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Review

Nanostructure-Based Oil–Water Separation: Mechanism and Status

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Abstract: Flexible and effective methods for oil–water separation are crucial for reducing pollutant emissions and safeguarding water and fuel resources. In recent years, there has been growing interest in fundamental research and engineering applications related to water and fuel purification, especially oil–water separation. To date, filter materials with special wetting characteristics have been widely used in oil–water separation. Nanostructured materials are one of the most attractive candidates for next-generation oil–water separation. This review systematically summarizes the mechanisms and current status of oil–water separation using nanostructured materials. Basically, this can be achieved by using nanostructured materials with specific wettability and nanostructures. Here, we provide a detailed discussion of two general approaches and their filtration mechanisms: (1) the selective filtration technique, based on specific surface wettability, which allows only oil or water to penetrate while blocking impurities; (2) the absorption technique, employing porous sponges, fibers, or aerogels, which selectively absorbs impure oil or water droplets. Furthermore, the main failure modes are discussed in this review. The purposes of this article are: (1) to summarize the methods of oil–water separation by nanotechnology; (2) to raise the level of environmental protection consciousness of water pollution by using nanotechnology; (3) to tease out the features of different approaches and provide a pivotal theoretical basis to optimize the performance of filtering materials. Several approaches for oil and water separation are compared. Furthermore, the principle and application scope of each method are introduced.

Keywords: water–oil separation; nanostructure; wettability; failure mode; filtration mechanism

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1. Introduction

Industrial oil–water mixtures cause environmental pollution; offshore oil spills, in particular, have worsened this oil–water pollution [1]. The treatment of oil–water mixtures has achieved more and more attention. As a kind of industrial wastewater, oil–water mixtures contain petroleum and organic solutions, and with the development of industry, huge amounts of oil–water have been produced. The simple discharge of a large amount of oil–water mixture will not only cause resource waste and economic loss but also destroy the ecological environment and seriously endanger human health. Therefore, it is urgent to make proper disposal of used oil–water mixtures and solve the problem of pollution [2–4]. Generally, depending on the physical form of the impurity phase, oil–water mixtures should exist in three main forms: an immiscible oil–water mixture, a free oil–water emulsion, and an oil–water emulsion with a stable emulsifier ("oil-in-water" or "water-in-oil"). In these three types of oil–water mixtures, the immiscible oil–water mixture can be fabricated by simply pouring and mixing without any reaction; therefore, it is easy to divide into layers and precipitate by simple filtration [5]. Although in free oil–water emulsion, the impurity phase, which is generally on a scale of nanometers, is well dispersed in the principal term. However, the dispersion system of the emulsified impurity phase is unstable, due to the absence of an external force among the emulsified droplets [6]. The treatment is very similar to that of the immiscible oil–water mixture. Depending on the function of the surfactant, an oil–water emulsion with a stable emulsifier shows high stability, which makes it difficult to deal with effectively. Although the traditional separation methods include the electrochemical method, precipitation method, biological method, centrifugal method, sol–gel method, and adsorption method, etc., they generally have disadvantages such as low separation efficiency, easy-to-produce secondary pollution, and high energy consumption. With the rapid development of interface science, separation membrane materials modified with special wettability were considered as candidates for separating [7].

A mesh membrane or filter bed is a straightforward preparation method among all demulsification technologies. It has advantages compared with other methods, including a high permeability of pore space, good oil–water separation effect, low energy consumption, simplicity, non-pollution–pollution-free, and so on [8]. The effectiveness of the physical oil–water separation method is contingent on the wettability of the filter material. Nanomaterials have been employed in the realm of oil–water separation. It is important to note that using nanomaterials in these applications will improve the special wettability [9]. Although oil–water separation technology has been greatly developed, the development of various oil–water separation technologies, especially membrane materials, has provided important support for oil–water separation [10]. In the existing research, a large number of studies were carried out. Several characteristics such as the preparation of various membrane materials, microstructure characterization, oil–water separation performance, and durability have attracted much attention, and a series of important successes have been achieved. Based on these results, the progress in the research into oil–water separation has advanced [11]. However, most of these previous studies focused on the preparation of new materials. The filtration mechanisms and failure modes of oil–water mixtures have been briefly analyzed and verified, but there was no systematic analysis based on the filtration mechanisms and failure mechanisms.

Here, the recent progress in this field in recent years will be summarized to provide an overview of the current research trend and achievements. Based on the oil–water separation principle, physical oil–water separation methods can be categorized into two types: absorptive and obstructive. In the context of surface modification with nanomaterials, two general approaches and their filtration mechanisms are discussed extensively.

2. Difficulty in the Field of Oil/Water Separation

Oil–water separation is becoming an urgent worldwide problem, which is significant in industry, environmental protection, and the energy field [12,13]. Under ordinary conditions, an oil–water emulsion contains many micrometer-scale emulsified droplets. This characteristic leads to the high stability of oil–water emulsions and significantly complicates the demulsification process [14,15]. Therefore, the key to a successful oil–water separation is to achieve the coalescence and demulsification of the emulsion [16]. As depicted in Figure 1, emulsified oil–water mixtures can be classified into two basic types: water-in-oil emulsions (W/O) and oil-in-water emulsions (O/W) [17].

In typical conditions, the influence of surfactants leads to remarkable emulsion stability, where droplet coalescence is rare, even upon collision with other droplets [18]. In other words, demulsification is difficult when there are no external corresponding anti-interference measures. As illustrated in Figure 2, the presence of a surfactant causes one oil droplet to come into contact with another [19,20].

