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IMPARTING SUPERHYDROPHOBICITY OF POLYESTER FABRICS WITH CONTROLLED RELEASE USING SIO_2 AEROGEL MICROCAPSULE COATING

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ABSTRACT

Developing polyester fabrics that simultaneously integrate diffusion-controlled fragrance delivery with durable superhydrophobic and oleophobic protection remains a critical challenge in smart and protective textiles. In this study, we introduce a hierarchical dual-functional surface engineering strategy that combines porous SiO_2 aerogel composite microcapsules as high-capacity fragrance reservoirs with Triethoxy-1H,1H,2H,2H-tridecafluorooctylsilane (POTS) molecular grafting as a low-surface-energy interfacial barrier. The resulting multiscale coating architecture stabilizes a Cassie-Baxter wetting regime through synergistic surface roughness amplification and surface energy minimization while enabling diffusion-controlled fragrance release from the interconnected nanoporous aerogel network. Scanning Electron Microscopy (SEM) confirmed uniform deposition of ~10 µm microcapsules, with optimal dispersion at 10 wt%. The functionalized polyester fabrics exhibit superhydrophobicity with water contact angles exceeding 150°, effective oleophobicity toward common oils, and pronounced self-cleaning behavior. Increasing microcapsule loading progressively reduces air and moisture permeability due to partial pore blockage, highlighting an intrinsic trade-off between protective functionality and comfort. Accelerated release tests at 80 °C demonstrate sustained fragrance delivery, with a cumulative release of 15.8% over 30 h, comparable to standalone aerogel microcapsules. Furthermore, washing durability evaluation reveals gradual microcapsule loss and partial attenuation of hydrophobicity. However, residual liquid repellency and fragrance retention persist after 20 laundering cycles. Therefore, this work demonstrates a scalable materials design strategy for constructing multifunctional polyester with integrated smart-release and protective performance.

HIGHLIGHTS

- Hierarchical SiO_2 aerogel microcapsule coatings with POTS grafting enable dual-functional polyester fabrics.
- Achieved superhydrophobicity with water contact angles above 150°.
- Fabrics exhibited strong oil repellency and self-cleaning capabilities.
- Diffusion-controlled fragrance release reaches 15.8% after 30 h at 80 °C.
- Maintained good wash durability and balanced comfort at 10 wt% loading.

KEYWORDS: Sio_2 Aerogel Microcapsule, Superhydrophobic Coating, Diffusion-Controlled Release, Multifunctional Polyester, Wash Durability

1. INTRODUCTION

In recent years, aromatic fabrics such as polyester[1] that incorporate microencapsulated fragrance compounds into their polymeric matrix have gained considerable attention, having the ability to combine functional performance with sensory appeal[2,3]. Techniques such as printing[4], padding[5], dipping[6], and electrospinning[7], are widely employed to incorporate microcapsules into textile materials, enhancing both functional and comfort properties. Moreover, certain encapsulated aroma compounds provide additional functionalities, including antibacterial[8,9], antiviral[10], and insect-repellent[11] properties, which broaden the potential applications of polyester fabrics[12]. However, traditional aromatic fabrics encounter two significant challenges: (i) the gradual loss of microcapsules during laundering, which reduces fragrance durability, and (ii) the vulnerability to contamination by water or oil-based liquids, which can impair both functionality and comfort. Therefore, extensive adoption of aromatic textiles in advanced and protective cloth applications emphasizes the need for innovative solutions to improve fragrance retention and resistance to environmental contaminants.

Hydrophobic and oleophobic surface finishing is a promising technique for polyester fabric to enhance liquid penetration and reduce microcapsule loss [13,14]. For example, fluorinated silane-based agents, particularly triethoxy-1H,1H,2H,2H-tridecafluorooctylsilane (POTS), are widely used in textile finishing, owing to forming low-surface-energy coatings [15]. The molecular structure of POTS consists of polar functional groups at one end and fluorinated $-CH_3$, $-CF_3$, and $-CF_2-$ groups at the other, as shown in Fig. 1. Upon adsorption onto polyester fiber surfaces, the polar groups penetrate to the substrate, while the fluorinated groups align outward to form a continuous film that lowers surface energy[14,16]. This molecular arrangement imparts durable hydrophobic and oleophobic characteristics to the resultant fabrics, allowing strong resistance against both aqueous and oily contaminants[17,18].

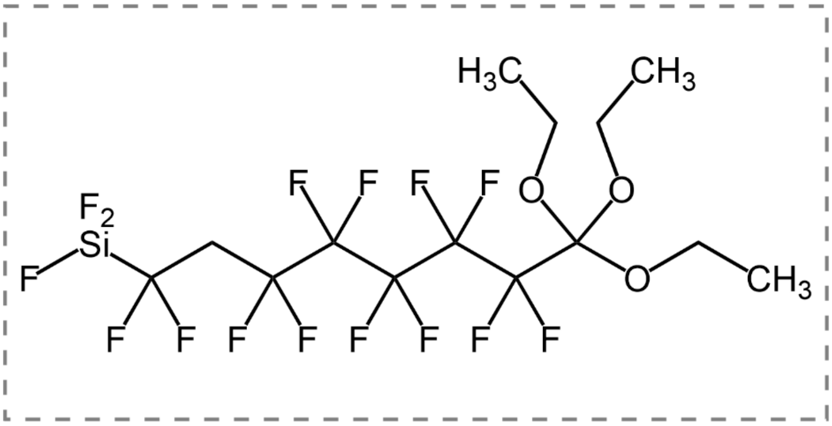


Figure 1: Molecular structure of Triethoxy-1H,1H,2H,2H-tridecafluorooctylsilane (POTS).

