Publishing Excellence Inspiring Progress
ARISTON PUBLICATIONS
Energy & Environment Advances
ISSN: 3066-5728 https://aristonpubs.com/energy-environment-advances https://doi.org/10.69626/eea.2025.0131

RESEARCH ARTICLE

Fabrication of a Mechanically Robust Superhydrophobic Polyurethane Sponge via CS/SiO_2/Polymer Composite Coating for High–Efficiency Oil–Water Separation

Mehejbin Mujawar [1], Deepak Kumbhar [2], Prashant Sanadi [1], Ankush Sargar [3], Vashishtha Gurame [4], Shivaji Kulal [1,*]

ABSTRACT: The increasing discharge of industrial oily wastewater poses severe risks to environmental integrity and public health, necessitating the development of efficient and sustainable treatment technologies. In this work, we report the synthesis of a superhydrophobic polyurethane sponge functionalized with a composite coating comprising candle soot (CS), silica nanoparticles (SiO_2), polystyrene (PS), and polydimethylsiloxane (PDMS). Superhydrophobic SiO_2 nanoparticles were first prepared via a sol–gel method using methyltrimethoxysilane as the precursor. These nanoparticles were dispersed into a polymer solution containing PS and PDMS, along with candle soot, and subsequently deposited onto a commercial polyurethane sponge through a simple dip-coating process. The resulting material exhibited exceptional wettability characteristics, with a water contact angle of 165° and an oil contact angle of 0°. The sponge demonstrated outstanding oil–water separation performance, achieving an efficiency of 99% over repeated cycles. Mechanical durability tests revealed that the coating withstands over 80 abrasion cycles without significant loss of superhydrophobicity. Furthermore, the sponge maintained high separation efficiency across a broad pH range, confirming its stability under harsh chemical conditions. Adhesion tests using peel tape validated the robustness and coating integrity. Due to its cost-effectiveness, reusability, and environmental sustainability, this superhydrophobic sponge presents a viable and scalable solution for treating industrial effluents and managing oil spills.

Keywords: Superhydrophobic coating; oil–water separation; silica nanoparticles; candle soot; polyurethane sponge; mechanical durability.

Received: 02 February 2025; Revised: 28 April 2025; Accepted: 29 May 2025; Published Online: 26 July 2025

[1] Department of Chemistry, Raje Ramrao Mahavidyalaya, Jath, Sangli-416404, Maharashtra, India
[2] Department of Chemistry, Dattajirao Kadam Arts, Science and Commerce College, Ichalkaranji, Kolhapur-416115, Maharashtra, India.
[3] Department of Chemistry, Dr. Patangrao Kadam Mahavidyalaya, Sangalwadi, Sangli- 416305, Maharashtra, India
[4] Department of Chemistry, Shri Shivaji Mahavidyalaya, Barshi, Solapur-413401, Maharashtra, India

* Author to whom correspondence should be addressed:
srkulalresearch@gmail.com (Shivaji Kulal)

1. INTRODUCTION

The exponential expansion of the global petroleum and chemical sectors has precipitated a corresponding surge in the generation of industrial oily wastewater and the frequency of catastrophic oil spills, representing one of the most pressing environmental challenges of the modern era [1, 2]. These hydrocarbon pollutants inflict severe damage on aquatic ecosystems, smothering marine life, degrading water quality, and disrupting food chains. Furthermore, they pose direct and indirect threats to human health through the contamination of drinking water sources and the accumulation of toxic

© Ariston Publications 2025. All rights reserved.

compounds in the food supply. Addressing this form of pollution is therefore critical for ecological preservation and public welfare. Conventional remediation technologies, including air flotation, gravity separation, centrifugal separation, incineration, and membrane filtration, have been deployed for decades [3–7]. However, these methods are frequently hampered by significant drawbacks that limit their practical and widespread application. Issues such as high operational energy costs, the generation of secondary pollutants, limited effectiveness for emulsified oils or at low contaminant concentrations, and complex, time-intensive processing protocols render them less than ideal for many real-world scenarios. These persistent limitations have catalyzed a concerted research effort towards the development of advanced separation materials, with a particular focus on surfaces engineered to exhibit extreme wettability contrasts.

In this context, superhydrophobic surfaces have emerged as a highly promising platform for efficient oil–water separation. By definition, these surfaces demonstrate a pronounced aversion to water, characterized by a static water contact angle (WCA) greater than 150°, coupled with a strong affinity for oils, evidenced by an oil contact angle (OCA) typically below 5° [8–11]. This dual functionality allows water to be effectively repelled while oils are readily absorbed or permeated. The fundamental principles governing superhydrophobicity are rooted in surface chemistry and topography. Achieving this state requires a synergistic combination of low surface energy materials and multiscale surface roughness, which together amplify the intrinsic hydrophobic properties and promote the formation of a stable composite air-liquid interface, as described by the Cassie-Baxter model [12].

Inspired by natural examples such as the lotus leaf, researchers have developed a diverse array of artificial fabrication strategies to create these functional surfaces. Widely employed techniques include the sol–gel process, which allows for the controlled synthesis and deposition of nanostructured metal oxides [13,14]; electrospinning, capable of producing fibrous membranes with tunable porosity [15,16]; layer-by-layer assembly for constructing precise nanoscale coatings [17]; and various vapor deposition methods for conformal thin-film application [18,19]. For instance, Fan and colleagues utilized a thermally induced phase separation method combined with hydrophobic SiO_2 nanoparticles to fabricate superhydrophobic polyphenylene sulfide films with a WCA of 156.9°, demonstrating robust separation performance [20]. Similarly, Gu et al. developed a flexible PDMS@F-SiO_2 coating via a spraying technique for drag reduction and self-cleaning applications [21], while Liu et al. created porous SiO_2 micro-nano fiber membranes via electrospinning that exhibited excellent separation efficiency and a very low water sliding angle [22]. Gao et al. also reported effective separation using spray-coated PVDF/SiO_2 membranes [23]. Despite these advances, many current approaches involve complex fabrication steps, expensive raw materials, or lack the mechanical robustness required for demanding and repeated use in industrial or environmental cleanup settings.

