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Core–Shell Based Superhydrophobic Materials: Design, Fabrication and Applications

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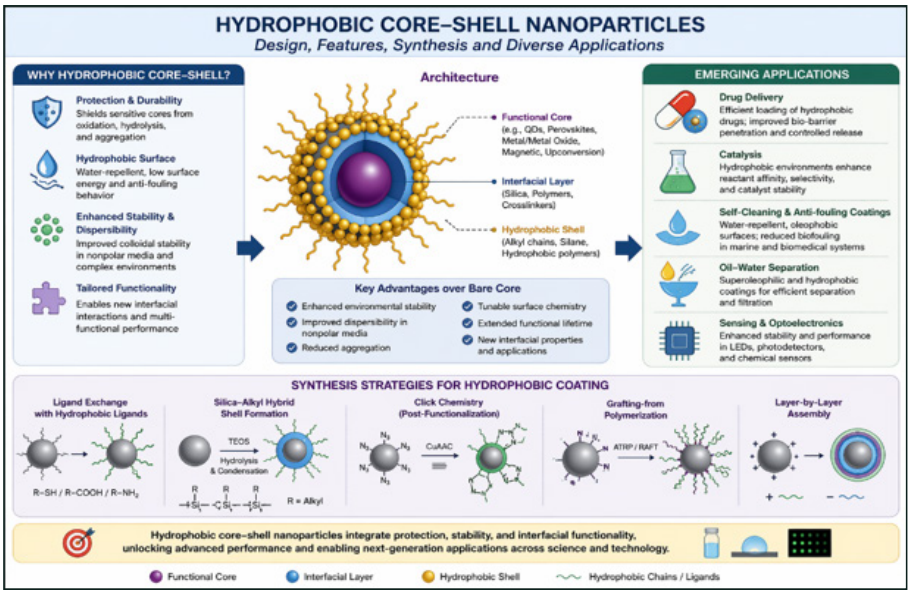
Abstract

Superhydrophobic core–shell nanoparticles represent an advanced material architecture in which a functional core is encapsulated by a low–surface-energy shell, enabling precise control over wettability, stability, and interfacial behavior. The core–shell configuration decouples structural roughness and mechanical integrity from surface chemistry, allowing the shell layer to impart superhydrophobicity while the core governs particle size, rigidity, or additional functionalities. This review article comprehensively examines the design principles, synthesis methodologies, and enhanced properties of core-shell superhydrophobic materials. The design of core–shell structured particles provides an effective strategy to achieve robust and multifunctional superhydrophobicity. In these systems, the core imparts mechanical, optical, or magnetic functionalities, while the shell contributes nanoscale roughness and low-surface-energy chemistry. This review summarizes recent advances in the synthesis, functionalization, and application of core–shell based superhydrophobic materials. We delve into how the distinct core and shell components synergistically contribute to mechanical robustness, chemical stability, and functional versatility. Finally, challenges and future perspectives for scaling up and enhancing the durability of these materials are discussed.



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Introduction

Superhydrophobicity, inspired by natural surfaces such as lotus leaves and butterfly wings, has emerged as a key area in surface engineering and nanotechnology. Superhydrophobic core–shell nanoparticles are increasingly employed in water-based systems due to their ability to maintain stable non-wetting interfaces under submerged conditions. By combining a mechanically robust or functional core—such as silica, metal oxides, polymers, or magnetic nanoparticles—with a low–surface-energy shell, these architectures effectively trap air layers at the solid–water interface, enabling persistent water repellency. Such properties are exploited in diverse underwater applications, including oil–water separation, where oleophilic shells selectively absorb hydrocarbons while repelling water, and anti-fouling or anti-bioadhesion surfaces that inhibit microbial and protein attachment in aquatic environments. In corrosion protection and barrier coatings, core–shell nanoparticles reduce water permeation and ionic transport, enhancing durability in submerged or humid conditions. Magnetic or catalytic cores further enable recovery, reuse, or in situ remediation in aqueous media, while polymer-shelled systems improve stability and dispersion resistance. The decoupled design of core–shell nanoparticles thus allows tailored performance under water by independently optimizing structural integrity, interfacial chemistry, and functional response. In such architectures, the **core** acts as a functional backbone (magnetic, optical, mechanical), while the **shell** provides hierarchical roughness and hydrophobic chemical groups. Although surface functionalization of nanoparticles with fluorinated or chlorinated groups is commonly used to impart hydrophobicity, such chemical modification alone is often insufficient to ensure long-term superhydrophobic performance, particularly in aqueous or mechanically demanding environments. Monolayer grafted fluoro- or chloro-silanes are susceptible to hydrolysis, mechanical abrasion, and desorption, leading to gradual exposure of the intrinsically hydrophilic nanoparticle surface and subsequent wetting. In contrast, core–shell nanoparticle architectures offer a more robust strategy by decoupling surface chemistry from structural integrity. A hydrophobic shell—composed of crosslinked siloxanes, fluoropolymers, or polymeric matrices—provides a physically continuous and chemically stable barrier that protects the core while sustaining low surface energy over extended periods This review highlights recent progress in the design, synthesis, and application of core–shell superhydrophobic materials.