Surface coating has emerged as a core strategy in functional textile finishing because it enables the stable immobilization of active agents on fiber surfaces without fundamentally disrupting the intrinsic fiber morphology and mechanical integrity [19–21]. Among coating materials, silica (SiO_2) aerogels have attracted considerable attention owing to their ultralow density, high specific surface area, and interconnected nano porous networks [22,23]. These physicochemical characteristics render aerogels highly efficient carrier matrices for functional compounds, enabling enhanced encapsulation stability and diffusion-controlled release performance [24]. When incorporated into microcapsules, SiO_2 aerogels further improve interfacial adhesion to textile substrates while preserving lightweight and breathable characteristics, thereby enabling multifunctional performance with minimal material loading [25].

In spite of these advantages, the rational engineering of SiO_2 aerogel-based coatings as multifunctional textile interfaces that simultaneously integrate sustained-release capability with superhydrophobic surface protection remains largely unexplored. In parallel, fluorosilane-based finishing agents, particularly triethoxy-1H,1H,2H,2H-tridecafluorooctylsilane (POTS), have been extensively employed to construct low-surface-energy siloxane networks on fiber surfaces, thereby imparting durable water and oil repellency, self-cleaning behavior, and stain resistance [26,27]. While such fluorinated architectures are highly effective in modulating interfacial wettability, they function predominantly as passive protective barriers and do not address the critical requirement for controlled encapsulation, retention, and diffusion-mediated release of active agents [28]. Consequently, the integration of nano-porous SiO_2 aerogel carriers with fluorosilane-derived surface energy regulation into a hierarchical coating architecture represents an unmet materials design strategy for next-generation functional textile applications [29]. Nevertheless, these applications have primarily focused on surface protection without addressing the integration of controlled release.

To achieve a high-performance multifunctional textile interface that excels in sustained fragrance delivery and superior liquid repellency, it is essential to strategically integrate a porous carrier structure with a low-surface-energy protective layer [30]. In this context, the present study proposes a hierarchical dual-functional surface engineering strategy that combines porous SiO_2 aerogel composite microcapsules as high-capacity fragrance reservoirs with fluorosilane molecular grafting as a liquid-repellent interfacial barrier, as shown in Fig. 2. This synergistic architecture stabilizes a Cassie-Baxter wetting regime [31] through multiscale surface roughness and surface energy minimization, while concurrently enabling diffusion-controlled fragrance release from the nano-porous aerogel network. As a result, this integrated coating platform addresses a critical materials design gap in the development of multifunctional, smart, and protective polyester fabrics.

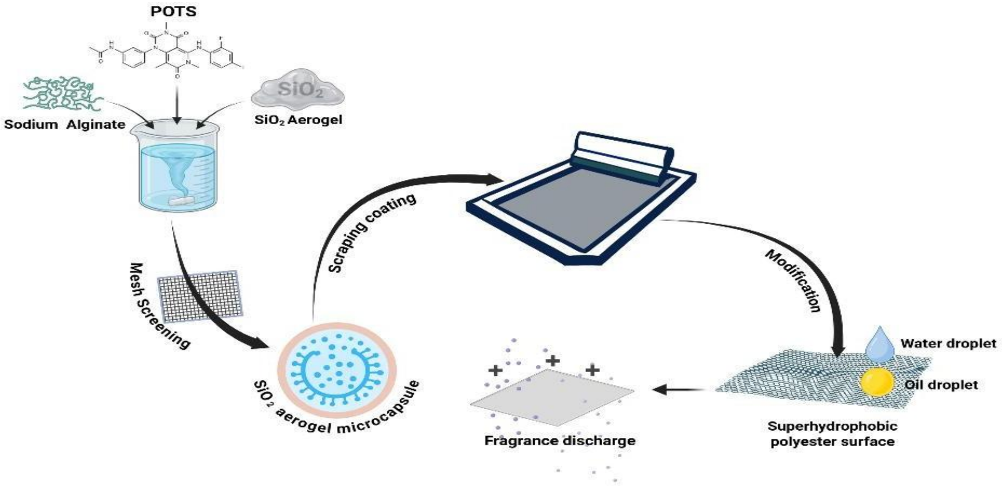


Figure 2: Schematic illustration of SiO_2 aerogel microcapsules coating on aromatic polyester.

2. EXPERIMENTAL PART

2.1 MATERIALS

Polyester fabric (plain weave GSM: 240 g/m²) was supplied by Qingdao Meiya Textile Co., Ltd. (Qingdao, China). For surface modification, sodium alginate ($(C_6H_7NaO_6)n$, ≥ 99% purity, triethoxy (1H,1H,2H,2H-tridecafluorooctyl) POTS ($C_{14}H_{19}F_{13}O_3Si$, ≥ 97% purity), and acid blue 9 ($C_{32}H_{24}N_2Na_2O_8S_2$, ≥ 85% purity) were purchased from Shanghai Aladdin Biochemical Technology Co., Ltd. (Shanghai, China). A water-based, eco-friendly JFC penetrant (nonionic surfactant, ≥ 98% purity) was obtained, and GS-2A softener (fatty acid derivative, ≥ 98% purity) from Ningbo Haishu Jianguo Chemical Additives Factory (Ningbo, China). Anhydrous ethanol (C_2H_6O, ≥99.7% purity) was sourced from Hangzhou Gaojing Fine Chemical Co., Ltd. (Hangzhou, China). SiO_2 aerogel composite microcapsules were synthesized in-house. To verify staining performance, soy sauce, homemade black coffee, milk, olive oil, and green tea were used and washed with laundry detergent. Deionized water was used throughout all experiments under ambient conditions.

