Chapter

Plant-Based Sustainable Self-Cleaners in Nanotechnology Era: From Mechanism to Assembling

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Abstract

Nature has always been a resource of inspiration for humans, providing valuable lessons that have led to innovative solutions throughout history. Observing the micro-nano roughness structure of bio-surfaces has led to the discovery of natural self-cleaning surfaces for over 25 years. This has sparked a new field of research with valuable applications. Numerous self-cleaning products made from plant extracts have been created by replicating the natural purifying abilities of plant surfaces. Significant literature exists on the development, classification, extraction, and production of self-cleaning agents for diverse industries through a thorough understanding of bio-cleaning mechanisms. Various methods have been developed to synthesize these surfaces, including immersion, electrochemical deposition, emulsion, electrospinning, phase-separation, Chemical-Vapor-Deposition (CVD), spray coating, wet chemical reaction, and three-dimensional printing (3D-printing), among others. Currently, the primary objective is to gain knowledge from nature and utilize it to develop novel products for food, pharmaceutical, and related industries. Natural plant-based self-cleaning surfaces can be characterized by their superhydrophobicity and superhydrophilicity regimes. The process of 3D-printing is a computer-based technique that builds up three-dimensional objects through the layer-by-layer deposition of materials. The creation of effective self-cleaning surfaces with unique wettability, chemical properties, and microstructure depends on the design and engineering of solid surfaces.

Keywords: plant-based, self-nano-cleaners, mechanism, food packaging, wettability, 3D printing, hydrophilic, hydrophobic

1. Introduction

In 1997, Barthlott and Neinhuis [1] discovered that the micro- and nano-roughness of lotus leaves accounted for the self-cleaning phenomenon. A self-cleaning surface maintains its cleanliness through the action of water, which lowers maintenance costs, requires less work, and requires fewer detergents [2]. By understanding this natural phenomenon, scientists started to mimic the structural properties of lotus leaves and apply them to different products, including self-cleaning roof tiles and paints and so many others. The main concept is based on two wettability regions hydrophilic (drawn to water/ water-attractant) and hydrophobic (away from water/water-repellent) phenomena.

This chapter will introduce the latest research developments in bioinspired self-cleaning surfaces inspired by plants. Specifically, we will examine a variety of plant-based self-nano-cleaners, investigating their mechanisms and exploring the diverse applications they have already been utilized in across various industries. Three-dimensional printing (3D-printing) is discussed as a new developing process. The process of creating objects through layer-by-layer computer design and building up materials is known as 3D-printing, also called additive manufacturing. This innovative technique allows for the creation of three-dimensional pieces.

2. Plant-based self-nano-cleaners in nature

Self-cleaning technology has made significant advancements since the late 20th century, resulting in numerous valuable applications. This technology has a wide range of uses, from solar cell panels to window glass.

In order to develop self-cleaning surfaces, it is important to identify the roles, structures, and underlying bases of different objects in nature that exhibit self-cleaning properties. Scientists have gained valuable insights from studying living nature, which has led to the creation of highly effective bioinspired surfaces. Water is an ideal medium for removing various types of contaminants from surfaces due to its abundance and ideal density and polarity. Nature has provided many innovative designs for using water energies and surface properties to clean material surfaces [2, 3].

Superhydrophobicity and superhydrophilicity are two distinct wettability regimes that apply to plant-based self-cleaning surfaces in nature. **Table 1** shows a number of plants that are introduced as plant-based self-cleaning surfaces in literature.

Surface	Plant (leaves)	wettability regimes [Reference]
Hydrophobic	Lotus	superhydrophobic, low adhesion, low drag [2–6]
	Rice	superhydrophobic, Anisotropic wetting [2, 3, 7, 8]
	India canna	superhydrophobic [2, 3]
	Taro	superhydrophobic [2, 3]
	Cabbage	superhydrophobic [9]
	Indian cress	superhydrophobic [9]
	Salvinia molesta	superhydrophobic hairs [10]

Surface	Plant (leaves)	wettability regimes [Reference]
Hydrophilic	Pitcher	superhydrophilic, low drag (slippery) [2]
	Anubias barteri	superhydrophilic [2, 3, 6]
	Heliamphora nutans	superhydrophilic [2, 3, 6]

Table 1.
Examples of plant-based self-cleaning surfaces.

