MATERIALS SCIENCE

Challenges and strategies for commercialization and widespread practical applications of superhydrophobic surfaces

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Superhydrophobic (SH) surfaces have progressed rapidly in fundamental research over the past 20 years, but their practical applications lag far behind. In this perspective, we first present the findings of a survey on the current state of SH surfaces including fundamental research, patenting, and commercialization. On the basis of the survey and our experience, this perspective explores the challenges and strategies for commercialization and widespread practical applications of SH surfaces. The comprehensive performances, preparation methods, and application scenarios of SH surfaces are the major constraints. These challenges should be addressed simultaneously, and the actionable strategies are provided. We then highlight the standard test methods of the comprehensive performances including mechanical stability, impalement resistance, and weather resistance. Last, the prospects of SH surfaces in the future are discussed. We anticipate that SH surfaces may be widely commercialized and used in practical applications around the year 2035 through combination of the suggested strategies and input from both academia and industry.

INTRODUCTION

Ollivier first reported superhydrophobicity in 1907 (*1*), which has received great attention in academia and industry since ~2000, as Barthlott and Neinhuis revealed in 1997 the self-cleaning mechanism of lotus leaves (*2*). There are >27,000 documents including papers, patents, and books in the Web of Science about "superhydrophobic*" as of May 2023 with a fast-growing trend (Fig. 1A). Superhydrophobic (SH) surfaces feature high water contact angle (CA ≥ 150°) and low CA hysteresis (≤10°) or sliding angle (SA ≤ 10°). On the basis of the unique wettability of SH surfaces, researchers have proposed numerous potential applications. Meanwhile, it is generally believed in the industry that SH surfaces will have extensive applications in various fields. However, the widespread practical applications of SH surfaces lag considerably behind their vibrant fundamental research. In this perspective, we show challenges and strategies for commercialization and widespread practical applications of SH surfaces after a survey of the current state of SH surfaces including fundamental research, patenting, and commercialization.

CURRENT STATE OF SH SURFACES

Fundamental research

The last 20 years are a brilliant era of SH surfaces (Fig. 1A). Great advances have been made in fundamental research of SH surfaces including preparation, bionics, wettability theory, and potential applications. These aspects are briefly summarized in the following paragraphs. Now, SH surfaces are of great interests all over the world (e.g., P.R. China, United States, South Korea, India, Germany, England, Japan, Canada, and France) in a wide range of disciplines (e.g., materials science, chemistry, engineering, physics, mechanics, environmental science, and energy) and are an interdisciplinary hot research topic.

Researchers have developed various preparation methods based on the design of surface structures and the discovery or synthesis of low–surface energy materials. Various micro-, nano-, and hierarchical micro-/nanostructures have been constructed. Lithography, etching, templating, deformation, and deposition are the most commonly used techniques, and new techniques are constantly being developed (*3*). In the meantime, researchers have found or synthesized many materials with alkyl or fluoroalkyl groups to reduce surface energy. The methyl groups are sufficient to make a rough surface SH, and long-chain alkyl and fluoroalkyl groups will make it easier. Surface structures (e.g., reentrant structure) that can trap more air help reduce dependence on low–surface energy materials. Similarly, low–surface energy materials help reduce reliance on surface structures.

The prosperity of SH surfaces has inspired researchers to reconsider the SH phenomena in nature. Many plants (e.g., succulents, rice leaf, and *Salvinia molesta*) and animals (e.g., water strider leg, mosquito eye, duck feather, and butterfly wing) have SH surfaces besides lotus leaves (*4*). However, their specific surface structures and superhydrophobicity (e.g., SA and underwater stability) are very different, and the functions are yet not very clear.

SH surfaces develop rapidly based on the classical Young's equation (*5*), Wenzel equation (*6*), and Cassie-Baxter equation (*7*). Meanwhile, SH surfaces have greatly enriched surface wettability theories (*8*, *9*). For example, the limits of the Wenzel and Cassie-Baxter equations and their extent of applicability are elaborated (*4*, *10*). In addition, numerous interesting dynamic wetting phenomena on SH surfaces are reported and theoretically discussed, e.g., pancake bounce (*11*), droplet transport/manipulation (*12*, *13*), and splash promotion/inhibition (*14*, *15*). Also, with the help of modern instrument (e.g., microscopic imaging and force measurement) and numerical modeling, the studies about microscopic solid-liquid interactions evolve rapidly, such as local CA measurement (*16*), Cassie-to-Wenzel transition (*17*), contact line receding

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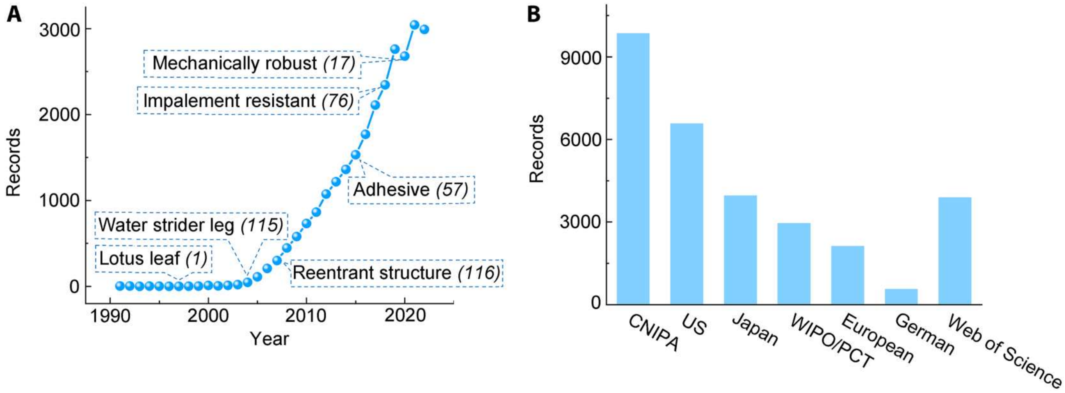

