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Review on Non-fluorinated Durable Water Repellent Alternatives for Textile and Fabric Coatings

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Abstract:

This review examines currently available alternatives to fluorinated chemicals for durable water repellent (DWR) and stain-resistant products, focusing on environmentally friendly options. It evaluates commercial products made from silicones, hydrocarbons, and dendrimers, based on chemical structure, repellency mechanism, and manufacturer-provided test results. Silicones offer hydrophobicity comparable to fluorinated chemicals, along with good feel, breathability, and cost-effectiveness. Hydrocarbons are eco-friendly and provide sufficient waterproofing for general use but fall short in extreme conditions. Dendrimeric DWR offers durability and breathability but is expensive and challenging to apply. All non-fluorinated DWR products share a common limitation: lack of oil repellency. Beyond surface chemistry, alternative approaches to liquid repellency include liquid-like surfaces that achieve low contact angle hysteresis through surface mobility, and designing surface texture and geometry to maintain a Cassie-Baxter state for high contact angles. The review concludes by highlighting future challenges in the field, including the development of oil-repellent, cost-effective, large-scale manufacturing technologies that align with the goals of a circular and sustainable economy.

Keywords: Durable Water Repellent, DWR; Non-fluorinated Alternatives; Surface Wettability; Silicones; Environmentally Friendly

1. Introduction

Textiles are an essential consumer product globally, but they are easily stained. To overcome this shortcoming, functional textile surface coatings that make fabrics superhydrophobic and stain-resistant, known as durable water repellent (DWR) coating, have attracted significant commercial interest[1-3]. Traditionally, perfluorinated and polyfluoroalkyl substances (PFASs), have dominated the DWR market textiles

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for their low surface energy and cost. However, PFASs are toxic and non-degradable in nature. Recent research has shown the potential of PFASs in causing developmental disorders in mice, thyroid disease, and the risk of testicular, kidney and bladder cancers[4-8].

As a solution, short-chain PFAS have been suggested, but its main functional structure is still similar to that of long-chain PFAS. Thus, it is important to search for fluorine-free DWR alternatives. Starting from the basic theory of surface science, this review examines natural water and oil repellent surfaces, and evaluates current non-fluorinated DWR products, putting forward the direction of future improvement.

2. Mechanism of liquid repellency & Natural inspiration

2.1 Young's Contact angle

Young's equation proposes that a liquid droplet on a non-textured, homogenous surface has a contact angle θ with the solid surface given by balance of the three types of interfacial tensions: solid-vapor (γ_{SV}, or surface energy) solid-liquid (γ_{SL}), and liquid-vapor (γ_{LV}, or surface tension), summarized as follows and visualized in Fig. 1 (a) [9]:

$$\gamma_{SV} = \gamma_{SL} + \gamma_{LV} \times cos\theta$$

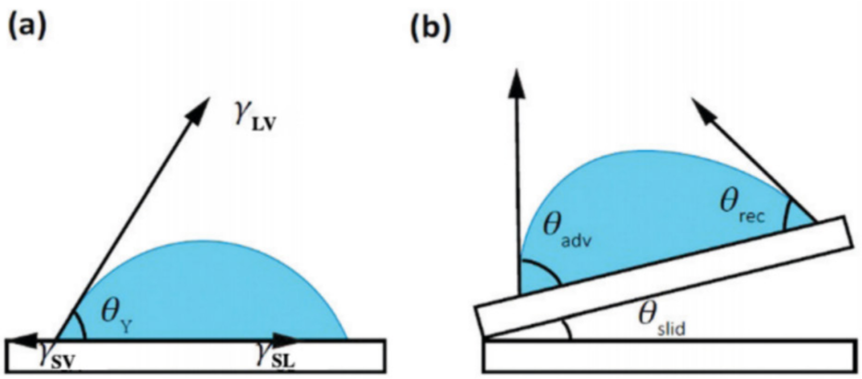

Figure 1. (a) Definition of Young's contact angle; (b) Definition of advancing contact angle, receding contact angle, and sliding angle[4]

Contact angle hysteresis is the difference between the advancing contact angle (θ_{adv}) and the receding contact angle (θ_{rec}), as shown in Fig. 1.

