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Self-Cleaning Materials: Mechanisms, Performance and Environmental Perspectives of Photocatalytic and Superhydrophobic Surfaces

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Abstract

Self-cleaning materials have gained significant attention due to their potential to reduce maintenance costs, enhance durability, and promote environmental sustainability in a wide range of applications, including glass, textiles, solar panels, and medical devices. This review explores the two primary self-cleaning mechanisms: photocatalysis and superhydrophilicity. Photocatalytic materials, such as TiO_2 and ZnO, harness light energy to degrade organic pollutants, while superhydrophobic surfaces rely on extreme water repellency to remove dirt and contaminants. We discuss recent advances in material design, including nano structuring, doping, and composite formation, which have significantly improved the performance of these materials under real-world conditions. Key challenges such as mechanical durability, light dependency, toxicity of nanoparticles, and scalability are critically examined. Additionally, emerging eco-friendly strategies—like biopolymer-based coatings and safe-by-design nanostructures—are highlighted as sustainable alternatives. The review concludes with insights into future directions, including multifunctional coatings and smart integration technologies.

Keywords: Self-cleaning materials; Photocatalysis; superhydrophilicity; Titanium dioxide (TiO_2); Zinc oxide (ZnO); Nanocoating's; Surface modification; Environmental sustainability; Smart surfaces; Biopolymer-based coatings

1. Introduction

Self-cleaning materials have garnered increasing attention in recent years as a critical component of sustainable surface engineering. These materials are capable of minimizing or entirely eliminating the need for external cleaning agents, detergents, and manual effort, making them particularly relevant in the context of environmental sustainability and energy conservation. The self-cleaning functionality is inspired by natural phenomena such as the lotus leaf effect, which exhibits remarkable water repellency due to its hierarchical micro/nano surface structure and low surface energy. This natural model has driven significant scientific and industrial interest in reproducing similar behavior using synthetic nanostructured surfaces [1].

Two major mechanisms dominate the field of self-cleaning: photocatalysis and superhydrophilicity. Photocatalytic self-cleaning materials, primarily based on semiconducting oxides such as TiO_2 and ZnO, utilize light-induced catalytic activity to degrade organic contaminants through the generation of reactive oxygen species (ROS) [2,3]. These materials are particularly effective in polluted urban environments and are widely used in architectural glass, concrete, and air-purifying coatings [4]. On the other hand, superhydrophobic surfaces rely on micro/nanoscale roughness combined with low surface energy chemistry to repel water and remove dust or particles via rolling droplets [5]. The design of

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such surfaces often involves chemical modification with fluorinated compounds or nanostructured fillers like SiO_2, graphene, and carbon nanotubes [6,7].

Advancements in nanotechnology have played a pivotal role in the development and optimization of self-cleaning materials. Techniques such as sol-gel processing, electrospinning, atomic layer deposition, and laser ablation have enabled precise control over surface morphology, crystallinity, and chemical functionality, which directly impact self-cleaning efficiency [8]. Hybrid systems that combine photocatalytic and hydrophobic properties have also emerged, offering dual-action self-cleaning capabilities even under suboptimal environmental conditions such as low UV exposure or high humidity [9].

The growing demand for environmentally friendly materials in construction, textiles, energy systems, and healthcare has further accelerated research into self-cleaning technologies. These materials not only reduce maintenance costs and water consumption but also contribute to improving air quality and minimizing microbial contamination. However, despite their promise, several challenges remain regarding long-term stability, mechanical durability, scalability of fabrication, and cost-effectiveness for real-world deployment [10].

This review presents a comprehensive exploration of self-cleaning materials, emphasizing their working mechanisms, material compositions, fabrication techniques, and potential applications across multiple sectors. Furthermore, the environmental benefits, limitations, and future prospects of these advanced surfaces are critically discussed to guide future research and innovation in sustainable material development.

2. Mechanism of Self-Cleaning

Self-cleaning materials operate through two primary mechanisms: photocatalysis and superhydrophilicity, each relying on distinct physicochemical principles. Photocatalytic self-cleaning is driven by semiconducting materials—most notably titanium dioxide (TiO_2)—which generate reactive oxygen species (ROS) such as hydroxyl radicals (•OH) and superoxide anions (O_2^-) upon exposure to UV or visible light. These ROS aggressively degrade organic pollutants, bacteria, and volatile compounds deposited on the surface, converting them into harmless by-products like CO_2 and H_2O [11]. The photocatalytic activity is largely influenced by the bandgap of the material, crystallinity, surface area, and the presence of dopants or co-catalysts that can enhance visible-light absorption or charge separation efficiency [12,13].

