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Environmental Applications of Advanced Superwetting Membranes for Oil-Water Separation

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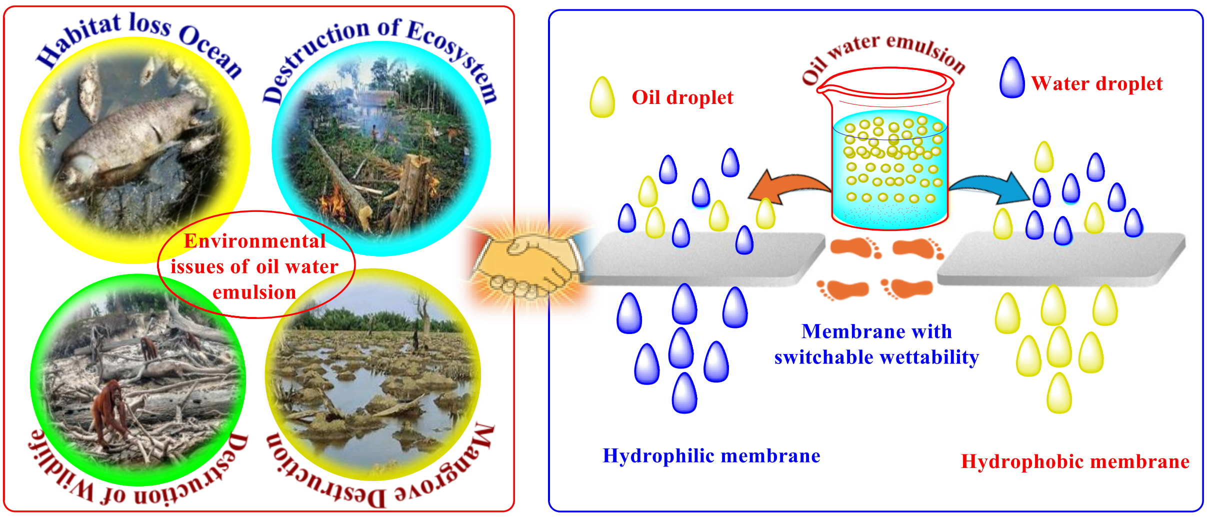
Abstract: The prevalence of oil pollution is steadily escalating due to the growing reliance on oil in human daily routines and industrial operations, with global consumption exceeding 100 million barrels per day. Membrane-based separation of oil-water emulsions has demonstrated critical performance characteristics essential for industrial applications, including affordability, environmental sustainability, simplicity of operation, and energy efficiency. The membranes show remarkable durability, maintaining over 98.5% separation effectiveness after 40 repeated operations. Investigating Membranes with distinctive super-wettability properties for filtration and various practical uses has become a highly compelling area of research in recent years. These super-wetting membranes are not just limited to Oil-water filtration but have a wide range of potential applications, making them a versatile solution to many environmental challenges. This review synthesizes recent advancements in membrane technology, highlighting key innovations and emerging trends, focusing on its exceptional super-wettability qualities and enhanced characteristics for separating oil and water. In addition, this article focuses on the wetting behavior of these versatile membranes and summarizes various surface-wetting categories, including superhydrophilic ($\theta < 10°$), underwater superoleophobic ($\theta_{oil} > 150°$), and superhydrophobic-superoleophilic ($\theta_{water} > 150°$, $\theta_{oil} < 10°$) membranes. It also analyses the possible difficulties and barriers associated with these membranes. This research summarizes the advancements in creating versatile super-wetting membranes for separating oil and water. It ends by proposing prospective areas for additional enhancement and alteration, instilling a sense of intrigue about the potential applications of these membranes.

Keywords: Surface wettability, Oil, water emulsion, Emulsion problems, Membrane separation.

Graphical Abstract



Research Highlights

Environmental problems of oil-water emulsion

Wettability of multifunctional membranes with bright surface.

Construction and fabrication of wetting multifunctional membranes.

Oil-water separation and toxic pollutants remediation application of super-wetting membranes

Possible future outlook and optimized technology of super-wetting membranes.

1. Introduction

The increasing occurrence of Unrefined oil mixing with salt water. Due to spills and Manufacturing discharge, including water, it is detrimental to water bodies Human actions characterized by a lack of caution, such as mishaps in the oil industry and the excessive volume of water used in oil field procedures, have collectively contributed to environmental catastrophes. Nevertheless, the need for fresh water is escalating due to the expanding human population, as it is an essential requirement for human survival. On the other hand, freshwater resources are declining at an alarming rate, sparking fears that current reserves may become insufficient to satisfy daily water needs. Therefore, the global concern for access to clean water has significantly increased. Developing methods to generate clean water through oil-water separation has emerged as a critical priority [1].

Scientists worldwide are developing advanced membrane-based systems for oil-water separation, including polymeric membranes and stainless-steel mesh materials. Recent research focuses not only on achieving high flux but also on creating multifunctional membranes capable of removing organic pollutants, dyes, metal ions, and bacteria. These membranes are attractive because they are cost-effective, environmentally friendly, easy to fabricate, and resistant to harsh conditions and biofouling. Depending on their surface properties, they may exhibit superhydrophilic, superoleophobic, superhydrophobic, superoleophilic, or underwater superoleophobic behavior. During membrane fabrication, key factors such as wettability, surface morphology, separation efficiency, and pollutant-removal ability are carefully controlled to improve water quality and overall treatment performance.

2. Oil-water Separation Using Super-Wetting Membranes

The water contamination caused by natural seeps, oil spills, and other oil foundations poses a significant threat to the survival of living organisms due to the presence of oily water and black tides. The presence of this contaminant in water is of considerable importance to scientists in the modern day. Meeting the need for a consistent supply of purified water has become a Major Obstacle The prevalence of oil pollution is steadily rising due to our regular activities and industrial procedures, such as those carried out in the petrochemical industry and oil and gas extraction, which heavily rely on oil. Significant and concerning damages have occurred in recent decades due to the ambiguous jurisdiction over petrochemicals and crude oil. The Mexican Gulf saw substantial damage when the Deepwater Horizon rig explosion caused in the release of 200 million gallons of oil into the ocean. Nevertheless, predominantly contaminated with harmful chemicals, Water contaminated with oil presents serious dangers to both marine environments and human populations [2]. Several techniques can be employed to separate oil from water, including gravitational pull (via flotation), skimming, centrifugal force (using a cyclone separator), electric possess certain disadvantages, including poor performance, costly operation, excessive power potential (by ionization/magnetic separation), and photocatalytic treatments. However, they consumption, the production of pollutants, and limited applicability to oil and water emulsions. Therefore, finding an optimal method for Oil-water emulsion separation is necessary to prevent excessive expenses and address the pressing need to protect the environment.