Fig. 1. Current state of SH surfaces. (**A**) Documents in the Web of Science about "superhydrophobic*" (topic) and some representative studies. (**B**) Patent data collected from CNIPA, https://www.freepatentsonline.com, and Web of Science about "superhydrophobic*" (topic).

on micro-pillars (*18*), gas meniscus formation (*19*), and wettability mapping (*20*).

Researchers in a variety of disciplines have suggested numerous potential applications of SH surfaces. Self-cleaning (*4*, *21*), oil/water separation (*22*, *23*), corrosion protection (*24*, *25*), anti-/deicing (*26*, *27*), and waterproof textiles (*22*, *28*) are the most popular subfields. SH surfaces have opened up interesting possibilities and ideas in these conventional fields. SH surfaces also have a wide range of potential applications in numerous other fields, such as drag reduction (*29*, *30*), water harvesting (*31*, *32*), heat transfer (*33*, *34*), liquid marbles (*35*, *36*), anti-scaling (*37*, *38*), anti-bacteria (*39*), blood repellent (*40*, *41*), cell screening (*42*, *43*), controlled release (*44*, *45*), trace analyte detection (*46*), surface enhanced Raman spectroscopy detection (*47*, *48*), energy conversion (*49*, *50*), catalysis (*51*, *52*), microsphere synthesis (*53*, *54*), and prevention of rain attenuation of 5G/weather radomes (*55*).

Patenting

In the last 20 years, there has been a sharp growth in the number of patents about SH surfaces. China, United States, Japan, and European Union have published the greatest number of patents (Fig. 1B). More than 9800 patents are registered with the China National Intellectual Property Administration (CNIPA) in Chinese, and >16,000 patents are available at www.freepatentsonline.com including >6500 U.S. patents, >3900 Japanese patent abstracts, >2900 World Intellectual Property Organization/Patent Cooperation Treaty (WIPO/PCT) patents, >2100 European patents, and >500 German patents. Additionally, Web of Science (Derwent Innovations Index) lists >3800 patents related to SH surfaces. Be aware

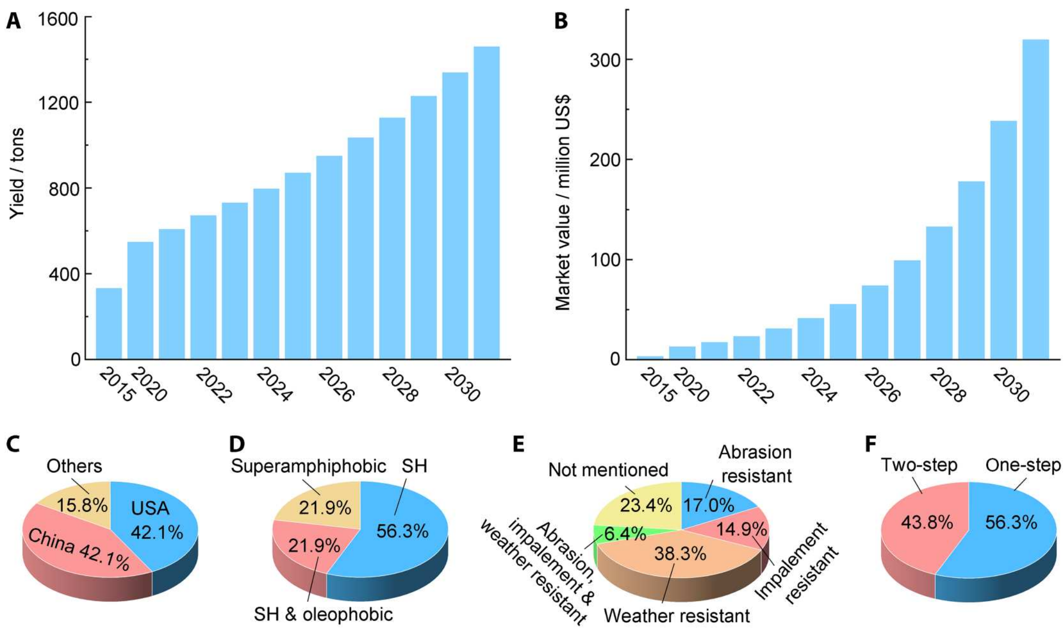

Fig. 2. Commercialization status of SH surfaces. Global (**A**) yield and (**B**) market value of SH surfaces. (**C**) Distribution of companies with commercial SH products appropriate for smooth substrates. Statistical analyses of 32 commercial SH products appropriate for constructing SH surfaces on smooth substrates: (**D**) wettability, (**E**) stability, and (**F**) preparation methods.

that it is challenging to incorporate all SH surface–related patents that exist in other languages.