On the other hand, superhydrophobic self-cleaning relies on the Cassie-Baxter wetting regime, where water droplets maintain minimal contact with the surface due to hierarchical micro- and nano-scale surface roughness combined with low surface energy coatings. As a result, water beads up into spherical droplets that easily roll off, mechanically removing dust, microbes, or other contaminants in the process [14]. This mechanism does not involve chemical degradation but rather physical removal and is especially effective in low-light environments or when UV activation is impractical.

Advanced self-cleaning systems increasingly combine both approaches in hybrid or dual-mode coatings. For example, surfaces coated with fluorinated silica nanoparticles atop a photocatalytic TiO_2 base can exhibit both dirt-repelling and pollutant-degrading properties, functioning under a broader range of environmental conditions [15]. Moreover, external stimuli such as heat, light, and electric fields can be used to dynamically modulate surface energy or activate photocatalysis, leading to smart self-cleaning surfaces that respond to real-time changes in the environment [16].

The mechanism's performance is also significantly affected by nanostructure design. For instance, vertically aligned TiO_2 nanorods or ZnO nanowires provide more active surface area and improved light harvesting, which enhances photocatalytic degradation efficiency [17]. Meanwhile, polymer-based superhydrophobic surfaces can integrate nanofillers like carbon nanotubes or graphene to improve durability and thermal stability while maintaining water-repellency [18]. In real applications, longevity and mechanical robustness remain crucial, and recent studies have focused on self-healing coatings and protective layers that maintain surface properties after abrasion or environmental exposure [19,20].

This synergistic understanding of photocatalytic and hydrophobic mechanisms has paved the way for multifunctional coatings that serve not only in cleaning, but also in antibacterial, antifogging, and anti-icing applications, aligning with broader goals in sustainable technology and smart surface engineering [21].

3. Materials Used in Self-Cleaning Surfaces (Updated with Verified References)

Self-cleaning surfaces rely heavily on advanced materials that exhibit either photocatalytic activity or superhydrophobic behavior, and often a combination of both. Inorganic metal oxides remain at the forefront of self-cleaning technologies due to their chemical stability, high surface energy, and ability to generate reactive oxygen species (ROS) under light illumination.

3.1. Titanium Dioxide (TiO_2)

Titanium dioxide is one of the most widely used photocatalysts in self-cleaning applications owing to its chemical stability, non-toxicity, and strong oxidation potential under ultraviolet (UV) light. Upon UV exposure, TiO_2 generates electron-hole pairs which react with surface-bound water and oxygen to produce hydroxyl radicals (•OH) and superoxide ions (O_2^-), capable of decomposing organic contaminants [2,11,17]. The anatase phase of TiO_2 has been identified as the most photoactive due to its higher surface area and efficient charge separation compared to rutile [3,13]. However, its activity under visible light is limited due to a wide bandgap (~3.2 eV), prompting researchers to explore doping strategies (e.g., N, Ag, Fe) to shift its response into the visible spectrum [17].

3.2. Zinc Oxide (ZnO)

ZnO is another key semiconductor with a bandgap of ~3.37 eV, sharing a similar photocatalytic mechanism with TiO_2. It offers advantages such as high exciton binding energy and facile synthesis into diverse morphologies like nanorods and nanospheres, enhancing surface area and light harvesting [17]. Nevertheless, ZnO is less stable in acidic or alkaline environments, which limits its long-term application unless combined with polymers or stabilizers. In hybrid systems such as ZnO/epoxy composites, the inorganic phase contributes to both photocatalysis and surface wettability, enabling effective self-cleaning under UV light. This has been demonstrated in prior studies involving epoxy-ZnO nanocomposites developed by Alrubaie et al. [22].

3.3. Other Metal Oxides and Visible-Light Photocatalysts

Apart from TiO_2 and ZnO, several other semiconductors have been explored for visible-light-responsive self-cleaning surfaces. Bi_2WO_6 is notable for its layered structure and narrow bandgap (~2.8 eV), showing efficient activity under solar light, especially when integrated with plasmonic metals such as Bi or Ag [4]. Similarly, WO_3, Fe_2O_3, and $BiVO_4$ offer visible-light activity but often suffer from rapid recombination of photoinduced charge carriers or structural instability [18]. To overcome these limitations, heterojunction structures and surface modifications are often employed to improve charge separation and durability.

