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Sustainable and efficient oil-water separation using bio tin oxide-based superhydrophobic membrane

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Introduction: Superhydrophobic materials are considered an ideal method for oil-water separation. However, existing oil-water separation methods have the problem of manufacturing complex and toxic chemical reagents. To address the limitation, we proposed a novel approach to sustainable and efficient oil-water separation using a superhydrophobic membrane based on the Bio Tin oxide nanoparticles (Bio-SnO_2 NPs).

Methods: The study involves synthesizing Bio-SnO_2 NPs from the sunflower leaf extract which was natural and non-toxic and modifying textile fabric with a superhydrophobic coating (S.T.F.). Characterization techniques including SEM, FTIR, and BET analysis are employed to assess the structural and textural properties of the modified membrane.

Results and Discussion: The textile fabric was modified with a superhydrophobic coating (S.T.F.), demonstrating enhanced wettability, oil absorption capacity, and oil-water separation performance. The Bio-SnO_2 NPs exhibited crystalline structures with a length of 90 nm and a diameter of 20 nm, as confirmed by SEM analysis. FTIR results revealed characteristic peaks at 3410 cm^{-1} and 642 cm^{-1}, indicating the presence of hydroxyl group and Sn-O bonds confirming the successful synthesis of Bio-SnO_2 NPs. BET analysis showed a substantial specific surface area of 413 m^2/g and a pore volume of 0.19 cm^3/g, emphasizing the textural properties. The FTIR and SEM techniques were used to study the characteristics of the textile fabric before and after modification with the superhydrophobic coat. The S.T.F. exhibited remarkable superhydrophobicity with a water contact angle of 152° and a water sliding angle of 4°. Absorption capacities for coconut oil, diesel, and hexane were found to be 70.4 g/g, 63.5 g/g, and 49.6 g/g, respectively, with excellent cyclic stability. Separation efficiency for hexane, diesel, and coconut oil was found to be 99.5, 97.1%, and 96.3%, respectively, with excellent cyclic stability. Mechanical stability test revealed superhydrophobicity retention even after an abrasion length of 200 mm. The chemical stability test indicated that the superhydrophobicity was maintained in the pH range of 3-11. Moreover, the flux for hexane, diesel, and coconut oil was 9400 L m^{-2} h^{-1}, 8800 L m^{-2} h^{-1}, and 8100 L m^{-2} h^{-1}, respectively, highlighting the membrane's efficient oil-water separation capabilities. These results collectively position the developed S.T.F. as a promising and sustainable solution for diverse oil-water separation applications.

KEYWORDS
oil-water separation, superhydrophobic membrane, biomimetic design, dip coating, biogenic synthesis, sustainable approach

1 Introduction

The global challenge of separating oil and water has intensified due to the increasing prevalence of oily wastewater generated by industrial processes and oil spills (Jones et al., 2008; Dong et al., 2022; Wu et al., 2024). Discharging oily wastewater into the environment can have severe ecological consequences, including water contamination, aquatic habitat destruction, oxygen depletion, and even harm to aquatic organisms (Neale et al., 2023; Yamini et al., 2023). Addressing this issue is crucial from both the environmental and economic perspectives, necessitating the development of functional materials capable of efficiently separating the oil and the water. Although various techniques, such as centrifugation separation, demulsifier, functional material absorption, and gravity separation, have been explored for oil-water (O-W) separation, these methods have some limitations of the high cost and the low separation efficiency (Xiao et al., 2009; Khan et al., 2019; Saleh et al., 2022; Sousa et al., 2022). Hence, there is an urgent need for advanced and effective techniques that offer superior performance in this field.

In recent years, biomimetic design of advanced and multifunctional materials has been at the forefront of research work. Superhydrophobic (SH) membranes which are characterized by a water contact angle (WCA) larger than 150° and water sliding angle (WSA) less than 10°, possess the unique ability to repel water droplets while allowing the passage of oil, rendering them ideal for O-W separation (Bai et al., 2019; Kang et al., 2019; Ma et al., 2020). SH surface has demonstrated promising fog collection ability and fluid transportation ability, for example, Yan et al. (2023a) proposed the super-fast fog collector based on the extreme wettability surface was promising to overcome the water crisis; Yan et al. (2023b) developed a superhydrophilic serial cycloid-shaped pattern could enhance water transportation capacity (Mohamed and Abd-El-Nabey, 2022; Mohamed et al., 2023; Yan et al., 2023a,b). Exploring biomimetic designs for extreme wettability materials has unveiled their immense potential in O-W separation, offering benefits such as high separation efficiency, the absence of additional reagents, minimal secondary pollution, low cost, and the smaller required surface areas. Therefore, numerous materials, including metal mesh, film, sponge, fabric, and so on, have been investigated for their superb O-W separation capacity (Zhao et al., 2022; Gupta et al., 2023).