The novelty of the present work lies in the development of a mechanically durable, cost-effective, and scalable superhydrophobic sponge through a straightforward dip-coating process, utilizing a uniquely formulated composite coating that integrates candle soot (CS) and in-situ synthesized methylated silica (SiO_2) nanoparticles within a binary polymeric matrix of polydimethylsiloxane (PDMS) and polystyrene. While individual components like SiO_2, PDMS, or carbon soot have been studied previously, their synergistic combination in this specific formulation, applied to a commercially available polyurethane sponge to create a stable, hierarchical micro-nano structure, presents a distinct approach. This design leverages the inherent hydrophobicity and nano-structuring role of the candle soot, the low surface energy and binding capability of PDMS, the structural reinforcement from polystyrene, and the roughness-enhancing properties of the methylated silica nanoparticles. The resulting material is engineered not only for high separation efficiency but specifically for exceptional mechanical durability and chemical stability, addressing key gaps in the existing literature regarding the practical longevity of superhydrophobic absorbents.

In this study, methyltrimethoxysilane (MTMS) was employed as the silica precursor in a modified Stöber process to generate hydrophobic silica nanoparticles directly. These nanoparticles, along with candle soot, were then dispersed into a polymeric solution containing PDMS and polystyrene. This composite suspension was used to functionalize a conventional polyurethane sponge via a simple dip-coating and drying technique. The objective was to create a reusable, eco-friendly, and high-performance absorbent material capable of efficient oil–water separation under a variety of challenging conditions, thereby offering a practical and accessible solution for industrial wastewater treatment and oil spill response.

2. EXPERIMENTAL DETAILS

2.1. Materials

Commercial polyurethane sponges, characterized by an open-cell structure with an average pore size of 450–550 µm, were used as the substrate. Methyltrimethoxysilane (MTMS, 98% purity) was employed as the silica precursor. Ammonia solution (28–30% NH_3 in water) served as the basic catalyst. Polydimethylsiloxane (PDMS, Sylgard 184 base resin) and general-purpose polystyrene (PS, average Mw ~192,000) were used as the polymeric binders and low-surface-energy modifiers. Analytical reagent-grade chloroform and absolute ethanol were used as solvents. All chemicals were procured from Shri Samarth Trading Company and used without further purification.

2.2. Synthesis of Hydrophobic Silica (SiO_2) Nanoparticles

 © Ariston Publications 2025. All rights reserved

Hydrophobic silica nanoparticles were synthesized via a modified Stöber sol-gel process [24]. In a typical synthesis, 40 mL of ethanol was mixed with 8 mL of distilled water in a 250 mL round-bottom flask under ambient conditions. To this mixture, 10 mL of methyltrimethoxysilane (MTMS) was added with continuous magnetic stirring. After 30 minutes of stirring to allow for preliminary hydrolysis, 10 mL of ammonia solution was introduced dropwise to initiate the condensation reaction. The reaction mixture was stirred vigorously at room temperature for 2 hours, during which the formation of a translucent silica sol progressed to a white gel. The resultant gel was then transferred to an oven and thermally cured at 70°C for 5 hours to complete the polycondensation process and evaporate residual solvents and by-products, yielding a fine powder of methyl-functionalized silica nanoparticles. The synthesis process is illustrated in Figure 1.

2.3. Fabrication of the Superhydrophobic Composite Sponge

The functional coating solution was prepared in a two-stage process. First, 0.5 mL of PDMS base resin was dissolved in 20 mL of chloroform with magnetic stirring for 30 minutes to achieve a homogeneous precursor solution. Subsequently, 0.8 grams of the as-synthesized silica nanoparticles were dispersed into the PDMS solution, followed by an additional hour of stirring to ensure uniform nanoparticle integration. Concurrently, a separate polymer solution was prepared by dissolving 0.2 grams of polystyrene in 20 mL of chloroform under 30 minutes of stirring. The two solutions were then combined and mixed for a further hour to form a stable, integrated composite coating suspension containing PDMS, PS, and SiO_2 nanoparticles. Commercial polyurethane sponge cubes (approx. 2 cm x 2cm x 2 cm) were meticulously immersed into the coating solution. To investigate the effect of loading on morphology and wettability, immersion times were varied at 10, 20, 30, and 45 minutes. Following immersion, the coated sponges were extracted and allowed to dry in a fume hood at room temperature for 24 hours, resulting in a firmly adhered, hydrophobic composite layer on the sponge skeleton (Figure 2).

2.4. Material Characterization

The surface morphology and microstructure of both uncoated and coated sponges were analyzed using scanning electron microscopy (SEM, JEOL JSM-IT200). The elemental composition and distribution of the coating were determined by energy-dispersive X-ray spectroscopy (EDX) coupled with the SEM. Chemical functionality and the successful incorporation of hydrophobic groups were verified using Fourier-transform infrared spectroscopy (FTIR, Shimadzu IRSpirit) in the range of 400–4000 cm^{-1}. The crystallographic structure of the coated layer was examined via X-ray diffraction (XRD, Rigaku Miniflex 600) using Cu Kα radiation. The wettability of the engineered surfaces was quantitatively assessed by measuring static water contact angles (WCA) and oil contact angles (OCA) using a sessile drop method on a Holmarc Opto-Mechatronics contact angle goniometer. For statistical reliability, contact angle measurements were taken at three distinct locations on each sample surface, and the reported values represent the average.