Based on contact angles with water (WCA), surfaces can be divided into four different types. If $\theta \approx 0°$, the surface is superhydrophilic; when $\theta < 90°$, it is hydrophilic; when $\theta > 90°$, it is hydrophobic; and when $\theta > 150°$, and the contact angle hysteresis <5°, the surface is superhydrophobic.

2.1 Surface roughness

Perfectly smooth surfaces do not exist, so it is necessary to introduce the concept of surface roughness (r), which is the ratio between actual surface area (A) and the projected surface area (A_0), i.e. $r = A / A_0$. In reality, r is always greater than 1. On rough surfaces, two wetting states are possible. In the Wenzel state, the droplet penetrates and wets fully into the roughened protrusions, as shown in Fig. 2a. The apparent contact angle θ^* and the equilibrium contact angle θ can be related according to the Wenzel relation:

$$cos\theta^* = r \times cos\theta(Wenzel)$$

In the Wenzel state, roughness enhances the original wetting or non-wetting property of the material. In other words, $\theta^* \gg 90°$, if $\theta > 90°$; and $\theta^* \ll 90°$ if $\theta < 90°$.

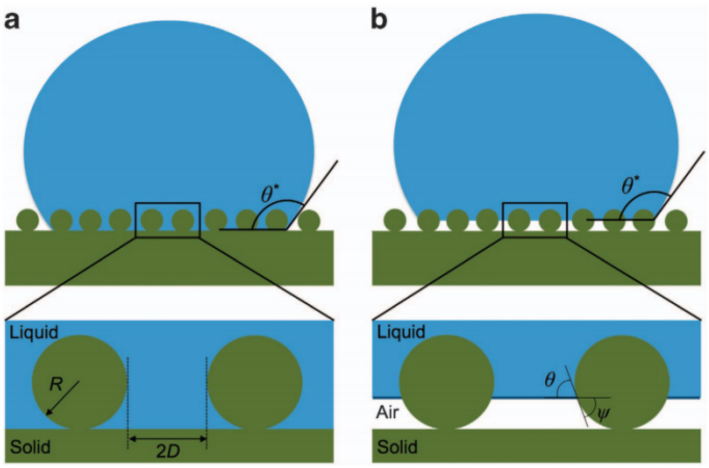

Figure 2. Liquid droplet on roughened surface (a, b). Visual explanation for liquid droplet in Wenzel state versus in Cassie-Baxter state.

In the Cassie-Baxter state, the air pockets are trapped beneath the contacting droplets, as shown in Fig. 2b. The liquid penetrates partially into the surface texture until the local texture angle (ψ) of the three-phase contact line equals the equilibrium contact angle (θ)[10,11].

The apparent contact angle (θ^*) in the Cassie-Baxter state is determined by[12,13]8</style></DisplayText><record><rec-number>427</rec-number><foreign-keys><key app="EN" db-id="xdvede29p2a95yeztf0vee2ls9wrva9v2w0a" timestamp="1724411163">427</key></foreign-keys><ref-type name="Journal Article">17</ref-type><contributors><authors><author>Kim, Sunghan</author><author>Polycarpou, Andreas A.</author><author>Liang, Hong</author></authors></contributors><titles><title>Electrical-potential induced surface wettability of porous metallic nanostructures</title><secondary-title>Applied Surface Science</secondary-title></titles><periodical><full-title>Applied Surface Science</full-title></periodical><pages>460-465</pages><volume>351</volume><section>460</section><dates><year>2015</year></dates><isbn>01694332</isbn><urls></urls><electronic-resource-num>10.1016/j.apsusc.2015.05.148</electronic-resource-num></record></Cite><Cite><Author>Milne</Author><Year>2012</Year><RecNum>429</RecNum><record><rec-number>429</rec-number><foreign-keys><key app="EN" db-id="xdvede29p2a95yeztf0vee2ls9wrva9v2w0a" timestamp="1724411172">429</key></foreign-keys><ref-type name="Journal Article">17</ref-type><contributors><authors><author>Milne, A. J. B.</author><author>Amirfazli, A.</author></authors></contributors><titles><title>The Cassie equation: How it is meant to be used</title><secondary-title>Advances in Colloid and Interface Science</secondary-title></titles><periodical><full-title>Advances in Colloid and Interface Science</full-title></periodical><pages>48-55</pages><volume>170</volume><number>1-2</number><section>48</section><dates><year>2012</year></dates><isbn>00018686</isbn><urls></urls><electronic-resource-num>10.1016/j.cis.2011.12.001</electronic-resource-num></record></Cite></EndNote>:

$$\cos\theta^* = f_{SL} \times \cos\theta + f_{LV} \times \cos\pi = f_{SL} \times \cos\theta - f_{LV} (Cassie - Baxter)$$

