Bui et al., 2023). These systems provide increased efficiency, a broader range of treatment choices, and decreased costs. Wastewater treatment facilities often use them to eradicate pollutants such as viruses, heavy metals, and organic substances (Bui et al., 2023; Kaleekkal et al., 2021). Hybrid systems are also beneficial for desalinating saltwater or brackish water, as they help decrease energy consumption and minimise the production of harmful byproducts. Compared to traditional techniques, they are ecologically benign since they promote water reuse, minimise chemical use, and reduce energy consumption (Barabadi et al., 2023; Othman et al., 2022). Recent developments in membrane technology have produced more robust membranes, thereby improving the efficiency and longevity of hybrid systems (Shon et al., 2015). Advancements in environmental science, such as forward and RO, bio-membrane systems, and renewable energy integration, have been noteworthy (Preiner et al., 2020). Hybrid systems provide benefits such as improved water quality, higher rates of recovery, and less waste generation. They can treat intricate wastewater, and conventional approaches may not be viable. Nevertheless, fouling, expensive initial expenditures, and the need for skilled operators continue to exist (Molinari et al., 2020). Continuous research and development are essential to overcome these limitations and promote the broader use of membrane technology-hybrid systems in water treatment. Several studies (Pramanik et al., 2017; Pramanik et al., 2016) have suggested several methods for membrane desalination, including NF, RO, MD, and membrane crystallisation (MCr). Nevertheless, while assessing the hybrid system NF-RO with MCr, it is evident that it exhibits the minimal energy consumption compared to other combinations. Scientists researched a hybrid desalination plant system incorporating NF, RO, and MD (Feria-Díaz et al., 2021). This study used NF as a pre-treatment, whereas MD was used to treat the rejection fluid produced by NF and RO. The MD application's implementation has dramatically improved permeate recovery, raising it from 30 % to 76 %, surpassing the performance of a combination of two-stage RO units. Furthermore, this hybrid system reduced the price of purified water from 1.29 $\$/m^3$ to 0.92 $\$/m^3$ compared to the two-stage RO units (Feria-Díaz et al., 2021; Kamel et al., 2023; Rajesh and Chiranjeevi, 2024).

7.6.1. MD-FO hybrid system

Conventional methods for treating oily wastewater often fall short in terms of efficiency and sustainability, necessitating the exploration of innovative and integrated treatment systems. Among these, the hybrid system combining MD and FO has shown promising results in recent studies. The system efficiently manages high-salinity and oil-contaminated streams, attaining substantial water recovery, reduced fouling, and superior elimination of oil, organics, and inorganics. In Nawaz, Alamoudi (Nawaz et al., 2022) study, Water-Oil Separator Outlet (WO) functioned as both the FO draw solution and MD feed solution, while Desalter Effluent (DE) and Wash Water (WW) acted as FO feed solutions. FO attained fluxes of 13.6 $L/m^2/h$ (DE) and 15.8 $L/m^2/h$ (WW), while MD fluxes were 13.2 $L/m^2/h$ and 11 $L/m^2/h$, respectively. Despite $CaSO_4$ scaling, NaCl crystallisation, and oil and grease obstruction, the system achieved >93 % removal of oil, organics, and inorganics, with a feed solution concentration of 77–84 %, significantly reducing disposal volume (Nawaz et al., 2022). The MD-FO hybrid system's performance was further validated by Nawaz, Son (Nawaz et al., 2021), where WO served as both FO draw and MD feed, achieving FO fluxes between 8.3 and 26.78 $L/m^2/h$ and MD flux of 14.41 $L/m^2/h$, with 6 % reduction due to $CaSO_4$ scaling and 2 % due to partial pore obstruction from emulsified oil. EDTA treatment effectively removed scaling, restoring the original MD flux. Son, Alpatova (Son et al., 2025), studied a pre-pilot scale FO-MD module to treat synthetic and real produced water streams, doubling MD permeate production with a 7:1 MD/FO membrane area ratio, achieving >99 % removal of major ions and a 90.1 % reduction in COD, with potable water conductivity (364.9 μS/cm). However, partial pore wetting and organic fouling due to oil and grease were observed, highlighting the need for pre-treatment.