The selection of an oil-water separation method depends mainly on the dimensions and stability of the dispersed oil droplets. There are three distinct groups defined according to the diameter of oil droplets: dispersed oil (oil droplets with a diameter ranging from 0.02 to 0.15mm), emulsified oil (Oil droplets with a diameter smaller than 0.02 mm, and free float (oil droplets with a diameter higher than 0.15 mm). Nevertheless, the separation of oil-in-water emulsions continues to pose significant difficulties owing to the minimal interfacial energy existing between oil and water phases**.** Oil-water emulsions are fundamentally classified into two types: oil-in-water (O/W) systems, characterized by oil droplets dispersed in a continuous water phase, and water-in-oil (W/O) systems, featuring water droplets dispersed in a continuous oil phase**.** In a mixture of water and oil, the water is in the continuous phase, while the oil is in the dispersed phase. The opposite is also true for a mixture of oil and water [3].

Research on oil-water separation is increasingly focused on membrane-based methods because they offer high efficiency, low operating cost, compact design, environmental compatibility, and suitability for continuous production. Membrane separation has been widely applied in desalination, bioreactors, food processing, wastewater treatment, refineries, gasification, and degasification. Pressure-driven processes such as microfiltration, ultrafiltration, nanofiltration, and reverse osmosis are commonly used, while forward osmosis, membrane distillation, and systems driven by electric, magnetic, or gravitational forces are also being explored. However, membrane performance is often limited by oil droplet blockage, surfactant adsorption, fouling, swelling, and pressure-induced compaction. Therefore, effective membranes should possess strong antifouling ability, mechanical stability, high selectivity, and improved permeability. Recent advances in nanotechnology provide new opportunities to enhance membrane design and oil-water separation performance.

3. Surface Wettability

Wetting phenomena arise at the interface between a liquid and solid surface. When two different phases interact, this phenomenon is described as an interfacial contact among two separate phases. When discussing oil-water parting, wetting is defined as the interaction among the air, oil, solid, and water (membrane) phases. The technology employed for separating oil from water is membrane-based, and it is cost-effective, user-friendly, highly effective, and, most significantly, environmentally safe. Therefore, we must comprehend the underlying factors that drive this technology. This is why it is imperative to know the concept of wettability. We initially establish a precise definition for the word "contact angle" to distinguish among different models. The contact angle (θ) is defined as the angle formed at the three-phase interface where a liquid droplet meets both a solid surface and surrounding gas phase**.** Typically, oils have lower surface tension than water [4].

3.1. Young's Equation

This represents the optimal scenario in which the droplet takes on a perfectly spherical shape on a flat and even surface (Figure 1a). Equation (1) expresses the contact angle as having three interfacial surface tension functions: solid-liquid (SL), liquid-vapor (LV) and solid-vapor (SV).

$$\cos\theta=(\gamma_{sv}-\gamma_{sl}) \qquad \gamma_{lv} \tag{1}$$

Here, γ_{SV} denotes the interfacial surface between the solid and vapor phases. The interfacial tensions γ_{LV} and γ_{SL} correspond to the liquid-vapor and solid-liquid phase boundaries, correspondingly. Furthermore, this framework presupposes that the surface is chemically consistent and has a consistently even topography. However, this assumption does not hold for actual surfaces [5].

3.2. Wenzel's Equation

Wenzel's model extends Young's equation by accounting for surface roughness effects, as illustrated in Figure 1b. Equation 2 now gives the adjusted contact angle.

$$\cos \theta_W = r \cos\theta \quad (2)$$

The variable θ_W represents the contact angle reached in the equilibrium state. The roughness factor (r) is determined by dividing the true surface area by its geometric projected area. The roughness factor r equals 1 for a Flat surface, while it is greater than 1 for rough surfaces. Once more, this model is limited in its assumption that liquid has a propensity to infiltrate the irregularities of rough surfaces. If the fluid cannot penetrate, the model becomes ineffective, necessitating the development of a new model [6].

3.3. Cassie-Baxter's Equation

The Cassie-Baxter model extends Wenzel's theory by incorporating additional surface parameters; in this model, Baxter and Cassie discussed the Wetting process of uneven surfaces. The rough surface has limited air pockets between the bumps, preventing liquid droplets from entering the Nano-structured area. This causes the droplets to tilt due to weak adhesive forces (Figure 1c). Thus, contact angle measurements indicate a significant increase, resulting in a θ_{CB} value exceeding 150 °. Furthermore, surfaces that exhibit these contact angles are referred to as superoleophobic/superhydrophobic surfaces. The Cassie-Baxter model allows for the calculation of the new contact angle using a specific equation (3).

$$\cos\theta_{CB} = r_f\, f_{SL} \cos\theta + f_{SL} - 1 \quad (3)$$

The variables in question are as follows: f_{sl} represents the portion of the solid-liquid interface within the contact area, and r_f denotes the Surface irregularity factor of the wetted section of the solid surface. Moreover, θ_{CB} represents the Cassie-Baxter contact angle. It is crucial to emphasize that rf is less than r, as illustrated in Figure 1.