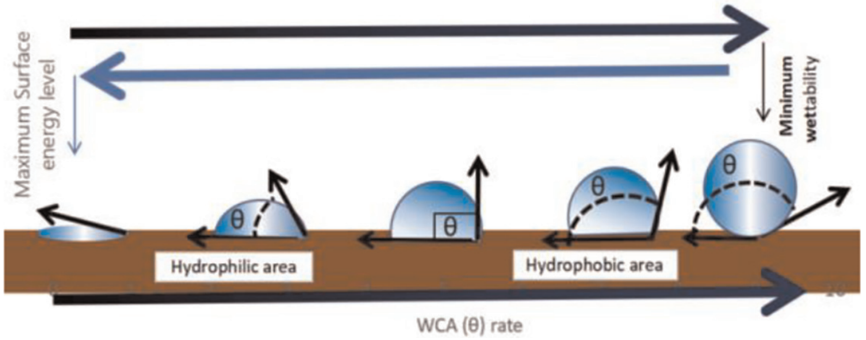

Figure 1.
Liquid drop schematic to show water contact angle (WCA) based on surface energy level ~ surface wettability.

Chemical characteristics and surface microstructure of a solid surface affect its wettability. If a surface has a water-contact-angle (WCA) greater than 90° is well-defined as a hydrophobic surface, and within WCA, more than 150°is a superhydrophobic surface. These surfaces are water-repellent. If a surface has a WCA lower than 90°, it is identified as a hydrophilic surface, and by displaying, WCA lower than 10° is a superhydrophilic surface. Superhydrophilic surfaces are extremely wettable and can reduce water contact angles (close to zero) to create water films (**Figure 1**) [2, 3].

3. Mechanisms of these self-control-cleaners

Plant surfaces have a variety of wettability characteristics, from wax-free, wet floating leaves to water-repellent leaves growing on land. The leaves of some plants are arguably well-known representatives of water repellency on the planet (**Table 1**). Bacterial and fungal spores are among the pathogens found in free water, which is protected by water-repellent surface structures. The plant's risk of infection is reduced by removing water from the surface. Additionally, removing dust from leaf surfaces reduces the risk of salt damage and protects the plant from overheating [7, 11].

The concept of self-cleaning was initially inspired by the superhydrophobic property observed in certain plant leaves. Among them, the lotus leaf is the most famous as it allows water droplets to effortlessly roll off its surface, keeping it clean. [3–5]. Another illustration of superhydrophobicity in nature can be found in cabbage leaves and Indian cress plants [9].

The spatial arrangement of topographical figures on the plant surfaces allows water-drops and surface contaminants to roll off effortlessly. Water drops can slide off grass leaves transiently, thanks to lines of topographical protuberances that run along the main leaf direction. Similar characteristics can be seen in rice, taro, and Indian canna leaves. Rice leaves exhibit an intriguing property accepted as anisotropic (diverse properties in different directions) wettability. The surface of the leaves is composed of a binary micro/nanostructure, and the papillae, which have an average diameter of 5–8 millimeters, are placed in a one-dimensional sequence parallel to the leaf edge (**Figure 2a–d**). Because of the peculiar anisotropic arrangement of the papillae, water droplets can roll along rice leaves easier in the way of the edge than in a perpendicular direction [2, 7, 12]. Quite a few research teams have tried to replicate these conditions by designing surfaces with uniformly anisotropic wettability models. Yoshimitsu and colleagues, for instance, provided proof that water flows more easily on substrates with pillar lines parallel to them than it does when moving orthogonally (5, 10).

While one dominant length scale is primarily responsible for the physical roughness effects that give rice leaves their ability to self-clean, there are other circumstances where multiple length scales are present and work together. The lotus leaf is a prime example of this, as it exhibits various roughness length scales on its surface, ranging from nanometers to microscopic ones, instead of just one. On the surface of the lotus leaf, water droplets remove contaminated particulate compared to other hydrophobic plant surfaces (**Figure 3**). The presence of assorted length sizes of roughness reduces the tendency of dirt particulate matter's adhesion on a leaf. The low and high magnification scanning electron microscope (SEM) of its surface is demonstrated in **Figure 3b** and **c**. Thus, facilitating the water droplets passing by to carry them away. Gao *et al*. offer a detailed explanation of how multiple-level roughness affects wettability in this scenario [7, 14].