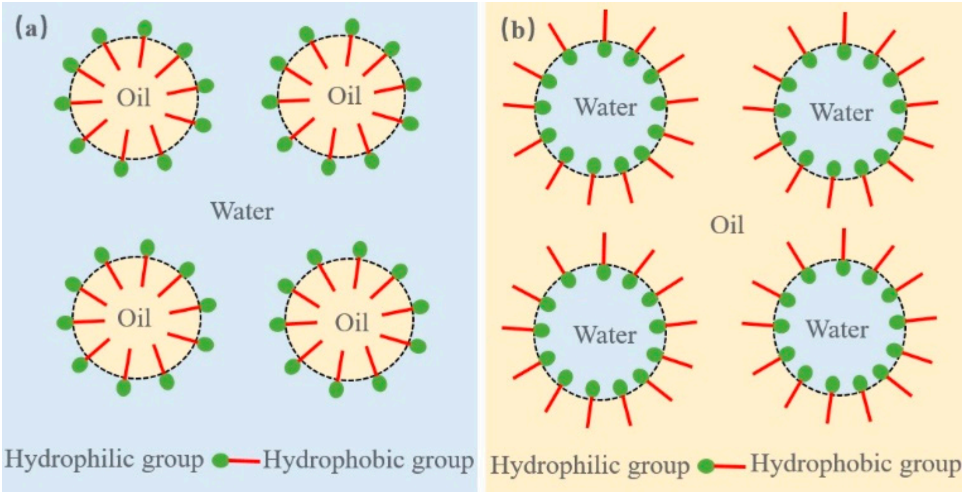

Figure 1. Schematic diagram of emulsion droplet under the action of surfactants. (**a**) Oil-in-water emulsion (O/W); (**b**) water-in-oil emulsion (W/O) [17].

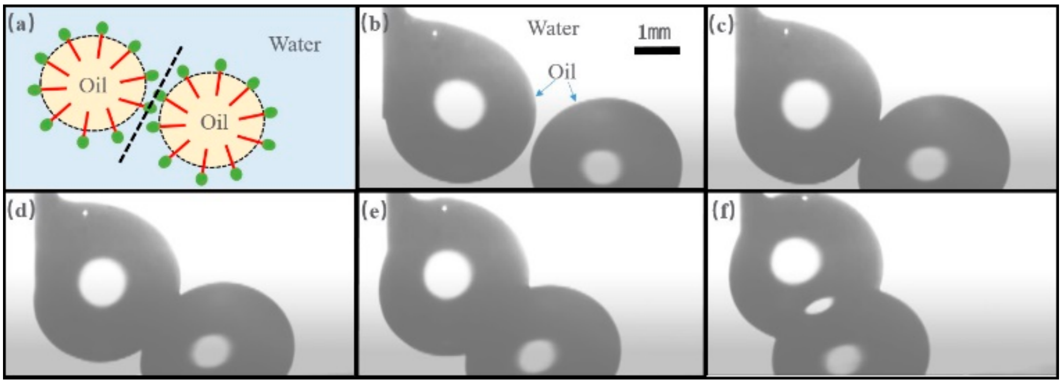

Figure 2. Representative examples of the emulsion droplet's stability in the presence of surfactants. (**a**) Schematic illustration; (**b**–**f**) time-lapse imaging of the contact process of oil droplets in water [19,20].

The primary strategy in the oil industry for separating crude oil and water relies on chemical demulsifiers [21,22]. Moreover, the chemical agents significantly affect the performance of surfactants at the oil–water interface (Figure 3). Therefore, the form of demulsification remarkably affects the demulsification performance. In contrast, gravitational settling and hydrocyclones have weak or ignorable effects [23]. Despite chemical treatment being an effective method, it may cause secondary pollution due to specific chemical reactions. Chemical treatment as a common method can be applied to deal with serious emulsification. Demulsifiers have an obvious impact on demulsification efficiency. Developing highly efficient and cost-effective demulsifiers presents a significant challenge, and there is an insufficient understanding of demulsification mechanisms [24–26]. This limitation is a primary challenge for chemical demulsification, especially under conditions of multiple loadings. There is an exception in chemical approaches; biochemical treatment can effectively achieve demulsification. However, the extra additives could cause secondary pollution. Furthermore, a low nitrification efficiency presents another challenge in demulsification [27]. Currently, it is hard to improve its treatment effectiveness because conventional biochemical treatments have reached their technical limits [28,29].

The remarkable stability and complexity of emulsions have posed significant technical and environmental challenges, particularly in crude oil production. Due to the complexity of emulsions, finding an efficient and economical demulsifier remains a challenge. Based on the different stabilization mechanisms of oil-in-water emulsions and water-in-oil emulsions [30], emulsion breakers and reverse emulsions have been proposed to treat the oil–water mixtures, respectively. To achieve the coalescence of water droplets in water-in-oil (W/O) emulsions, qualified emulsion breakers must not only enter the oil–water interface film but also modify its properties. This includes reducing interfacial tension, dilution, and softening of the interfacial film [31]. Notably, the modification methods could be variable, depending on the types and concentrations of the explored emulsion breakers. When surface activity is moderate or the demulsifier concentration is low, emulsion breakers typically infiltrate the interfacial film, coexisting with surfactants at the oil–water interface, thereby altering the properties of the interfacial film. In contrast, a demulsifier with high interfacial activity is adsorbed on the oil–water interface and replaces the active component in the original interfacial film to form a completely reversible interfacial film, giving the ability of water droplets to bond. The main purpose of adding reverse emulsion breakers is to neutralize the negative surface charge on the surface of oil droplets in O/W emulsions, which brings together distant oil droplets with the action of van der Waals forces. The cationic reverse emulsion breakers or ionic liquids move in the direction of the emulsion demulsifier and are applied in demulsifying W/O and O/W emulsions [30]. They move toward the oil–water interface due to electrostatic attraction, replacing the original interface-active substances. Consequently, the interfacial film tension at the oil–water interface is reduced, leading to the destruction of the interfacial film and promoting the coalescence of oil droplets in the O/W emulsion. It is important to note that a synergistically enhanced demulsification effect of emulsion breakers and reverse emulsion breakers has been frequently observed. However, despite the widespread use of concentrated EBs and REBs to stabilize W/O and O/W emulsions, in-depth mechanism studies are lacking [8,32,33].