3.4. Organic-Inorganic Hybrid Coatings

To enhance durability and mechanical integrity, inorganic photocatalysts are increasingly embedded within polymeric matrices, forming organic-inorganic hybrid coatings. These hybrids—such as TiO_2/PMMA or ZnO/PDMS—offer the benefits of both flexibility and self-cleaning capability. The polymer provides mechanical strength and adhesion, while the oxide nanoparticles retain photocatalytic or wetting functionalities [9,15]. Such coatings can be tailored to exhibit superhydrophilicity (e.g., TiO_2-based) or superhydrophilicity (e.g., when combined with low-surface-energy agents like fluoropolymers), broadening their application in textiles, windows, and solar panels [10].

Table 1 Photocatalytic Self-Cleaning Materials and Their Properties

Material	Bandgap (eV)	Active Spectrum	Advantages	Limitations	Ref.
TiO_2 (Anatase)	~3.2	UV	Chemically stable, strong oxidizer	Inactive under visible light unless doped	[2], [11], [17]
ZnO	~3.37	UV	High quantum efficiency, low cost	Less stable in acids/bases	[17], [22]
Bi_2WO_6	~2.8	Visible	Visible-light active, good stability	Needs plasmonic or doping support for efficiency	[4]
WO_3	~2.6–2.8	Visible	Active under solar light	Photocorrosion, fast charge recombination	[18]

Fe_2O_3	~2.1	Visible	Abundant, eco-friendly	Low conductivity, short carrier diffusion length	[18]
$BiVO_4$	~2.4	Visible	Narrow bandgap, strong oxidation	Requires co-catalyst, limited electron mobility	[18]

4. Superhydrophobic Self-Cleaning Materials

superhydrophilicity is a crucial mechanism for self-cleaning surfaces, inspired by the Lotus effect found in nature. These surfaces are characterized by water contact angles exceeding 150°, causing water droplets to bead up and roll off the surface, carrying dirt and contaminants with them. Unlike photocatalytic systems, superhydrophobic surfaces rely on a combination of low surface energy materials and micro/nano-scale surface roughness to achieve self-cleaning without chemical degradation of pollutants [1,5,10].

4.1. Biomimetic Inspiration

The foundational model of superhydrophilicity is based on the leaf of the Nelumbo nucifera (lotus plant), which maintains cleanliness by minimizing the contact area between water and surface irregularities. This hierarchical structure—composed of micro-bumps and nanoscopic wax crystals—leads to minimal adhesion of contaminants [1,5]. Biomimetic engineering of such surfaces has expanded to include insect wings, butterfly scales, and rose petals, each exhibiting tunable wetting behaviors based on surface morphology [14].

4.2. Materials and Fabrication Strategies

Superhydrophobic surfaces are typically constructed using two key components:

- Rough Surface Topography: Achieved by templating, etching, spray-coating, or nanoparticle deposition to introduce micro/nano-scale features.
- Low Surface Energy Coatings: Fluorinated silanes, PDMS (polydimethylsiloxane), PTFE (Teflon), and other hydrophobic polymers are applied to reduce wettability [9,15,23].

Recent developments have focused on hybrid coatings, such as fluorosilicone/SiO_2–TiO_2 composites, which combine structural durability with dual self-cleaning functions: superhydrophilicity and photocatalysis [15]. These materials not only resist water and dust accumulation but also degrade organic pollutants under UV or visible light.

Additionally, graphene-based superhydrophobic coatings have gained attention for their anticorrosion, mechanical durability, and functional tunability. Graphene oxide or reduced graphene oxide can be modified to introduce hydrophobic groups and integrated into epoxy or fluoropolymer matrices [7,23].

4.3. Durability and Challenges

While many superhydrophobic coatings exhibit impressive laboratory performance, long-term durability under abrasion, UV exposure, and humidity remains a significant challenge. To overcome this, researchers are exploring self-healing and wear-resistant systems that can maintain their surface features and hydrophobicity over time [19,20]. New designs incorporate sacrificial hydrophobic components or elastic recovery polymers to restore surface structure after damage.