Several methods have been employed for fabricating SH membranes, such as chemical vapor deposition, electrodeposition, spraying, and more (Abd-El-Nabey et al., 2022; Xue et al., 2022; Huang et al., 2023). However, these methods had some problems, such as the high cost, the lengthy processing time, and the requirement for specialized equipment. In this manuscript, we proposed a simple and scalable method for fabricating SH membranes via dip coating. Dip coating was a promising approach for creating SH surfaces because it enabled convenient manipulation of surface composition and structure to achieve desired wetting properties (Zhao et al., 2022; Gupta et al., 2023). Additionally, it facilitated the production of functional coating on a wide range of substrates on a large scale, making it used for the O-W separation.

The key requirements for preparing SH surfaces are twofold: fabricating surface roughness by depositing micro-nano structures and modifying the rough surface with low surface energy materials (Ragheb et al., 2022). Researchers have explored various nanomaterials to enhance surface roughness. However, conventional methods of nanoparticle synthesis involving hazardous chemicals pose environmental risks, necessitating the development of alternative, eco-friendly approaches (Kumar et al., 2014; Daniel et al., 2023). Biogenic synthesis has emerged as an efficient, clean, and environmentally friendly method. Bio tin is a sustainable and versatile material with a wide range of applications. Its unique characteristics, including chemical stability, low toxicity, and moderate electrical conductivity, make it suitable for diverse fields such as energy storage, catalysis, sensing, biomedical, SH coating, and sustainable packaging (Yang et al., 2020; Mishra and Ahmaruzzaman, 2022). The environmentally friendly synthesis methods employed in bio tin production further contribute to its sustainable nature. As research and development in this field continue, bio tin is expected to play a significant role in addressing environmental challenges and promoting sustainable development across various industries. Biogenic synthesis of bio tin NPS utilizes molecules derived from living organisms and biomass waste as substitutes for the reducing agents and stabilizers typically employed in chemical methods. While previous studies have indeed explored the biogenic synthesis of tin oxide nanoparticles for various applications such as antibacterial, antioxidant, and photocatalytic activities, we would like to emphasize the distinctiveness of our methodology and its application in our research. Various studies have explored the biogenic synthesis of tin oxide nanoparticles for a range of applications. Vidhu and Philip (2015) focused on the antibacterial and antioxidant activities of SnO_2 nanoparticles synthesized using *Saraca indica* flower. Meena Kumari and Philip (2015) investigated the synthesis of biogenic SnO_2 nanoparticles from ripe pomegranate seed, studying their thermal, rheological, antibacterial, and antioxidant properties. Dong et al. (2007) explored the biogenic synthesis of tubular SnO_2 with hierarchical intertextures using glycoprotein which has a potential application in gas sensors, dye-sensitized solar cells, and photocatalysts. Ma et al. (2020) examined the potential of *L. acidissima*-mediated tin oxide nanoparticles for cervical carcinoma treatment. Lastly, Mohanta and Ahmaruzzaman (2020) investigated the synthesis of SnO_2 quantum dots using *Allamanda cathartica* leaf extract for the removal of bisphenol from aqueous solutions, showcasing their photocatalytic adsorbent properties.

Moreover, fluoro silanes or fluorocarbon molecules have traditionally served as low surface energy materials due to their low surface energy. However, the using of fluorocarbons with long chains poses concerns related to environmental persistence, bioaccumulation, and potential harm to ecosystems (Mohamed et al., 2023). Therefore, designing SH surfaces is a challenge, necessitating the development of inexpensive and eco-friendly methods and materials for fabricating surfaces with low surface energy. Stearic acid is a cheap and environmentally friendly low surface energy material; therefore, it is used as a low surface energy material in our research.