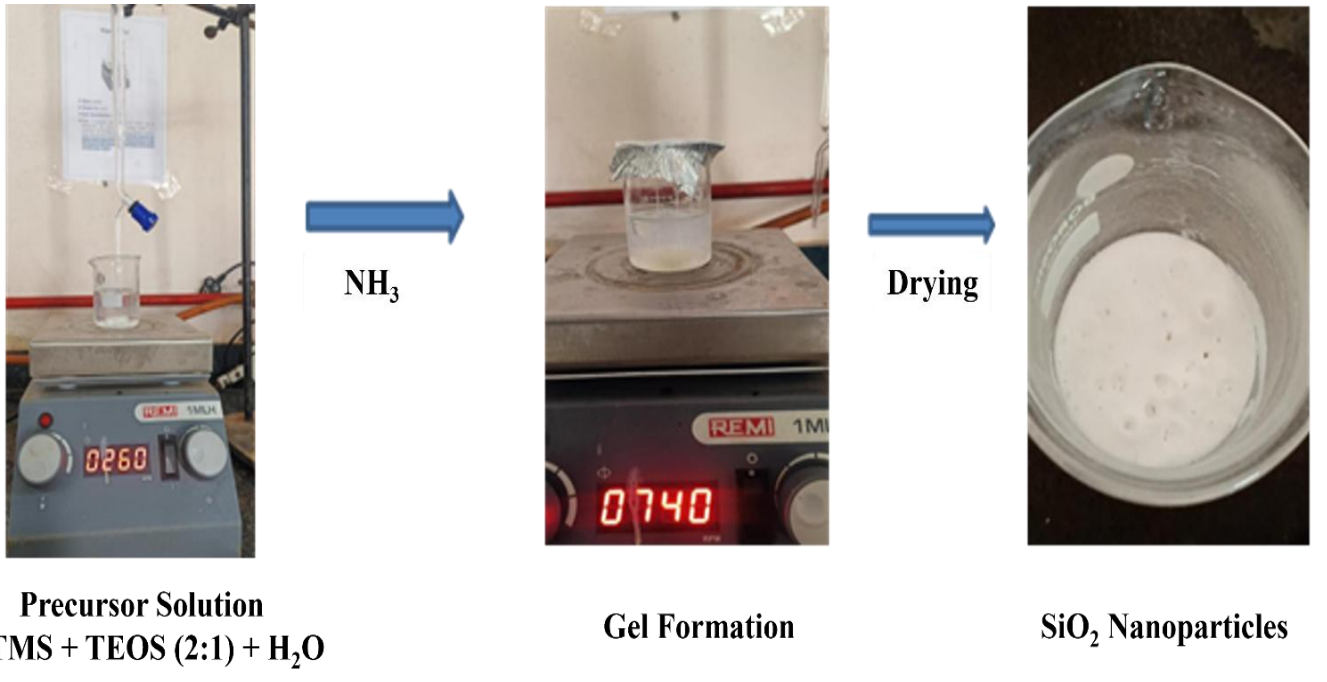


Fig. 1. Synthesis process of SiO_2 nanoparticles.

© Ariston Publications 2025. All rights reserved.

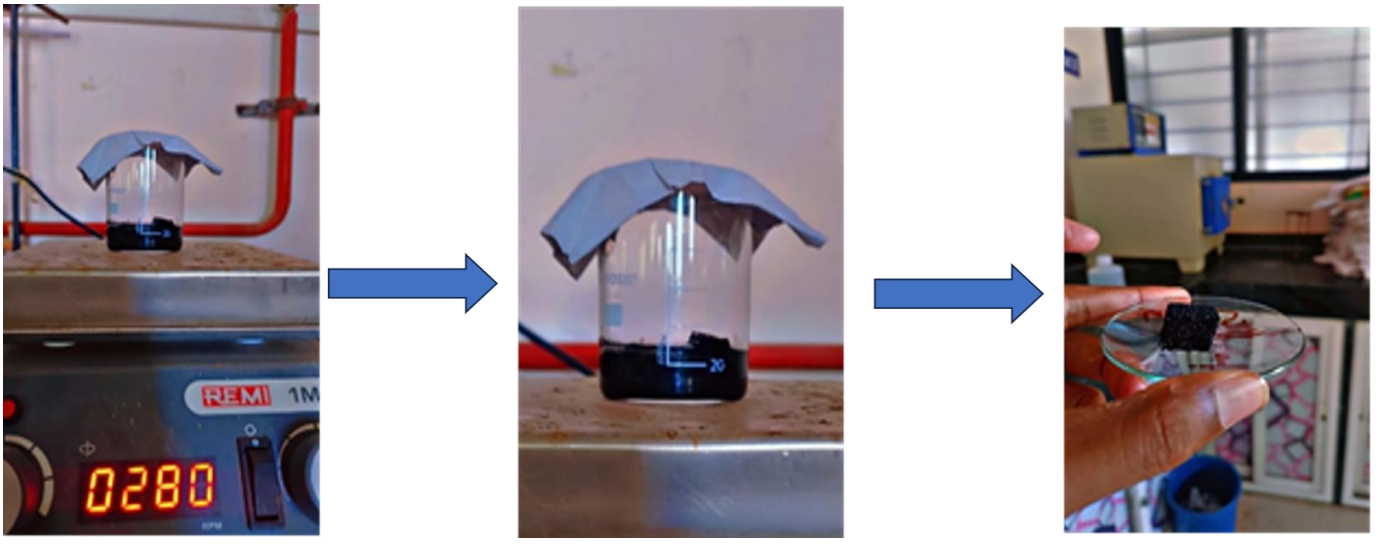


Fig. 2. Synthesis process of superhydrophobic sponge.

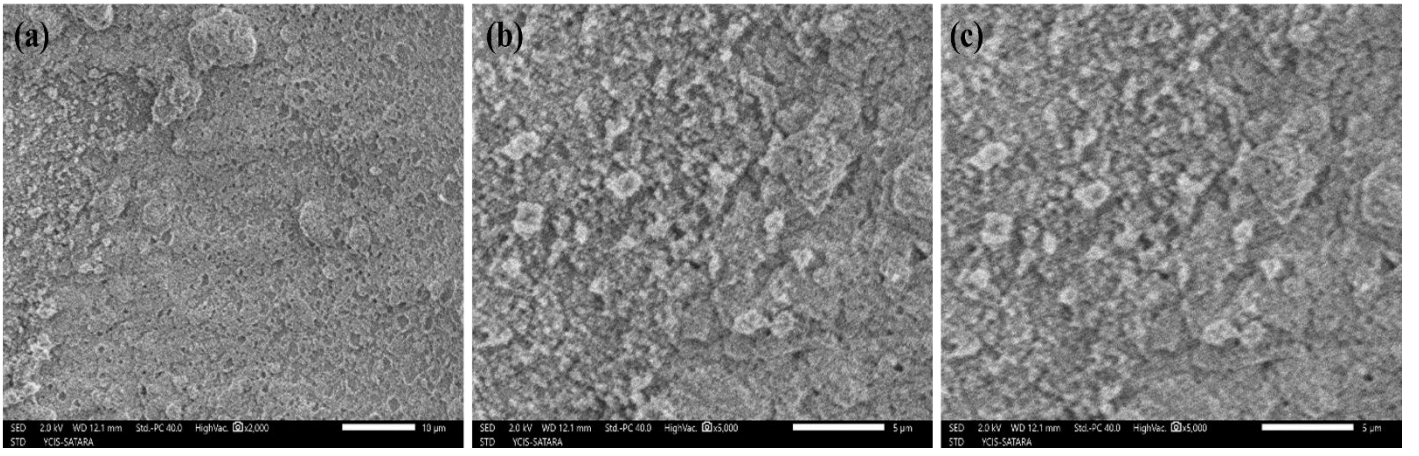


Fig. 3. (a-c) SEM images of silica nanoparticles at different magnification.