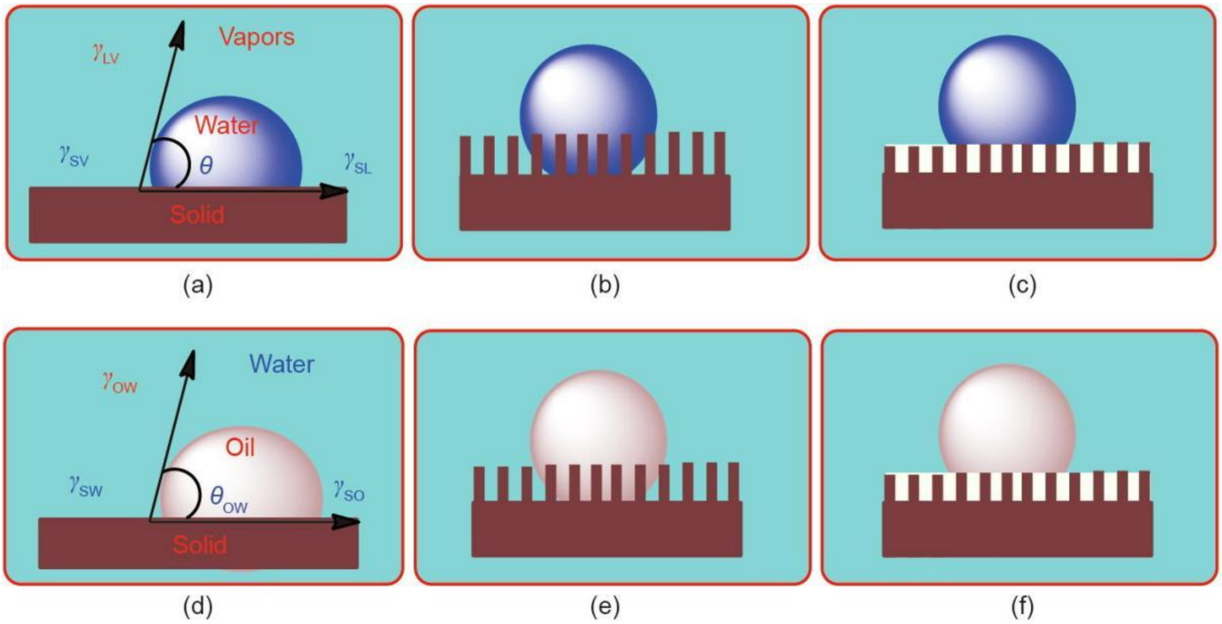


Figure 1. Liquid droplets exhibit distinct wetting properties when deposited on textured solid surfaces in a gaseous (vapor) environment. Include (a) Young's state, (b) Wenzel's state, and (c) Cassie's state. For oil droplets on different solid surfaces submerged underwater, the wetting states are represented as (d) underwater Young's state, (e) underwater Wenzel's state, and (f) underwater Cassie's state [7]

4. Super-Wetting Membranes Development and Versatile Applications

4.1. Super Hydrophilic and Underwater Superoleophobic Functionalized Membrane

Superhydrophilic and underwater superoleophobic functionalized membranes are effective materials for oil-water separation. Their water-attracting surface allows water to pass through the membrane easily, while their oil-repelling behavior under water prevents oil droplets from sticking to the surface. This special wettability helps improve separation efficiency, reduce membrane fouling, and maintain stable performance during oily wastewater treatment. Hydrodynamic irreversible oil fouling of membranes poses a significant challenge. A membrane composed of Al_2O_3 coated with TiO_2, designed to resist fouling with exceptional wettability, was developed by wang et al. by applying a sol-gel technique to form A layer of nano-TiO_2 anatase that was applied to the alumina (Al_2O_3) ceramic membrane's surface (Figure 2A). the evaluation of the separation efficiency of an Al_2O_3 @TiO_2 membrane using modeled o/w emulsions. Analysis revealed a TiO_2-coated membrane surface with a 0.8 mol·L^{-1} deposition concentration. The combined effect of The Al_2O_3 @TiO_2 membrane, along with a UV light and hydrophilic nano-TiO_2, exhibited enhanced wettability and self-cleaning properties while retaining an excellent separation rate (769.23 L·m^{-2}·h^{-1}, 97.75%, 1.23 mg·L^{-1}), After six consecutive hours filtering real oilfield-produced water, the membrane's flow rate was fully restored following a 30-minute UV irradiation treatment. This occurs because the active species (e.g., $1O_2$, OH, and O_2) produced in situ on the Titanium dioxide surface following UV exposure reduce the membrane surface fouling interactions, leading to decreased oil fouling. Furthermore, the Al_2O_3@TiO_2 membrane exhibited exceptional oil resistance, recoverability, and stability throughout Hydraulic flushing at high intensity and 25 testing cycles. The water contact angle (WCA) of the Al_2O_3 @TiO_2 ceramic membrane remained consistently at 0°

after the intense blushing, while the underwater oil contact angle (UWOCA) varied between 151.67° and 153.98°. This research provides a conceptual foundation for employing ceramic-based filtration systems in oilfield wastewater remediation [8].

A ceramic membrane enhanced with an amino-functionalized inorganic metal oxide and a synthetic polymer was developed by Baig et al. to improve surface wettability for both water and oil, while also enhancing its self-cleaning capabilities through photocatalytic action. The membrane produced was used for treating wastewater contaminated with crude oil using a Cross-flow membrane filtration system (Figure 2B). The primary functional material, aminopropyl triethoxysilane-modified tungsten oxide nanoparticles, was synthesized and applied to the surface of a ceramic support made from alumina through interfacial polymerization. During this process, the material forms Covalent cross-links within the active layer of the membrane, with terephthaloyl chloride (TPC) functioning as a cross-linking agent. At the same time, piperazine (PIP) serves as an external amine. The essential factor in creating a ceramic membrane composed of NH_2-WO_3/PA@alumina that allows water to pass through is achieving a distinctive Composite wetting properties. The fabricated membrane displayed extreme hydrophilicity, showing 0° water contact angles in air, along with exceptional underwater oil-repellency evidenced by 160.25° oil contact angles. The membrane's second significant advantage is its self-cleaning ability, which is attributed to the inherent ability of WO_3 nanoparticles to catalyze photochemical reactions, a crucial characteristic. Enhancements were achieved via amino functionalization, table 1 presents numerous types of hydrophilic/superhydrophilic and underwater superoleophobic films, along with their multifunctional applications. The filtration process utilized an NH_2-WO_3/PA-coated alumina ceramic membrane as the substrate in a cross-flow configuration to separate a crude oil-in-water emulsion containing 50 ppm oil. A permeate flux of water of 250 L m^{-2} h^{-1} was achieved, along with an oil/water separation efficiency approaching 100%. after approximately 210 minutes of operation, the permeate flux dropped to around 25% of its initial value. This decrease occurred because organic contaminants in oil-rich water clogged the membrane pores. *UV irradiation restored the permeate flux by activating the membrane's inherent photocatalytic self-cleaning properties*. Its capacity to permit water flow guarantees enhanced efficiency. the self-cleaning feature eliminates the need for chemical cleaning methods, making it globally sustainable [9].