Here, to address the limitation of complex, high-cost, and toxic fabricating oil-water separation method, we proposed a new fabrication method based on the bio tin oxide NPs superhydrophobic coating on textile fabric (T.F.) for efficient O-W separation. Bio tin NPs were synthesized from biomass waste materials (sunflower leaves extract), representing a green and sustainable approach that used natural materials without toxicity. Stearic acid, an inexpensive and environmentally benign substance, was employed as a low surface energy material. The chemical composition, size, and morphology of the prepared bio tin NPS will be thoroughly investigated. Moreover, the wettability, oil absorption capacity, O-W separation performance, mechanical stability, chemical stability, and flux of the prepared superhydrophobic textile fabric will be studied.

2 Experimental

2.1 Materials

The following substances were used in the experiment: n-hexane (Hex.) (98%), sulphuric acid (99%), bromothymol blue (95%), tin chloride dihydrate (98%), sodium hydroxide (97%), and stearic acid (SA) (98.5%) were bought from Chematek company. A commercial diesel (Die.) and coconut oil (Coc.) were used. The spotless TF was bought from the Arabo filter company (Egypt).

2.2 Preparation method

2.2.1 Synthesis of bio-SnO_2 NPS

Local residents picked sunflower leaves, dried them in the shade, and then pounded them into a fine powder in a mortar. One hundred milliliters of deionized water and 5 g of powdered sunflower leaves were refluxed at 100°C for 15 min. Filtered extract was used in subsequent studies.

By adding 10 mL of extract dropwise to 30 mL of 0.5 M tin chloride solution at room temperature and rapidly stirring for 10 min, tin oxide nanoparticles were created. The emergence of a light brown precipitate indicates the presence of tin oxide nanoparticles. The samples were centrifuged and submersed in deionized water before being thoroughly cleaned. The sample was annealed for a whole hour at 400°C.

2.2.2 Construction of superhydrophobic textile fabric

For 1 h, a circular T.F. with a 10.5 mm diameter was immersed in a bio-SnO_2 NPs solution. The TF was next dried for 2 h at 30°C and then for 1 h at 135°C. The TF is then immersed for 30 min in an ethanolic solution that contains 0.01 M stearic acid. The S.T.F., T.F.@ bio-SnO_2 @SA, was then dried for 2 h at 30°C and 1 h at 60°C.

2.3 Characterization techniques

A scanning electron microscope (SEM) was employed to analyze the morphology of the bio-SnO_2 NPs that were prepared. The Brunauer–Emmett–Teller method was used to analyze the bio SnO_2 NPs' textural properties (BET-Beckman Coulter, SA3100). The composition of the synthesized bio-SnO_2 NPs was studied via a Bruker Tensor 37 FTIR Fourier transform infrared spectrophotometer.

2.4 Wettability, absorption capacity, chemical and mechanical stability of the S.T.F.

The wettability of the pristine textile fabric and S.T.F. was measured via measuring the WCA and WSA. The WCA and WSA were determined using a Rame-hart CA instrument (model 190-F2) and 5 μL water droplet, and the provided WCA and WSA results are the average of three tests carried out at various positions on the S.T.F. Using sulfuric acid and sodium hydroxide, the pH of the water droplets was changed. The absorption capacity measurements were conducted following the methodology described in previous research conducted by our group (Beagan et al., 2024).

A mechanical stability assessment was conducted on the S.T.F. through an abrasion test. This involved dragging the prepared S.T.F. across 800-mesh sandpaper at 5 kPa pressure, with measurements of WCA and WSA taken every 5 cm. Additionally, to evaluate its chemical stability, multiple samples were soaked in solutions ranging from pH 1 to 13 for 2 h. The impact of this chemical exposure on WSA and WCA values was then analyzed. The absorption capacity, mechanical, and chemical stability data presented are averages derived from the results of these three tests (Lv et al., 2020).

2.5 Separation performance measurements

Using an oil-water separation assembly and a variety of model oils, including Hex, Die., and Coc., the ability of the developed S.T.F. to separate oil from water was studied. A mixture of water and oil (20 mL each) was poured over the modified membrane while the O-W separation assembly was tilted at an angle of 30°. Bromothymol blue was used to color the water to make observations much clearer. The reported separation efficiency results are the average of three tests on different S.T.F. membranes. The separation efficiency and flux rate were estimated using previously published methodologies (Mohamed and Abd-El-Nabey, 2022).