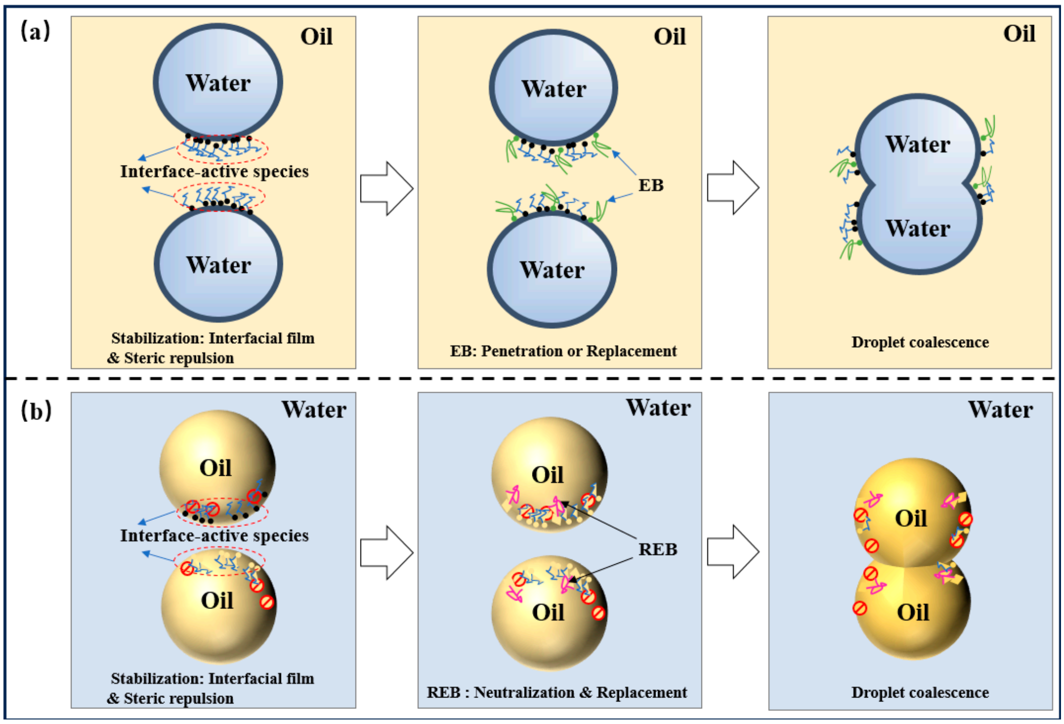

Figure 3. Schematic of stabilization of water–oil mixture and demulsification mechanisms by chemical demulsifiers. (**a**) W/O emulsions. (**b**) O/W emulsions [23].

3. Membrane Used for Oil–Water Separation

The membrane filtration method for oil–water separation is closely related to surface wettability [34]. The interception or adsorption of the impurity phase should be achieved based on the reasonable selection of the surface wettability of the filter material [35]. Surface wettability is a very important property, which is determined by the surface structure and chemical composition. Wetting behavior can be described by the contact angle of droplets on solid surfaces, which can provide a basis for designing functional surfaces and further improve the surface's performance [36]. Considering the effects of surface structure and chemical modification, the preparation, characterization, and theoretical research on the function of a surface, based on the surface's wettability, have received much attention. For example, the coating of gelatin—tannic acid—g-C_3N_4 (GE-CNTA) and polyvinyl alcohol can achieve an underwater contact angle of more than 150° [37].

In the field of oil–water separation, with the gradual improvement in wetting theory, the theoretical research has gradually changed from idealization to what is suitable for the actual conditions [38]. However, there are many factors affecting the wettability of the material surface, as depicted in Table 1. It is difficult to achieve single-factor control in the preparation of various microstructures for oil–water separation [39]. In this field, the function of selective interception or adsorption for the impurity phase is the key to the separation of an oil–water mixture. Therefore, there is still a lack of effective characterizations of the complex geometry texture.

Table 1. Critical material and methods used in oil–water separation.

Critical Material	Methods	Type of Solution for Oil–Water Separation	References
LDH–SiO_2	Electrospun and Co-deposited	Emulsified	3D Multiscale Superhydrophilic Sponges with Delicately Designed Pore Size for Ultrafast Oil/Water Separation. *Adv. Funct. Mater.* **2017**, 1704293 [40]
CA Polymer	Deposition	Emulsified	Caffeic acid polymer rapidly modified sponge with excellent anti-oil-adhesion property and efficient separation of oil-in-water emulsions. *J. Hazard. Mater.* **2021**, *404*, 124197 [41]
Fe_3O_4/CS-PFNA	One-step Dip-coating	Oil–water mixtures	A magnetic superhydrophilic–oleophobic sponge for continuous oil–water separation. *Chem. Eng. J.* **2017**, *309*, 366–373 [42]
PDMS	Coating	Oil–water mixtures	Emulsion dipping-based superhydrophobic, temperature-tolerant, and multifunctional coatings for smart strain sensing applications. *Compos. Sci. Technol.* **2021**, *216*, 109045 [43]
PDMS	Coating	Oil–water mixtures	Llorca-Isern. Superhydrophobic PDMS coated 304 stainless-steel mesh for the removal of HDPE microplastics. *Prog. Org. Coat.* **2022**, *170*, 107009 [44]
Gelatin—Tannic Acid—g-C3N4 (GE-CNTA)	Coating	Emulsified	Double network cross-linked hydrogel coating membrane with photocatalytic self-cleaning performance for efficient oil-water separation. *Prog. Org. Coat.* **2023**, *185*, 107882 [37]
Polyvinyl Alcohol	Coating	Emulsified	Aggregation-induced demulsification triggered by the hydrophilic fabric for the separation of highly emulsified oil droplets from water. *Aggregate* **2022**, 3, e131 [15]

3.1. Metal Base Film Material

Because of the low cost, chemical stability, high strength, ease of preparation and modification, etc., metal mesh has been considered an ideal industrial separation substrate in the oil–water separation field [45]. Copper mesh and stainless steel mesh have been commonly used due to their good mechanical properties. Due to its advantages, metal has been widely used for the preparation of oil–water separation material; special wettability film material has been one of the most common applications [46–50]. However, if the pore size of the membrane is larger than that of the droplet diameters, this results in failure in separating oil–water emulsions [48]. It should be noted that the inherently large holes make it difficult to satisfy the requirements, so surface modification methods are usually used to solve these problems [49]. Although the surface modification of a hydrophobic/hydrophilic coating can adjust the aperture and improve the separation efficiency, the pore size of the membrane should be smaller than the emulsified drop diameter, which improves the accuracy of the metal filter. In practical separation applications, as the number of separations increases, the surface function of the layers will diminish and wear, which will inevitably affect the separation efficiency.

3.2. Polymer Materials

In the field of oil–water mixture separation, polymer membrane materials with tiny pores should ensure that the polymer membrane can effectively intercept an oil–water emulsion with small droplets of diameter less than 20 µm stabilized by surfactants [50]. Polymer membrane materials have the advantages of low cost, excellent flexibility, simple operation, etc. In addition, the pore size of the polymer membrane material is controllable, which is more conducive to serving as the substrate for the separation of an oil–water emulsion [51]. The modification of the polymer membrane material with special wettability can significantly improve the filtration flux and separation efficiency of the membrane [52]. Although the polymer-based film material has good tensile flexibility, tiny pores, and good controllability, because of the fragile structure and temperature resistance, it cannot be applied to large-scale industrial mold production. Therefore, it is still an urgent problem to extend the service life of polymer films and improve their anti-pollution performance.