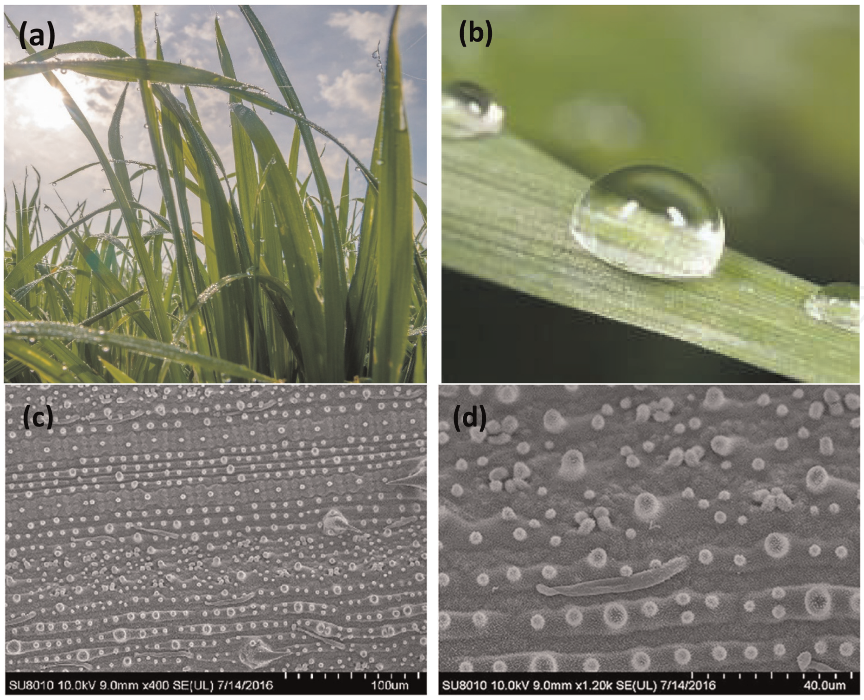

Figure 2.
a) Rice leaves, which exhibit extraordinary water repellence on their upper and downsides. (b) A few water droplets float on a rice leaf. (c, d) The scanning electron micrograph (SEM) of the rice leaf surface image of the upper leaf side. Source: [47].