Additionally, Alqulayti (Alqulayti, 2021) demonstrated that integrating FO with MD significantly improved permeate flux, achieving up to 95 % oil removal with lower energy consumption. Almarzooqi (Almarzooqi, 2023) highlighted the impact of feed temperature and flow rates on system performance, while Zielińska and Bułkowska (Zielińska and Bułkowska, 2025) emphasized the role of high-selectivity and thermally stable membranes in enhancing MD-FO integration. Furthermore, Rahimi et al. (2023) achieved a 99 % hydrocarbon removal efficiency, reducing COD from 350 mg/L to below 10 mg/L after 123 h, and Li, Li (Li et al., 2020a) reported lower operational costs due to reduced energy and chemical usage, despite higher initial investment. However, challenges remain in developing sustainable draw solutions and improving membrane materials for long-term scalability. The MD-FO hybrid system has proven highly effective in treating offshore oily wastewater, offering high water recovery, minimal fouling, and excellent removal of oil, organics, and inorganics. The integration of pre-treatment methods (e.g., Electrocoagulation) and advanced membrane materials (e.g., ENM) significantly improves system efficiency and mitigates membrane fouling. The MD-FO hybrid system stands as a sustainable and economical alternative to RO-FO systems, capable of reducing brine disposal volume by up to 84 % and producing high-quality water for reinjection or reuse with minimal energy consumption, especially when utilizing waste heat from offshore platforms. MD-FO systems are extremely effective for providing efficient removal of oil and contaminants, reduced contamination, and high-water recovery. MD reduces energy consumption by utilizing residual heat, while FO prevents membrane contamination and extends the operational lifespan. Furthermore, the system enhances both cost efficiency and sustainability by reducing saline disposal. Nevertheless, the installation of membrane modules and auxiliary components is a challenging task in confined offshore environments due to the energy and space requirements. Although MD profits from the incorporation of residual heat, its thermal energy requirements continue to be substantial.

7.7. RO-FO hybrid system: An optimal solution for offshore platforms

FO can be combined with other treatment methods to regenerate the draw solution and provide filtered water (Xu et al., 2022). This process leads to nearly zero liquid discharge because the draw solution dilution reconcentrates. However, when dealing with heavily contaminated source waters, FO may serve as a highly efficient pre-treatment method for the subsequent procedure susceptible to fouling (Johnson et al., 2018; Peters, 2021; Ahmad et al., 2020b). It is anticipated that FO-oriented hybrid methods will surpass conventional techniques in performance. The combination of FO with NF, RO, MD, and other membrane separation technologies offers exciting potential for enhanced efficiency and sustainability in various applications. This integration leverages the strengths of each method, optimizing factors like energy consumption, water recovery, and overall process effectiveness. Researchers have employed RO and FO for the remediation of sludge (Li et al., 2019). At a pressure of 8.7 bar (0.87 MPa), the weak draw solution was pushed through the low-fouling composite polyamide (LFC) RO membrane. The FO-RO process combination kept the flow rate steady for a long time, even though it lost a lot of nutrients, including ammonia (84.3 %), total Kjeldahl nitrogen (TKN) (8.7 %), and orthophosphate (99.8 %). Even when working with high beginning concentrations, the process consistently maintained a constant flow and limited the accumulation of particles on the membrane.

7.7.1. An optimal solution for offshore platforms

The current situation on offshore platforms includes an existing RO desalination system that produces distilled water from seawater to meet the daily needs of the offshore facilities. The direct discharge of concentrated brine from desalination facilities into the ocean presents considerable environmental issues. The increasing salinity and warmth may damage marine ecosystems by modifying water chemistry, diminishing oxygen levels, and adversely affecting aquatic animals (Panagopoulos et al., 2019; Shah et al., 2022; Sirota et al., 2024). The release of oily wastewater into the ocean exacerbates the problem by adding hydrocarbons and other hazardous contaminants that may accumulate in marine organisms, damage water quality, and jeopardise biodiversity (Thiagarajan and Devarajan, 2024; Saidu et al., 2025; Tariq and Mushtaq, 2023). The cumulative effect of these two significant waste streams, brine from desalination and effluent from oily wastewater treatment, constitutes a substantial risk to marine ecosystems, possibly resulting in enduring ecological imbalances and declining biodiversity. A more sustainable and efficient approach would be to integrate FO with the existing RO system.

This hybrid FO-RO design provides an eco-friendly method for treating oily wastewater by markedly improving water recovery and reducing environmental impact. This technology successfully reduces salinity to levels akin to seawater, therefore obviating the need for brine discharge and alleviating the detrimental impacts of high-salinity effluents on marine ecosystems. Furthermore, it enhances resource utilisation by increasing water reuse efficiency, making it a more ecologically sustainable and economically feasible method for wastewater treatment. Fig. 8 depicts the authors' proposed hybrid system that integrates FO/RO technologies for offshore oil installations. This method employs FO to create an osmotic pressure gradient across a semi-permeable membrane by using a concentrated draw solution, hence enabling water transfer (Rufuss et al., 2022; Wibisono and Bilad, 2020). The FO process demonstrates less sensitivity to fouling relative to RO, making it a more robust and efficient choice for wastewater treatment in offshore settings.