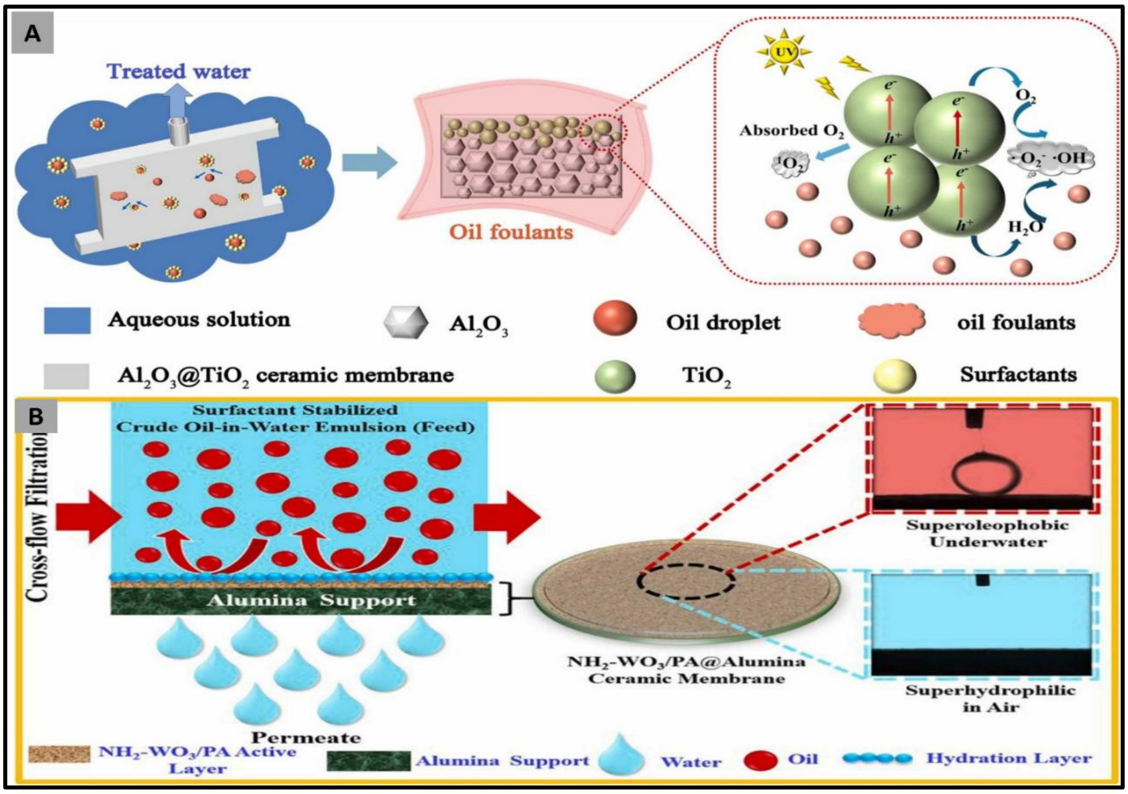


Figure 2. (A) A novel Al_2O_3@TiO_2 ceramic membrane was engineered to demonstrate simultaneous superhydrophilic and underwater superoleophobic characteristics, exhibiting efficient oil/water emulsion separation [8]. (B) The process of amino-functionalizing tungsten oxide nanoparticles enables their stable integration into the functional layer of an inorganic-organic hybrid membrane, which is supported by alumina. This membrane integrates super-wettable surfaces with photocatalytic self-cleaning functionality, specifically engineered for high-performance crude oil/water emulsion separation [9]

Table 1. Hydrophilic/Superhydrophilic and Underwater Oleophobic/Superoleophobic High-performance multifunctional materials

Material	Wetting behavior	Contact angle	Multifunctional applications	References
Multiscale absorbent silica/graphene oxide hybrid film	Hydrophilic and Underwater	WCA (In air) = ~14° OCA (Under water) = ~156°	Methylene blue elimination, Oil-water emulsion separation	[10]
PDA-modified RGO-SiO2/PVDF asymmetric membrane	Hydrophilic and Underwater Oleophobic	WCA (In air) = ~39.8° OCA (Under water) = ~130°	O/W emulsion demulsification	[11]
SS mesh with GO-SiO_2 nanocomposite coating.	Superhydrophilic and Underwater Oleophobic	WCA (In air) = ~4° OCA (Under water) = ~143.5°	Oil-water separation, Antibacterial activity	[12]
Glass fiber substrate with DKGM hydrogel coating	Superhydrophilic and Underwater super-oleophobic	WCA (In air) = ~0° OCA (Under water) = ~157.6°	O/W emulsion demulsification, Adsorption of chromophores and toxic metals	[13]
SS mesh with Fe-doped TiO_2 nanoparticle deposition	Superhydrophilic and Underwater superoleophobic	WCA (In air) = ~0° OCA (Under water) = ~148°-160°	O/W emulsion demulsification, Photocatalytic toxin decomposition	[14]
KGM-grafted fabric with dual capabilities	Superhydrophilic and Underwater superoleophobic	WCA (In air) = ~0° OCA (Under water) = ~161°	Oil/water partitioning , Methylene blue (MB) remediation from wastewater	[15]
Palygorskite nanorod films strengthened with cellulose nanocrystals	Super-hydrophilic and Underwater super-oleophobic	WCA (In air) = ~0° OCA (Under water) = ~161.7°	O/W emulsion demulsification, Oil-water emulsion separation, and Elimination of hydrophilic pollutants	[16]
PAA-grafted CNT nanocomposite filter	Superhydrophilic and Underwater superoleophobic	WCA (In air) = ~0° OCA (Under water) = ~152°	Oil-water separation, Oil-water emulsion separation, Dye removal	[17]
Multiscale TiO_2 nanotube-architected membranes.	Superhydrophilic and Underwater superoleophobic	WCA (In air) = ~0° OCA (Under water) = ~156.7°	MB dye removal, Oil-water separation	[18]