In the above equation, f_{SL} is the fraction of area at the solid-liquid interface ($f_{SL} = r_{\varnothing} \times \varnothing_s$); while f_{LV} is the fraction of area at the liquid-vapor interface. $r_{\varnothing}$ is the roughness ratio of the wet region and $\varnothing_s$ is the area fraction of the projected liquid-gas interface obscured by the surface texture[14]. As long as the f_{SL} value is small and the f_{LV} value is large enough, Cassie-Baxter state results in an apparent contact angle $\theta^* \gg 90°$, whether $\theta > 90°$ or $\theta < 90°$, thus making Cassie-Baxter state the preferred choice for creating superomniphobic surfaces.

2.2 Natural inspiration

The lotus leaf's surface is roughened by micro-scale papillae. The top of each papilla is covered with wax clusters and wax tubules at nanometer scale. This micro- and nano-scale hierarchical structures allow millions of air pockets to be trapped at multiple scales, greatly reducing the actual surface of contact. In terms of durability, lotus leaves can maintain their water repellent surfaces in nature for a long time through their secretion of waxy

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substances after damage to the leaf epidermal wax layer, a mechanism known as the release and migration of low surface energy substances[15]. Inspired by the self-healing mechanism, studies have been conducted to construct self-healing superhydrophobic coatings.

Compared with lotus leaf, springtail skin has three barriers to achieving omniphobicity, meaning high contact angle against liquids of all surface tensions. The hairy covering and bristles are the first barrier. The second barrier, which is the interconnected nanoscale primary particles, effectively retains gas in the nanocavity. The third barrier is the overhanging topographies that provide a negative curvature. The three barriers lead to a Cassie-Baxter state, resulting in a high contact angle, and allowing the surface to prevent wetting with low surface tension liquid at a high pressure.[16].

3. Functionality evaluation of non-fluorinated liquid repellent materials

3.1 Silicones

3.1.1 Chemical properties and water repellent mechanism of silicones

Silicones are a family of polymers with the general chemical formula R_2SiO, constituting of basic monomer repeating units of siloxane, as shown in Fig. 3[17].

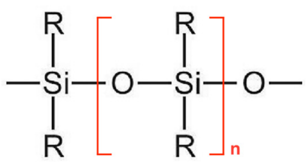

Figure 3. The chemical structure of silicone (polymer) and siloxane (bracketed monomer unit) Adapted from Silicone Biomaterials: History and Chemistry & Medical Applications of Silicones[18].

Although the Si—O siloxane backbone chain is hydrophilic, the orientation of the molecules ensures hydrocarbon side chains align on the outside. Hydrocarbon side chains are non-polar, and their weak intermolecular force provides a low surface energy (around 22 mN/m) to repel water molecules, which have a high surface tension of around 72 mN/m[19]. However, most silicones are unable to repel oils, which have a much lower surface tension.

3.1.2 Different types of silicone-based durable water repellent chemicals

i) Polydimethylsiloxane (PDMS)

Polydimethylsiloxane is the most widely used silicone. Its structure composes of methyl group side chains, as shown in Fig. 4, providing a low surface energy of around 20-25 mN/m, making it hydrophobic[20].

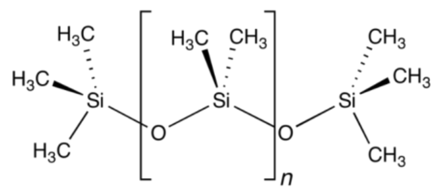

Figure 4. Chemical structure of PDMS

Below are selected examples of PDMS-based DWR products produced by different manufacturing companies. An assessment and analysis of their water repellency are organized into the following table.