2.2 PRETREATMENT OF POLYESTER FABRIC

To prevent contamination from oils, sizing agents, or other substances on the polyester fabric that may interfere with the experimental results, the fabric must be pretreated before the test. The polyester fabric was placed in deionized water and subjected to ultrasonic treatment at 60 °C for 10 minutes. Afterward, the fabric was removed and dried in an oven at 60 °C.

2.3 PREPARATION OF PRINTING PASTE CONTAINING SIO2 COMPOSITE MICROCAPSULES

To prepare an 8 wt% sodium alginate solution, sodium alginate was dissolved in deionized water at 25 ± 2 °C under continuous magnetic stirring (500 rpm) for 1 h until complete dissolution. Subsequently, JFC penetrant (1 wt%) and GS-2A softener (1 wt%) were added sequentially and stirred at 300 rpm for 30 min to ensure homogeneous dispersion. Finally, SiO_2 aerogel composite microcapsules were incorporated at predetermined loadings (1, 5, 10, and 15 wt%), and the mixture was stirred at 400 rpm for 1 h to obtain uniform printing pastes. Four different formulations were prepared by varying the SiO_2 aerogel composite microcapsule content, as documented in Table 1.

Table 1: Composition of printing pastes.

Sodium alginate (%)	**SiO_2 aerogel composite microcapsules (%)**	**Penetrant (%)**	**Softener (%)**
8	1	1	1
8	5	1	1
8	10	1	1
8	15	1	1

2.4 PREPARATION OF SUPERHYDROPHOBIC AROMATIC POLYESTER FABRICS

Polyester fabric samples (10 cm × 10 cm) were coated using a scraping printing technique. The printing paste was evenly spread across the fabric surface through a screen-printing mesh using a stainless-steel scraper to ensure uniform deposition with a controlled coating thickness of approximately 10 μm. The printed fabrics were dried at 80 °C and thermally cured at 150 °C for 120 s.

For hydrophobic modification, POTS was dissolved in anhydrous ethanol and magnetically stirred for 2 h to ensure complete hydrolysis and silane activation. The coated fabrics were immersed in the hydrophobic solution for 5 min, followed by baking at 140 °C for 5 min to promote siloxane network formation. This process was repeated three times to ensure full surface coverage. The fabric samples containing 1%, 5%, 10%, and 15% SiO_2 aerogel composite microcapsules were labeled M1%, M5%, M10%, and M15%, respectively. An untreated polyester fabric sample served as the blank control and was labeled M0.

2.5 CHARACTERIZATION

SURFACE MORPHOLOGY

To observe the surface morphology, fabric samples were mounted on aluminum stubs with conductive adhesive, sputter-coated with gold (20 mA, 120 s, Quorum Q150R S, UK), and examined using scanning electron microscopy (SEM, Hitachi SU8010, Japan) at 3 kV and 200 x magnification.

SURFACE WETTABILITY AND STAIN RESISTANCE

Water contact angles (WCAs) and oil contact angles (OCAs) were measured using a contact angle goniometer (Dataphysics OCA 25, Germany) with ~4 μL water and ~2 μL oil droplets. Three measurements were taken per sample, and average values were reported. Oil resistance was further evaluated by placing olive oil, milk, coffee, soy sauce, water, and green tea onto fabric surfaces before and after hydrophobic treatment. The appearance of stains was observed after 60 seconds.

COMFORT PROPERTIES

To measure air permeability according to GB/T 5457-1997 using an air permeability tester (FX 3300, Textest Instruments, Switzerland) under standard conditions (20 ± 2 °C, 65 ± 4% RH, 100 Pa, 20 cm^2 test area). Additionally, moisture management was determined using the desiccant method (GB/T 12704.1-2009) with a moisture permeability tester (YG(B)216, Ningbo Textile Instruments, China). Fabric performance (softness, stiffness, smoothness, and drape) was evaluated using a PhabrOmeter intelligent fabric evaluation instrument (PhabrOmeter 3.1, Nu Cybertek, USA) with circular samples (100 cm^2). All measurements were conducted in triplicate, and averages were reported.

DURABILITY PERFORMANCES

Washing durability was evaluated using a laboratory washing machine with a 1 kg load, including AATCC standard dummy fabrics. Samples were washed with 2.5 g L^{-1} detergent at a liquor ratio of 1:12 and 30 °C for 30 min, followed by two dehydration cycles (15 min each) and drying at 40 °C. One washing cycle was defined as one complete washing process.

SUSTAINED RELEASE PERFORMANCE

The sustained release behavior of essential oils from the treated polyester fabrics was evaluated under accelerated thermal conditions in a ventilated oven (DHG-9140A, Shanghai Yiheng, China) maintained at 80 °C. Fabric samples were collected at 5 h intervals over a total duration of 30 h. The released fragrance was quantified by UV-Vis spectrophotometry (UV-2600, Shimadzu, Japan), and cumulative release profiles were calculated based on a pre-established calibration curve.