4.2. Superhydrophobic and Superoleophilic Dual-Functional Membranes

Superhydrophobic and superoleophilic dual-functional membranes are useful materials for oil-water separation, especially for removing oil from water. Their water-repelling surface prevents water from passing through, while their oil-attracting property allows oil to spread and penetrate easily. This selective wettability improves separation efficiency and makes these membranes suitable for treating oily wastewater and recovering oil from contaminated water. As we know, the release of industrial oily wastewater poses environmental risks. To resolve this challenge**,** Liu et al. designed a nitrocellulose film with superhydrophobic and superoleophobic properties, utilizing a combination of cobalt hydroxide and stearic acid (STA) to achieve these characteristics. This is for efficient oil separation from water and the concurrent elimination of dissolved dyes. The Structural strength of the $Co(OH)_2$/STA-based SSNMs was enhanced by coating cellulose fibers with STA and $Co(OH)_2$, as shown in (Figure 3A). The fabricated SSNM exhibits excellent superhydrophobic properties, featuring a Surface wetting angle of $164 \pm 2°$ and exceptional superoleophilicity, with the Oil wettability angle approaching 0°. The membrane established firm consistency in use, achieving high separation efficiencies of over 94.0% and Permeation rates exceeding 130 $L \cdot m^{-2} \cdot h^{-1}$ for four different lubricants. The efficiency and Filtration rate for N-hexane remained virtually unchanged after multiple separation cycles. It demonstrated consistent photocatalytic performance, aiding in reducing organic pollutants. Table 2 represent numerous Superhydrophobic and superoleophilic membranes, the $Co(OH)_2$/STA-based SSNM exhibits excellent promise for real-world uses, including the photocatalytic breakdown of organic contaminants and oil-water segregation [19].

Satria et al. developed polyurethane foam-based superhydrophobic/superoleophilic materials coated with three distinct polymers and extensively modified using an iron/magnetic nanocomposite. The primary goals include investigating the influence of the polymer coating and removing oil contaminants from the oil-water mixture, which is essential for advancing environmental technologies. These materials were produced by means of a simple two-step dip-coating procedure on the surface of polyurethane foams (PUF), which is shown in (Figure 3B). Layers of polypyrrole, polydopamine, and polyaniline (PDA/PPy/PANI) were applied to the PUF, followed by incorporation of Fe-stearic acid (Fe-SA) nanocomposites using ultrasonication and reflux techniques. Additionally, characterization through TGA, XRD, SEM/EDX, and FTIR verified the successful coating of the PUF surface by the polymer layers and Fe-SA nanocomposites, attributed to the coordination interaction between the carboxylate groups and the reactive sites on the iron particles, enabled by the company of Dipole-dipole hydrogen bonding. Notably, the Water droplet angle (WCA) analysis of the Nanostructured composites showed a notable rise, reaching as high as 164°. Following 20 rounds of oil absorption, the WCA consistently stayed around 153°, demonstrating the material's superhydrophobic solid characteristics. The materials' capacity for oil absorption was also assessed through standard Separation of oil and water techniques, including tests for oil permeate flux, reusability, and separation efficiency. The findings showed that enhanced PUFs exhibited an absorption ability of up to 44 times their weight, achieved a separation effectiveness of 99%, and reached an Oil flow rate of approximately 8000 $L \cdot m^{-2} \cdot h^{-1}$. *The dyed oil was swiftly absorbed by the material, promoting effective separation, which occurred in just* 2 seconds. *These materials demonstrated exceptional performance in large-scale oil-water separation, confirming their high efficiency.*

The PDA-coated PUF nanostructured composites produced the most advantageous outcomes due to their excellent interfacial adhesion characteristics; these also offer extra active functional groups that enable hydrogen bonding interactions between the PUF surface and Fe-SA Nanostructured composites [20].