The most often mentioned preparation techniques in these patents are spray-coating and dip-coating, most likely due to their practicality and scalability. Reick (*56*) reported in 1974 abrasion-resistant SH surfaces by coating a suspension of hydrophobic fumed SiO_2 particles and a resinous binder onto substrates. After around 40 years, this technique was shown to be extremely effective for the creation of mechanically resistant SH surfaces (*57*) and is still widely used today (*55*, *58*). As a result, we need to pay greater attention to some important early literature during research and development (R&D) of SH surfaces. On the other hand, the very early applications of SH surfaces in these patents are minimizing friction for toys with a trackway, slide, maze, or other surface (*56*), separation of immiscible liquids (*59*), drag reduction during swimming (*60*), and educational dolls for young children (*61*).

Commercialization

Before 2015, the global yield and market value of SH surfaces were quite low, which have increased gradually in these years. An analytical report from QYResearch (2020) estimated that the global yield of SH surfaces was 546.29 tons in 2020 as shown in Fig. 2A (*62*). The global market for SH surfaces was predicted to reach US$12.67 million in 2020, according to a different analytical report from Transparency Market Research (2022) as shown in Fig. 2B (*63*, *64*).

We find 29 companies worldwide that deal with SH surfaces and provide a thorough analysis (table S1). The products of 10 companies are only appropriate for substrates with inherent surface structures, like fabrics, wood, and paper. Only products of 19 companies, mostly from China and United States, are appropriate for constructing SH surfaces on smooth substrates like glass and metals (Fig. 2C). Thirty-two commercial SH products are available from these 19 companies (table S2), 56.3% of which are SH, 21.9% are SH and oleophobic, and 21.9% are superamphiphobic (Fig. 2D). Moreover, 23.4% of the products do not mention stability at all, 38.3% of the products claim to be weather resistant, 17.0% of the products are abrasion resistant, and 14.9% of the products are impalement resistant (Fig. 2E). Only 6.4% of the products, mostly from Xinna Superhydrophobic New Materials LLC, are simultaneously abrasion, impalement, and weather resistant. Remember that it is unavailable and challenging to compare the precise wettability and stability data of these 32 commercial SH products. This shows the necessity of using the standard test methods. In addition, most of these SH products are solvent-borne and only one product (HIREC 300-W) is waterborne, 56.3% of which are one-step design (Fig. 2F). According to the aforementioned survey, commercial SH products with excellent comprehensive stability and good environmental friendliness are rare. However, they are crucial for commercialization and widespread practical application of SH surfaces.

Among these commercial SH products, there are some representative ones like NeverWet, Nasiol, Ultra-Ever Dry, TOYAL LOTUS, and Xinna (*64*). For example, Ultra-Ever Dry is a two-layer SH and oleophobic coating with good adhesion and abrasion resistance (*65*). TOYAL LOTUS is an SH aluminum packaging material with good safety and has been put to practical use in yogurt container lids (*66*). Xinna are a series of one-layer abrasion, impalement, and weather resistant superamphiphobic coatings for a variety of real-world uses, such as anti-icing of high-voltage transmission tower and prevention of rain attenuation of 5G/weather radomes (*55*, *67*).

CHALLENGES AND STRATEGIES FOR COMMERCIALIZATION OF SH SURFACES

According to the above survey of the current state of SH surfaces, the commercialization and widespread practical applications of SH coatings lag well behind the remarkable fundamental research and patenting. After decades of energetic research, it is time to find a solution to this issue. Therefore, we analyze the obstacles preventing the broad use of SH surfaces in practical applications and their commercialization, and then suggest the corresponding actionable strategies in this section. In particular, the comprehensive performance of SH surfaces, preparation methods, and application scenarios should be considered simultaneously, which are explained in detail below (Figs. 3 to 5).

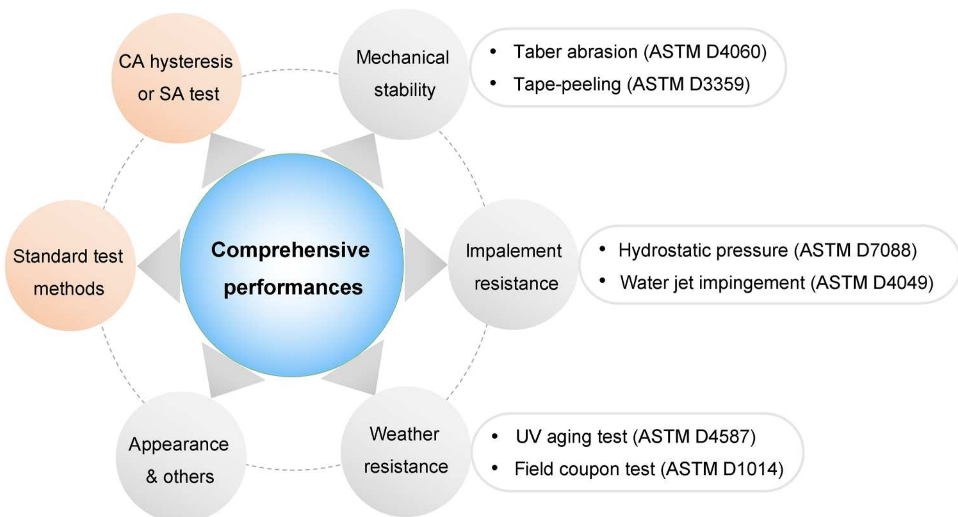

Fig. 3. Challenges and standard test methods of comprehensive performances for commercialization and widespread practical applications of SH surfaces. The listed items should be improved, considered, and/or measured.