3. RESULTS AND DISCUSSION

3.1 Reaction Mechanism and Characterization of Methylated Silica Nanoparticles

The foundational step in this work involved the synthesis of hydrophobic silica nanoparticles, which serve as the primary roughness-enhancing agents. The synthesis was accomplished via a modified Stöber process, a well-established sol-gel method for producing monodisperse silica particles [24]. In this reaction, methyltrimethoxysilane (MTMS) was used as the sole precursor, with ethanol as the solvent and aqueous ammonia as the basic catalyst. The mechanism proceeds through a series of hydrolysis and condensation reactions. Initially, the methoxy ($-OCH_3$) groups attached to the silicon atom in MTMS undergo hydrolysis in the presence of water and the ammonia catalyst, yielding intermediate silanol species ($CH_3Si(OH)_3$) and methanol [25, 26]. Subsequently, these silanol groups condense with one another, forming siloxane (Si-O-Si) bridges and liberating water molecules. The use of MTMS is critical, as the non-hydrolyzable methyl ($-CH_3$) group remains attached to the silicon throughout the process. This directly incorporates hydrophobic organic moieties into the nascent silica network, eliminating the need for a separate surface modification step. The final thermal curing at 70°C drives the condensation reaction to completion, yielding a fine powder of methyl-functionalized silica (SiO_2) nanoparticles. The morphology of these synthesized nanoparticles was confirmed by scanning electron microscopy (SEM), as presented in Figure 3. The images at different magnifications reveal aggregates of spherical to near-spherical nanoparticles with a primary particle size ranging between 50 and 150 nanometers. This aggregated, nanoscale morphology is ideal for creating the hierarchical micro/nano-structured roughness necessary for

 © Ariston Publications 2025. All rights reserved

superhydrophobicity when incorporated into the polymer matrix on the sponge surface.

3.2. Surface Morphology and Chemical Composition Analysis

The transformation of the pristine polyurethane sponge into a functional material is visually and chemically evident from the comprehensive characterization conducted. Figure 4 presents SEM micrographs of the unmodified polyurethane sponge, displaying its inherent three-dimensional, open-cell framework with interconnected micropores typically between 1 and 100 µm in diameter [27]. This porous architecture is essential for providing high surface area and capillary forces for oil absorption. Figure 5 shows the morphology of the sponge after the dip-coating process with the CS/SiO_2/polymer composite. A dramatic change in surface texture is observed. The formerly smooth struts of the sponge are now uniformly coated with a rough, heterogeneous layer. At higher magnification, this coating is revealed to be a composite film embedding the silica nanoparticles and candle soot particles within the PDMS/polystyrene binder. This structure creates a hierarchical roughness, featuring both the microscale pores of the sponge skeleton and the nanoscale features from the embedded particles, which is a quintessential requirement for achieving stable superhydrophobicity. To corroborate the chemical success of the functionalization, Fourier-transform infrared (FTIR) spectroscopy was performed, with key spectra compared in Figure 6(a). The spectrum of the coated sponge shows characteristic peaks that confirm the presence of all designed components.

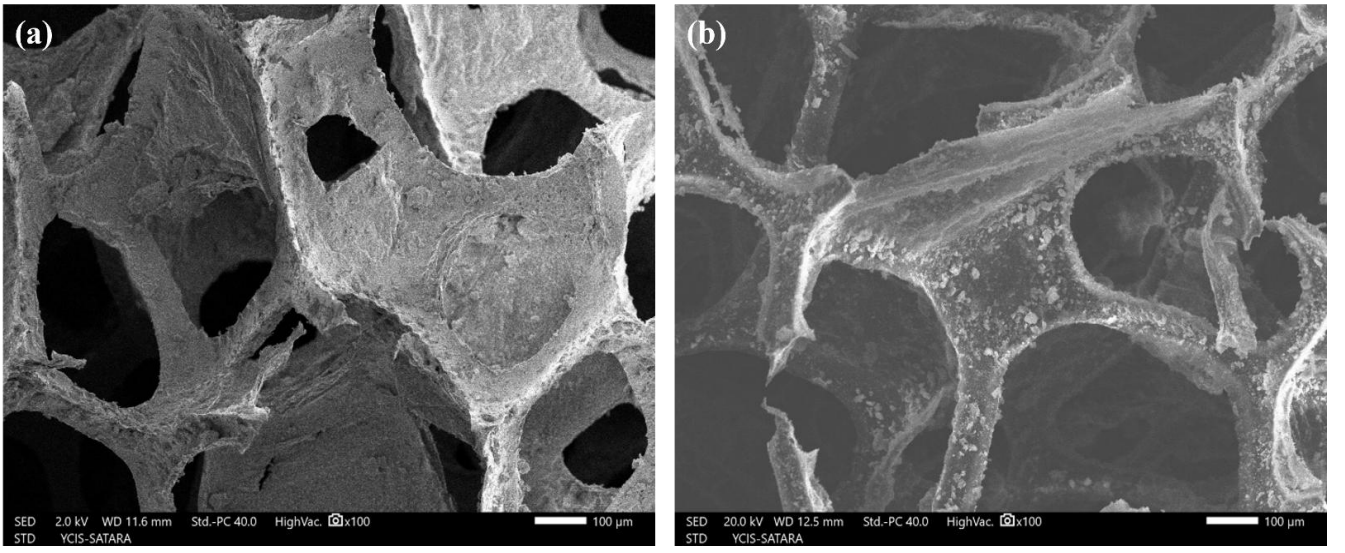


Fig. 4. (a-b) SEM images of superhydrophobic sponge at different magnification.