3 RESULTS AND DISCUSSION

3.1 SURFACE MORPHOLOGY OF COATED POLYESTER

To evaluate the surface morphology of untreated and coated polyester fabrics, SEM was employed, which clearly demonstrated the effectiveness of microcapsule deposition, as shown in Fig. 3. The untreated polyester fabric had a smooth and pristine surface [32] as depicted in Fig. 3a. Following treatment with the SiO_2 aerogel composite microcapsule-based printing paste, a large population of microcapsules is observed to adhere both to the fiber surfaces and within the inter-fiber voids, indicating successful interfacial anchoring of the composite carriers. The average diameter of individual composite microcapsule remains around 10 μm, as displayed in Fig. 3(b-e). With increasing mass fraction of SiO_2 aerogel composite microcapsules in the printing paste, the surface coverage density increases accordingly. However, at a loading of 15% wt (see Fig. 3e), pronounced microcapsule agglomeration was observed, which is attributed to particle overcrowding and reduced dispersion stability at high solid content. In contrast, the fabric treated with a printing paste containing 10% wt SiO_2 aerogel composite microcapsules showed a uniformly distributed (see Fig. 3d) hierarchical coating architecture without significant aggregation, indicating an optimal balance between surface coverage and dispersion stability.

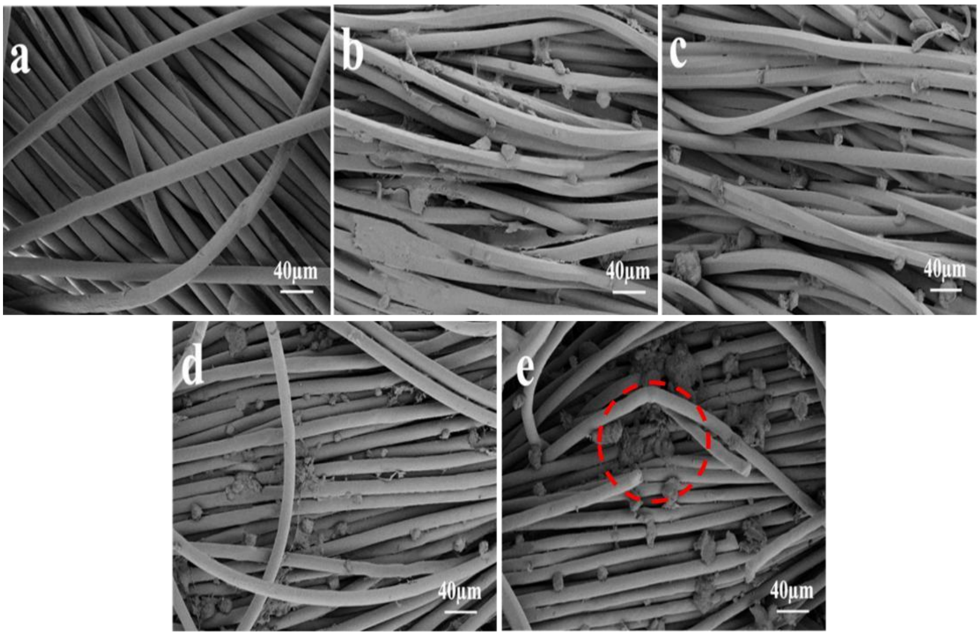


Figure 3: SEM images of polyester fabrics, (a) untreated fabric (M0) and an aromatic polyester fabric treated with different SiO_2 aerogel microcapsule concentrations of (b) M1%, (c) M5%, (d) M10%, and (e) M15% respectively.

3.2 HYDROPHOBIC PERFORMANCE

The hydrophobic performance of the treated aromatic polyester fabrics was shown in Fig. 4. The untreated polyester fabric exhibited rapid water penetration due to its intrinsically high surface energy and capillary-driven liquid transport within the fiber network. In contrast, the POTS-finished fabric containing 10 wt% SiO_2 aerogel microcapsules remained submerged on the water surface, indicating a pronounced reduction in surface free energy. This behavior originates from the combined effects of fluorosilane molecular grafting, which lowers the solid-liquid interfacial energy, and the hierarchical micro-nano roughness generated by microcapsule deposition, which promotes air entrapment at the interface. The resulting composite interface stabilizes a Cassie-Baxter wetting regime [31], thereby suppressing liquid penetration and enabling superhydrophobic behavior.

The hydrophobic performance of aromatic polyester fabrics before and after surface modification is illustrated in Fig. 4. The untreated fabric, shown in Fig. 4a, became fully wetted upon immersion in water, which was consistent with the inherently high surface energy of polyester fibers that promotes capillary-driven water penetration into the fibrous network. In contrast, the treated fabric (see Fig. 4b) with 10% wt SiO_2 aerogel microcapsules remained buoyant on the water surface even after increasing immersion, indicating a significant reduction in surface free energy due to the addition of hydrophobic functional groups. This surface modification effectively suppresses solid-liquid interfacial adhesion and inhibits water infiltration, thereby enhancing liquid resistance. Additional immersion tests in an aqueous acid blue dye solution revealed that the untreated fabric (see Fig. 4c) was evenly stained, confirming deep liquid infiltration and poor resistance to wetting. Conversely, the treated fabric (see Fig. 4d) exhibited no visible staining, indicating that the dye solution was unable to penetrate the coated fiber surface. This superior liquid repellency originates from the synergistic coupling of low-surface-energy surface chemistry with hierarchically structured micro-nano roughness introduced by the SiO_2 aerogel microcapsules, which together stabilize a Cassie-Baxter wetting regime characteristic of superhydrophobic surfaces [33].