3 Results and discussion

3.1 Characterization of the bio-SnO_2 nanoparticles, T.F. and S.T.F.

3.1.1 Characterization of the bio-SnO_2 nanoparticles

Figure 1 illustrates the outcomes of the bio-SnO_2 nanoparticles' characterization through SEM, FTIR, and BET analyses. As shown in Figure 1A, the SEM image revealed that the synthesized Bio-SnO_2 exhibited nano-scale dimensions. The average length of the nanoparticles was measured to be 80 nm, indicating their elongated morphology. The diameter of the nanoparticles was about 20 nm, signifying their nanoscale dimensions. As shown in Figure 1B, FTIR analysis shows two prominent peaks, providing insights into the functional groups present on the surface of the bio-SnO_2 nanoparticles. The peak at 3,410 cm^{-1} corresponds to the stretching vibration of hydroxyl groups, suggesting the presence of –OH groups, possibly originating from the bio-reducing agent. The peak at 642 cm^{-1} may be associated with the characteristic vibrations of Sn–O bonds, indicating the formation of tin oxide. As shown in Figure 1C, BET analysis is employed to determine the textural properties of the bio-SnO_2 NPs. The BET-specific surface area was found to be a substantial 413 m^2/g, indicating a high surface area available for potential interactions. The significant pore volume of 0.19 cm^3/g suggests the presence of pores, which can contribute to enhanced surface roughness.

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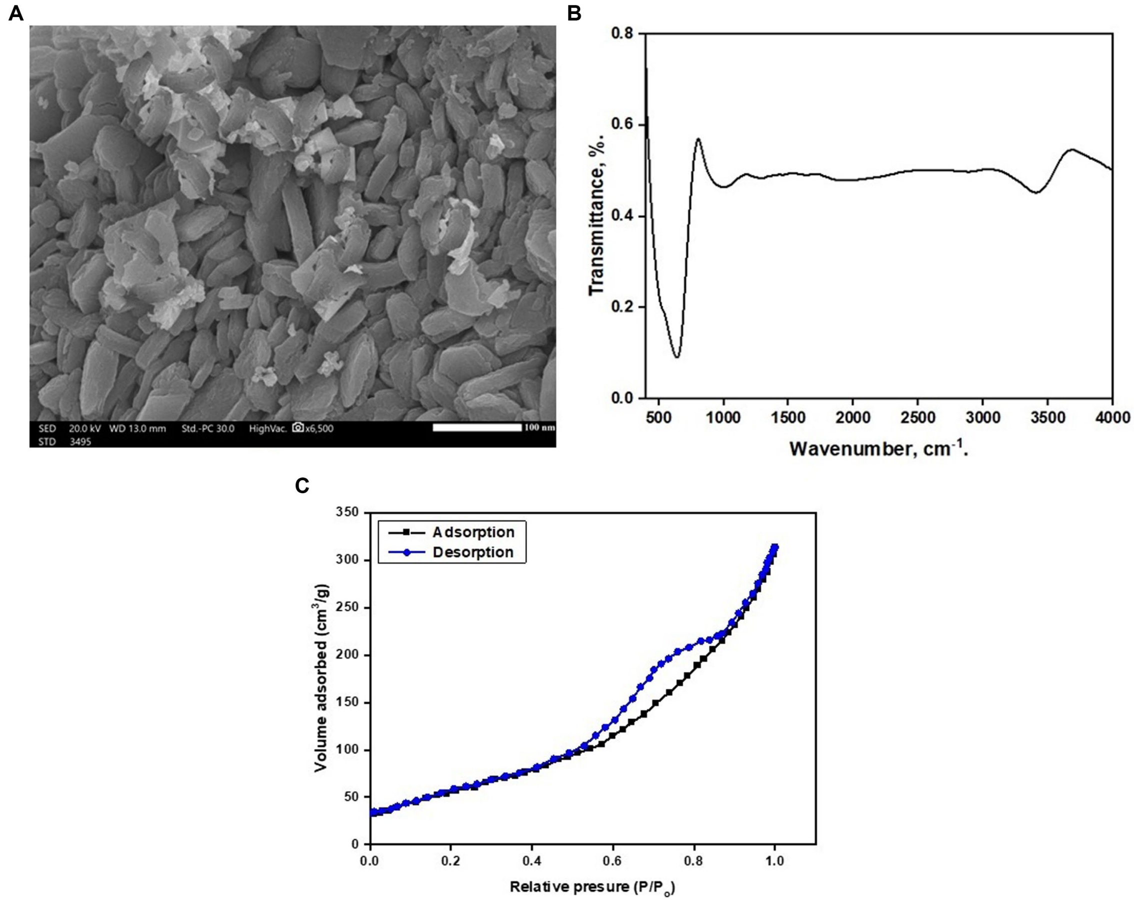

FIGURE 1
(A) SEM micrograph, **(B)** FTIR micrograph, and **(C)** BET isotherm of the prepared bio-SnO_2 NPs.