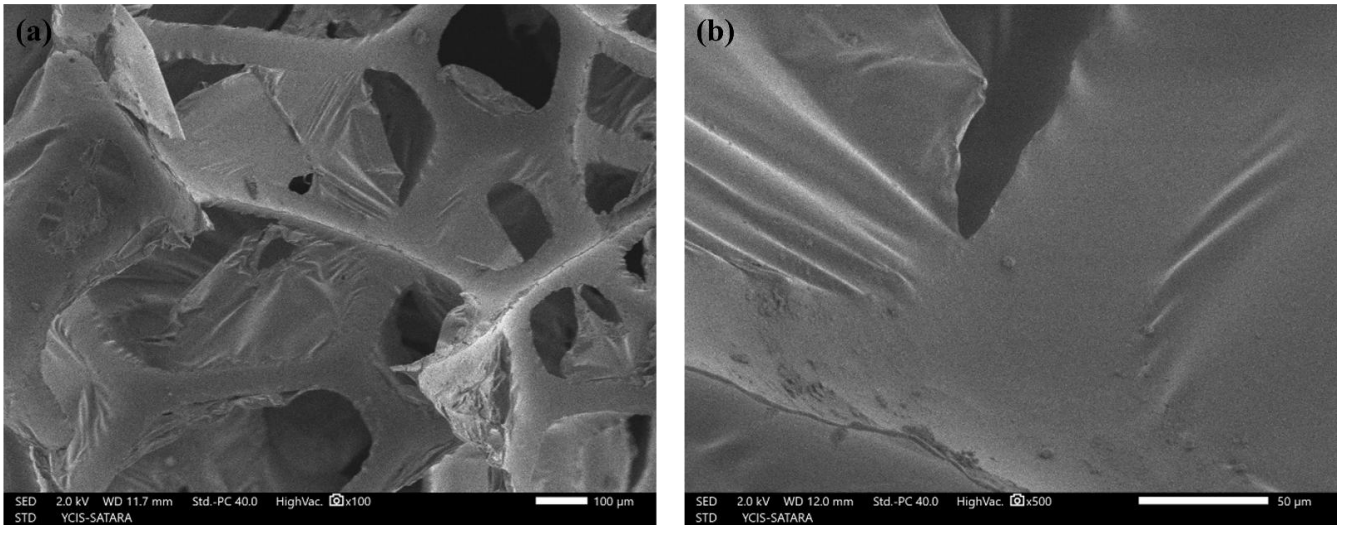


Fig. 5. (a-b) SEM images of polyurethane sponge at different magnification.

© Ariston Publications 2025. All rights reserved.

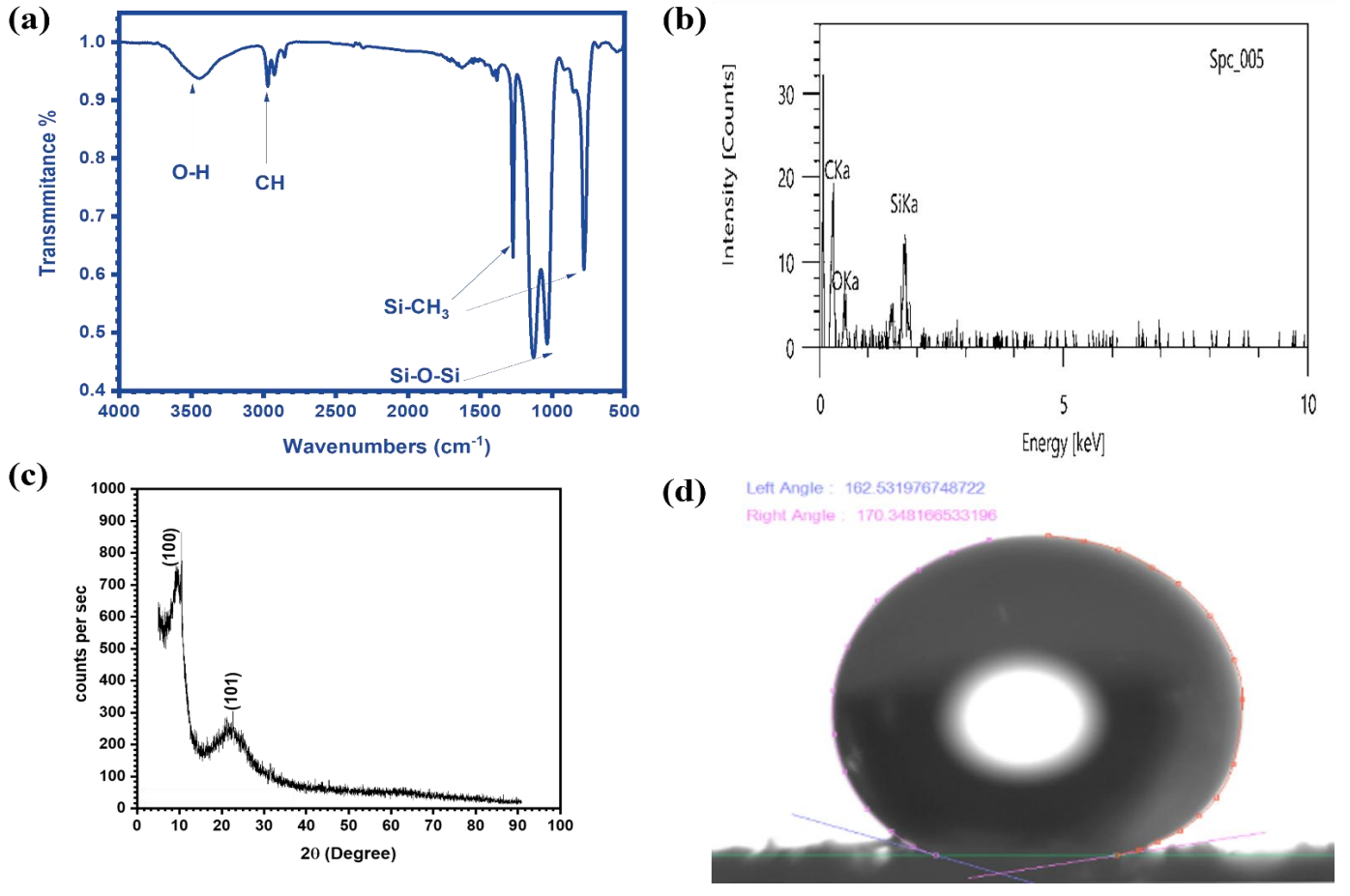


Fig. 6. (a) FTIR image of superhydrophobic sponge, (b) EDAX image of superhydrophobic sponge, (c) XRD image of superhydrophobic sponge, (d) WCA of superhydrophobic sponge.

The broad peak in the 3400-3600 cm^{-1} region, indicative of O-H stretching vibrations from surface silanol groups, is significantly attenuated compared to pure silica, confirming the reduction of hydrophilic sites. The strong, broad absorbance centered around 1130 cm^{-1} is assigned to the asymmetric stretching vibration of the Si-O-Si network. Crucially, the presence of C-H stretching vibrations from methyl groups is confirmed by peaks near 2970 cm^{-1} and 2900 cm^{-1}, originating from both the MTMS-derived SiO_2 and the PDMS/PS polymers. Furthermore, the distinct peaks at 1270 cm^{-1} and 780 cm^{-1} are characteristic of $Si-CH_3$ symmetric bending and rocking vibrations, respectively, providing direct evidence for the successful incorporation of the hydrophobic methyl functionalities from the MTMS precursor [25]. Energy-dispersive X-ray (EDX) spectroscopy analysis, presented in Figure 6(b), provides elemental confirmation. The spectrum from the coated sponge shows clear peaks for silicon (Si) and oxygen (O), confirming the incorporation of silica nanoparticles. The presence of a carbon (C) signal is strong, attributable to the polymer matrix, the candle soot, and the methyl groups on the silica. The structural nature of the coating was further investigated using X-ray diffraction (XRD). The diffraction pattern, shown in Figure 6(c), displays a broad hump centered around 21.5° (2θ), which is characteristic of amorphous silica and the amorphous phases of polystyrene and PDMS. The absence of sharp crystalline peaks confirms the amorphous nature of the composite coating, which is advantageous for forming a uniform and adherent film on the flexible sponge substrate.