Table 1. Selected commercial DWR products composed of PDMS chemistry

Product name	Producer company	Water repellency test 1	Water repellency test 2	Durability
DOWSIL™ IE-8749 Emulsion[1]	DOW	*Spray rating test AATCC TM22* -Perfect (100) for non-washed textiles of both polyester and nylon. -Perfect for after 20 washes textiles of both polyester and nylon.	*Bundesmann rain-shower test ISO 9865* a) Bundesmann appearance -Perfect (5) for non-washed textiles of both polyester and nylon. -Perfect and moderate (3) for 20 washes textiles of both polyester and nylon, respectively. b) Bundesmann absorption -Lower than 5% for non-washed textiles of both polyester and nylon. -Lower than 5% and around 25% for 20 washes textiles of polyester and nylon, respectively. c) Bundesmann penetration -Near 20 and 10 for non-washed textiles of polyester and nylon surface, respectively. -Near 13 and 0 for 20 washes textiles of polyester and nylon surface, respectively.	*Change in spray rating test* -Perfectly durable after washing. *Change in Bundesmann rain-shower test* -Durable after washing. The water repellent functionality does not change much for coating on polyester surfaces. However, there can be an obvious decrease in hydrophobic functionality of coating on nylon surfaces.
DM-FLUID series	ShinEtsu	*Surface tension* -The general range of surface tension of the products is around 20-21 mN/m, which is lower than conventional oils (mineral oil has a surface tension of 29.7 mN/m)	*Contact angle with water* -WCA on a baked-on coating of DM-FLUID is between 90 degrees – 110 degrees.	*Resistance against shear* -High shear resistance at high speeds and high loads, allowing the product to have a long operating life.

1 file:///Users/barbie/Downloads/26-2762-01-dowsil-ie-8749-emulsion.pdf

ii) Amino functional silicone

Amino functional silicones have two different types of repeating monomer units in its structure, as shown in Fig. 5, one of which contains silicon bonded to one methyl group and one alkyl amine. Besides acting as DWR products, a significant property of amino functional silicones is its softness[21].

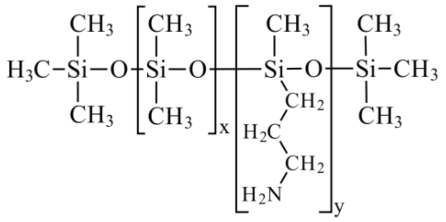

Figure 5. The chemical structure of amino functional silicone.

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Table 2. Selected commercial DWR products composed of amino functional silicone chemistry

Product name	Producer company	Water repellency test 1	Water repellency test 2	Durability
MAG-NASOFT NFR-A	Momentive Performance Materials	*Spray rating test AATCC TM22 + comparison with C6-& C8-based fluorocarbon DWR* Non-washed: -95 on cotton. (same for C6 and C8) -100 on polyester. (slightly higher than C6 and C8) -90 on nylon. (lower than C6 and C8) After 20 washes: -0 on cotton. (same for C6 and C8) -95 on polyester. (same for C6, lower than C8) -60 on nylon. (slightly higher than C6, lower than C8)	*Spray rating test AATCC TM22 + comparison with C6- & C8-based fluorocarbon DWR + Laundry Air Drying (LAD) Effect* After 5 washes: -Dry at 30C, 60C, or ironing all show no change in water repellency (WR) on cotton. (WR increases to 60 and 70- from 0 for C6 and C8, respectively) -All show no change in WR on polyester. (remains at 100-) (Same for C6 and C8) -All show no change in WR on nylon. (Ironing improves WR of both C6 and C8 by a small amount) After 10 washes: -Dry at 30C, 60C, or ironing all show no change in WR on cotton. (No WR improvement shown in C6 or C8 either) -All show no change in WR on polyester. (remains at 100-) (Same for C6 and C8) -All show no change in WR on nylon. (Ironing improves WR of both C6 and C8 by a small amount)	*Change in spray rating test* -Not very durable on cotton. But has a much higher durability than both C6 and C8 fluorocarbon DWR when applied on cotton, with a test value of 50+ after 10 washes while both fluorocarbons fall to 0. -Highly durable on polyester. Durability is similar to C6, but a little less durable than C8. -Moderately durable on nylon. Slightly better durability than C6, but worse durability than C8 especially after 20 washes. *LAD Effect (recovery in water repellency after drying)* -Durability is not improved by the LAD Effect on all types of fabric.

iii) Methyl hydrogen silicone / Polymethylhydrosiloxane (PMHS)

Polymethylhydrosiloxane (PMHS), or methyl hydrogen silicone, is a type of silicone with the two R groups substituted to one hydrogen atom and one methyl group, while the two ends of the polymer are trimethylsilyl capped, as shown in Fig. 6. The hydrophobic property of PMHS results from the hydrolysis of Si—H bond that reacts to form Si—OH groups, which can dehydrate, condense, and crosslink to form a water repellent film layer.