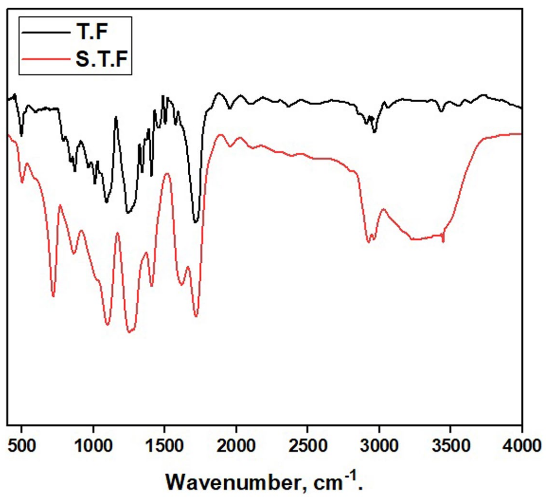

FIGURE 2
FTIR micrograph of the T.F. and S.T.F.

3.1.2 Characterization of the T.F. and S.T.F.

The superhydrophobic property is estimated via both chemical composition and surface morphology. In Figure 2, the FTIR spectra of the T.F. and the S.T.F. are illustrated. The FTIR spectrum of T.F. exhibits several peaks corresponding to various functional groups. Specifically, the peak at 3,431 cm^{-1} is due to the N–H groups stretching, while peaks at 2,901 cm^{-1} and 2,952 cm^{-1} arise from the –CH_2-group asymmetric and symmetric stretching, respectively (Abdel-Gaber et al., 2022). The peak at 1,726 cm^{-1} corresponds to the C=O stretching, and the peak at 1,408 cm^{-1} is attributed to the bending of C–H. Additionally, peaks at 1,236 cm^{-1} and 1,008 cm^{-1} arise from the C–N stretching, and the peak at 864 cm^{-1} corresponds to the out-of-plane bending of N–H. The spectrum of S.T.F. exhibits the same peaks as T.F., with the addition of a broad peak corresponding to OH stretching at 3309 cm^{-1} of the low surface energy stearic acid and a peak at 699 cm^{-1} due to the Sn–O bonds of the synthesized bio-SnO_2. The FTIR results confirm the grafting of the T.F. with the prepared bio-SnO_2 and the low surface energy material stearic acid.

The morphology of T.F. and S.T.F. was investigated using SEM, as shown in Figure 3. The surface of T.F. appears smooth in the image, while the surface of S.T.F. exhibits significantly enhanced roughness due to the presence of extensive micro/nanostructures of bio-SnO_2.

3.2 Wettability and absorption capacity measurements

The wettability results showed that the WCA of TF is close to 0°, which indicated superhydrophilic behavior, where water droplets

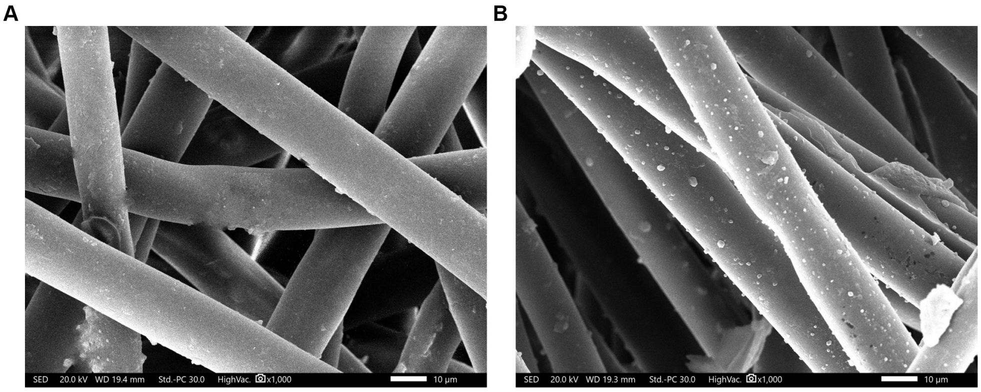

FIGURE 3
SEM micrograph of the **(A)** T.F and **(B)** S.T.F.