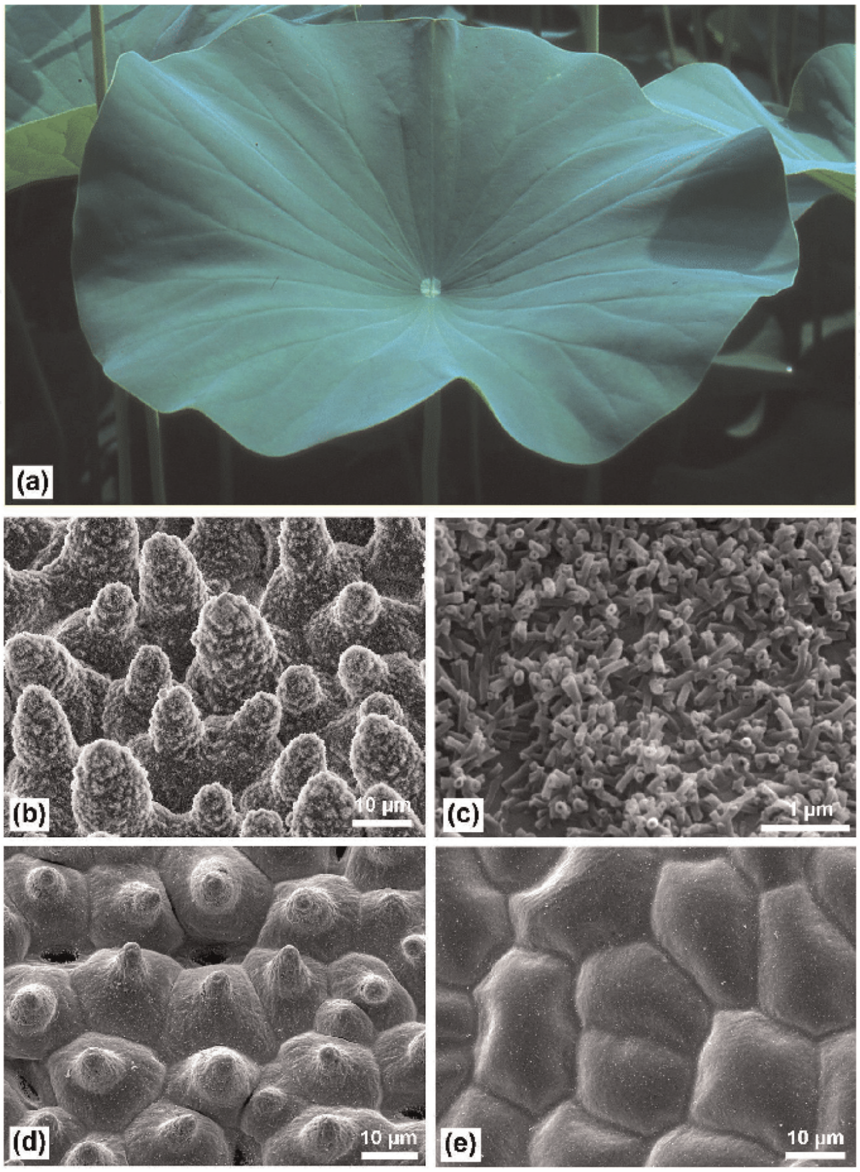

Figure 3.
(a) Lotus leaves, which exhibit extraordinary water repellence on their upper side. (b) Scanning electron microscopy (SEM) image of the upper leaf side prepared by 'glycerol substitution' shows the hierarchical surface structure consisting of papillae, wax clusters, and wax tubules. (c) Wax tubules on the upper leaf side. (d) Upper leaf side after critical-point (CP) drying. The wax tubules are dissolved; thus, the stomata are more visible. Tilt angle 15°. (e) The leaf underside (CP dried) shows convex cells without stomata. Source: [48].

Young and his colleagues have put forward wetting models that shed light on how lotus leaves clean themselves. Young's equation for the WCA is shown below (1), where θ_0 is the WCA of the droplet on the surfaces, γ_{SA} and γ_{SL} display the surface energies of the solid against air and liquid, respectively, and γ_{LA} is the liquid-air interfacial energy (**Figure 4**).

$$cos\,\theta_0 = \frac{\gamma_{SA} - \gamma_{SL}}{\gamma_{LA}} \tag{1}$$

Using Young's equation, a water droplet on a flat, homogeneous surface can successfully predict the WCA. Wenzel's Eq. (2) can be employed to determine the WCA if the surface is rough, and the actual surface area exceeds the flat expected area (**Figure 5**), where Rf is the ratio of the actual surface area to its flat expected area.

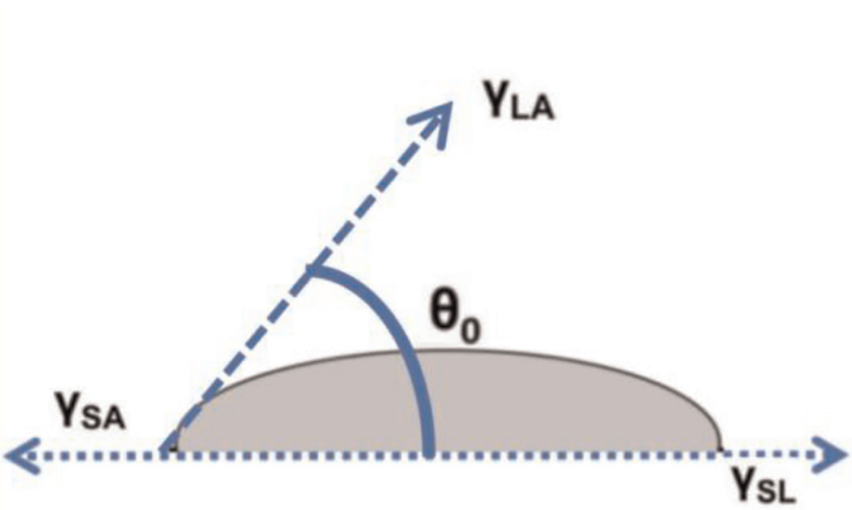

Figure 4.
Liquid drop schematic to show the values in Young equation.

$$\cos\theta_w = R_f \cos\theta_0 \tag{2}$$

For a rough surface, $R_f > 1$, which means that for rough surfaces, hydrophilic surfaces grow more hydrophilic, and hydrophobic surfaces get more hydrophobic. The Cassie Eq. (3) can also be derived for heterogeneous surfaces made of two fractions.

$$\cos\theta = f_1 \cos\theta_1 + f_2 \cos\theta_2 \tag{3}$$

where f_1 and f_2 are the fractional area with CA θ_1 and θ_2, respectively.