Comprehensive performances

Excellent mechanical stability is a prerequisite for practical applications of SH surfaces (Fig. 3). However, most SH surfaces inherently have poor mechanical stability because abrasion can easily disrupt their hierarchical structures due to mechanical stress concentration. This is the primary roadblock impeding their practical implementations (*68*). Researchers have known this problem for a long time and have made substantial advancements in improving mechanical stability by enhancing coating/substrate bonding using adhesives (*57*), designing self-healing surfaces (*69*–*71*), constructing self-similar structures (*72*), shielding nanostructures with micro-armor (*17*), and using elastic materials (*68*). For example, Deng and colleagues (*17*) reported mechanically robust SH surfaces using an armored structure, which could withstand 240 cycles of Taber abrasion (250-g load) or 100 cycles of tape-peeling. Zhang *et al.* (*58*) designed a skin-inspired mechano-chemical-thermal robust SH surfaces, which remained superhydrophobic after 3000 cycles of Taber abrasion (250-g load). Among these strategies, the use of adhesives is convenient for large-scale preparation and practical applications of SH surfaces (*26*, *58*). However, adhesives frequently greatly increase the surface energy of SH surfaces by covering low–surface energy materials and hence lead to poor superhydrophobicity (*73*, *74*). To increase mechanical stability while preserving low surface energy, proper choice and use of adhesives (e.g., phase separation) are crucial (*55*). Also, a self-healing function for the reconstruction of surface chemistry and micro-/nanostructures like biological surfaces is particularly important for practical applications of SH surfaces (*75*). Obtaining SH surfaces with outstanding self-healing capability is still highly tough and hard, despite the fact that many self-healing SH surfaces have been documented (*75*). Up to now, the mechanical stability of SH surfaces is still difficult to meet widespread practical applications.

Excellent water impalement resistance (hydrostatic pressure and dynamic impact) is another prerequisite for practical applications of SH surfaces (Fig. 3) (*76*). This is because SH surfaces frequently encounter dynamic water (e.g., rainfall) or persistently contact with water (e.g., drag reduction and anti-fouling). When the hydrostatic pressure or water hamper pressure (P_h) is larger than the capillary pressure (P_c) generated within the surface structures, the air layer trapped at the solid-liquid interface will be squeezed out. Consequently, transition of water from the Cassie-Baxter state to the Wenzel state will happen (*77*), leading to adhesion of water on SH surfaces, i.e., loss of the unique self-cleaning performance. Unfortunately, most SH surfaces have poor impalement resistance and can only endure water impacting at low velocity (e.g., 1.4 m s^{-1}) (*78*). However, the velocity of heavy rain is 8 to 9 m s^{-1}, and thus, SH surfaces should at least be able to withstand such impacting for outdoor applications. Much higher water impalement resistance is needed for various other applications like drag reduction of ships and underwater weapons. Moreover, researchers only lately become aware of this problem. In nature, there are several SH surfaces that are impalement resistant, such as *S. molesta* and water spiders. Also, pressure, air diffusion, and water condensation determine the air layer stability and impalement resistance, which can be characterized by optical, force, acoustic, and electrochemical methods (*79*). Thus, impalement resistance can theoretically be enhanced by learning from nature, controlling the air layer environment and regeneration/recovery of the air layer, but remains to be substantially enhanced by designing mechanically flexible SH coatings (*76*) and/or creating the right microstructures and nanostructures (*77*) to meet real-world applications.

For droplets impacting a horizontal surface, P_h can be calculated using Eq. 1 (*77*)

$$P_h \approx 0.2\rho C v \tag{1}$$

Here, ρ is the water density, C is the sound velocity ($C_{water} = 1497$ m s^{-1}), and v is the impact velocity.

P_c can be calculated using Eq. 2 (*77*)

$$P_c \approx 2\gamma r \sin^2\left(\frac{\theta_{adv}}{2}\right)/d^2 \tag{2}$$

Here, d is the mean distance between protrusions, r is the radius of the constituting particles, γ is the surface tension of the liquid, and θ_{adv} is the advancing CA_{water} on a smooth fluorosilane-coated substrate.

The equations show that penetration of impacting droplets can be successfully hindered when $P_c > P_h$. Moreover, P_c increases with decreasing d. Therefore, a dense surface structure can enhance impalement resistance (*55*).

Excellent weather resistance is also very important for SH surfaces, especially for outdoor applications (Fig. 3). In the outdoor environment, SH surfaces are directly exposed to a variety of harsh circumstances for an extended period of time, such as continuous raindrop impact, sand and dust erosion, ultraviolet (UV) radiation, corrosive media, high/low temperature, icing/melting, and snow. These will substantially shorten life span of SH surfaces. Although a few researchers have mentioned the importance of weather resistance in some studies, they still have not given this much thought. In addition, simulated UV aging tests are common in the literature, whereas long-term outdoor weather resistance test is rare (*80*). This gap has to be filled in the future. Weather resistance of SH surfaces may be improved by using chemically inert, UV-resistant, and thermostable components (*55*). The other stabilities including corrosion resistance, chemical stability, and temperature stability should also be guaranteed for many real-world applications.

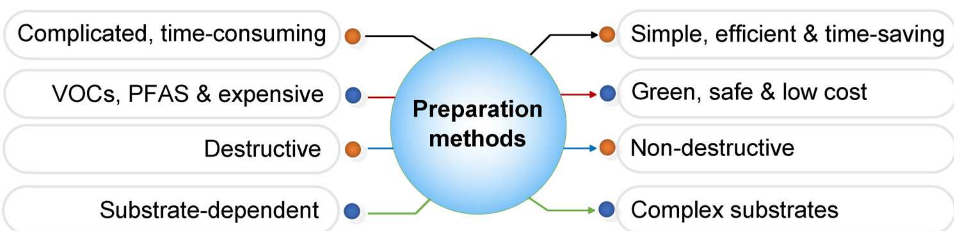

Fig. 4. Challenges of preparation methods for commercialization and widespread practical applications of SH surfaces.