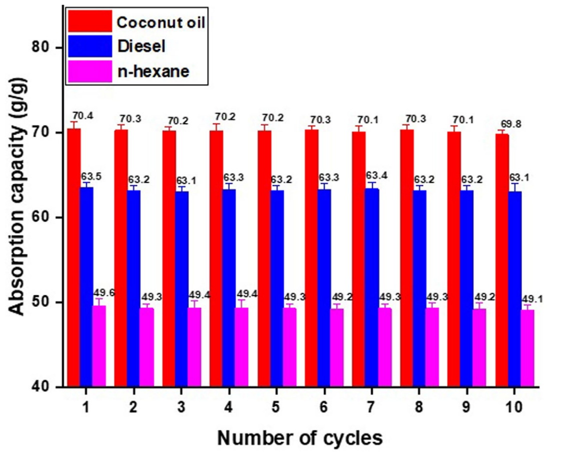

FIGURE 4
The absorption capacity of the S.T.F. for different O-W combinations with the cycle number.

adhere to the surface, and sliding off is difficult even when the fabric is tilted. The superhydrophilic nature had a strong affinity for water, which might not be desirable for applications involving O-W separation. The S.T.F. demonstrates remarkable SH properties. The measured WCA of 152° ± 0.4° indicated a significant transformation from superhydrophilicity to superhydrophobicity. The water sliding off the surface demonstrated the effectiveness of the Bio-SnO_2-based superhydrophobic coating. The low WSA value of 4° ± 0.4° showed the ability of the S.T.F. to repel water efficiently. This low WSA indicated that even a small tilt of the fabric results in water droplets rolling off, emphasizing the robust SH nature.

The absorption capacity of the S.T.F. was assessed for three different oils: Coc., Die., and Hex., as shown in Figure 4. The absorption capacity values of 70.4 g/g for Coc., 63.5 g/g for Die., and 49.6 g/g for Hex. showcase the versatile oil absorption capability of the S.T.F. Earlier research had established a correlation between heightened viscosity and increased oil density, showing a positive impact on oil absorption capacity (Xu et al., 2015; Lv et al., 2018; Shi et al., 2020; Parsaie et al., 2021; Shang et al., 2021). This phenomenon was explained by the delayed release of oils with elevated viscosities and densities from the SH membrane. Consequently, more oil was retained in the porous structure, augmenting the membrane's absorption capacity. The weightier nature of oils with higher viscosity and density within the identical number of pores in the SH membrane, in comparison to lighter oils, contributed to a superior absorption capacity.

The absorption capacity of the S.T.F. was evaluated over 10 cycles for each oil. The S.T.F. membrane was sequenced between cycles to desorb the absorbed oil. Remarkably, the absorption capacity showed only a minimal reduction with increasing cycle number, highlighting the mechanical and chemical stability of the S.T.F. This cyclic stability was crucial for real-world applications, which ensured the prolonged effectiveness in the O-W separation. The impressive oil absorption capacities, combined with the stability over multiple cycles, emphasize the practical utility and longevity of the S.T.F. for efficient oil absorption and separation. The S.T.F. exhibited superior absorption capacities compared with previously identified O-W separation materials (Zhou et al., 2017; Xu et al., 2020).

3.3 O-W separation efficiency

Figure 5 depicts the O-W separation efficiency of the developed S.T.F. over 10 cycles of use for three distinct oils: Hex., Die., and Coc. Among these oils tested, Hex. demonstrated the highest separation efficiency at 99.5%, showing the excellent capability of the S.T.F. in efficiently separating Hex. from water. Die. follows with a separation efficiency of 97.1%, and Coc. with 96.3%, indicating robust performance in the different oil types. Notably, the separation efficiency of the S.T.F. exhibited a gradual minimal decrease with an increase in the number of cycles. The sustained high separation efficiency over multiple cycles highlights the coating's durability and stability, which was critical for the practical applications. The overall high separation efficiencies across multiple cycles confirm the effectiveness of the developed S.T.F. in the O-W separation. The varying separation efficiencies among different oils showed that the S.T.F. could effectively handle oils with distinct properties, making it a versatile solution for diverse O-W mixtures. Table 1 summarizes a comparison of the separation efficiency of the prepared S.T.F. with that of the recent literature studies.