The Cassie-Baxter Eq. (4) can be applied to a composite interface that consists of the solid-liquid fraction ($f1 = f_{SL}$ and $\theta_1 = \theta_0$) and the liquid–air fraction ($f_2 = f_{LA}$ and $\cos\theta_{21} = -1$) (**Figure 5**).

$$\cos\theta_{CB} = R_f \cos\theta_0 + f_{LA}\left(R_f \cos\theta_0 + 1\right) \tag{4}$$

Based on these suggested models, a surface can develop the potential to self-clean itself by manipulating surface microstructures to encourage the free, spontaneous

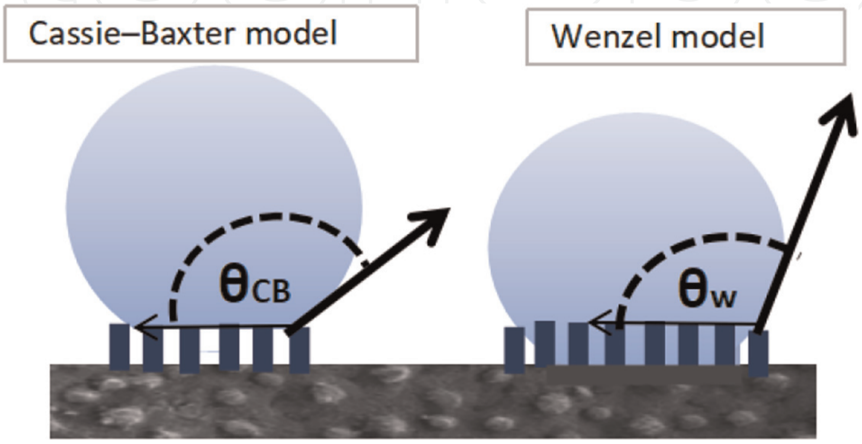

Figure 5.
Droplets display on rough surfaces; Cassie–Baxter model and Wenzel model (adapted from [6, 15, 16]).

movement of liquid droplets on the surface, which enables the removal of contaminants from the surfaces. Therefore, ensuring that droplets can flow or roll off smoothly from the connected surface with no resistance will be the main objective for a surface to accomplish self-cleaning. To enable free liquid droplet movement, natural or bio-surfaces primarily increase or decrease the droplets' contact angles. To create this unrestricted movement, the surface energy of the three phases—liquid, air, and solid—is controlled [3].

Droplets move freely across the surface of the leaf when the WCA is close to 180° (e.g., lotus leaves), dissolving dirt components along the droplets' motion in the liquid [15].

The opposite strategy (super-hydrophilic surfaces) is used by a number of other natural systems, for instance, pitcher plants, *Anubias barteri,* and *Heliamphora nutans*. Water droplets spread quickly on a super-hydrophilic surface; a water film is formed on them. Additionally, the tiny WCA droplets can be used as a sharp knife to remove contaminants from the surface and separate dirt. Therefore, super-hydrophilic surfaces have also attracted interest for their self-cleaning surface design. For example, the pitcher plant's slick surface is thought to be one of its most crucial characteristics for catching insects. Due to the surface microtopography and hygroscopic nectar secretion, the peristome exhibits superhydrophilicity. As a result, when the air is humid, stable water films form. The oils on the insects' feet make this water film repellent, causing insects that tread on it to slip over the rim and into the pitcher plant's bottom, which is filled with digestive liquid [2, 3, 6].

4. Reassembling and formulation

Recently, Lotus leaves have inspired many synthetic superhydrophobic surfaces fabricated by applying self-cleaning coatings on different substrata such as textiles, tiles, and glass [17].

Super-hydrophobicity can be produced in one of two ways: either by chemically altering a hierarchically structured surface with low surface energy material or; and by building micro/ nanostructures on hydrophobic substrates. Numerous techniques for synthesizing these surfaces have been documented in published literature, including immersion, electrochemical deposition, emulsion, electrospinning, phase separation, Chemical vapor deposition (CVD), spray coating, wet chemical reaction, 3D-printing, etc. [18, 19].

Zhao and colleagues [20] used poly(dimethylsiloxane) (PDMS) replication material and a natural rice leaf as a template to fabricate a rice leaf replica on an Au surface. Gao *et al.* [21] used a three-step process (I) negative replication of a rice leaf using PDMS; (II) positive replication of a PDMS template using poly (N-isopropylacrylamide) (PNIPAAm) in hot water; and (III) separation of the replicated PNIPAAm film from the template. The synthesized rice leaf replica showed good, responsive anisotropic wettability as a result of the polymer structure's change in thermal responsiveness. The WCA was 119 ± 10° at 50°C and dramatically decreased to 77 ± 9° at 20°C when measured in the parallel direction of the grooves. However, the WCA was 87 ± 9° at 50°C and 49 ± 6° at 20°C in the perpendicular direction. Smart surfaces are, therefore, those that respond to stimuli, such as surfaces that are wettable and switch between pH, temperature, light, and electric field. Combining the responsiveness of these surfaces with self-cleaning surfaces is a strategy for new applications [2].