Design Principles of Core-Shell Superhydrophobic Materials

The Core

The core gives multi faceted functionalities like electromagnetic, optical, magnetic, catalytic, or conductive properties, mechanical strength with structural integrity. Core materials are typically chosen for their hardness, toughness, or thermal/chemical stability. Common examples include:

- Inorganic Cores: SiO_2, TiO_2, ZnO, Al_2O_3 nanoparticles. These provide excellent mechanical rigidity and are often inexpensive.
- Polymeric Cores: Polystyrene (PS), poly(methyl methacrylate) (PMMA), epoxy resins. These offer flexibility, low density, and ease of synthesis.
- Hybrid/Magnetic Cores: Fe_3O_4 nanoparticles. These introduce magnetic responsiveness, enabling remote control or manipulation of the coating.

Even though the shell dominates surface interactions, the core's electromagnetic, optical, magnetic, catalytic, or conductive properties are not "blocked" they either pass through the shell or interact indirectly, enabling multifunctional superhydrophobic materials.

Inorganic Cores

Inorganic cores play a central role in tailoring the mechanical strength, optical properties, magnetic

responsiveness, and catalytic activity of core–shell superhydrophobic particles. Unlike purely organic systems, inorganic cores often provide higher thermal, chemical, and structural stability, making them suitable for harsh environments. Their unique physicochemical properties determine not only the durability of superhydrophobicity but also the multifunctional performance of the material.

Mechanical strength

Fabrication of nano core–shell superhydrophobic coatings using SiO_2–$TiO_2$and SiO_2-ZnO nanoparticles where SiO_2 core provides mechanical strength due to its high mechanical stiffnes [1]. This improves the mechanical robustness, adhesion, scratch resistance (up to 20 N), and flexibility of polymer-based films, strongly enhancing durability for marine and outdoor applications [2,3]. Highly durable superhydrophobic surfaces made from polydimethylsiloxane (PDMS) and silica nanoparticles (SiO_2) show excellent abrasion, UV, and chemical resistance as a result of the inorganic core's structural robustness and resistance to mechanical degradation [4]. Using adhesive/fluorinated silica core/shell microspheres demonstrates exceptional mechanical robustness and wear resistance in superhydrophobic coatings, confirmed by extensive abrasion and tape-peeling tests [5,6].