A rational combination of the aforementioned strategies, the creation of new surface structures and low–surface energy materials, the synthesis of adhesives with strong adhesion and low surface energy, and the selection and synthesis of suitable elastic materials are all necessary for a substantial improvement in the overall performances (mechanical stability, impalement resistance, weather resistance, and others). Machine learning and high-performance computing may hasten this process (*81*). Additionally, bioinspiration not limited to SH surfaces in nature (e.g., nacre-inspired structural materials) is still an effective method. Moreover, interdisciplinary design of SH surfaces not confined to wettability theories may be essential. For example, there are numerous high wear-resistant coatings in the field of friction and lubrication. The theories and strategies in the field may be helpful to greatly enhance the mechanical stability of SH surfaces.

Besides improvement in the comprehensive stabilities, standard test methods are equally important but have not yet been established. Accompanying the rapid progress of SH surfaces, various test methods have been used as shown below. However, it is difficult to compare the results among studies and products, because the specific test methods and settings are different (*82*). Ideal methods should have precisely controllable test conditions (e.g., force and pressure), big enough and uniform test area for wettability measurement and other analyses (e.g., surface microstructure and chemical composition), good repeatability, and readily available equipment. On the basis of these criteria and previous studies (*17*, *58*) as well as our expertise (*26*, *55*, *83*), we now propose the standard test methods for the comprehensive stabilities of SH surfaces (Fig. 3). Note that some of the methods may not be generally applicable to all the existing rich and diverse SH surfaces.

(i) For evaluating mechanical stability, Taber abrasion (ASTM D4060) is preferred as a surface abrasion method compared with the others such as sandpaper abrasion (*83*, *84*). Taber abrasion has all the merits of an ideal test method as mentioned above. Note that the changes in CA, SA, and others should be monitored following Taber abrasion rather than the mass loss of SH surfaces. In contrast, it is difficult to keep SH surfaces parallel to sandpaper very well during sandpaper abrasion, causing uneven stress distribution and thus poor repeatability. Additionally, there is no standard test method of sandpaper abrasion, making it impossible to compare the results throughout the literature. When assessing the adhesion strength between SH surfaces and substrates, the tape-peeling method (ASTM D3359) is favored (*55*, *58*), as it is extensively used in both academia and industry. Briefly, regular grids with an interval of 1 mm are formed using a hundred-grid knife on the SH surface. Then, the tape with an adhesion strength of 3000 N m^{-1} to standard stainless steel is pressed onto the SH surface under a load of 2 kg and then peeled off. The intactness of the SH surface is checked. For SH surfaces on special substrates, it is better to use specific methods from respective disciplines. For example, the Martindale abrasion (ASTM D4966) and the washing test (AATCC 61) are the two most used methods for assessing the mechanical stability of SH textiles (*85*, *86*).

(ii) For evaluating impalement resistance, both the hydrostatic pressure test (ASTM D7088) and the high-speed water jet impingement test (ASTM D4049) are good choices (*76*, *87*). The critical pressure and duration that the Cassie-Baxter state can sustain are the key factors to consider when assessing impalement resistance. For SH textiles, we can assess the water impalement resistance by the hydrostatic pressure test (AATCC 127) and the spray test (AATCC 22).

(iii) For evaluating weather resistance, the long-term field coupon test (ASTM D1014) in the outdoor environment in different regions is essential besides the UV aging test (ASTM D4587). While the UV aging test is convenient and timesaving, the field coupon test is more accurate and realistic.

(iv) Additional methods such as falling sand abrasion (*88*), linear abrasion by specific materials (e.g., polypropylene probe) (*17*), and qualitative methods (e.g., steel wool abrasion, steel-blade scratching, and screwdriver scratching) (*17*, *26*) are good supplements. The experimental results must be accompanied by the precise test conditions.

In the above tests, the change in CA hysteresis or SA is the indispensable parameter besides CA to evaluate the stability of SH surfaces, since it determines self-cleaning performance and is more sensitive than CA (*89*). We should continuously monitor the SA changes until >10°, which denotes failure of superhydrophobicity. The so-called high stability in some studies based on the retention of high CA without CA hysteresis or SA assessment is inappropriate or even deceptive. Additionally, the CA and SA should be tested according to the following operation specifications to pursue the comparability of future research results (*78*). The water droplet (5 μl) dispensed from a syringe should contact SH surfaces on the inclinable table before leaving the needle. There should be a proper distance between the tip of the syringe needle and SH surfaces to avoid droplet impacting on SH surfaces or squeezing of the droplet. Tilting angle of the inclinable table should be adjustable smoothly and precisely, which allows the SA measurement at the same position after the CA measurement. Also, analyses of progressive changes in surface structure, chemical composition, and air layer are necessary to identify damage mechanisms and enhance comprehensive performances. For these analyses, it will be highly beneficial to use in situ or real-time analytical techniques, such as visual real-time tracking of air layer by optical methods (*79*), real-time tracking of the average surface wettability changes by acoustic methods (*79*) and electrochemical impedance (*90*), and real-time visualization of the solid-fluid interface on the micro-/nanoscale by synchrotron x-ray imaging (*91*).