3.4 Mechanical stability

The study of the mechanical stability of the S.T.F. involved examining the impact of abrasion length on both the WCA and WSA of the membrane, as depicted in Figure 6. The investigation focused on understanding how varying abrasion lengths affect the crucial wetting parameters of the membrane. Figure 6 shows that the S.T.F. exhibits superior mechanical stability as it maintains superhydrophobicity up to an abrasion length of 200 mm. The resistance to changes in wetting angles under abrasion implied practical resilience, making the S.T.F. suitable for applications where mechanical stress was common. The enhanced mechanical stability broadened the potential applications of the S.T.F., making it a promising candidate for use in various industries and environments. This enhanced mechanical stability surpasses values reported in previous studies, highlighting the durability of the developed SH coating (Zhou et al., 2017; Chen and Guo, 2018).

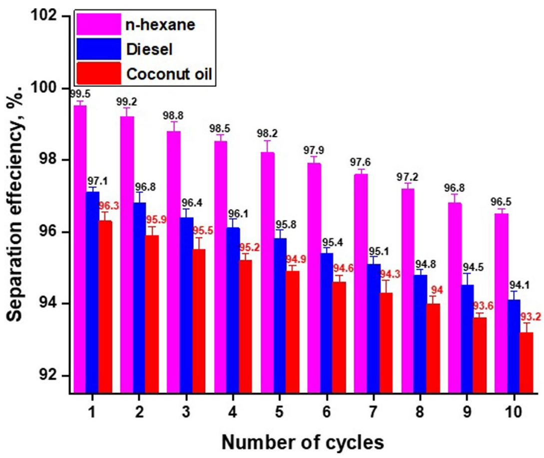

FIGURE 5
The separation efficiency of the S.T.F. for O-W mixture with the separation cycles number.

3.5 Chemical stability and flux rate

The chemical stability of the developed S.T.F. was systematically investigated under varying pH conditions. Figure 7 presents the outcomes of these investigations, illustrating the impact of solution pH on the chemical stability of the S.T.F. The study evaluated the S.T.F.'s response to the different pH values, examining how it retained S.P. properties in different pH solutions. Notably, the results showed that the developed S.T.F. maintains its S.P. characteristics within the pH range of 3–11. The well-synthesized SnO_2 nanoparticles, characterized by their small size uniform morphology, and high surface area contribute to the high mechanical stability of the superhydrophobic textile fabric. This wide pH stability was significant for applications where the membrane might come into contact with solutions of varying acidity or alkalinity. The chemical stability of the S.T.F. with a wide pH range enhanced the S.T.F.'s versatility for applications in diverse environments, including those with fluctuating pH conditions.

The flux rate is a crucial parameter that influences the efficiency of the O-W separation process. The flux rate of the developed S.T.F. for these three distinct oils, Hex., Die., and Coc., was systematically studied. We measured the flux rates of the S.T.F. for

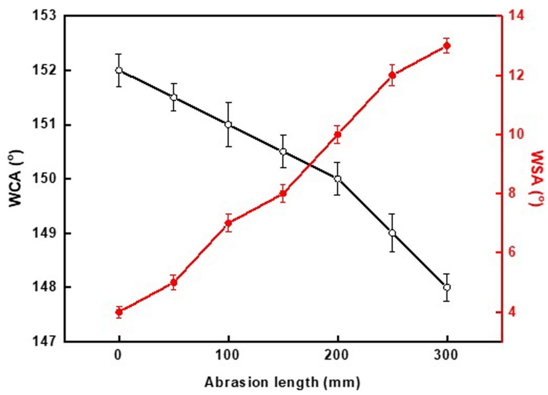

FIGURE 6
The abrasion test of the prepared S.T.F.

TABLE 1 A comparison of the separation efficiency of the prepared S.T.F. in our study with that of the recent literature studies.