In the past, low surface energy materials were used to create superhydrophobic surfaces. One of the most popular fluorine-containing polymers with superhydrophobicity is polytetrafluoroethylene (PTFE). By adding organic groups like CF_3, CH_3, and CH_2, etc., the hydrophobicity of materials can be increased. Superhydrophobic materials can also be produced using Polyesters and Polyurethanes (PUs), Polyethylene, Polystyrene, Polyvinyl chloride, and Polydimethylsiloxane (PDMS). However, fluorinated hydrocarbon compounds, which pose serious risks to both human health and the environment, are frequently used in the development of these surfaces [17, 22].

Using hydrophobic dual-scaled SNPs and PDMS via a hybrid route combining soft imprinting and spin-coating, Ghasemlou and colleagues [17] discovered a straightforward and environmentally friendly method to fabricate multifunctional superhydrophobic surfaces on SPC films with a well-defined micro - nanoscale hierarchical structure. Direct soft-imprinting lithography on starch -polyhydroxyurethane - cellulose nanocrystal (SPC) films resulted in micro-scaled features that resembled lotus leaf pillar architecture. A thin layer of low-surface energy material, poly (dimethylsiloxane) (PDMS), was assembled over these microstructures using a spin-coating technique. Functional silica nanoparticles (V-SNPs) were created by grafting silica nanoparticles (SNPs) with vinyltriethoxysilane (VTES). These V-SNPs were then used to create superhydrophobic coatings. A further modification of the DPMS@SPC film with V-SNPs allowed the interlocking of V-SNP microparticles within the cross-linked PDMS network. It was claimed that an extremely hydrophobic surface was synthesized, which had a water contact angle (WCA) of 150° and a sliding angle (SA) of 10°. He pointed out that when compared to uncoated films, the water vapor transmission rate of the PDMS/V-SNP@SPC films decreased by 52%. These findings suggested that the coating effectively protected the film substrate from moisture and gave it good hydrophobicity. The film surface with coating displayed exceptional mechanical strength as they could withstand severe knife scratches, rubbing with fingers, jet-water impact, 20 cycles of sandpaper abrasion tests, and ten repetitions of tape-peeled tests without losing their superhydrophobicity. When artificial dust and various food liquids were removed from the surfaces, self-cleaning behavior was also observed [17].

Bohn [23] and Wong *et al.* [24] were motivated by the system observed on the slippery surface of the pitcher plant. They created "slick liquid-infused porous surface (s)" (SLIPS), which they referred to as synthetic liquid-repellent surfaces. A micro/nano-porous substrate holds the film of a lubricating liquid in place in SLIPS. The materials for SLIPS were selected according to the following criteria: (I) the lubricating liquid must moisten the substrate, wick into it, and securely attach to it; (II) the solid must be preferentially moistened by the liquid one wants to repel; and (III) the immiscible nature of the moistening and impinging test liquids [2].

5. Application in food, pharmaceutical, and related industries

In recent years, bio-inspired materials and surfaces with self-cleaning properties have been developed rapidly due to the advancement in nanotechnology and engineering nanoscience [25]. In addition to lotus leaves, it is possible to create materials with superhydrophobic and superhydrophilic properties by imitating the structures of plants like rice leaves and pitcher plants. [2]. Different fabrication techniques have been utilized to create biomimetic self-cleaning coatings by modifying rough surfaces with low-surface energy materials or roughening the surface of low-surface energy materials [26]. Several self-cleaning products have been commercialized based on these techniques, such as construction materials, glasses, solar panels, and windows. Besides, self-cleaning materials and surfaces are drawing attention for their potential application in the food, pharmaceutical, and detergent industries. A summary of recently reported applications is provided in **Table 2**.

In the food industry, research has been focused on applying self-cleaning coatings on food packaging materials and food processing equipment. For instance, Cai *et al.* [27] fabricated a food packaging material - hydrophobic starch nanofibrous film (SNF) by assembling stearic acid (STA) onto SNF to create a hierarchical micro-nano structure inspired by lotus leaves. This hydrophobic SNF exhibits self-cleaning properties by enabling water to roll freely in all directions. The self-assembled coated SNF from STA shows great potential as a food packaging material due to its biodegradable, edible, and waterproof properties. Additionally, its self-cleaning capabilities aid in preventing fouling on the packaging surfaces. In addition, self-cleaning surfaces are demonstrated to exhibit antibacterial and antimicrobial properties by reducing the adhesion of bacteria and microorganisms to the surface. For instance, the nanocomposite surface coating developed by Yoon *et al.* [29] demonstrated effective inhibition of bacterial adhesion with 80% fewer bacteria adhered on the metal surface in comparison to those on the uncoated surface. The superhydrophobic surface coating was fabricated using a cluster of carbon nanotubes (CNTs) with low surface energy nanoscale roughness and polytetrafluoroethylene (PTFE). This CNT-PTFE composite was then spray-coated on stainless-steel plates to exhibit self-cleaning properties via the lotus effect.