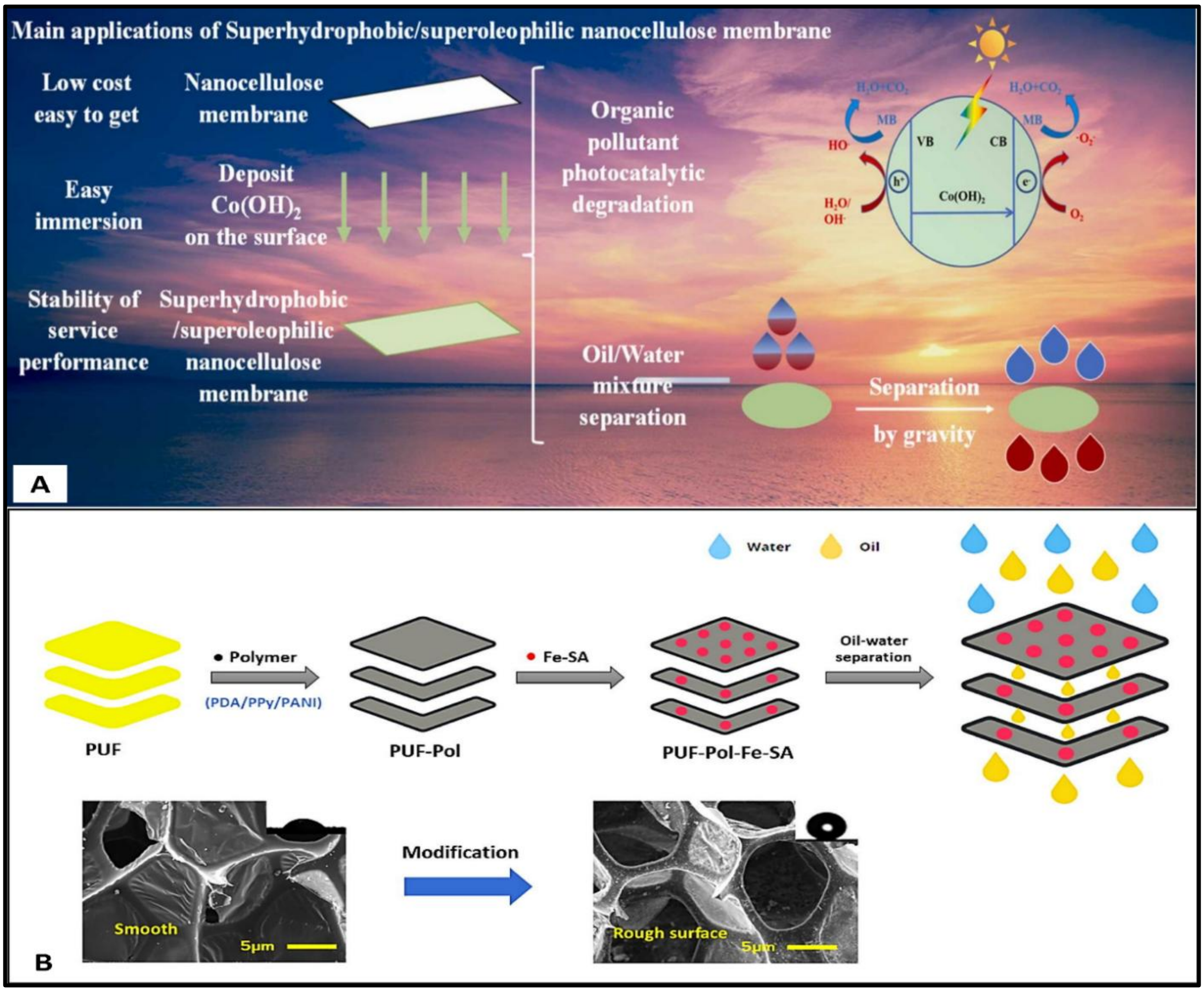


Figure 3. (A) Robust nanocellulose membrane based on stearic acid and cobalt hydroxide with superhydrophobic and superoleophilic properties engineered to separate water and oil while eliminating dissolved dyes effectively [19]. (B) Development of superhydrophobic/super oleophobic magnetic polyurethane modified with stearic acid and polymer for the Oil-water demulsification [20]

Table 2. Superhydrophobic and superoleophilic membranes

Material	Wetting behavior	Contact angle	Multifunctional applications	References
FAS-functionalized PU foam	Superhydrophobic and superoleophilic	WCA (Air) = ~155° OCA (Air) = ~0°	Self-cleaning, Oil-water filtration	[21]
MTES-derived polymeric membrane	Superhydrophobic and superoleophilic	WCA (Air) = ~150° OCA (Air) = ~0°	Advanced automotive air filtration systems, Oil-water filtration	[22]
ODP-grafted TiO_2-deposited metallic mesh	Superhydrophobic and superoleophilic	WCA (Air) = ~165° OCA (Air) = ~0°	Dye removal, Oil-water separation	[23]
SS mesh with a CeO_2 nanoparticle layer	Superhydrophobic and superoleophilic	WCA (Air) = ~150° OCA (Air) = ~0°	MB dye elimination, Oil-water separation	[24]
Superhydrophobic SiO_2 hollow microsphere-coated substrates	Superhydrophobic and superoleophilic	WCA (Air) = ~153° OCA (Air) = ~0°	Oil-water emulsion separation, Self-cleaning	[25]

4.3. Oleophobic, Super-Oleophobic, And Superhydrophilic Multifunctional Membranes

Oleophobic, superoleophobic, and superhydrophilic multifunctional membranes are advanced materials designed for efficient oil-water separation and wastewater treatment. Their water-attracting surface allows rapid water permeation, while their oil-repelling behavior prevents oil droplets from attaching to the membrane. This combination helps reduce fouling, improve separation efficiency, and maintain stable performance, making these membranes useful for treating oily wastewater containing different pollutants. Oily wastewater poses serious environmental and health risks, making efficient oil-water separation essential. Chen et al. developed a self-cleaning underwater superoleophobic/superhydrophilic membrane through the electrochemical oxidation of polypyrrole doped with sodium lignosulfonate. The membrane showed strong water affinity and oil-repellent behavior in both air and underwater conditions while maintaining stable performance in oxidized and reduced states as shown in Figure 4A. It achieved oil-water separation efficiencies above 98.44% for various organic compounds and retained high efficiency and flux over 70 cycles, exceeding 97.18% and 70.14 $L \cdot m^{-2} \cdot h^{-1}$, respectively. These results indicate that the membrane has excellent recyclability, stability, superhydrophilicity, and underwater superoleophobicity, making it a promising material for oily wastewater treatment and oil recovery [26]. Raj et al. demonstrated the use of a strontium-based metal-organic framework (Sr-MOF) for efficient oil-water separation. The Sr-MOF was synthesized using strontium nitrate as the metal precursor and 1,4-benzenedicarboxylic acid (H_2BDC) as the organic ligand. Owing to its superhydrophilic and underwater oleophobic properties, the MOF achieved more than 99% oil rejection under gravity-driven separation as shown in Figure 4B. It also showed underwater oil contact angles above 132° for various oils, supporting its strong oil-repellent behavior based on the Cassie-Baxter model. The membrane flux depended on the support material, exceeding 500 $L \cdot m^{-2} \cdot h^{-1}$ on cotton fabric and 5000 $L \cdot m^{-2} \cdot h^{-1}$ on steel mesh. Reusability tests over at least 20 cycles showed stable oil rejection and structural durability, indicating that Sr-MOF is a promising material for oil-water separation applications [27].