3.3. Wettability Performance and pH Stability

The ultimate performance metric for the fabricated material is its wettability. Figure 6(d) presents a photographic image of a water droplet resting on the surface of the modified sponge, demonstrating a highly spherical shape. Quantitative measurement yielded an average static water contact angle (WCA) of approximately 165°, which firmly classifies the surface as superhydrophobic. Conversely, when an oil droplet (such as diesel or hexane) was placed on the same surface, it was instantaneously absorbed, corresponding to an oil contact angle of 0°, denoting superoleophilicity. This extreme contrast in behavior between water and oils is the fundamental principle enabling selective oil absorption. The achievement of this high WCA is a direct consequence of the

 © Ariston Publications 2025. All rights reserved

synergistic effects described earlier: the low surface energy imparted by the methyl groups and the PDMS/PS polymer blend, combined with the multiscale surface roughness created by the sponge microstructure and the embedded nanoparticles.

The stability of this superhydrophobicity under chemically challenging conditions is vital for practical applications. This was evaluated by measuring the water contact angle using droplets of solutions with different pH values, as summarized in Table 1. Under neutral conditions (pH 7, deionized water), the sponge exhibited its maximum WCA of 165°. When exposed to a basic solution (0.1 N NaOH, pH ~9.9), the WCA remained high at 148°, indicating good resistance to alkaline environments. Exposure to an acidic solution (0.1 N HCl, pH ~2.6) resulted in a measurable decrease, with a WCA of 142°. While this represents a reduction, the surface maintains a strongly hydrophobic state. The decreased angle under acidic conditions can be attributed to the potential protonation of any residual silanol groups and the possible slight degradation of the polymer matrix over the measurement period. Nevertheless, the retention of high repellency across a wide pH range confirms the robustness of the coating and its potential utility in treating industrial effluents with variable chemistry.

Table 1. Contact angles at different pH of different solutions.

S. No.	Solution	pH	CA (°)
1.	0.1 N HCl	2.6	142
2.	0.1 N NaOH	9.9	148
3.	Water	7	165

3.4 Mechanical and Adhesive Durability Assessment

For a material intended for repeated use in potentially abrasive environments, mechanical durability is as important as chemical stability. The coating's resilience was tested through a series of qualitative and semi-quantitative mechanical tests [28]. First, a cross-cut test was performed by slicing the sponge in half with a sharp blade. Observation of the newly exposed interior surface revealed that it remained non-wetting, with water droplets beading up, indicating that the coating process successfully penetrated and adhered to the sponge's internal porous network, rather than merely forming a superficial skin. Second, a tape-peel test (analogous to ASTM D3359) was conducted by pressing and subsequently peeling a standard adhesive tape firmly against the coated surface. After multiple peel cycles, no visible delamination of the coating was observed, and the WCA on the tested area showed no significant decline. This confirms excellent interfacial adhesion between the composite coating and the polyurethane substrate, a result of the chloroform solvent partially swelling the sponge surface during immersion, allowing the polymer solution to infiltrate and anchor mechanically.

Third, and most demanding, was an abrasion resistance test. The coated sponge was subjected to cyclic abrasion under a controlled pressure against standard sandpaper. Remarkably, the coating withstood over 80 such abrasion cycles before any noticeable loss of hydrophobicity occurred. After this point, the WCA gradually decreased but remained above 150° for many more cycles. This exceptional abrasion resistance is attributed to the tough, cross-linked nature of the PDMS/PS composite matrix, which firmly embeds the silica nanoparticles, preventing them from being easily scraped away. The candle soot, acting as a nano-reinforcement and filler, may also contribute to enhancing the coating's toughness and wear resistance. These durability tests collectively demonstrate that the superhydrophobic sponge is not a fragile laboratory curiosity but a robust material capable of sustaining its performance through the physical stresses expected in real-world deployment and cleaning cycles.

3.5 Oil-Water Separation Efficacy and Process Demonstration

The practical application of the developed sponge was demonstrated through a series of oil-water separation experiments, visually documented in Figure 7. The superhydrophobic and superoleophilic properties of the sponge enable a simple, gravity-driven absorption process. When the sponge is introduced into a biphasic mixture of water and a floating oil (such as coconut oil, castor oil, or engine oil), it selectively and rapidly absorbs the oil phase within seconds, leaving the water phase behind. The high porosity and capillary action of the polyurethane substrate facilitate a large absorption capacity, typically many times its own weight. The absorbed oil is then easily recovered by simple mechanical squeezing or wringing of the sponge into a collection vessel, after which the sponge can be reused. The process, illustrated for different oils in Figure 7, is highly efficient, cost-effective, and energy-efficient, requiring no external power input or complex apparatus. Quantitative analysis of the separation efficiency, measured by comparing the weight of oil recovered to the initial oil content, consistently exceeded 99% for various light and viscous oils over multiple absorption-squeezing cycles.

This high efficiency, coupled with the demonstrated durability and chemical stability, underscores the significant potential of this CS/SiO_2/polymer composite sponge for addressing oil pollution in scenarios ranging from industrial wastewater treatment to accidental oil spill remediation.

4. CONCLUSION

In summary, this study successfully fabricated a superhydrophobic polyurethane sponge through a dip-coating process using a composite formulation of candle soot, silica nanoparticles, polystyrene, and polydimethylsiloxane.

© Ariston Publications 2025. All rights reserved.