The application of self-cleaning nanocomposite coating on food contact surfaces (e.g., food processing equipment) is an ideal solution to reduce bacterial adhesion and biofilm formation, leading to a lower risk of cross-contamination and food safety hazards. Besides, the nanocomposite coatings also help reduce the use of water and chemicals for the cleaning process.

It is also feasible to employ such self-cleaning materials or surfaces within the pharmaceutical industry to improve the safety and efficiency of drug manufacturing processes. For instance, filtration is the process widely used in industry for the concentration, separation, and purification of chemical solutions. However, filtration with conventional filters may affect the quality and safety of pharmaceutical products, such as the potential adsorption of drug components to the filter membranes, which reduces the concentration of adsorbed components and the leaching of filter biofilms into the pharmaceutical products, which may lead to undesirable toxicity [40, 41]. Therefore, filters with self-cleaning coatings shall be adopted in the filtration process to prevent the adsorption of drug components, reduce bacterial adhesion, and prevent biofilm formation.

Other than filters, self-cleaning materials can also be applied to the surface coatings of production equipment. Hence, the equipment can be operated continuously without the need for manual cleaning and sterilization. Such a continuous production system can help to increase the efficacy of production and reduce the risk of cross-contamination.

Self-cleaning materials also play a crucial role in the detergent industry to make cleaning easier and more convenient for consumers and mitigate environmental pollution problems. Traditional detergents containing petroleum-based surfactants are effective at removing dirt and stains, but they are also hazardous to human health and the environment [42]. Therefore, there has been a trend towards developing detergents that are more sustainable and eco-friendlier. For instance, Yang

Area	Material	Method	Self-cleaning action	Application	Reference
Food Packaging/ Food Processing Equipment	Starch nanofibrous film (SNF)/ stearic acid (STA)	Temperature-assisted electro spinning	Hydrophobic	Biodegradable, self-cleaning food packaging.	[27]
	Multi-walled Carbon nanotubes/ perfluorooctanesulfonyl fluoride	Surface fluorination	Superhydrophobic with antibacterial	Antibacterial, self-cleaning food packaging.	[28]
	Carbon nanotubes (CNTs)/ Polytetrafluoroethylene (PTFE)	Spray coating	Superhydrophobic with antibacterial	Reduce bacterial adhesion on food processing and packaging equipment.	[29]
	Lignin-coated cellulose nanocrystal (L-CNC)/ polyvinyl alcohol	Spray coating and chemical vapor deposition	Superhydrophobic	Self-cleaning food packaging with excellent abrasion resistance and nontoxicity.	[30]
	SiO_2 nanoparticles/ polydimethylsiloxane/ varnish	Modification of the overprint varnish	Superhydrophobic with anti-frosting	Waterproof, easy cleaning, anti-frost paper food packaging.	[31]
	STA modified organic montmorillonite/ poly(dimethylsiloxane)	Self-assembly	Superhydrophobic with anti fouling	Self-cleaning surface to reduce liquid-food residue	[32]
Fabrics/Textiles	Titania nanosols	Sol-gel	Photocatalytic	Self-cleaning cotton with easy stain removal	[33]
	Poly(methylmethacrylate) nanofibers/ ZnO nanorods/Ag nanoparticles	Electrospinning	Photocatalyti	Self-cleaning protective clothing with antibacterial and antiviral properties	. [34]
Glass	3-Aminopropytriethoxysilane (APTS)-modified hollow silica nanoparticle	Dip coating and chemical vapor deposition	Superhydrophobic	Self-cleaning glass with high transparency	[35]
	TiO_2 nanoparticles	Sol-gel	Superhydrophilicity	Self-cleaning glass with antifogging	[36]
	TiO_2/SiO_2 nanoparticle	Layer by layer deposition	Superhydrophilicity	Self-cleaning glass with antifogging and anti-reflection	[37]
Wastewater treatment	SiO_2 nanoparticles	Dip coating	Superhydrophobic and superoleophilic	Self-cleaning sponge for oil-water separation	[38]
Solar cells	SiO_2 nanoparticles array/poly(ethylene terephthalate)	Dry coating and chemical vapor deposition	Hydrophobic and oleophobic	Self-cleaning solar cells with light scattering properties	[39]