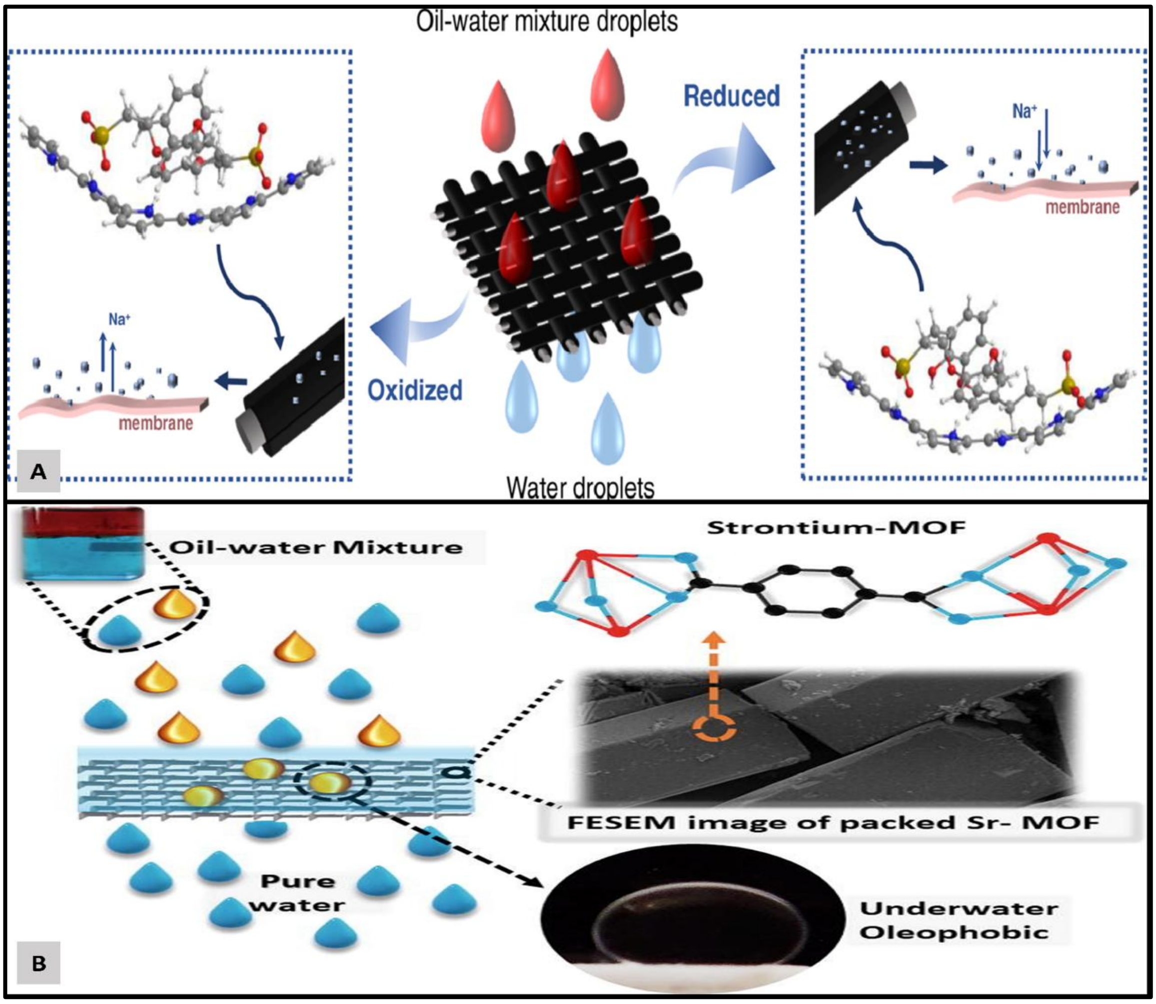


Figure 4. (A) robust underwater super-oleophobic and super-hydrophilic conductive polymer membrane designed for oil-water separation [26]. (B) Strontium-MOF with underwater oleophobic and super-hydrophilic properties for effective oil/water separation [27]

5. Conclusions and Recommendations

Membrane-based oil-water separation has emerged as an effective approach for treating oily wastewater because of its high separation efficiency, low energy demand, environmental compatibility, and operational simplicity. In particular, superwetting membranes, including superhydrophobic-superoleophilic, superhydrophilic-superoleophobic, and underwater superoleophobic membranes, have shown strong potential for separating oil-water mixtures and emulsions. These membranes can be fabricated using nanoparticles, metallic materials, and polymeric materials to achieve desirable surface wettability. Beyond oil-water separation, multifunctional membranes also show promise in dye removal, heavy metal filtration, degradation of organic pollutants, water purification, air filtration, self-cleaning, antifouling, and improved mechanical performance.

Despite these advances, several challenges remain before large-scale commercialization. Many membrane materials are fragile, costly, and difficult to produce continuously. Their performance may decline due to fouling, mechanical damage, biofouling, and exposure to complex real wastewater containing oils, acids, salts, surfactants, bacteria, and other impurities. Most existing studies still rely on simulated oily water, which does not fully represent real industrial wastewater or oil spill conditions. Therefore, future research should focus on developing durable, reusable, low-cost, and scalable membranes with high flux, strong mechanical stability, antifouling ability, and multifunctional purification performance. Further studies should also investigate demulsification mechanisms, oil droplet coalescence, long-term reusability, and hybrid treatment technologies to improve sustainability and practical application.

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References

[1] Cao, H., Li, D., Fu, J., Yang, Y., Zheng, Y., Que, Y., & Zhou, H. (2024). Multifunctional biomass-based solar evaporator with enhanced sterilization performance for solar-driven clean water evaporation. Desalination, 591, 118052. https://doi.org/10.1016/j.desal.2024.118052

[2] Baguley, J. G., Rostami, M. A., Baldrighi, E., Bang, H. W., Dyer, L. A., & Montagna, P. A. (2024). Harpacticoid copepods expand the scope and provide family-level indicators of the Deepwater Horizon oil spill deep-sea impacts. Marine Pollution Bulletin, 202, 116343. https://doi.org/10.1016/j.marpolbul.2024.116343

[3] Chen, Y., Chen, Y., Jiang, L., Yang, Z., Fang, Y., & Zhang, W. (2023). Shear emulsification condition strategy impact high internal phase Pickering emulsions stabilized by coconut globulin-tannic acid: Structure of protein at the oil-water interface. LWT, 187, 115283. https://doi.org/10.1016/j.lwt.2023.115283

[4] Roosta, A., Zendehboudi, S., & Rezaei, N. (2024). Estimating contact angle of pure and mixed liquids on smooth solid surfaces using dispersive-to-attractive surface energy ratio from PCP-SAFT model. Chemical Engineering Science, 120607. https://doi.org/10.1016/j.ces.2024.120607

[5] Blank, M., Nair, P., & Pöschel, T. (2023). Modeling surface tension in smoothed particle hydrodynamics using Young-Laplace pressure boundary condition. Computer Methods in Applied Mechanics and Engineering, 406, 115907. https://doi.org/10.1016/j.cma.2023.115907

[6] Zhang, Z., Ahmed, A. I. S., Malik, M. Z., Ali, N., Ali, F., Hassan, M. O., & Bilal, M. (2023). Cellulose/inorganic nanoparticles-based nano-biocomposite for abatement of water and wastewater pollutants. Chemosphere, 313, 137483. https://doi.org/10.1016/j.chemosphere.2023.137483

[7] Ali, N., Bilal, M., Khan, A., Ali, F., Ibrahim, M. N. M., Gao, X., & Iqbal, H. M. N. (2021). Engineered hybrid materials with smart surfaces for effective mitigation of petroleum-originated pollutants. Engineering, 7(10), 1492–1503. https://doi.org/10.1016/j.eng.2021.04.022

[8] Wang, D., Huang, L., Miao, X., Sun, X., Zhou, S., Zhao, R., & Li, Z. (2023). Preparation of super hydrophilic-underwater super oleophobic photoinduced self-cleaning Al_2O_3@TiO_2 ceramic membrane and separation performance of oil-in-water emulsion. Journal of Environmental Chemical Engineering, 11(6), 111613. https://doi.org/10.1016/j.jece.2023.111613