Multi-stage direct-pass RO reduces the system's average hydraulic pressure for feed to flow through membrane components, reducing energy losses and boosting energy efficiency (Li et al., 2020b). A multi-stage RO process (typically up to three stages) pumps the high-pressure concentrate of the previous stage into the next stage as feed. Stage recoveries vary from 75 % to 90 %, depending on feed type (Li et al., 2020b). In this scenario, the first stage, RO, is typically the first step, concentrating wastewater to around 70,000 mg/L, which corresponds to an osmotic pressure of approximately 59 bar (Davenport et al., 2018). The recovery rate, which refers to the percentage of feedwater converted into freshwater, is crucial in determining the salt concentration in the brine concentrate. In this proposed multi-stage design, brine concentrations will progressively increase at each stage to optimize water recovery. The first stage will concentrate the brine to 90,000 mg/L, setting the foundation for further intensification. The second stage will then push the concentration up to 95,000 mg/L; finally, the third stage will reach a peak of 100,000 mg/L (ppm). This stepwise concentration method maximizes water recovery and efficiently manages high-salinity brine, reducing waste.

$$c_f Q_f = c_b Q_b + c_p Q_p \tag{1}$$

$$c_f Q_f = (c_{b1} Q_{b1} + c_{b2} Q_{b2} + c_{b3} Q_{b3}) + (c_{p1} Q_{p1} + c_{p2} Q_{p2} + c_{p3} Q_{p3}) \tag{2}$$

where c_f and Q_f represent the molar concentration and flow rate of the feed, respectively; c_b and Q_b denote the molar concentration and flow

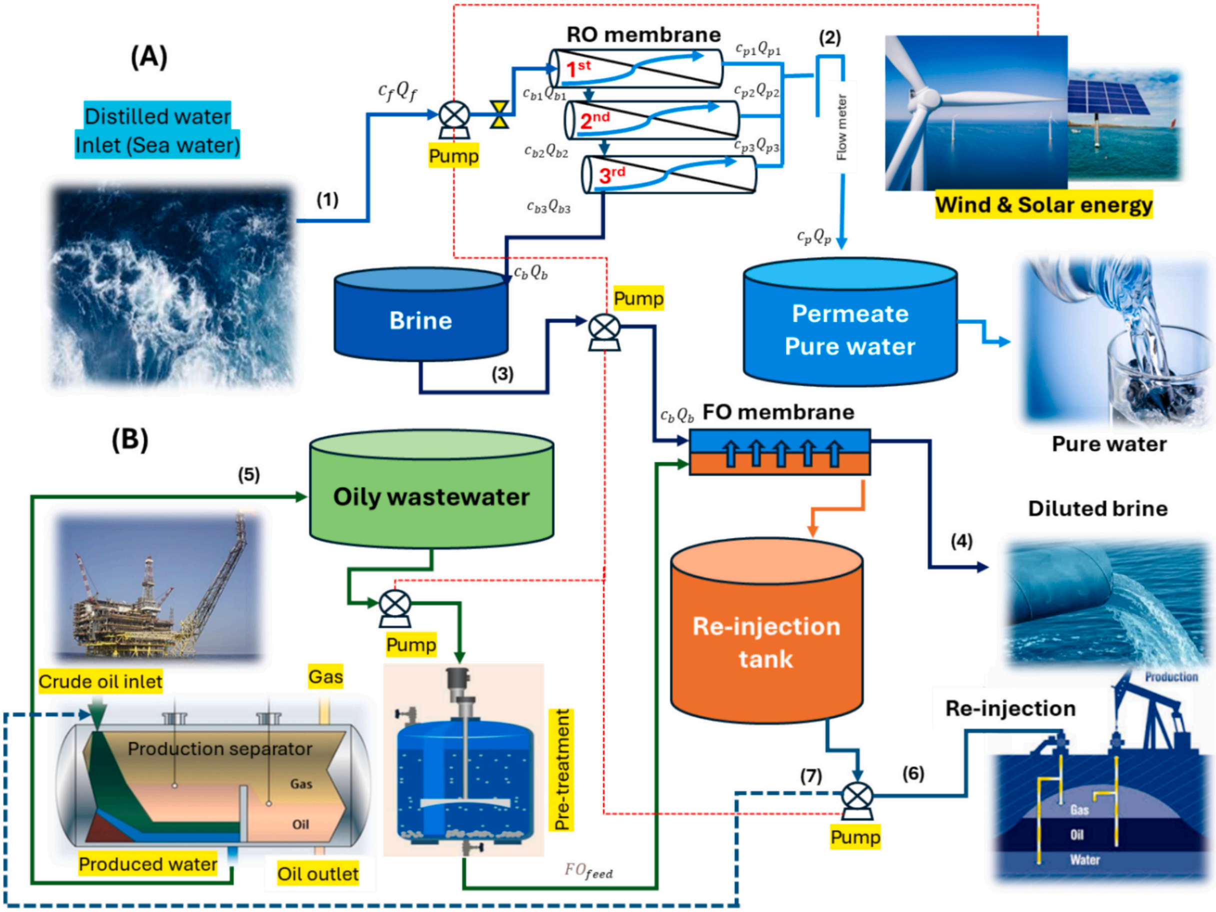

Fig. 8. Schematic of experimental RO/FO lab scale hybrid system, as one of the possible combinations among others.

rate of the brine, respectively, and c_f and Q_f refer to the molar concentration and flow rate of the permeate, respectively.