The appearance of SH surfaces including transparency, haze, chalking, and color also affects the usability. Transparent SH surfaces are necessary in some situations, but their surface structures often cause severe light scattering and thus greatly impair transparency. Today, transparent SH surfaces have achieved notable progress by designing uniform surface structures with low roughness (<100 nm) (*92*). However, it is still incredibly challenging to combine high transparency with excellent comprehensive stabilities mentioned above. In addition, most studies disregard haze, another crucial aspect of transparent SH surfaces in addition to transmittance (*93*). For a specific application, superhydrophobicity, comprehensive stabilities, and transparency should be balanced by carefully regulating surface structures and chemical composition. Moreover, chalking of SH surfaces—the formation of fine powder on SH surfaces—is common, particularly for those prepared via bottom-up techniques. This is rarely mentioned in the literature despite being crucial for practical applications, since the powder of SH surfaces will contaminate water/aqueous samples contacting with them and come into natural environment. The improvement in mechanical stability will aid in reducing or avoiding chalking. Additionally, some applications require colorful SH surfaces (*94*). Introduction of pigments or structural colors to SH surfaces will make them colorful (*95*, *96*), but should not have an impact on superhydrophobicity and other performances.

Besides the aforementioned performances, the other properties of SH surfaces, such as hardness, impact strength, thickness, and flexibility, should also be taken into account, just like conventional coatings. Unfortunately, these properties are seldom measured in previous studies. These properties should also be tested using standard methods.

Preparation methods

The preparation method also largely determines whether an SH surface is scalable and practically useful. Although various methods have been explored, the existing methods share the following common shortcomings (Fig. 4), which substantially impede commercialization and widespread practical use of SH surfaces. The corresponding strategies to solve these issues are proposed and should be considered simultaneously in preparation of SH surfaces.

Many methods like lithography and layer-by-layer assembly are complicated, time-consuming, restricted to small substrates, and dependent on sophisticated and expensive equipment, which make SH coatings stay in the laboratory scale. So, we should pay more attention to developing simple, energy-efficient, and time-saving preparation methods like spray-coating, dip-coating, blade-coating, and brush-coating, which is a prerequisite for large-scale production and applications.

For the preparation of SH surfaces, volatile organic compounds (VOCs) like alcohols, alkanes, and ketones are widely used as solvents because of their good solubility or dispersibility for low–surface energy materials. VOCs will cause environment pollution and potential safety hazards. This can make a method difficult or even impossible to be used realistically, even if the SH surfaces have excellent performances. For instance, SH fabrics are often prepared using VOC-based methods in the literature. However, the fact is large-scale production of SH fabrics must use waterborne methods, since VOC-based formulas are incompatible with the traditional fabric finishing line. Therefore, the best option is to develop solvent-free methods (*97*). Meanwhile, waterborne methods are highly desirable but very challenging, as it is difficult to dissolve or disperse low–surface energy materials very well in water. There are a few so-called waterborne methods in the literature, but most of them are just partially waterborne. Totally waterborne SH surfaces are still rare (*83*). If VOCs are inevitable, their recycling is necessary. Alternatively, VOCs can be replaced with greener organic solvents, e.g., dimethyl carbonate and dipropylene glycol dimethyl ether.

Fluorinated materials like silanes, fatty acid, and thioalcohols are widely adopted to substantially reduce surface energy of a rough surface. Nevertheless, fluorinated materials and their degraded products are toxic to the environment and living things (*98*). The simplest safe way is to use fluorine-free materials like alkylsilanes, polydimethylsiloxane, and waxes, which is a good strategy for academic research (*99*). SH surfaces with high water CA and low SA can be readily obtained via fluorine-free approaches (*22*, *40*). However, we should be careful during designing fluorine-free SH surfaces for practical applications. Fluorine-free SH surfaces will inevitably have lower impalement resistance and a shorter life span since complex liquids rather than pure water are widely used in real-world applications. Thus, it is important to strike a compromise between performances of SH surfaces and use of fluorine-free materials. One approach is to reduce their content without sacrificing performances. The alternative is to choose or synthesize fluorinated materials with low or negligible environmental and biological impacts, such as those with short fluoroalkyl chains. Note that the European Union and many other countries including United States, China, and Canada are banning per- and polyfluoroalkyl (PFAS) substances and PFAS-containing products (*100*–*102*). We must abide by the laws about banning PFAS during preparation and applications of SH surfaces.

The present preparation methods are often expensive or even regardless of cost. To achieve excellent performances, innovative nanomaterials and low–surface energy materials are synthesized (*12*), interesting surface structures are constructed (*11*, *12*), and expensive equipment and processes are used *(68)*. Moreover, another widely overlooked point is that solvents make up a notable portion of the production cost for the solvent-based formulas (*83*). The cost advantage of SH surfaces can be enhanced by replacing synthetic nanomaterials with abundant natural ones like clays (palygorskite, halloysite, and sepiolite) (*103*) or using nanoparticles commonly used in industry like silica and Al_2O_3 (*26*). Additionally, SH surfaces should be prepared using industrial raw materials rather than reagents. To reduce the cost, the expensive and complicated equipment and processes should be replaced with simple preparation methods like spray-coating, dip-coating, and blade-coating, if possible. Furthermore, solvent-free techniques like powder coating can substantially reduce costs (*104*).