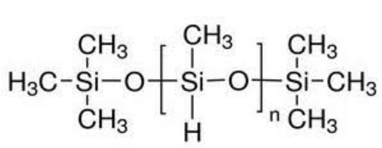

Figure 6. Chemical structure of PMHS[2]

2 https://www.vi-sight.com/methyl-hydrogen-silicone-fluid/

XIAMETER™ MEM-0075 Emulsion manufactured by DOW is a PMHS water repellent coating suggested to be applied with a catalyst. Evaluating by Spray Rating Test AATCC TM22, for non-washed fabrics, a rating of 70 or 90 are given for spunbonded PE nonwoven fabric treated with PMHS without or with a catalyst, respectively. After 5 washes, the rating dropped to 50 or 90. The same test is carried out again on woven PE/cotton fabric, with the result of 0 dropping to 0 or 90 dropping to 50 for fabric treated with PMHS without or with a catalyst after 5 washes, respectively. Thus, on spunbonded PE nonwoven fabric, the coating is weakly durable if directly treated, and moderately durable if with catalyst. On woven PE/cotton fabric, it is weakly durable even with catalyst, and no hydrophobicity at all if directly treated.

iv) Blended mixture and others

Some of the silicone-based water repellent products may be a mixture of different silicone chemicals or others, and thus are listed below. DOW Corning's DOW Corning®

DWR-7000 Soft Hydro Guard has premium softness, good stability, and simple application. However, it lacks strong oil repellency. Evaluating by Spray Rating Test and comparing with C6 fluorocarbon, the treated khaki twill fabric has perfect initial repellency of 100 and a rating of 90 after 20 washes and 80 after 30 washes, showing stronger durability compared to C6. DOWSIL™ FBL-0563 Formulated Blend, also by DOW, showed all perfect (100) ratings of initially treated fabric on red cotton sateen, green corduroy, white 802 cotton, charcoal wool, and light blue acetate. However, it has a low flash point, does not have oleophobicity, and may lack durability as washing tests are not provided.

The following graph summarizes the water repellent functionality of different types of silicone products introduced above, using the Spray Rating Test AATCC TM22 as the standard for comparison.