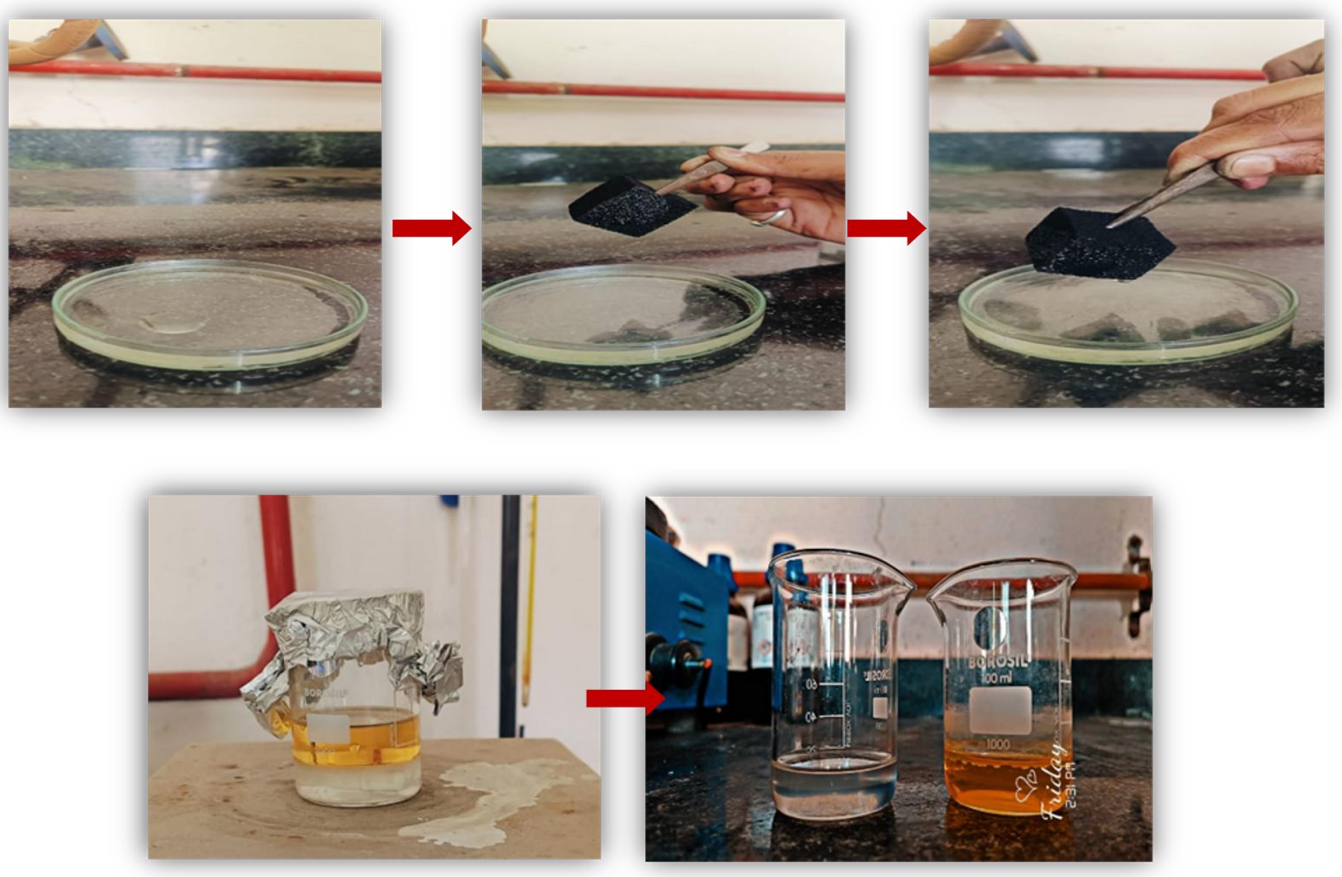


Fig. 7. Oil-water separation by using superhydrophobic sponge.

The modified sponge exhibited excellent hydrophobic and oleophilic properties, characterized by a water contact angle of 165° and an oil contact angle of 0°. Comprehensive evaluation confirmed its high efficiency in separating various oils, including castor oil, coconut oil, and engine oil, from oil–water mixtures, with a consistent separation efficiency reaching 99%. The sponge also demonstrated remarkable mechanical resilience, retaining its superhydrophobicity after extensive physical stress such as twisting, compression, cutting, and over 80 abrasion cycles. Chemical stability tests indicated that the material maintains performance across acidic, basic, and elevated temperature environments, underscoring its suitability for diverse and challenging operational conditions. The strong adhesion of the coating, verified through peel tape tests, further ensures long-term usability. These attributes, combined with the simplicity and low cost of the fabrication method, make the sponge an economically viable and environmentally friendly option for oil–water separation applications. The developed material holds significant promise for implementation in industrial wastewater treatment, particularly within chemical, pharmaceutical, and petroleum sectors, as well as for emergency response in oil spill scenarios. Given its scalability, durability, and high performance, this superhydrophobic sponge technology offers a practical pathway toward mitigating oil pollution and contributes to the advancement of sustainable water purification strategies. Future work may focus on optimizing coating formulations for specific industrial effluents and evaluating long-term performance under continuous flow conditions.

DECLARATIONS

Ethical Approval

We affirm that this manuscript is an original work, has not been previously published, and is not currently under consideration for publication in any other journal or conference proceedings. All authors have reviewed and approved the manuscript, and the order of authorship has been mutually agreed upon.

Funding

Not applicable

Availability of data and material

The datasets generated and/or analyzed during the current

 © Ariston Publications 2025. All rights reserved

study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no financial or personal interests that could have influenced the research and findings presented in this paper. The authors alone are responsible for the content and writing of this article.

Authors' contributions

All authors contributed equally to this work.

REFERENCES

[1] Broje, V. and Keller, A.A., **2006.** Improved mechanical oil spill recovery using an optimized geometry for the skimmer surface. *Environmental Science & Technology*, *40*(24), pp.7914-7918.

[2] Wang, J., Han, F., Chen, Y. and Wang, H., **2019.** A pair of MnO2 nanocrystal coatings with inverse wettability on metal meshes for efficient oil/water separation. *Separation and Purification Technology*, *209*, pp.119-127.

[3] Al-Shamrani, A.A., James, A. and Xiao, H., **2002.** Separation of oil from water by dissolved air flotation. *Colloids and surfaces A: Physicochemical and Engineering Aspects*, *209*(1), pp.15-26.

[4] Chen, L., Wu, S., Lu, H., Huang, K. and Zhao, L., **2015.** Numerical simulation and structural optimization of the inclined oil/water separator. *PLOS One*, *10*(4), p.e0124095.

[5] Liang, H.W., Guan, Q.F., Chen, L.F., Zhu, Z., Zhang, W.J. and Yu, S.H., **2012**. Macroscopic-scale template synthesis of robust carbonaceous nanofiber hydrogels and aerogels and their applications. *Angewandte Chemie International Edition*, *51*(21), pp.5101-5105.