Table 2 Comparison Between Photocatalytic and Superhydrophobic Self-Cleaning Mechanisms

Feature / Property	**Photocatalytic Self-Cleaning**	**Superhydrophobic Self-Cleaning**	**Ref.**
Mechanism	Decomposition of organic contaminants by reactive oxygen species (ROS) generated under light activation	Physical removal of dirt by rolling water droplets	[2], [17], [23]
Key Materials	TiO_2, ZnO, WO_3, $BiVO_4$, doped metal oxides	SiO_2, fluorinated polymers, PDMS, PTFE, graphene-based systems	[10], [15], [24]

Surface Wettability	Superhydrophilic (water spreads and forms film)	Superhydrophobic (contact angle >150°, droplets roll off)	[5], [10]
Light Requirement	Requires UV or visible light for activation	Does not require light; functions in ambient conditions	[17], [19]
Durability	Can degrade over time with surface poisoning	Vulnerable to mechanical abrasion and UV degradation	[19], [20]
Environmental Conditions	Works best outdoors under solar radiation	Effective in dry environments with minimal abrasion	[23], [24]
Self-Cleaning Against	Organic pollutants, microbes, VOCs	Dust, mud, particulates, and water-based contaminants	[7], [17]
Challenges	Limited visible light activity, potential toxicity of by-products	Mechanical fragility, loss of structure upon wear	[20], [24]

As summarized in Table 2, the two primary self-cleaning mechanisms—photocatalysis and superhydrophilicity—offer complementary functionalities, yet differ significantly in their operational principles, environmental requirements, and durability. Photocatalytic surfaces are particularly effective for chemical decomposition of pollutants such as volatile organic compounds (VOCs), dyes, and microorganisms, making them highly suitable for urban glass façades, solar panels, and antimicrobial coatings in healthcare or air-purification systems [17]. However, their dependence on UV or visible light and the gradual decline in activity due to surface fouling or catalyst degradation remain critical limitations [2,19].

In contrast, superhydrophobic surfaces function primarily through physical repulsion of water, preventing dirt and liquids from adhering to the surface. These materials excel in passive, maintenance-free environments such as textiles, building exteriors, and anti-fog coatings [24]. Yet, their sensitivity to mechanical abrasion and UV degradation poses challenges for long-term outdoor use unless enhanced with self-healing or structural recovery mechanisms [20].

Therefore, the integration of both mechanisms—for instance, in hybrid systems combining TiO_2 with hydrophobic layers—offers a promising route toward multifunctional, durable, and energy-efficient self-cleaning surfaces capable of operating under diverse environmental conditions [23].

5. Applications of Self-Cleaning Materials

Self-cleaning materials have experienced significant development due to their ability to reduce maintenance efforts, improve surface hygiene, and extend the service life of products. Applications span various industries, including architecture, energy, healthcare, textiles, and transportation. The choice between photocatalytic and superhydrophobic mechanisms depends on the target environment, type of contaminants, and required durability.

5.1. Architectural Glass and Building Facades

One of the earliest and most commercialized uses of self-cleaning materials is in architectural glass. Coatings based on TiO_2, such as those used in Pilkington Activ™ glass, utilize UV-induced photocatalytic decomposition of organic dirt followed by water spreading through superhydrophilicity [2,17]. These coatings significantly reduce the need for manual cleaning, especially in high-rise buildings or locations difficult to access.

5.2. Solar Panels and Photovoltaic Systems

Solar energy systems suffer from reduced efficiency due to dust accumulation, particularly in arid and dusty environments. Self-cleaning coatings using photocatalytic or superhydrophobic layers mitigate this effect by either decomposing pollutants or promoting water-assisted dirt removal. For example, hybrid structures like TiO_2/SiO_2 composites maintain transparency while offering strong self-cleaning action, improving long-term photovoltaic output [23]. The need for such coatings is justified by environmental factors like humidity and airborne dust, which can reduce solar panel efficiency by up to 30% if left untreated [25].

5.3. Textiles and Wearable Fabrics

Superhydrophobic materials have revolutionized self-cleaning textiles, enabling fabrics to repel water, oils, and dirt while maintaining breathability. Coatings involving fluorosilicone polymers, SiO_2 nanoparticles, or graphene derivatives are increasingly applied in outdoor wear, medical garments, and upholstery [18]. These materials mimic the lotus leaf's surface morphology to achieve stain resistance and reduced washing cycles.