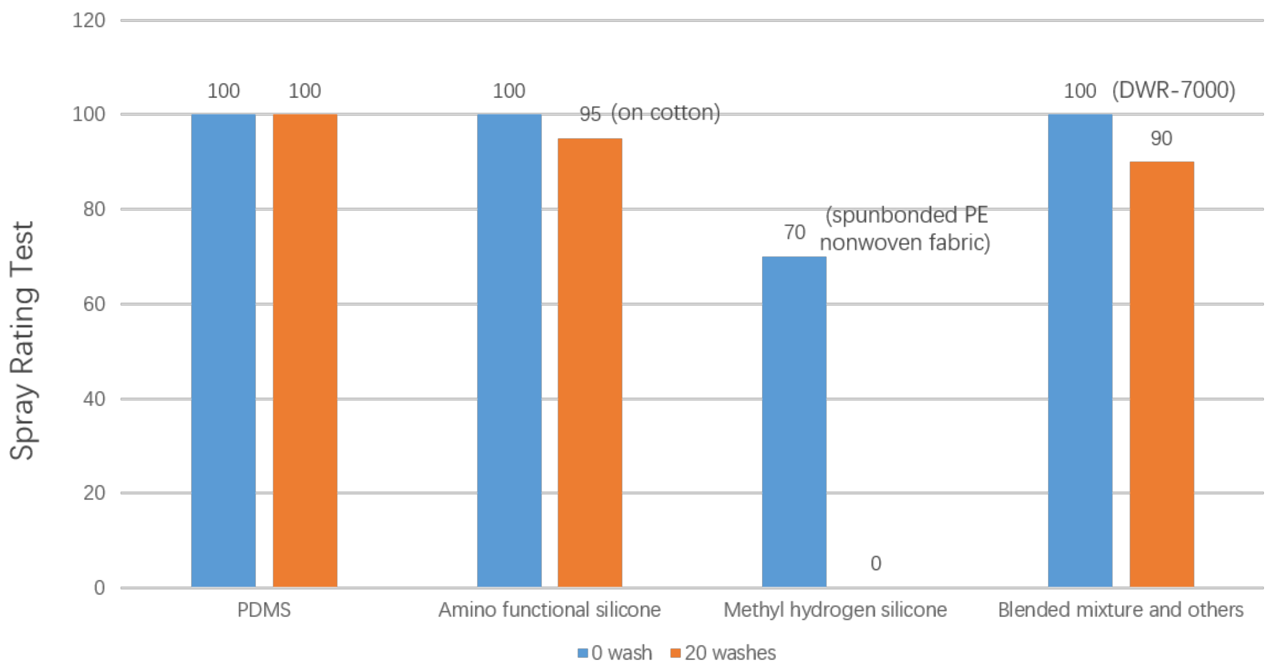

Figure 7. Comparison of Spraying Rating Test result of initially treated fabric and fabric after 20 washes across different types of silicones.

3.2 Hydrocarbons

Hydrocarbon-based DWRs are replacing traditional fluorinated DWRs due to their minimal environmental harm[22]. Its core component is crystalline linear n-alkyl chains, forming an effective hydrophobic membrane to prevent water penetration. Hydrocarbons contain paraffin and alkanes with low environmental biotoxicity, but products containing stearic acid-melamine resin may release formaldehyde, which should be carefully selected.

3.2.1 Different types of hydrocarbons based on contact angle sizes

Hydrocarbon chain branch types affect surface structure and superhydrophobicity, including linear, asymmetric and symmetric branches. The branch type of hydrocarbon affects surface properties, where the linear chain exhibits superior superhydrophobicity, while branched chains yield lower contact angles. As the carbon chain grows, the contact angle increases[23].

Below are selected examples of hydrocarbons-based DWR products produced by different manufacturing companies.

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Table 3. Selected commercial DWR products composed of hydrocarbon chemistry

Product name	Producer company	Characteristics
Arkophob FFR	Archroma	-Improved tear strength and abrasion resistance, good hand feel, high breathability. -Durability that endures 20+ laundering cycles, making its durability comparable to C6 fluorocarbons, and superior compared to multiple other non-fluorinated alternatives.
EcoRepell	Schoeller Textil AG	-Paraffin-based DWR and SR: A mixture of long-chain biodegradable paraffin, fatty acid-modified melamine resin, and blocked polyisocyanates in dispersion form. -Paraffin chains surround the fabric fibers to generate a low surface energy film.
Phobotex range	Huntsman and Chemours Company FC	-Protection against rain and staining. -APK: Aluminum salt added. -ZAN: Zirconium salt added. -JVA, RHP, RSH, RHW: Dispersion of paraffin oil and fat-modified melamine resins. -RCO: Dispersion of paraffin wax and acrylic copolymer. -Durability of 30 washings at 40℃.
Zero F1 Itoguard NFC	CHT/Bezema LJ Specialities	-Paraffin-based. -Fatty-acid derivative included in paraffin that contains melamine.
Texfin HTF	texchem	-Modified wax dispersion. -Applications in outing activities garment and operational clothing.
Neoseed NR-158	Nicca Chemical Company Ltd	-Similar water repellency as fluorinated coating.

3.3 Dendrimeric DWRs

Dendrimeric DWRs are hyperbranched polymeric structures that comprise ester or polyurethane sections, as shown in Fig. 8[24]. After being dried, dendrimers will self-assemble to form a repellent film on the coated surface.