[9] Baig, U., Waheed, A., Dastageer, M. A., Khairuddin, N. F. M., & Aljundi, I. H. (2024). Amino-functionalization of tungsten oxide nanoparticles for stable decoration in the active layer of alumina-supported inorganic-organic hybrid membrane with super-wettable and photocatalytic self-cleaning surfaces for crude oil-in-water emulsion separation. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 683, 133007. https://doi.org/10.1016/j.colsurfa.2024.133007

[10] Liu, Y., Zhang, F., Zhu, W., Su, D., Sang, Z., Yan, X., et al. (2020). A multifunctional hierarchical porous SiO_2/GO membrane for high-efficiency oil/water separation and dye removal. Carbon, 160, 88–97. https://doi.org/10.1016/j.carbon.2020.01.013

[11] Peng, Y., Yu, Z., Li, F., Chen, Q., Yin, D., & Min, X. (2018). A novel reduced graphene oxide-based composite membrane prepared via a facile deposition method for multifunctional applications: Oil/water separation and cationic dyes removal. Separation and Purification Technology, 200. https://doi.org/10.1016/j.seppur.2018.04.047

[12] Liu, J., He, W., Li, P., Xia, S., Lü, X., Liu, Z., et al. (2016). Synthesis of graphene oxide-SiO_2 coated mesh film and its properties on oil-water separation and antibacterial activity. Water Science and Technology, 73(5), 1098–1103. https://doi.org/10.2166/wst.2015.594

[13] You, H., Jin, Y., Chen, J., & Li, C. (2018). Direct coating of a DKGM hydrogel on glass fabric for multifunctional oil-water separation in harsh environments. Chemical Engineering Journal, 334, 2273–2282. https://doi.org/10.1016/j.cej.2017.10.171

[14] Ezazi, M., Shrestha, B., Kim, S., Jeong, B., Gorney, J., Hutchison, K., et al. (2020). Selective wettability membrane for continuous oil-water separation and in situ visible light-driven photocatalytic purification of water. Global Challenges, 4, 2000009. https://doi.org/10.1002/gch2.202000009

[15] Zeng, M., Echols, I., Wang, P., Lei, S., Luo, J., Peng, B., et al. (2018). Highly biocompatible, underwater superhydrophilic and multifunctional biopolymer membrane for efficient oil-water separation and aqueous pollutant removal. ACS Sustainable Chemistry & Engineering, 6(3), 3879–3887. https://doi.org/10.1021/acssuschemeng.8b00642

[16] Zhan, H., Zuo, T., Tao, R., & Chang, C. (2018). Robust tunicate cellulose nanocrystal/palygorskite nanorod membranes for multifunctional oil/water emulsion separation. ACS Sustainable Chemistry & Engineering, 6(8), 10833–10840. https://doi.org/10.1021/acssuschemeng.8b02091

[17] Yan, L., Zhang, G., Zhang, L., Zhang, W., Gu, J., Huang, Y., et al. (2019). Robust construction of underwater superoleophobic CNTs/nanoparticles multifunctional hybrid membranes via interception effect for oily wastewater purification. Journal of Membrane Science, 569, 32–40. https://doi.org/10.1016/j.memsci.2018.12.049

[18] Li, L., Liu, Z., Zhang, Q., Meng, C., Zhang, T., & Zhai, J. (2015). Underwater superoleophobic porous membrane based on hierarchical TiO_2 nanotubes: Multifunctional integration of oil-water separation, flow-through photocatalysis, and self-cleaning. Journal of Materials Chemistry A, 3(3), 1279–1286. https://doi.org/10.1039/C4TA05343A

[19] Liu, K., Yin, Z., Luo, R., Qiu, B., Chen, Y., Yang, C., & Xue, M. (2023). Durable $Co(OH)_2$/stearic acid-based superhydrophobic/superoleophilic nanocellulose membrane for highly efficient oil/water separation and simultaneous removal of soluble dye. Industrial Crops and Products, 203, 117190. https://doi.org/10.1016/j.indcrop.2023.117190

[20] Satria, M., & Saleh, T. A. (2023). Synthesis of superhydrophobic/superoleophilic stearic acid and polymer-modified magnetic polyurethane for oil-water separation: Effect of polymeric nature. Journal of Colloid and Interface Science, 629, 522–534. https://doi.org/10.1016/j.jcis.2023.05.087

[21] Zhang, X., Li, Z., Liu, K., & Jiang, L. (2013). Bioinspired multifunctional foam with self-cleaning and oil/water separation. Advanced Functional Materials, 23(23), 2881–2886. https://doi.org/10.1002/adfm.201203233

[22] Lim, H. S., Baek, J. H., Park, K., Shin, H. S., Kim, J., & Cho, J. H. (2010). Multifunctional hybrid fabrics with thermally stable superhydrophobicity. Advanced Materials, 22(19), 2138–2141. https://doi.org/10.1002/adma.200903298

[23] Gao, C., Sun, Z., Li, K., Chen, Y., Cao, Y., Zhang, S., et al. (2013). Integrated oil separation and water purification by a double-layer TiO_2-based mesh. Energy & Environmental Science, 6(4), 1147–1151. https://doi.org/10.1039/C3EE43635A

[24] Baig, U., Matin, A., Gondal, M. A., & Zubair, S. M. (2019). Facile fabrication of superhydrophobic, superoleophilic photocatalytic membrane for efficient oil-water separation and removal of hazardous organic pollutants. Journal of Cleaner Production, 208, 904–915. https://doi.org/10.1016/j.jclepro.2018.10.103

[25] Guo, F., Wen, Q., Peng, Y., & Guo, Z. (2017). Multifunctional hollow superhydrophobic SiO_2 microspheres with robust self-cleaning and oil/water emulsion separation properties. Journal of Colloid and Interface Science, 494, 54–63. https://doi.org/10.1016/j.jcis.2016.12.073

[26] Chen, N., Chen, S., Yin, H., Zhu, B., Liu, M., Yang, Y., & Wei, G. (2023). Durable underwater super-oleophobic/super-hydrophilic conductive polymer membrane for oil-water separation. Water Research, 243, 120333. https://doi.org/10.1016/j.watres.2023.120333

[27] Raj, A., Rego, R. M., Ajeya, K. V., Jung, H. Y., Altalhi, T., Neelgund, G. M., & Kurkuri, M. D. (2023). Underwater oleophobic-super hydrophilic strontium-MOF for efficient oil/water separation. Chemical Engineering Journal, 453, 139757. https://doi.org/10.1016/j.cej.2023.139757