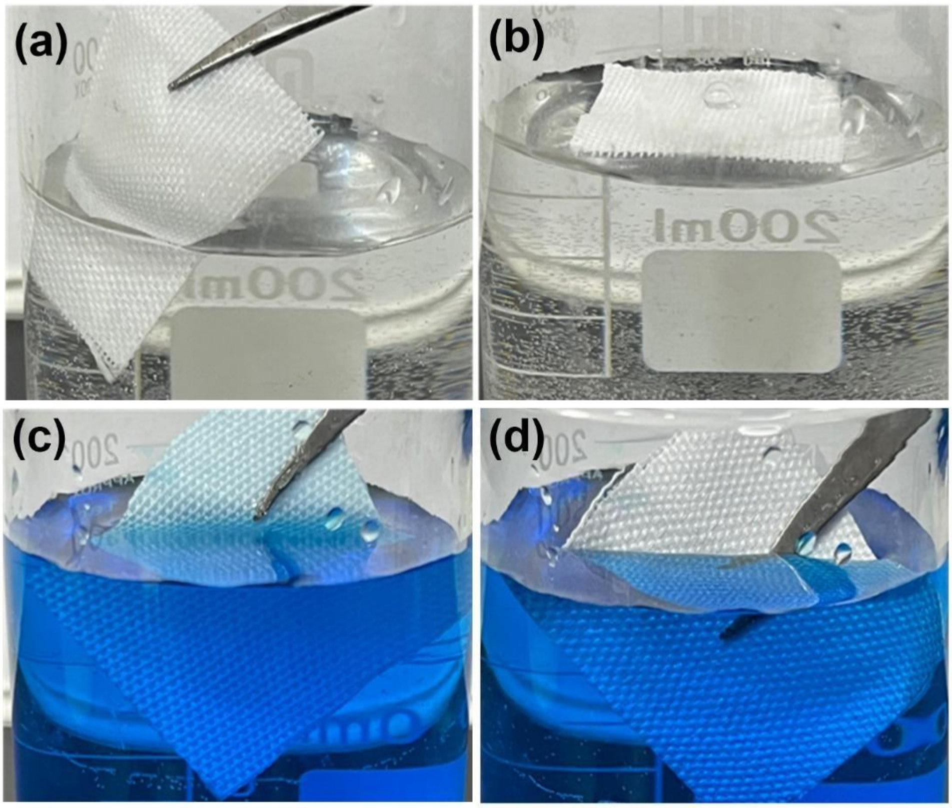


Figure 4: Hydrophobic and superhydrophobic performances of polyester fabrics, (a) untreated fabric, (b) treated fabric (10%), (c) untreated fabric after immersion in acid blue dye, and (d) treated fabric with no dye penetration.

To evaluate the wettability of raw polyester fabric, untreated aromatic polyester fabric, and hydrophobically modified aromatic polyester fabric, as illustrated in Fig. 5, static water droplet tests were conducted under controlled ambient conditions to ensure measurement consistency. On raw polyester, a 4 µL water droplet was completely absorbed as illustrated in Fig. 5a within just 13 seconds, demonstrating the intrinsically high surface energy and strong hydrophilic character of polyester fibers, which promotes capillary-driven liquid infiltration [34]. In comparison, the untreated aromatic polyester fabric (Fig. 5b) exhibited even faster droplet penetration, occurring within approximately 5 s. This accelerated wetting behavior is attributed to the presence of sodium alginate within the surface coating matrix, which introduces abundant hydroxyl and carboxyl functional groups that enhance surface hydrophilicity and facilitate rapid liquid spreading.

In sharp contrast, the hydrophobically finished aromatic polyester fabric (Fig. 5c) retained a nearly spherical water droplet for over 60 s, indicating the successful construction of a superhydrophobic interface with a significantly reduced solid–liquid contact area. These observations confirm the formation of a low-surface-energy surface in combination with hierarchical micro–nano roughness, which together stabilize a Cassie–Baxter wetting regime.

Although these measurements provide a qualitative assessment of wettability, they remain sensitive to droplet volume, surface heterogeneity, and environmental conditions, which should be considered when interpreting the results [35]. Furthermore, the low contact angle hysteresis and stable droplet mobility observed on the treated fabric suggest excellent roll-off behavior, thereby enabling efficient dust removal through a self-cleaning mechanism [36].