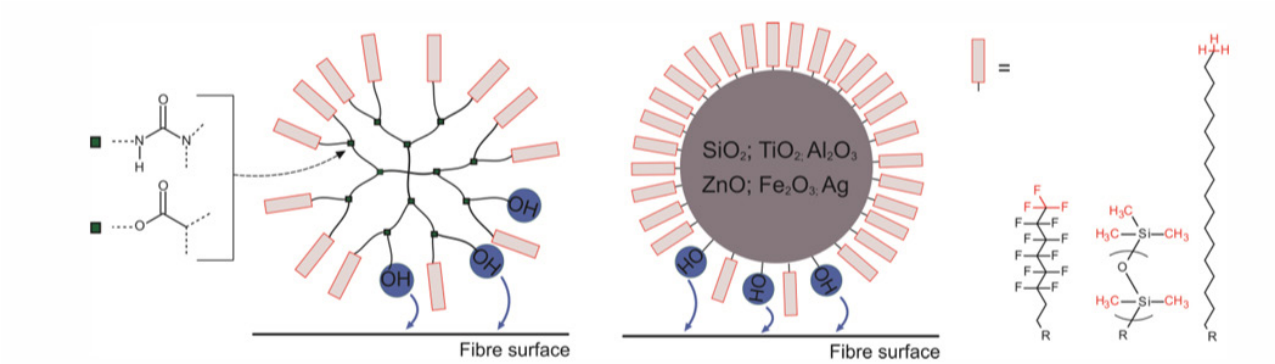

Figure 8. Simplified water repellent mechanism and structure of dendrimers (left) and nanoparticles (right)[25]

Dendrimers can be modified using substances such as polyalkylsiloxanes or with fatty acids, to achieve repellent properties[26]. Other modifications such as free hydroxyl or epoxy groups can provide cross-linking points covalently bonding with the fiber surface[27]. Inorganic nanoparticle, such as SiO_2 or Al_2O_3 (Figure 8), can also be added to dendrimer solution to enhance the surface area of treated fabrics and provide cross-linking points to achieve hydrophobicity[28,29].

BIONIC-FINISH® ECO technology developed by Rudolf has a special focus on the use of dendrimers that can essentially be applied to all types of fibers. The company claims that up to 90% of the components are "renewable bio-based raw materials." Based on Spray Test Rating data provided by the company, the durability and repellency performance of dendrimer DWR is worse on cellulosic fibers than on synthetic fibers.

3.4 Summary of the limitations of the alternatives to current long chain perfluoroalkyl substance

Here we compared the limitations of different long-chain PFAS substitutes across various aspects.

Table 4. Summarized evaluation and comparison over fluorinated and non-fluorinated DWR chemistries across different aspects

Evaluation parameters Long-chain PFAS substitutes		Functional limitations and potential areas of improvement	Cost efficiency for producers	Market competitiveness	Potential environmental problems
Fluorinated chemicals	Short chain PFAS	-The fluorinated part is difficult to remove, forming persistent dead-end transformants.	-Simple chemical structure. -Simple production process. -Low production cost.	-Strict environmental regulations may limit the market performance of short-chain PFAS in Europe and North America.	-Toxicity (especially its long-term effects) is uncertain. -Multiple side effects. -The bioaccumulation of these chemicals in terrestrial ecosystems needs to be assessed.
	Perfluoroether carboxylic acid	-Stable but difficult to degrade. -Easy to cause problems in high temperatures or chemical reactions. -Need for improvement in its environmental adaptability.	-Expensive raw materials and equipment. -High production costs.	-Performance cannot entirely replace PFAS, limiting its market. -Low technology maturity, low production efficiency, and unstable product quality, affecting its market competitiveness. -Market awareness and acceptance are low.	-Degrade to a greater extent, but the degraded products may still be harmful to the environment. -Complex environmental impact and degradation processes, making it difficult to assess the risks.
	Sulfoacid	-Insufficient surface activity, poor durability, unstable at high temperature, and sensitive to pH. -Changing properties and stability in different environments.	-Raw material from a wide range of sources. -High production technology maturity. -Low cost. -Low R&D investment cost.		-Difficult to degrade and easy to accumulate in the organism. -Volatile, easy to spread through the atmosphere.