3.3. Biomass-Based Membrane Materials

To solve the current problems existing in oilfield sewage treatment, it is of great significance to seek environmentally friendly raw materials. Nanofiber membrane with special wettability has always been the main strategy to improve the separation performance of water-in-oil emulsions [53]. As a kind of biomass raw material, cotton fabric has the advantages of flexibility, low cost, high porosity, light weight, and corrosion resistance, etc., so has attracted a wide range of attention. Therefore, a cotton fabric-based membrane is a good choice [54]. Sponges, foams, straw, herb residues, shrimp shells, waste peanut shells, and recycled cellulose are also raw materials for biomass membranes. Biological materials can also be applied to different substrates to enhance wettability or provide the required functions. Biomass film has gradually become a substitute for metal and polymer materials; based on the compatibility of natural materials, the modified film has good structural stability and resistance to water expansion deformation [55]. Although biomass-based membranes have the advantages of low cost, toughness, and environmental friendliness, their mechanical durability is low, and their resistance to physical wear and cutting limits their application.

3.4. Inorganic Material

As a kind of inorganic material, ceramic membranes have been widely used in emulsion separation, due to their high mechanical strength and excellent chemical properties [56]. However, they have not been widely promoted, because in practical applications of emulsion separation, ceramic membranes will be polluted to different degrees [57]. Notwithstanding, these membranes have the advantages of hydrophilicity, a strong anti-pollution ability, and excellent chemical stability, and have become an alternative material in the separation process.

4. Absorbability

For the absorption approaches, porous filter materials such as porous sponges, fibers, and aerogels have commonly been adopted, because these materials can selectively absorb oil or water droplets of impurity into their cavity structure and repel another phase.

4.1. Adsorbing Porous Materials

When nanostructures and low-surface-energy materials are applied to modify porous sponges, they exhibit hydrophobic and lipophilic properties. Therefore, they could be regarded as a kind of self-swelling oil-absorbing material. These porous materials can not only directly absorb oil but also absorb oil floating on the water surface or oil in an oil–water mixture [58]. As one of the major environmental problems, marine oil spilling accidents seriously harm marine ecosystems and coastal environments, resulting in a severe loss of fuel resources [59]. Obviously, novel oil spill-cleaning technology and effective treatment methods are urgent for marine and coastal environmental protection. These measures and techniques also facilitate recycling oil from the separated oil–water mixtures to achieve economic benefits. Given these reasons, the investigation of oil–water separation has attracted significant attention and has recently experienced rapid growth. A number of interesting works have been reported to demonstrate the effective, low-cost, and simple processes for oil–water separation based on nanomaterials with special superwettability.

In previous studies, high-oil-absorbing sponges were prepared via diverse methods, which can be used for large-scale absorption, further achieving the effective separation of oil from water. Based on the incorporation of a porous structure and low surface energy materials, the prepared sponge showed an excellent ability to absorb oil from water [60]. Moreover, this sponge can separate oils up to thousands of times its own weight. Such sponges also showed excellent special wettability, even when used in various harsh environments More importantly, these sponges performed excellently even after being used in dozens of cycling tests.

4.2. Filter Material Based on Adsorption Property

Due to selective adsorption characteristics, a filter bed composed of adsorbing material can adsorb the impurities in a flowing oil–water mixture. For example, as shown in Figure 4, hydrophobic and oleophilic materials exhibit a higher affinity for oil than for water. This is why oil droplets are adsorbed as impurities when an oil–water mixture flows through the filter layer. On the other hand, hydrophilic and oleophobic materials could be used as filter materials for filtering out water droplets from oil. In addition, natural sands have hydrophilic and oleophobic characteristics, and they could be considered an adsorption material to remove the water droplet impurities from oil [61–64].

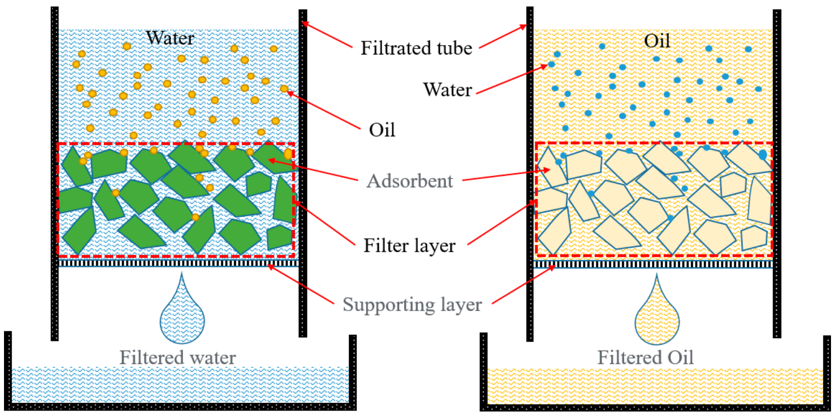

Figure 4. Schematic of oil–water separation mechanism by adsorption materials [64].

Due to the adsorptive capacity of the filter material, the absorption-based approaches are just one example of water–oil separation [65]. Once the filter material becomes saturated with impurities, the filter layer becomes ineffective. To solve the problem, the main mechanism of adsorption capacity was analyzed. Coalescing fibrous materials could be used to avoid the gradual enrichment of impurities. This principle is summarized here, and it attributes the movement of impurities to the fibers [66,67]. As shown in Figure 5, when the fiber adsorbed the emulsifying impurity, the droplet is adsorbed on the fiber, moved along the fiber, and finally combined at the cross or end of the fiber. As a result, the impurity droplet gradually increases in size, and, eventually, the impurity will fall out due to gravity. When the oil–water mixture passes through the filter layer woven with coalescing fibers, it collects the emulsifying impurities and achieves demulsification.