From the water mass balance,

$$Q_f = Q_b + Q_p \tag{3}$$

where Q_f is the flow rate of feed water, $Q_b$is he total concentrated brine and Q_p is the flow rate of freshwater.

A multi-stage RO system elevates the brine concentration as more water is removed as permeate. The ultimate concentration is dictated by the recovery rate, which specifies the proportion of water transformed into permeate. The first phase starts with a brine concentration of 70,000 ppm, increasing the fluid's osmotic pressure. RO systems generally function well, with brine concentrations reaching around 70,000 ppm (Al-Amoudi et al., 2023; Mann et al., 2020). The second step achieves a recovery rate of 50 %, increasing the brine content to around 95,000–105,000 ppm. The concentration is contingent upon the system's design and efficacy, and the kind of membranes used. If the recovery rate stays stable, the concentration in the third stage may reach 130,000–150,000 ppm. Multi-stage systems are designed to enhance recovery, improving water extraction efficiency yet leading to elevated amounts of brine. When selecting a draw solution, the main criterion is that the solution has a higher osmotic pressure than the feed solution in terms of producing high water flux because the osmotic difference is the driving force in FO (Xu et al., 2022; Johnson et al., 2018). The second important criterion in some applications of FO is selecting a suitable process for re-concentrating the draw solution after it has been diluted in the FO process. The third criterion considers the solute diffusion from the draw solution through the membrane. Based on these criteria, several inorganic compounds (salts) have been used as draw solutions in the FO process, including seawater (Chaoui et al., 2019), Dead Sea water (Lee et al., 2024), and salt lake water (Bacaksiz et al., 2021). The highly concentrated brine ($Q_{b=\sim 130,000-150000\ mg/L\ (ppm)}$), generated through this process, is suitable for integrating FO systems as a draw solution. It is viable for applications requiring high osmotic pressures and efficient solute recovery. This design approach enhances the system's versatility and offers a sustainable solution for advanced water treatment and zero oily wastewater liquid discharge (ZLD) scenarios.

8. Conclusion

Managing oily wastewater on offshore platforms is crucial to safeguarding marine ecosystems, and selecting efficient, adaptable treatment technologies can greatly enhance environmental protection. This review evaluated various treatment strategies and underscored the unique offshore challenges, such as high operational costs, membrane fouling, and space limitations.

- Forward Osmosis (FO), while not yet widely implemented in oily wastewater treatment, demonstrates strong potential due to its operation under ambient conditions, high rejection of dissolved organics, and compatibility with high-salinity feedwaters typical of offshore settings. Its reduced fouling propensity and ability to operate without high hydraulic pressure make it especially suitable for space-constrained and energy-limited offshore environments. Continued research should focus on improving FO membrane durability, optimizing draw solution regeneration, and enhancing system scalability to lower costs and boost operational feasibility.
- A hybrid FO-RO system emerges as one of the most promising configurations for offshore platforms. This combination delivers high contaminant removal efficiency and energy savings, particularly when integrated with appropriate pre-treatment to mitigate fouling. Membrane Distillation (MD) is another viable option, especially where waste heat is available, offering a pathway toward achieving Zero Liquid Discharge (ZLD). Integrating FO with MD or RO augmented by advanced membrane materials, nanotechnology for antifouling enhancements, and biotechnology for biofouling resistance represents a significant future direction.
- Moreover, powering membrane systems with renewable energy, such as solar, aligns with the operational demands of remote offshore sites. The brine generated from these systems holds additional potential for hydrocarbon recovery or use in geopolymer concrete production, offering both environmental and economic benefits. However, further studies are required to validate the long-term performance of such brine applications in sustainable construction.

In summary, FO stands out as a promising candidate for the next generation of offshore oily wastewater treatment technologies. Its future lies in technological refinement, system integration in hybrid systems, and leveraging synergies with emerging innovations to overcome current limitations and meet sustainability goals.

CRediT authorship contribution statement

Rajab Abousnina: Writing – original draft, Project administration, Methodology, Formal analysis, Conceptualization. **Noreddine Ghaffour:** Writing – review & editing, Validation, Conceptualization. **Long D. Nghiem:** Writing – review & editing, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no conflict of interest.

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Data availability

No data was used for the research described in the article.

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