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Non-fluorinated alternatives	Silicone	-Unable to resist nonpolar liquids, less water soluble, and usually less durable than PFAS. -Silicon materials that perform well under laboratory conditions may not be applicable to practical applications. -The toxicity data of different in silicone compounds still need further evaluation.	-Mature production process. -Low cost.	-The range of application increases, and the market demand increases. -Technological innovation and product improvement allow higher performance to meet industrial and environmental demands.	-Less harm to the environment. -Generate less pollutants in the production process. -Lower persistence and bioaccumulability, short residual time in the environment, and less impact on the organisms.
	Hydrocarbon	-Easy to degrade, and most benign environmental impact. -Not resistant to high temperatures. -Poor performance in a strong acid and alkali environment is inferior to long-chain PFAS. -Poor performance in high surface activity applications, and weak cleaning and anti-fouling ability.	-Mature production process. -Low cost. -High long-term maintenance cost.	-Environmental friendliness and low cost make this material more competitive in the market.	-The most environmentally benign. -The degradation rate is faster than PFAS but may produce unknown intermediates during the process of degradation.
	Dendrimeric	-Hyperbranched polymer structure containing ester or polyurethane fragments. -Form a continuous polymer film and can be modified with fatty acids, polyalkylsiloxanes, etc. to obtain hydrophobicity. -The durability and hydrophobicity on cellulose fibers are not as good as those on synthetic fibers.	-The synthesis process is complex, the production cycle is long, and the research and development cost is high.	-Multi- medium distribution makes environmental risk assessment difficult.	-Additional environmental protection treatment processes are required. -Greatly affected by regulatory uncertainty.

4. Evaluation of limitations and future areas for improvement

Although fluorinated durable water repellent fabrics have been dominating the market, their environmental harm and toxicity lead to restriction of their use. Considering a more sustainable approach, non-fluorinated chemistries that provide similarly low surface energy have been discussed in this review.

Silicones offer hydrophobicity comparable to fluorinated chemicals, with a good feel, breathability, and cost-effectiveness. Though less durable, its performance varies with chemical modifications. However, silicones lack oleophobicity. Thus, silicones can be applied at low concentrations for effective performance, at a low cost, making it appealing for large-scale production. Hydrocarbons are eco-friendly, cheaper, and sufficiently waterproof for general outdoor wear. However, they underperform in extreme conditions and high-performance applications, with poor surface activity and cleaning ability. Dendrimeric DWR provides durability and breathability but can be harder to apply on fabrics, and expensive to produce. Non-fluorinated materials generally lack low surface tension liquid repellency, limiting their use. While suitable for outdoor wear with low stain-resistance needs, they may not suffice for protective wear exposed to low surface tension liquids, like medical gear contacting blood and body fluids.

Other potential methods in reaching water and stain repellency focus on achieving a low contact angle hysteresis by utilizing surface mobility, rather than searching for higher contact angles, aiming at the ease for the liquid to slide or roll-off from a surface. Liquid-like surfaces are products resulting from this approach. They are often made with low glass transition temperature material such as PDMS. These surfaces can repel liquids of low surface tension and complex liquid mixtures, meaning that liquid-repellent surfaces can potentially be applied in medical protective textile areas, filling the gap of non-fluorinated hydrophobic coatings. However, the liquid that stays on liquid-like surfaces tends to have a lower contact angle, which means a lower breakthrough pressure. This also limits the application as liquid-like surfaces cannot resist incoming liquid at high pressure, such as splashing.

Learning from natural superhydrophobic and superoleophobic surfaces, surface texture and geometry are much more promising areas of investigation compared to low surface energy chemistry. Natural surfaces use hierarchical structure and re-entrant texture to achieve a high contact angle with low surface tension liquid. Hierarchical structures are already being created and tested using the blending of nanoparticles or plasma treatment to etch the surface itself and have proven to generate higher contact angles. The current limitations and future considerations in this field are, firstly, the improvement of surface texture generation methods and technologies to have better control of the geometrical design on surfaces. This will facilitate the experimental testing of the multifaceted functionality of DWR surfaces produced with different textures and geometries. Secondly, to find a balance between functionality and practicality. Many textural technologies can have a precise etching of the surface to create structures like micro-hoodoo, however, these technologies may not be suitable for the textile application. Both large-scale manufacturing's requirement for productive efficiency and the producers' need for lower costs should be taken into consideration. To fulfill those practical needs in textile manufacturing, automated surface designing processes may be required to model texture in bulk at an acceptable cost. Finally, durability should also be considered in creating durable water repellent surfaces, aligning with the sustainable development goal. Being durable means that finished textiles should be able to endure multiple cycles of use, which is already being improved upon with current knowledge in chemistry and texture, but it can also suggest the ability to be recycled and reused, serving the purpose of a circular economy and minimizing environmental effects. The industry of recycling functional garments and restoration of liquid repellent functionalities can also be a future point of consideration.

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