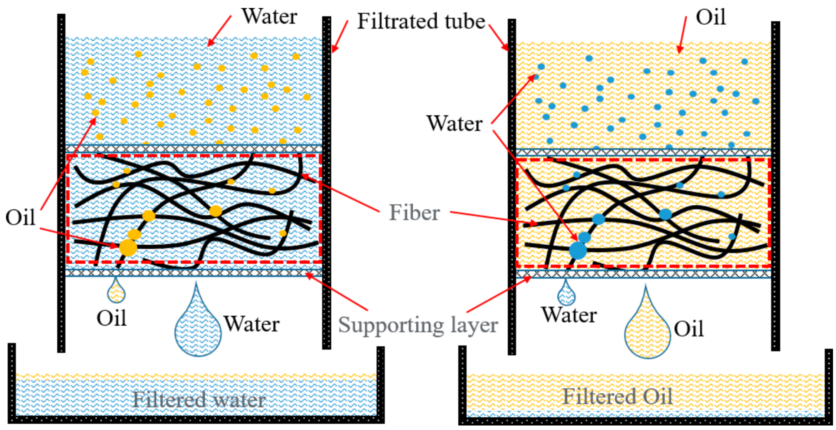

Figure 5. Schematic of oil–water separation mechanism by coalescing fibrous materials [64].

5. Obstruction

5.1. Oleophylic and Water-Repellent

The scientific principle underlying filtration techniques using materials with specific wettability is that one of the phases (either oil or water) is allowed to penetrate while the other phase is prevented from passing through. The filter's structure may be in the form of meshes or textile membranes [68,69]. Fibrous membranes with super-wetting ability have been widely used in the separation of oil–water mixtures. Generally, the existing filter materials, such as filter paper, blankets, metal nets, non-woven fabric, and so on, have commonly been considered for substrate materials, which can filter materials with special wettability by low surface energy matter and nanostructure modification. The main strategies for oil–water separation using existing membranes include modifying steel mesh, using fabric, employing phase inversion membranes, and utilizing electrostatic spinning fibrous membranes. In previous studies, a superhydrophobic stainless steel mesh was constructed for oil–water separation by depositing candle soot [70]. The candle smoke and PDMS synergistic effect realized a water contact angle of 156°, which is hydrophobic. The nanoscale roughness was constructed on the filter material to achieve a specially selective wettability. This filter material modified by nanostructures can be recycled several times [71]. Modifying the existing steel mesh and other filter materials has some advantages, such as its easy preparation process and low-cost operation. In comparison, its limitation is that the pore size distribution of the existing materials is generally large, which can only be used to separate the large-scale droplets of impurity from oil–water mixtures, with a low separation efficiency.

To enhance separation efficiency, various methods have been employed to fabricate mechanically durable and highly efficient fibrous separation membranes. For example, the electrostatic spinning approach combined with low surface energy modification was employed to fabricate a filter material with selectivity, which could filter out water droplets. The filter material, modified with fumed silica, attained a water contact angle of 151.6°. Due to the specific wettability that only allows the oil phase to penetrate but prevents the water phase from passing through, filter materials with specific wettability can achieve ideal water–oil separation performance (Figure 6) [72].

However, these membranes may have problems when they are used in an oil–water mixture containing high-viscosity fuel, especially crude oil. Owing to the strong adhesion between viscous substances and the filter material, the membrane would often become contaminated and clogged with debris. As a result, the pores were blocked, leading to a significant drop in separation performance and increased operational costs for cleaning or replacement. Therefore, it is still an urgent, uncompromising challenge to design filter membranes with an excellent self-cleaning effect to deal with high-viscosity crude in practical applications.

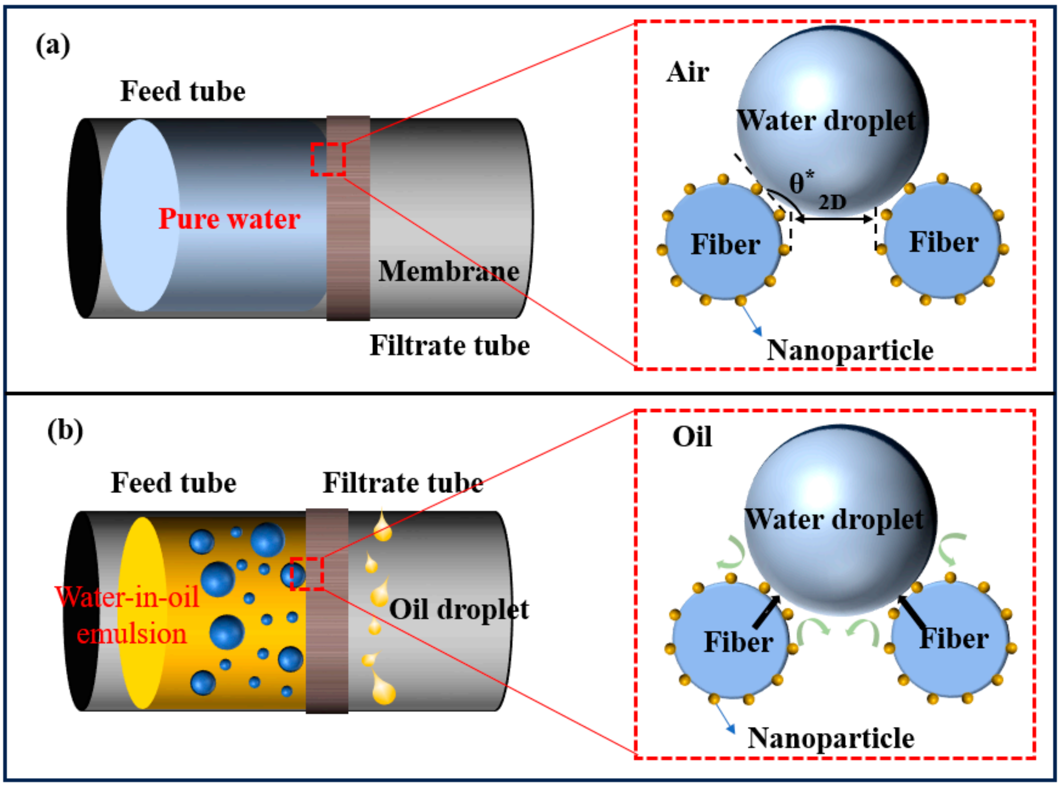

Figure 6. Schematic of oil–water separation mechanism by filter materials with specific wettability, (**a**) mechanism of preventing the water phase from passing through, (**b**) water-oil separation performance [72].