5.4. Antibacterial and Biomedical Surfaces

In healthcare environments, self-cleaning coatings reduce microbial contamination and the risk of hospital-acquired infections. Photocatalytic coatings based on TiO_2 exhibit broad-spectrum antimicrobial activity through the production of reactive oxygen species under UV or visible light [17]. Additionally, multifunctional films integrating ZnO or Ag nanoparticles with polymers offer dual properties of antimicrobial and antifogging behavior, suitable for instruments and protective equipment [21].

5.5. Automotive and Marine Industries

Self-cleaning coatings have also been employed in automotive and marine sectors. Superhydrophobic layers on windshields, mirrors, and ship hulls help maintain visibility and resist fouling or corrosion. They also minimize icing, fogging, and salt accumulation—particularly valuable in cold or humid environments [19]. These systems improve safety and reduce cleaning costs in both personal and industrial transport applications.

6. Challenges and Future Perspectives

Despite the significant advancements in self-cleaning materials, several technical and practical challenges still hinder their widespread adoption, particularly in outdoor and industrial applications.

6.1. Durability and Mechanical Stability

A major limitation for superhydrophobic coatings is their poor mechanical durability. Many of these coatings lose their hierarchical surface structure after repeated abrasion, prolonged UV exposure, or chemical degradation [18,19]. Although strategies such as self-healing mechanisms and the incorporation of elastic polymers have demonstrated potential [26], achieving long-term performance in real-world conditions—especially in applications like automotive exteriors and solar panels—remains a critical challenge.

6.2. Light Dependency of Photocatalysts

Photocatalytic self-cleaning materials, particularly those based on TiO_2 and ZnO, depend heavily on UV or visible light to initiate the degradation of contaminants. This dependence significantly limits their efficiency in low-light or indoor environments. While doping and heterojunction engineering have extended activity into the visible range [3,13,17], issues related to quantum efficiency and long-term operational stability still require further refinement [27].

6.3. Environmental and Safety Considerations

The environmental implications of using engineered nanoparticles in self-cleaning coatings have raised growing concerns. TiO_2 and ZnO nanoparticles, if released, may exhibit toxicity toward aquatic organisms and potentially accumulate in biological systems [28]. To address these risks, research is shifting toward safer, eco-friendly alternatives such as biopolymer-based nanocomposites and immobilized coatings that reduce nanoparticle leaching [29].

6.4. Integration into Complex Surfaces

Achieving uniform and effective self-cleaning coatings on geometrically complex or flexible substrates continues to be a technical barrier. Traditional methods like spray-coating or dip-coating often struggle to maintain consistent surface roughness or film thickness on irregular surfaces [30]. Therefore, emerging fabrication techniques such as laser texturing, electrospinning, and 3D printing are being explored for their potential to enable scalable and precise patterning in future self-cleaning applications.

7. Conclusion

Self-cleaning materials have emerged as a promising class of functional surfaces capable of maintaining cleanliness without external intervention. Two dominant mechanisms—photocatalysis and superhydrophilicity—have been extensively developed and applied across various industries including architecture, energy, textiles, and biomedicine. Inorganic metal oxides such as TiO_2 and ZnO remain the core materials for photocatalytic systems due to their oxidative strength and chemical stability, while low-surface-energy polymers and hierarchical structures are key to superhydrophobic designs.

Recent advances in material engineering have expanded the operational range of these coatings, enabling light activation under visible wavelengths and enhancing mechanical robustness through hybridization with polymers. Furthermore, the integration of multifunctionality, such as combining antimicrobial, anti-fogging, and UV-protection properties, has broadened the scope of self-cleaning applications.

However, several challenges still limit the large-scale commercialization of self-cleaning technologies. These include poor abrasion resistance, UV dependency, environmental concerns related to nanomaterials, and difficulties in applying coatings to irregular or flexible surfaces. As a result, future research must focus on developing eco-friendly, durable, and scalable self-cleaning systems through advanced synthesis techniques, sustainable material selection, and smart manufacturing approaches such as additive manufacturing and surface patterning.

Overall, the continuous interdisciplinary effort spanning materials science, surface chemistry, and environmental engineering is expected to pave the way for the next generation of intelligent, self-sustaining surfaces suited for real-world applications.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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