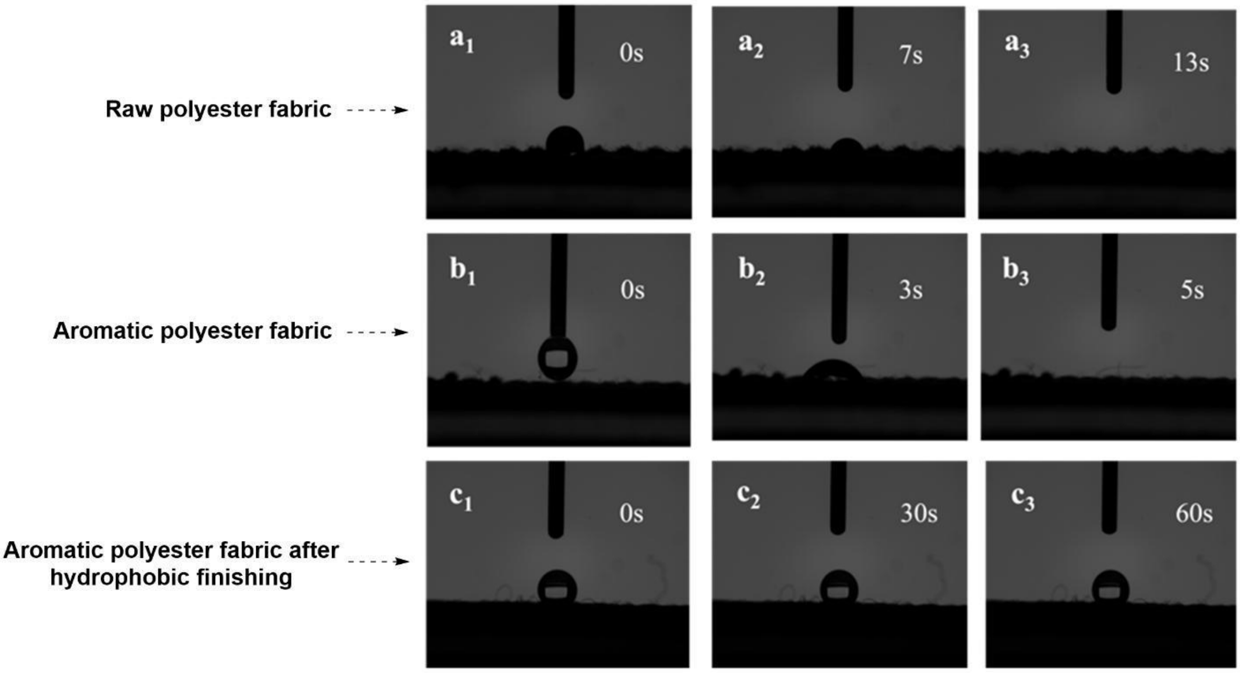


Figure 5: Contact angle behavior of (a) untreated polyester fabric, (b) untreated polyester fabric, and (c) superhydrophobic polyester fabric.

3.3 PERFORMANCE OF OIL-STAIN RESISTANCE

Oil stains are a substantial limitation of conventional superhydrophobic surfaces, as the lower surface tension of oils enables rapid wetting and penetration into the fabric microstructure. To address these limitations, a dual-repellent surface combining hydrophobicity and oleophobicity was achieved through POTS finishing of aromatic polyester fabric. As shown in Fig. 6a, the untreated fabric was easily wetted and stained by common liquids, resulting in irreversible discoloration and poor washing resistance. In contrast, the treated fabric (10% SiO_2 aerogel), as shown in Fig. 6b, exhibited simultaneous resistance to aqueous and oily liquids, with water, milk, tea, coffee, soy sauce, and olive oil droplets forming stable, spherical shapes that either rolled off or were easily wiped away from the surface [37].

Quantitative contact angle measurements (see Fig. 6c) further confirmed that the water, milk, and tea droplets exhibited static contact angles exceeding 150°, characteristic of a superhydrophobic surface, while soy sauce and olive oil droplets maintained high contact angles above 130°, indicative of effective oleophobic behavior. Thus, this dual-repellent performance is attributed to the synergistic coupling of low-surface-energy fluorinated POTS moieties with hierarchically ordered micro-nano surface roughness, which together stabilize a Cassie-Baxter wetting regime and minimize solid-liquid interfacial adhesion [38]. Consequently, the enhanced stain resistance reduces liquid fouling and mitigates contaminant-induced degradation of the coating, thereby contributing to prolonged functional performance.

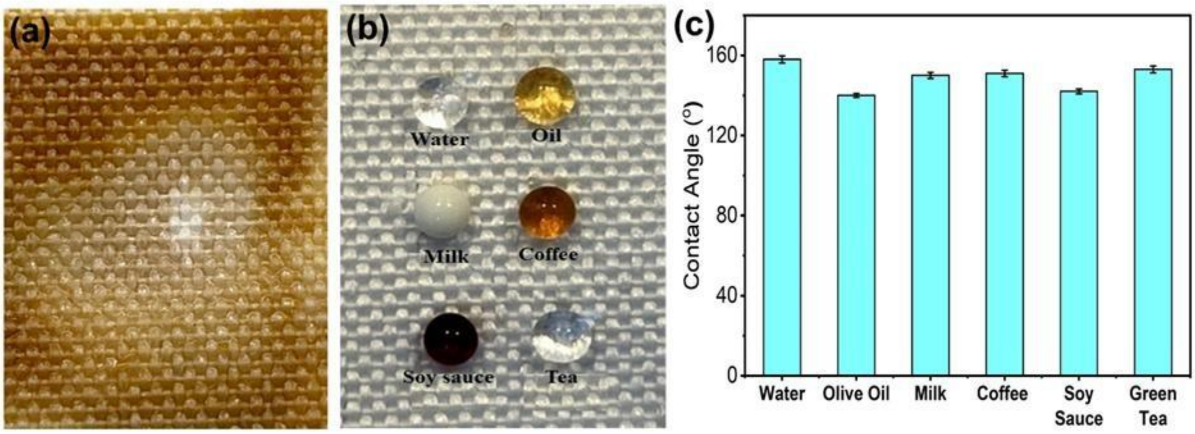


Figure 6: Hydrophobic properties of aromatic polyester fabric (a) untreated, (b) treated, and (c) contact angles of different liquids on the surface of superhydrophobic fabric.

3.4 COMFORT PERFORMANCES

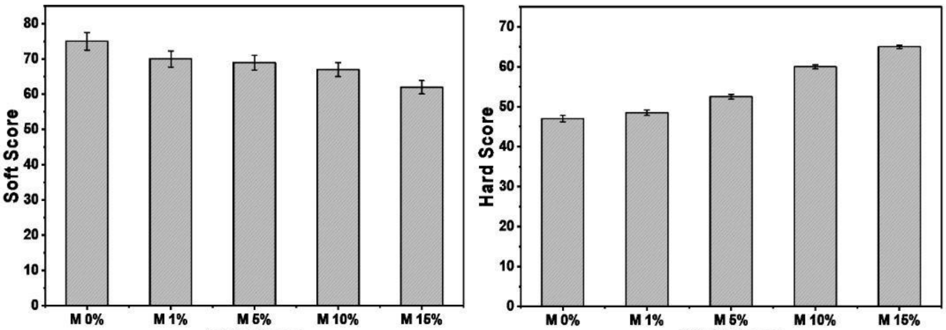
The comfort performance of textile materials is a critical determinant of their practical applicability and is primarily governed by air permeability, moisture transport, and fabric handle, including softness, drapability, stiffness, and surface smoothness. In this study, the incorporation of SiO_2 aerogel composite microcapsules, followed by hydrophobic finishing, induced measurable changes in these comfort-related parameters.