5.2. Underwater Hydrophilic and Oil-Repellent

As oil and water have different polarities, they will attempt to repel each other. Therefore, the oil-resistance property of filter membranes derived from a hydrated layer or absorbed water layer plays a role in preventing oil from directly contacting and sticking to the filter membrane surface [73,74]. Therefore, to exploit the oil-repelling mechanism, it is crucial to establish a long-lasting water-retaining layer on the filter membrane surface. The chemical composition and surface structure, when combined effectively, significantly influence the retention of water within the filter membrane's surface structures. In addition, the nanostructures can reduce the contact area between the oil and membrane surface, and it is considered a novel approach to obtaining a low oil-adhesive membrane. As shown in Figure 7, a filter membrane with a bioinspired anti-oil-fouling hierarchical structure was processed to achieve water–oil separation for the O/W mixture. $Cu(OH)_2$ nanowire array-based biomimetic membranes were fabricated, allowing for adjustable pore sizes and controllable porosity of the filter membrane. The experimental results indicated that the filter membrane could not only separate common layered oil–water mixtures but also effectively deal with immiscible surfactant stabilized oil-in-water emulsions. The hierarchically structured membrane exhibited exceptional superhydrophilicity, superoleophobicity, moisture retention capability, and desirable oil-repelling properties [75].

Generally, to effectively prepare a filter membrane with excellent effective separation effect for oil–water separation, the following conditions are the basic requirements to be examined (Figure 8): the membrane interface should have excellent selective wettability, appropriate surface roughness, and a suitable pore structure size [76,77].

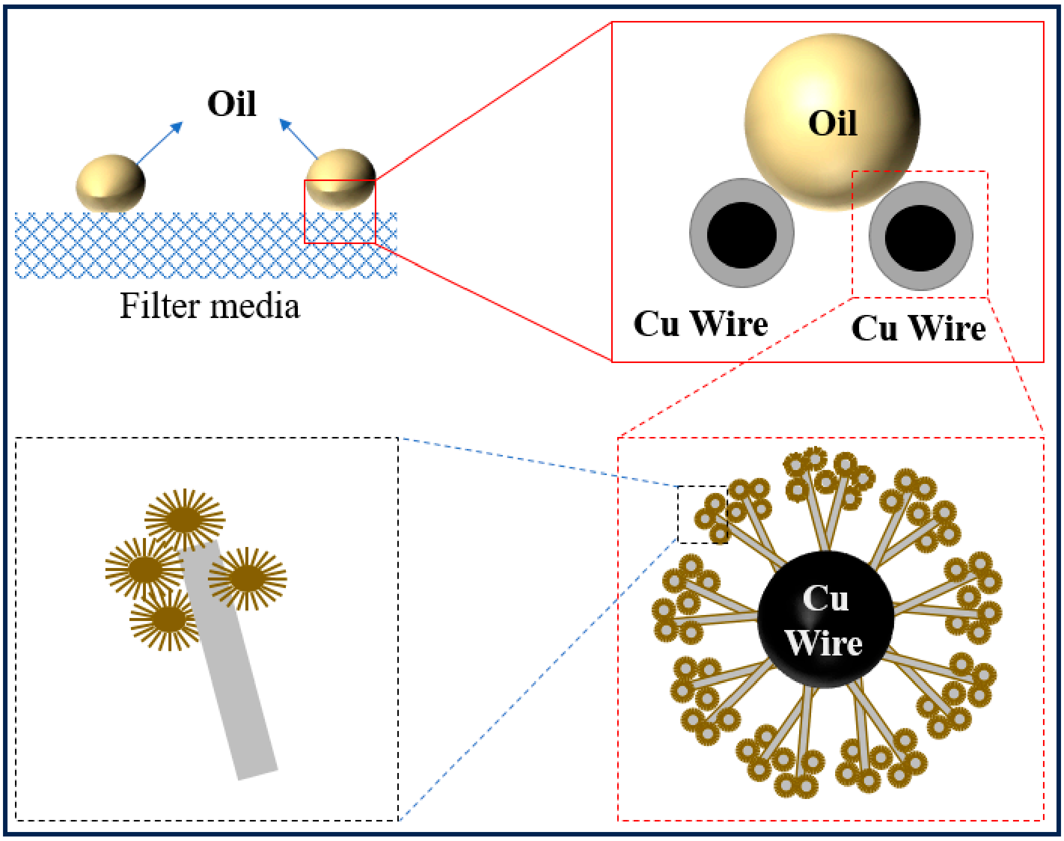

Figure 7. Schematic of oil–water separation mechanism by filter materials with specific wettability [75].

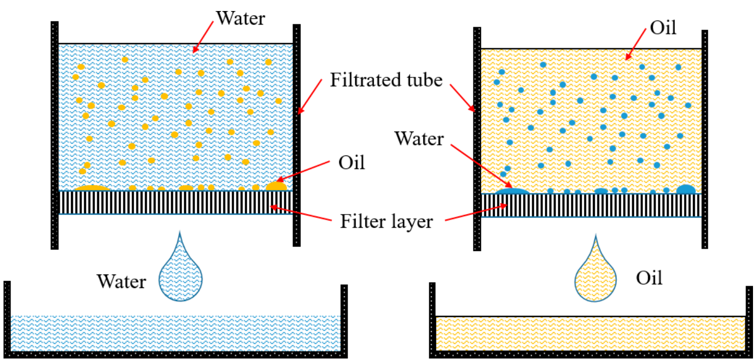

Figure 8. Principal oil–water separation mechanism by filter material with specific wettability [76,77].

Briefly, the filtration technique based on specific wettability filter material is based on the filter layer's mechanism allowing a selected phase (either oil or water) to penetrate but avoiding other impurity phases going through. Generally, the wettability materials should be specifically selected under different working conditions to meet the filtration requirements. For example, an underwater hydrophilic and oil-repellent material is suggested to be used to separate the O/W mixture. However, because of their nanostructures, some filter materials are both hydrophobic in oil and oleophobic in water. Therefore, these can be used in both O/W and W/O separation. As shown in Figure 9, these ZnO nanostructures present such a characteristic [78].

ZnO nanostructures have both superhydrophobicity in oil and superoleophobicity in water. As illustrated in Figure 9, the mechanism of double wettability properties is summarized here. Double wettability is caused by excellent amphiphilic properties. When the prepared surface was used in the process of filtration, it would be immediately extensively wetted by the bulk phase, because it preferentially interacted with the bulk in an oil-in-water emulsion under general conditions. Therefore, the filter material wetted by water allowed the water phase to pass through easily. And, when ZnO first came into contact with oil, the prepared surface was extensively wetted in the oil phase, resulting in a superhydrophobicity in oil.