The superhydrophobic membrane	The nanomaterials	Low surface energy material	Separation efficiency
Superhydrophobic coated cotton (Singhal et al., 2024)	Zirconium dioxide nanoparticles	Hexadecyl trimethoxysilane	99.9%
Superhydrophobic cotton fabric (Ahmad et al., 2023)	Titanium oxide nanoparticles	Fluorine-free aminopropyl triethoxysilane + myristic acid	95%
Polyethylene terephthalate/polyamide nonwoven fabric (Feng et al., 2022)	Titanium dioxide-ferric oxide nanoparticles	Stearic acid	98%
Superhydrophobic-superoleophilic fabrics (Bhatt et al., 2021)	Titanium oxide nanoparticles and nano-silica	1,1,3,3-Hexamethyl disilazane and, polydimethylsiloxane	95%
Superhydrophobic rayon fabrics (Görgülüer et al., 2021)	Titanium dioxide and silver nanoparticles	Poly-dimethyl siloxane	98.3%
Superhydrophobic cotton fabric (Biswas and Jana, 2021)	Silica nanoparticles and N,F codoped titanium oxide nanoparticles	Octadecyl trimethoxysilane	85%
Our work	Bio tin oxide nanoparticles	Stearic acid	99.5%

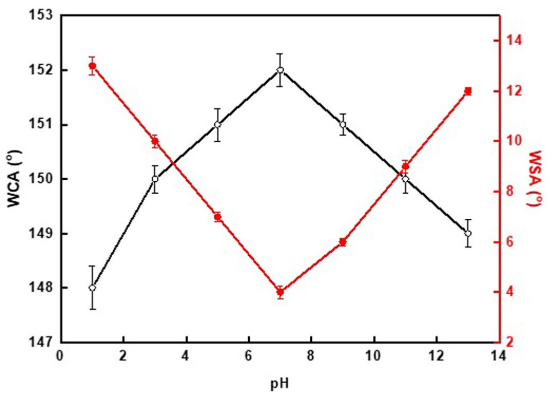

FIGURE 7
Variation of the WCA and WSA of the prepared S.T.F. with the values of a solution pH.

each oil type, providing insights into its efficiency in facilitating the flow of oil through the membrane during the O-W separation process. The results revealed that the flux rate of the S.T.F. was highest for Hex., with a value of 9,400 L m^{-2} h^{-1}. Diesel follows with a flux rate of 8,800 L m^{-2} h^{-1}, and coconut oil exhibits a flux rate of 8,100 L m^{-2} h^{-1}. The varying flux rates showed that the S.T.F. was particularly efficient in separating Hex., demonstrating the highest flux rate among the three oils. The high flux rates for Die. and Coc. further signified the membrane's versatility in handling different types of oils. The observed flux rates were crucial for applications where the rapid and efficient separation of oil and water is essential, such as in industrial or environmental settings. The variations in flux rates among different oils showed the membrane's adaptability and effectiveness across various oil types, making it a promising solution for applications requiring rapid and efficient O-W separation. The flux rates exhibited by the S.T.F. surpass those of numerous absorbents reported in the literature (Chen and Guo, 2018; Yan et al., 2018).

4 Conclusion

This work successfully proposed a superhydrophobic textile fabric (S.T.F.) via the bio tin oxide nanoparticles synthesized from sunflower leaf extract, which was low-cost and non-toxic. This S.T.F. demonstrated good characteristics, including high wettability, superior oil absorption capacity, and efficient oil-water separation performance. The scanning electron microscope, SEM, characterization confirmed the nano-scale dimensions of the prepared nanoparticles. Additionally, FTIR analysis was utilized to confirm the structure of the prepared nanoparticles, while BET analysis was employed to measure the surface area. FTIR and SEM techniques were employed to examine the characteristics of the textile fabric both before and after modification with the superhydrophobic coating. Mechanical stability test revealed remarkable durability, with superhydrophobicity retention even after 200 mm abrasion. The S.T.F. exhibited strong chemical stability with a broad pH range, ensuring sustained superhydrophobicity. Additionally, flux rate analyses demonstrated efficient oil flow during oil-water separation, further emphasizing the practicality of the developed membrane. These findings collectively position the S.T.F. as a promising, sustainable, and versatile solution for various oil-water separation applications, contributing to advancements in environmentally friendly technologies.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

AB: Conceptualization, Resources, Validation, Writing – review & editing. JL: Writing – review & editing. YL: Writing – review & editing. MM: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frwa.2024.1390739/full#supplementary-material

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