On the other hand, top-down methods and substrate preactivation often adopt destructive procedures like etching, radiation, high temperature, and dissolution, which may cause a serious decline in mechanical strength of substrates. Hence, nondestructive bottom-up methods like spray-coating and dip-coating are favored. Additionally, substrate preactivation may be replaced by appropriate primers (*105*).

In addition, irregular-/complex-shaped substrates (e.g., tubes, bottles, and grooves) are widely used in daily production and life, but the existing methods like spray-coating and templating are in

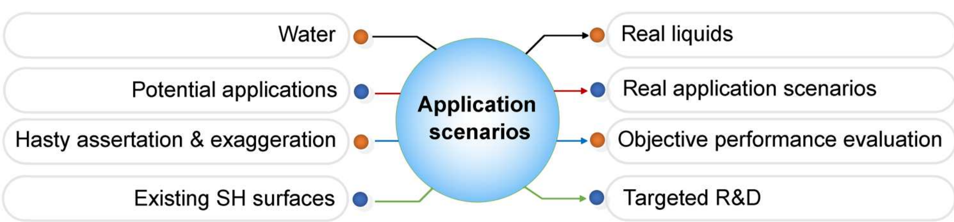

Fig. 5. Challenges of application scenarios for commercialization and widespread practical applications of SH surfaces.

most cases not suitable for such substrates (*39*). So, it is highly desirable to develop ways for creating SH surfaces on these substrates. Dip-coating and streamlined chemical vapor deposition at room temperature and atmospheric pressure are both good choices (*106*, *107*). Other methods that can solve the issue are urgently needed.

Application scenarios

There is a substantial disconnect between R&D and practical applications of SH surfaces. For the commercialization of SH surfaces, we must give a lot of consideration to the application scenarios during their preparation and performance optimization. The four key concerns regarding application scenarios of SH surfaces are given below, along with the related solutions (Fig. 5).

Most studies simply use pure water as the probing liquid to evaluate performances and application potential of SH surfaces. This is crucial yet insufficient, since various liquids including solutions, suspensions, and emulsions are used in academic research, industrial production, and our daily life (*108*). There are great differences in the properties of these real liquids, e.g., composition, temperature, density, surface tension, and viscosity. In a real environment, SH surfaces come into contact with these liquids most of the time. Studies on the static and dynamic interactions of SH surfaces with such liquids are scarce, nonetheless. This must be strengthened urgently to promote real-world uses.

Most R&D stays in artificially set potential applications during preparation of SH surfaces, which are often very different from actual ones. For example, the anti-icing/deicing performances of SH surfaces are often tested on cooling lates at room temperature and low humidity in the literature, which is substantially different from the real icing/deicing conditions of low environment temperature and high humidity. Consequently, the optimized and tested performances will be incomplete or deviated from practical application scenarios. In the future, R&D of SH surfaces should be driven by actual needs. We should integrate preparation and performance optimization of SH surfaces with specific application scenarios. Simulated tests in the laboratory should be as close as possible to real conditions, which will promote practical applications of SH surfaces. Furthermore, we must consider both basic performances (e.g., superhydrophobicity and comprehensive stabilities) and additional requirements (e.g., preparation methods, appearance, thickness, and color) for specific application scenarios. For instance, the basic performances of anti-icing/deicing SH surfaces are superhydrophobicity, stability, water freezing time, and ice adhesion force (*109*). Besides these basic performances, there are other additional different requirements when used for anti-icing/deicing of power transmission lines, wind turbines, refrigerators, and air conditioners. These additional requirements likewise govern applicability of an SH surface. Additionally, there are currently just a few practical applications of SH surfaces, although researchers have suggested numerous potential applications. More practical application scenarios remain to be explored through tight collaboration between scholars and industry.

For a specific application, we should objectively evaluate the comprehensive performances of SH surfaces. For instance, one of the primary potential applications of SH surfaces is corrosion protection (*25*). Many studies, however, hastily asserted excellent corrosion protection without performing the neutral salt spray test. This is an indispensable test for evaluating performance of conventional corrosion protection coatings. Similar to this, the separation of immiscible oil/water mixtures using SH surfaces is unnecessary. Such a hasty conclusion is often deceptive or even cause the false prosperity of a potential application.

Numerous papers, patents, and companies assert excellent performances (e.g., mechanical stability) and tremendous potential applications (e.g., anti-icing/deicing). Some of them have varying degrees of exaggeration. This misleads consumers into searching the universities, institutes, or market for SH surfaces that satisfy all of their needs rather than funding researchers to explore techniques or products appropriate for their applications. It is very unlikely to find such techniques or products directly, and targeted R&D of SH surfaces is necessary.

LOOKING FOR THE FUTURE

SH surfaces have received great progress in the past two decades. The future prospect of SH surfaces is very promising but full of challenges with respect to their comprehensive performances, preparation methods, and application scenarios. Superamphiphobic surfaces face the same problems but are more challenging, due to their higher demands for surface structures and low–surface energy materials. The global market of SH surfaces is expected to grow even faster in the future and will cross US$319.52 million by 2031 according to an analytical report from Transparency Market Research (2022) (Fig. 2B). Another analytical report from QYResearch (2020) predicted that the global yield of SH surfaces will reach 1458.39 tons by 2031 (Fig. 2A). We anticipate that SH surfaces may be widely commercialized and used in real-world applications around the year 2035 based on the commercialization status of SH surfaces (e.g., global yield, market value, and the increasing tendency; Fig. 2) by integration of the proposed strategies summarized below (Fig. 6).