[6] Kota, A.K., Kwon, G., Choi, W., Mabry, J.M. and Tuteja, A., **2012.** Hygro-responsive membranes for effective oil–water separation. *Nature Communications*, *3*(1), p.1025.

[7] Padaki, M., Murali, R.S., Abdullah, M.S., Misdan, N., Moslehyani, A., Kassim, M.A., Hilal, N. and Ismail, A.F., **2015.** Membrane technology enhancement in oil–water separation. A review. *Desalination*, *357*, pp.197-207.

[8] Feng, L., Li, S., Li, Y., Li, H., Zhang, L., Zhai, J., Song, Y., Liu, B., Jiang, L. and Zhu, D., **2002.** Super-hydrophobic surfaces: from natural to artificial. *Advanced materials*, *14*(24), pp.1857-1860.

[9] Wu, D., Wang, J.N., Wu, S.Z., Chen, Q.D., Zhao, S., Zhang, H., Sun, H.B. and Jiang, L., **2011.** Three-level biomimetic rice-leaf surfaces with controllable anisotropic sliding. *Advanced Functional Materials*, *21*(15), pp.2927-2932.

[10] Zhang, X., Li, Z., Liu, K. and Jiang, L., **2013.** Bioinspired multifunctional foam with self-cleaning and oil/water separation. *Advanced Functional Materials*, *23*(22), pp.2881-2886.

[11] Lu, Y., Sathasivam, S., Song, J., Crick, C.R., Carmalt, C.J. and Parkin, I.P., 2015. Robust self-cleaning surfaces that function when exposed to either air or oil. *Science*, *347*(6226), pp.1132-1135.

[12] Xu, L.P., Peng, J., Liu, Y., Wen, Y., Zhang, X., Jiang, L. and Wang, S., **2013.** Nacre-inspired design of mechanical stable coating with underwater superoleophobicity. *ACS Nano*, *7*(6), pp.5077-5083.

[13] Rao, A.V., Latthe, S.S., Nadargi, D.Y., Hirashima, H. and Ganesan, V., **2009.** Preparation of MTMS based transparent superhydrophobic silica films by sol–gel method. *Journal of Colloid and Interface Science*, *332*(2), pp.484-490.

[14] Kumar, D., Wu, X., Fu, Q., Ho, J.W.C., Kanhere, P.D., Li, L. and Chen, Z., **2015**. Development of durable self-cleaning coatings using organic–inorganic hybrid sol–gel method. *Applied Surface Science*, *344*, pp.205-212.

[15] Wu, J., Li, X., Wu, Y., Liao, G., Johnston, P., Topham, P.D. and Wang, L., **2017.** Rinse-resistant superhydrophobic block copolymer fabrics by electrospinning, electrospraying and thermally-induced self-assembly. *Applied Surface Science*, *422*, pp.769-777.

[16] Su, C., Li, Y., Dai, Y., Gao, F., Tang, K. and Cao, H., **2016.** Fabrication of three-dimensional superhydrophobic membranes with high porosity via simultaneous electrospraying and electrospinning. *Materials Letters*, *170*, pp.67-71.

[17] Amigoni, S., Taffin de Givenchy, E., Dufay, M. and Guittard, F., **2009.** Covalent layer-by-layer assembled superhydrophobic organic− inorganic hybrid films. *Langmuir*, *25*(18), pp.11073-11077.

[18] Li, F., Du, M. and Zheng, Q., **2016.** Dopamine/silica nanoparticle assembled, microscale porous structure for versatile superamphiphobic coating. *ACS Nano*, *10*(2), pp.2910-2921.

© Ariston Publications 2025. All rights reserved.

[19] Li, D. and Guo, Z., **2017.** Versatile superamphiphobic cotton fabrics fabricated by coating with SiO2/FOTS. *Applied Surface Science*, *426*, pp.271-278.

[20] Fan, T., Miao, J., Li, Z. and Cheng, B., **2019.** Bio-inspired robust superhydrophobic-superoleophilic polyphenylene sulfide membrane for efficient oil/water separation under highly acidic or alkaline conditions. *Journal of Hazardous Materials*, *373*, pp.11-22.

[21] Gu, J., Xiao, P., Chen, J., Liu, F., Huang, Y., Li, G., Zhang, J. and Chen, T., **2014.** Robust preparation of superhydrophobic polymer/carbon nanotube hybrid membranes for highly effective removal of oils and separation of water-in-oil emulsions. *Journal of Materials Chemistry A*, *2*(37), pp.15268-15272.

[22] Liu, Z., Tang, Y., Zhao, K. and Zhang, Q., **2019.** Superhydrophobic SiO_2 micro/nanofibrous membranes with porous surface prepared by freeze electrospinning for oil adsorption. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *568*, pp.356-361.

[23] Gao, Y., Zhou, Y.S., Xiong, W., Wang, M., Fan, L., Rabiee-Golgir, H., Jiang, L., Hou, W., Huang, X., Jiang, L. and Silvain, J.F., **2014.** Highly efficient and recyclable carbon soot sponge for oil cleanup. *ACS Applied Materials & Interfaces*, *6*(8), pp.5924-5929.

[24] Stöber, W., Fink, A. and Bohn, E., **1968.** Controlled growth of monodisperse silica spheres in the micron size range. *Journal of Colloid and Interface Science*, *26*(1), pp.62-69.

[25] Nakamura, M., Ozaki, S., Abe, M., Doi, H., Matsumoto, T. and Ishimura, K., **2010.** Size-controlled synthesis, surface functionalization, and biological applications of thiol-organosilica particles. *Colloids and Surfaces B: Biointerfaces*, *79*(1), pp.19-26.

[26] Lin, J., Chen, H., Fei, T. and Zhang, J., **2013.** Highly transparent superhydrophobic organic–inorganic nanocoating from the aggregation of silica nanoparticles. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *421*, pp.51-62.

[27] Zhang, X., Zhi, D., Zhu, W., Sathasivam, S. and Parkin, I.P., **2017.** Facile fabrication of durable superhydrophobic SiO_2/polyurethane composite sponge for continuous separation of oil from water. *RSC Advances*, *7*(19), pp.11362-11366.

[28] Das, A., Deka, J., Rather, A.M., Bhunia, B.K., Saikia, P.P., Mandal, B.B., Raidongia, K. and Manna, U., **2017**. Strategic formulation of graphene oxide sheets for flexible monoliths and robust polymeric coatings embedded with durable bioinspired wettability. *ACS Applied Materials & Interfaces*, *9*(48), pp.42354-42365.

 © Ariston Publications 2025. All rights reserved