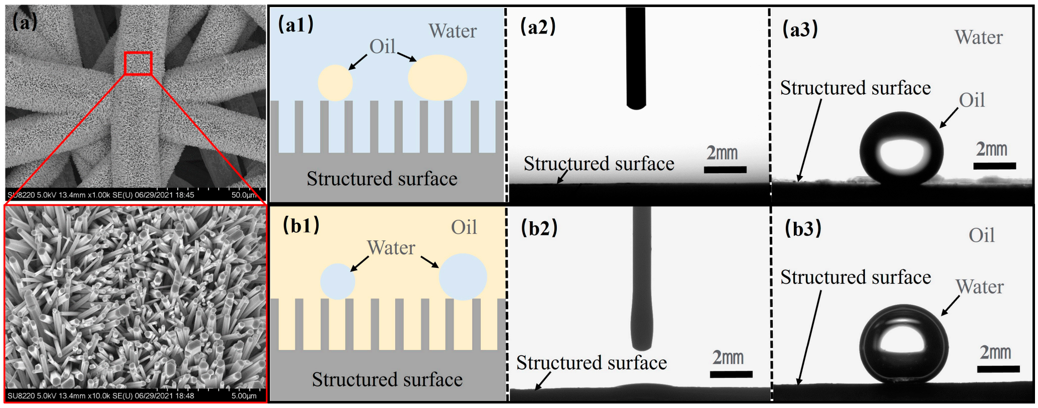

Figure 9. Both superhydrophobicity in oil and superoleophobicity in water are the result of excellent amphiphilic properties, which is due to their nanostructures. (**a**) SEM of ZnO nanostructures and (**a1**–**a3**) their superoleophobic properties in water. (**b1**–**b3**) Superhydrophobicity in oil [78].

5.3. Mechanism and Failure Mode

Adhesion is the result of molecular or atomic forces between objects, causing them to bond closely [79]. This phenomenon involves various mechanisms of adhesion, among which van der Waals forces generate short-range attractions between molecules, including London dispersion forces and Debye polarization forces, creating temporary charge distributions and resulting in attraction [48,80,81]. Electrostatic forces, also known as Coulomb forces, arise from interactions between charges and can lead to attractions or repulsions between positively and negatively charged entities [82]. Additionally, hydrogen bonds form between hydrogen atoms and more electronegative atoms, creating stable structures [83]. Metallic bonding arises from atoms in metals sharing free electrons, contributing to the metals' distinct adhesive and conductive properties [84]. Covalent bonds promote adhesion through electron sharing, whereas electrostatic adsorption involves adhesion arising from surface charges. Physical adsorption relies on weak interactions such as van der Waal forces, while chemical adsorption involves adhesive molecules chemically reacting with surfaces. Mechanical interlocking occurs when microscopically uneven surfaces interlock with each other [85,86]. These mechanisms can operate individually or in combination, depending on the properties of the objects and environmental conditions. They play a crucial role in choosing suitable adhesive materials and methods.

Adhesive failure occurs when the bond between adhered objects weakens or breaks, resulting in the inability to maintain their initial connected state [87,88]. Adhesive failure can be caused by various factors, including several common scenarios. Chemical modification can arise from reactions between substances at the adhesive interface and environmental chemicals or gases, resulting in altered chemical properties and diminished bond strength [89]. Temperature fluctuations, either high or low, can induce expansion, contraction, or deformation of adhered objects, disrupting the adhesive interface and reducing bond strength [90]. Humidity and moisture infiltration can lead to swelling, softening, or corrosion of adhered materials, triggering adhesive failure [91]. Mechanical stresses, including external tension, shearing, twisting, or vibrations, can weaken the adhesive interface, leading to bond failure. Interface contamination, the buildup of grease, dust, pollutants, and other foreign particles, can degrade the quality and stability of the adhesive connection. Material incompatibility, marked by differences in thermal expansion coefficients or significant variations in hardness, can lead to adhesive failure [92–94]. Over time, the aging and decomposition of adhesive agents can diminish bond strength [95]. Inadequate design choices, inappropriate geometries, or insufficient contact areas in adhesive interfaces can likewise contribute to adhesive failure. To prevent adhesive failure, meticulous selection of suitable adhesive materials, consideration of environmental conditions, and the implementation of appropriate measures during design and manufacturing processes are necessary to enhance the quality and durability of adhesion.

Anti-adhesion encompasses strategies aimed at inhibiting the adhesion between the surfaces of objects, thereby precluding unintended adhesion [96]. Numerous established methodologies exist for the prevention of adhesion [97]. These approaches involve applying specialized anti-adhesive coatings to object surfaces. These coatings create smooth interfaces, reduce contact with other objects, and thus decrease the likelihood of adhesion [98]. The integration of lubricants or oils assumes a pivotal role in diminishing friction and adhesion between objects, particularly within mechanical components, thereby forestalling undesirable adherence during motion [99]. Specifically designed anti-adhesive coatings can form protective layers on object surfaces, preventing other objects or substances from sticking. Additionally, the utilization of materials inherently possessing low adhesion properties, akin to non-stick cookware, represents a potent strategy [100]. Modulation of surface attributes, such as surface roughness or chemical composition, has the capacity to ameliorate the impact of adhesive forces [101]. Additionally, in environments susceptible to adhesion, it is helpful to avoid high humidity or moisture, regularly clean object surfaces, and implement measures to eliminate static electricity [102]. Depending on the specific situation, carefully choosing the right anti-adhesion methods can effectively prevent adhesion incidents [103,104].

Regarding adsorbing approaches, the selected phase droplets are constantly agglomerated and adsorbed to the filter layer during emulsion separation. As shown in Figure 10, the results illustrate that the selected phase (water or oil) was blocked from entering the filter layer. The filtering flux going through the filter membrane is determined by these factors: membrane porosity and pore size. For instance, the larger the pore size or porosity, the higher the membrane flux [48,96]. As shown in Figure 11, impurity droplets were attached to the surface of the adsorbing material, which weakened the adsorbing surface's performance. The size of the impurity droplets was too small to affect the pore size or the filter layer's porosity. Even with the flux of the oil–water mixture passing through the filter layer, it was difficult for the adsorbing material to effectively come into contact with the impurity phase because of the number of impurity droplets attached to the surface of adsorbing material [105,106]. Therefore, the adsorbing material surface was saturated over time, significantly decreasing the oil–water separation efficiency.