Table 2.
Applications of self-cleaning materials in various industries.

et al. [43] have developed an eco-friendly, non-toxic detergent using the halloysite clay nanotube (HNT), which demonstrated high cleaning capacity to remove different strains from various substrates. These hydrophilic nanoparticles can be potentially designed to exhibit superhydrophilicity so the dirt can be removed easily with the quick spreading of water, leading to improved decontamination and cleaning effects [44].

Besides, the self-cleaning nanoparticles can be designed to attach themselves to the surfaces and prevent future dirt accumulation, resulting in extended cleanliness of surfaces over long periods of time.

These nanoparticles have been well-developed to produce self-cleaning materials with anti-fouling and antimicrobial properties, but they are also associated with some drawbacks in toxicity, stability, and durability. An example of a concern related to nanoparticles is the potential for them to dissociate from surface coatings and be inhaled by humans, which could have unintended consequences. New fabrication technologies, such as encapsulation, should be taken into consideration to overcome those shortcomings.

Brown and Bhushan [45] fabricated the nanoparticles-encapsulated surfaces using SiO2 nanoparticles. The nanoparticles-encapsulated surface exhibited good self-cleaning properties because it removed more than 90% of the contaminants on the surface. Besides, it demonstrated high durability with no noticeable wear scar on the treated surfaces after 200 cycles of tribometer wear experiment [45]. The highly durable surface can be attributed to the high hardness of SiO2 nanoparticles for wear resistance and the encapsulation technique.

The encapsulation technique directly incorporated nanoparticles into the surface during the softening process of polymer material, compared to other techniques in which nanoparticles are employed as a coating. The durability of the self-cleaning surface typically relies on the adhesion of nanoparticles to the coating materials [46]. Therefore, the nanoparticles-encapsulation technique will be one of the most anticipated alternatives for fabricating the self-cleaning surface due to the improved mechanical durability and stability.

In summary, self-cleaning technology has the potential to improve performance and efficiency in the food, pharmaceutical, and detergent industries. Further research is needed to explore new fabrication techniques, such as nanoparticle encapsulation, in order to create materials that are self-cleaning and have excellent durability and stability.

6. Design a self-cleaning structure

As described in this chapter, understanding the basic principles of self-nano-cleaning surface structures can be used as a guide and applied to various applications. One possible solution for creating a self-cleaning surface with various nano/micro surfaces is to utilize advanced 3D printing technology. It enables the fabrication of biomimetic functional surfaces by digitally controlling the complex hierarchical microstructures. An interesting example of biomimicry is the fabrication of artificial hairs resembling the eggbeater heads of *Salvinia molesta* leaves, which were produced by the immersed surface accumulation 3D printing process [10]. This involves designing the microstructures of bio-inspired models using computer-aided design software, which was subsequently sliced into layers and mapped onto the object surfaces. The photopolymers were then cured layer by layer through the projection of UV light onto the surface. Finally, a functional surface with designed microstructures is fabricated. The results show that the fabricated functional surfaces have controllable hydrophobic properties. In general, 3D printing technologies open a new door for the design and assembly of functional textures with desired properties. It shows a promising future around the fabrication of functional surfaces area with hydrophobic and hydrophilic properties. However, it is important to acknowledge that this technology still has certain limitations. One potential drawback is that this method tends to be slower than some other fabrication methods. Additionally, it's important to note that only certain types of photopolymers are suitable for use with this method. Unfortunately, these materials may not be food-safe or biocompatible, which can limit their applications.

7. Conclusions

The self-cleaning surface found in plant structures is ultimately determined by two factors: 1) the diverse textures of the leaf's surface and 2) the presence of various chemicals, waxes, and other components that affect its surface energy level. The surface can vary from highly rough to highly smooth, and the coverage of wax on leaves can range from high-surface energy to low-surface energy. This can result in surfaces that are super-hydrophobic or super-hydrophilic. This phenomenon is the basic knowledge to understand the mechanism and reassembling of the self-nano/micro-cleaning surface [16]. To design and make the self-cleaning surface with different nano/micro surfaces, 3D printing can be one of the accessible solutions. The advantage of 3D printing machinery is that the surface can be designed and assembled according to the required texture with various degrees of roughness/smoothness (low to high).

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