As summarized in Table 2, all coated fabrics exhibited reduced air permeability compared with the untreated control (M0), with a monotonic decrease observed as microcapsule loading increased. This behavior is attributed to the deposition of microcapsules within inter-yarn and inter-fiber voids, which partially obstruct continuous airflow channels. At higher add-on levels, microcapsule accumulation leads to more pronounced pore constriction and localized blockage, thereby further limiting air transport. Such permeability reduction represents a well-recognized trade-off in functional textile coatings, where enhanced functionality is commonly accompanied by diminished porosity and breathability due to coating-induced modification of the fibrous network [39]. Correspondingly, moisture permeability (water vapor transmission) decreased with increasing microcapsule content. This trend arises from two concurrent mechanisms: (i) physical obstruction of vapor diffusion pathways due to microcapsule deposition and coating layer formation within inter-fiber and inter-yarn pores, and (ii) increased surface hydrophobicity imparted by POTS finishing, which reduces fiber surface energy and suppresses vapor sorption–desorption processes. The combined effect limits effective moisture transport through the fabric thickness. Such behavior is consistent with reported findings that highly hydrophobic textile finishes, while improving water repellency, often compromise vapor permeability, underscoring the intrinsic design trade-off between moisture management and surface hydrophobicity [40]. Thus, the results emphasize the intrinsic balance required between the durability of functional surface treatments and the preservation of moisture management properties in textile substrates.

Table 2: Air permeability, moisture permeability, and softener content of untreated polyester fabric (M0) and superhydrophobic aromatic polyester fabrics treated with different concentrations of SiO_2 aerogel microcapsules (M1–M15).

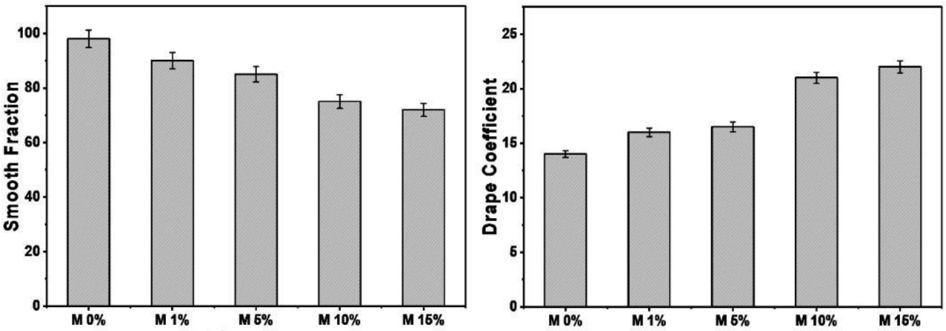
Samples	Air permeability (mm/s)	Moisture (g/(m^{-2}.h^{-1})
M0	281	3720
M1	210	3320
M5	203	3100
M10	193	2700
M15	182	2455

Fabric handle properties, including softness, stiffness, smoothness, and drapability, were evaluated, as shown in Fig. 7(a-d). With increasing microcapsule content, the fabrics exhibited a progressive reduction in softness and surface smoothness, accompanied by increased stiffness and higher drape coefficients. These trends are attributed to the formation of a sodium alginate-based coating layer that rigidifies the fiber surfaces, together with deposited microcapsules that enhance inter-fiber friction and constrain fiber mobility and slippage. The combined effect leads to a mechanically reinforced fabric structure with diminished flexibility but improved dimensional stability and drape behavior [41]. SEM observations further corroborate these trends, revealing dense microcapsule deposition and a markedly roughened fiber surface. Such morphological changes are known to increase surface asperities and contact points between fibers, thereby elevating inter-fiber friction and bending rigidity. Consistent with prior reports on functional textile coatings, high microcapsule loadings or thick coating layers commonly result in increased fabric stiffness and a deterioration of hand feel, reflecting the inherent trade-off between functional enhancement and tactile comfort.



(a) Softness

(b) Stiffness



(c) Smoothness

(d) Drape Coefficient

Figure 7: Style (handle) parameters of untreated polyester fabric (M0) and SiO_2 aerogel composite-coated fabrics at 1%, 5%, 10%, and 15% microcapsule loadings, (a) softness, (b) stiffness, (c) smoothness, (d) drape coefficient.

Although the SiO_2 aerogel composite coating obtained polyester fabrics with superior hydrophobicity, oleophobicity, and sustained release capability, it simultaneously compromised key comfort-related attributes such as breathability and softness. This intrinsic trade-off between protective functionality and wearability has been widely acknowledged in advanced textile coatings literature, where achieving breathable yet liquid-repellent interfaces remain a persistent materials design challenge. In this present study, a microcapsule loading of 10% (M10) represents an optimal balance point, as it produces a uniformly distributed hierarchical surface architecture without severe aggregation, while retaining moderate breathability and acceptable hand feel alongside robust liquid repellency and controlled fragrance release.