The rapid increase in global market relies on finding applications in various end-use industries including electronics and telecommunication, building and construction, textile and leather, automotive, and medical and health care. Among all the potential applications, the most promising breakthrough points for widespread practical applications are preventing rain attenuation of 5G/weather radomes, waterproof textiles, superamphiphobic membranes for consumer electronics, anti-icing/deicing, and food packing. Upgrading of traditional coating industry can also promote practical applications of SH surfaces for self-cleaning, anti-icing/deicing, and corrosion protection. Moreover, functionalization of SH surfaces (e.g., photothermal, electrically conductive, flame retardant, antibacterial, electromagnetic shielding, stimuli-responsive, and sustainable) will also boost the market of SH surfaces. Additionally, numerous fresh applications (e.g., electricity generation, lab-on-a-chip, drop sensors, and microfluidic systems) based on the distinct wettability of SH surfaces will be beneficial (*49*).

Interdisciplinary R&D of SH surfaces in conjunction with other fields such as energy conversion and storage [e.g., battery separators (*110*) and solar interfacial evaporation (*111*)], biomedical science [e.g., blood-repellent (*40*) and controlled drug delivery (*44*)], military (*112*), and human motion monitoring (*113*, *114*) is being carried out and should be continuously strengthened. Future development of SH surfaces should not only be limited to macroscopic two-dimensional surfaces but also extend to surface modification of micro-/nanoparticles (e.g., catalysts) and three-dimensional porous

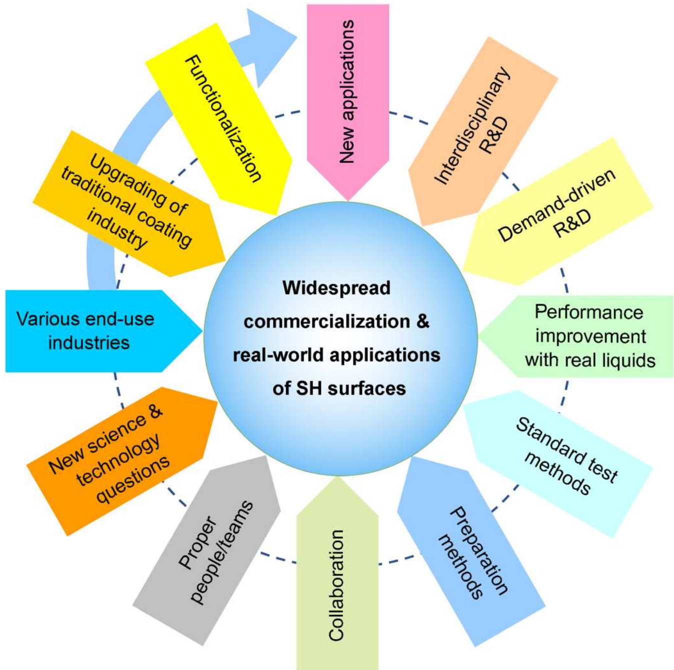

Fig. 6. Looking for the future of SH surfaces (2023–2035).

materials (e.g., sponges and aerogels). These will be additional growth spots of SH surfaces.

Obviously, to achieve widespread practical applications in the above scenarios, we need to change our mind and conduct demand-driven R&D of SH surfaces. The market segments and their value should be investigated from various aspects (e.g., user demands, performances of existing products, and cost analysis) before R&D of the corresponding SH surfaces. Moreover, the comprehensive performances, preparation methods, and application scenarios of SH surfaces must all be taken into account at once. The comprehensive performances should be optimized and balanced according to the specific application scenarios. For example, Zhang and colleagues (*55*) optimized and balanced impalement resistance, mechanical robustness, and weather resistance of SH coatings for efficient prevention of rain attenuation of 5G/weather radomes.

Specifically, the comprehensive performances of SH surfaces, particularly the mechanical stability, impalement resistance, and weather resistance, still need to be greatly improved. This will always be a hot topic in the evolution of SH surfaces and depends on rational integration of existing/new surface structures and low–surface energy materials. Moreover, great attention must be paid to the real liquids rather than the model liquids (e.g., water) contacting with SH surfaces during optimization and evaluation of the comprehensive performances. Also, all of the performances should be evaluated according to the standard test methods like batteries and perovskite solar cells. Additionally, long-term evaluation of superhydrophobicity and the life span of SH surfaces under practical conditions is essential.

Besides that, the preparation methods must be appropriate for the practical application scenarios of SH surfaces. On the premise of meeting actual demands, the preparation methods should be simple, efficient, low-cost, sustainable, and environmentally friendly. These benefits are helpful for the continuous and large-scale production of SH surfaces, which is a prerequisite for their commercialization and widespread use.

Close collaboration between scholars and industry is crucial to the successful commercialization and practical applications of SH surfaces. In the meantime, people and/or teams that are knowledgeable in SH surfaces, market demand, and commercialization will be highly beneficial. Platforms for technical and scientific collaboration, such as NineSigma, may also aid in the promotion of this process.

During practical applications, many fresh science and technology questions that are difficult to be found in laboratories will emerge. We should attach great importance to these valuable questions and conduct in-depth research. These questions offer us a priceless opportunity to logically reconsider the design, preparation, and applications of SH surfaces. Obviously, this will greatly accelerate commercialization of SH surfaces and will also enrich and promote development of the fundamental scientific theories relating to surface wettability.

Supplementary Materials

This PDF file includes:
Tables S1 and S2

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