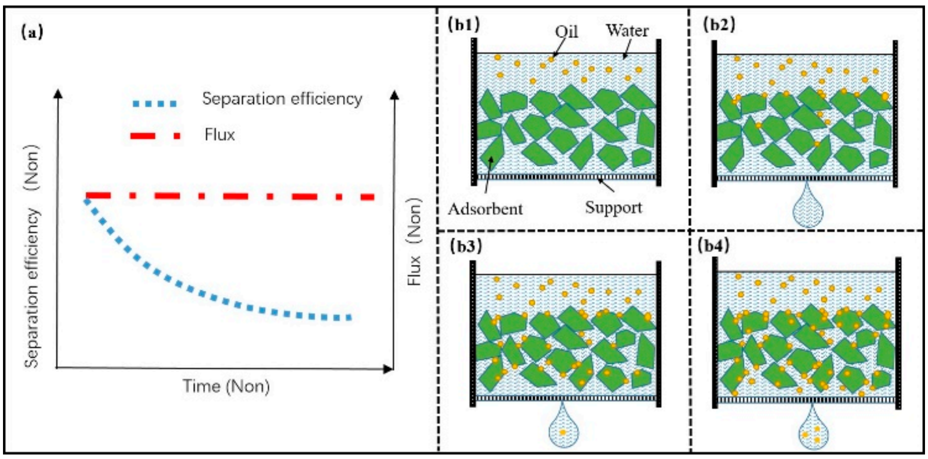

Figure 10. Principal mechanism and failure mode. (**a**) Variation tendency of separation efficiency and flux; (**b1**–**b4**) the process of emulsified droplet adsorbing on the filter material [96].

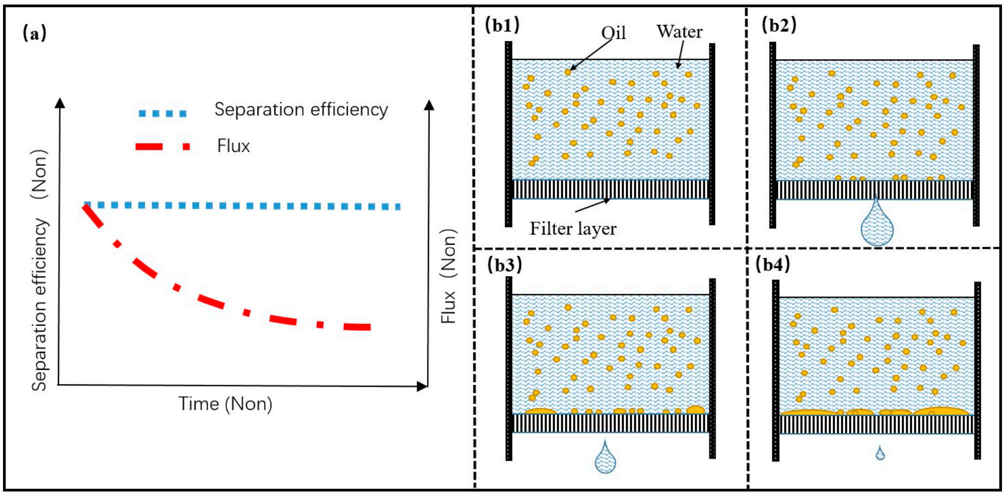

Figure 11. Principal mechanism and failure mode. (**a**) Variation tendency of separation efficiency and flux. (**b1**–**b4**) Schematic illustration of the emulsified droplet adsorbing on the filter material [106].

For effective oil–water separation, the emulsified impurities, whether in water-in-oil or oil-in-water emulsions, need to be effectively intercepted. Based on the oil–water separation mechanism, the emulsified oil droplets were firstly intercepted by the water-wetted filter membrane and then adsorbed on the filter layer [107]. Finally, as the impurity-emulsified oil droplets, blocked by the filter layer, attracted and coalesced with other emulsified droplets on the surface of the filter materials, while the wetted filter layer allowed the bulk phase to pass through, the oil-in-water emulsions were separated [108]. Moreover, those oil droplets were continually captured by the filter material with the extension of the filtration time. The intercepted impurity droplets were gradually coalesced into bigger droplets. With the enrichment of the impurities, parts of the porous membrane would be blocked by the intercepted oil droplets, which resulted in a decline in porosity [109,110]. Therefore, the filtration flux sharply decreased when the emulsified impurities continually collected and reached their limit, which could be considered as the saturated value of the impurity, as shown in Figure 11.

6. Conclusions

In summary, oil–water separation technology has been greatly developed. The filtration methods for oil–water separation are closely related to surface wettability. The interception or adsorption of the impurity phase should be achieved based on the reasonable selection of the surface wettability of the filter material. Surface wettability is a very important property, which is determined by the surface structure and chemical composition. Surface structure and modification have been widely used in oil–water separations, because they can be used to achieve specific wettability, which is one of the key factors for oil–water separation. The different technologies have been determined by the special wettability. Regardless of the influence of the specific degree of wettability on the oil–water separation efficiency, the wettability of filter materials determines the oil–water separation mechanism and failure. Here, two general approaches and their mechanisms have been discussed in detail: (1) the filtration technique, which depends on specific wettability that only allows the bulk phase to pass through and intercepts the impurity phase; (2) the absorption approach, which uses adsorbing materials with selective adsorption ability for the impurity droplets, such as modified porous sponges, fibers, and aerogels. Furthermore, the main failure mode was discussed at the end of the paper as well. The purposes of this article are (1) to summarize the methods of oil–water separation by nanotechnology; (2) to raise the level of environmental protection consciousness of water pollution by using nanotechnology; (3) to discuss the specific features of different approaches, and to provide an important theoretical basis for optimizing the effect of filtering materials. Several methods of oil and water separation have been compared, and each method's principle and scope of application are discussed in depth, respectively. The separation equipment tends to solve problems of oil–water separation more effectively, while a deep understanding of separation mechanisms and failures is necessary for the design and selection of filter materials. The understanding and interpretation of separation mechanisms and failures should contribute to the rapid development of the separation industry.

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