3.5 WASH DURABILITY

The durability of the hierarchical coating (10% SiO_2 aerogel) architecture was evaluated through repeated laundering. SEM analysis (refer to Fig. 8a-b) reveals that after five washing cycles, the fabric surface (see Fig. 8a) retains a relatively uniform microcapsule distribution with minor surface disruption, indicating satisfactory interfacial adhesion between the coating layer and polyester substrate. However, after 10 cycles, partial microcapsule detachment (see Fig. 8b) and localized aggregation became evident, leading to a gradual reduction in hierarchical surface roughness.

These morphological changes reflect the progressive mechanical and chemical degradation of the coating architecture under hydrodynamic shear, detergent action, and thermal stress [42]. Although the POTS-modified hierarchical structure provides strong initial repellency, repeated laundering induces gradual microcapsule detachment and partial degradation of surface roughness. This leads to a progressive transition from a Cassie-Baxter wetting regime toward a mixed wetting state, resulting in a moderate reduction in hydrophobic performance.

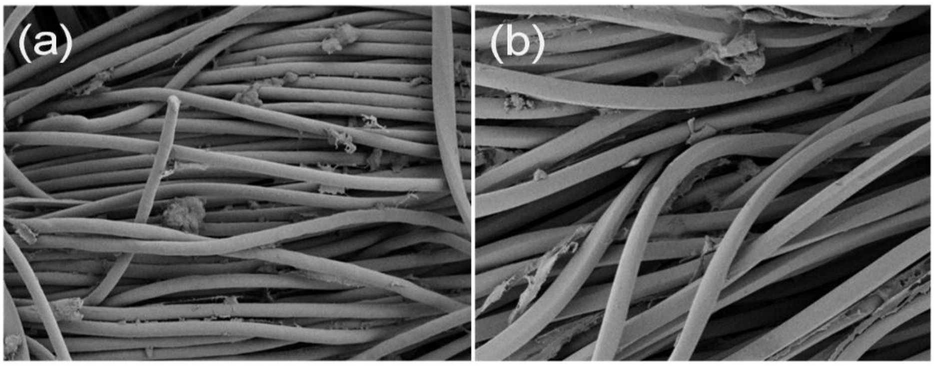


Figure 8: SEM images of POTS-treated aromatic polyester fabric after washing (a) 5 cycles and (b) 10 cycles.

3.6 SUSTAINED RELEASE EVALUATIONS

The sustained-release behavior of essential oils from the treated aromatic polyester fabric was investigated under accelerated thermal conditions at 80 °C to simulate long-term volatilization. As shown in Fig. 9, the cumulative release increased progressively with time, reaching 15.8% after 30 h, while the fabric retained a perceptible fragrance intensity. This diffusion-controlled release behavior demonstrates that the nano-porous SiO_2 aerogel microcapsule network effectively retards essential oil volatilization by providing a high surface area adsorption matrix and tortuous diffusion pathways [43].

Notably, the release curve was closely matched by that of standalone SiO_2 aerogel composite microcapsules, indicating that incorporation into the polyester substrate does not compromise the intrinsic release kinetics [44]. Instead, the polyester fabric serves as a mechanically stable support that preserves microcapsule integrity and functional durability under thermal stress.

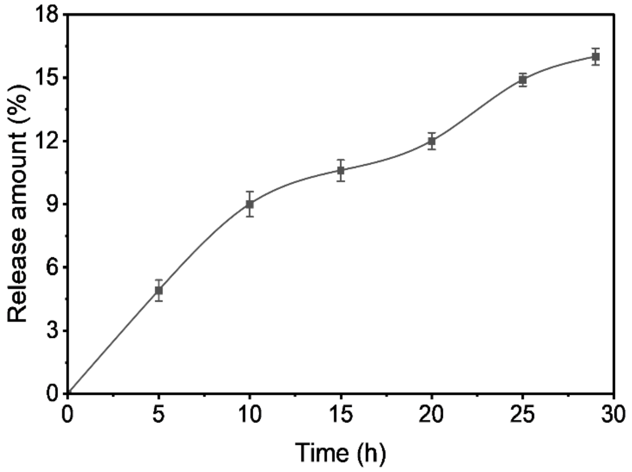


Figure 9: Sustained release of essential oil by POTS-treated polyester fabric (80 °C, 30 h).

4. CONCLUSION

In this study, polyester fabrics were functionalized with SiO_2 aerogel composite microcapsules followed by fluorosilane (POTS) surface modification to construct a hierarchical dual-functional interface with integrated sustained-release and liquid-repellent properties. The treated fabrics exhibited superhydrophobicity with water contact angles exceeding 150° and effective oleophobicity with oil contact angles above 135°. SEM analysis confirmed uniform microcapsule distribution at moderate loadings (1-10 wt%), while higher loadings (15 wt%) induced aggregation and pore blockage.

The incorporation of microcapsules and hydrophobic finishing progressively reduced air and moisture permeability and altered fabric handle, resulting in decreased softness and smoothness but increased stiffness and drape. Washing durability tests demonstrated gradual microcapsule loss and partial reduction of hydrophobicity with repeated laundering. However, residual repellency and fragrance-release capability were retained after 20 cycles, indicating good functional persistence rather than permanent durability.

Furthermore, diffusion-controlled fragrance release was achieved under accelerated thermal conditions, with a cumulative release of 15.8% over 30 h at 80 °C. These findings demonstrate that the integration of nanoporous SiO_2 aerogel microcapsules with fluorosilane surface engineering provides an effective and scalable strategy for the development of multifunctional polyester fabrics with combined protective and controlled-release functionalities.

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CONFLICT OF INTEREST

There is no conflict of interest among the authors.

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