Optical Properties

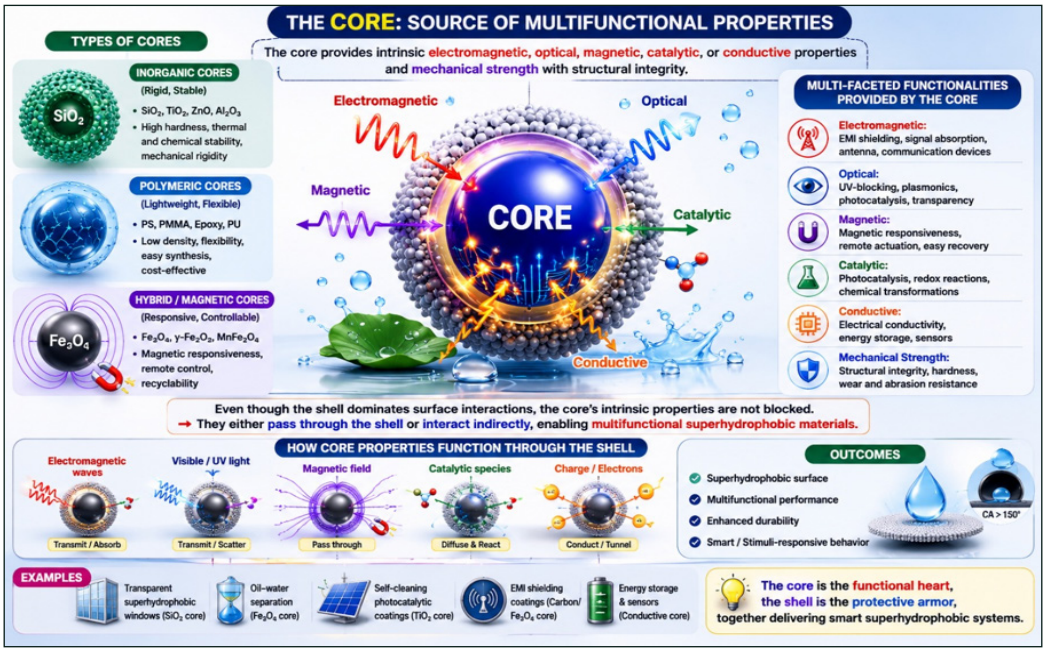
Transparent superhydrophobic surfaces based on core–shell nanoparticles have been successfully demonstrated on a variety of optically sensitive substrates where both high light transmission and water repellency are required. Examples include self-cleaning architectural glass and smart windows, where silica@siloxane or silica@fluoropolymer nanoparticles form ultrathin coatings that repel water while maintaining high optical clarity. Similar core–shell systems are applied to optical lenses, camera covers, and protective sensor windows to prevent fogging and contamination without degrading image quality. In photovoltaic panels, transparent silica@polymer nanoparticle coatings reduce dust adhesion and water retention on glass covers, thereby improving long-term power output. Touchscreens and display panels also benefit from such coatings, which provide water repellency and easy cleaning while preserving low haze and high transmittance. In automotive and marine environments, transparent superhydrophobic core–shell nanoparticle layers are used on windshields and optical instruments to resist rain, fouling, and moisture accumulation. In all these cases, transparency is retained by employing sub-wavelength nanoparticle dimensions, thin hydrophobic shells, and uniform dispersion that minimize light scattering while sustaining durable superhydrophobicity. A work demonstrates that SiO_2-core-based superhydrophobic coatings achieve high optical transparency by forming micron and nanoporous networks on glass substrates. The hierarchical SiO_2 structures maintain up to 96.1% light transmittance compared to bare glass, proving the crucial role of the inorganic core in light transmission [7]. Another work details how functionalized SiO_2 nanoparticles both raise surface hydrophobicity and tailor optical properties such as visible and near-infrared (NIR) reflectance, with coatings exhibiting more than 80% NIR reflectance and superhydrophobic behavior [8]. shows that silica nanoparticle-based core–shell coatings deliver sub-100 nm surface roughness, high optical transparency, and superhydrophobicity (water contact angle >160°, sliding angle <5°), establishing SiO_2 as central for advanced optical features [9]. A work describes transparent coatings produced by applying SiO_2 nanoparticles onto polymer substrates, explicitly connecting the inorganic core with improved optical clarity and water repellence [10].

Superhydrophobic core–shell coatings containing CuO nanoparticles demonstrate enhanced photocatalytic absorption and self-cleaning capabilities, showing the ability to decompose organic dyes more efficiently, as confirmed by optical absorption spectra and degradation tests [11]. The thickness and permittivity of the inorganic core influence plasmon resonance, enabling tailored optical properties in magnetic-plasmonic core–shell structures—these show clear wavelength shifts and resonance tuning based on core characteristics.

Magnetic Responsiveness

Magnetic-plasmonic core–shell nanoparticles created from magnetic cores (e.g., iron oxide) and gold shells simultaneously deliver strong magnetic and optical (plasmonic) responsiveness, which can be tuned by core size and shell architecture, supporting multifunctional sensing and separation systems. A study demonstrated that inorganic iron oxide core particles (from banded iron formation ore) enable both strong magnetic responsiveness and superhydrophobicity when coated

with zinc stearate, allowing magnetic manipulation and oil–water separation [12]. A work described nanoparticles with inorganic magnetic cores (such as Fe_3O_4) surrounded by superhydrophobic organosilica shells, resulting in materials suitable for magnetically guided separation tasks due to their magnetic and hydrophobic properties [13]. A work details the design of core–shell magnetic nanoparticles, showing how inorganic magnetic cores provide both superhydrophobicity and adjustable magnetic manipulation in fluidic environments [14]. This research further supports the multifunctionality achieved by using inorganic magnetic cores in superhydrophobic core–shell systems, facilitating robust surface construction and active manipulation by external magnets [15]. Superhydrophobic coatings with magnetic cores are demonstrated by fabricating magnetic sorbents (e.g., ZS@BIF structures with superhydrophobic shells), enabling magnetic separation and manipulation for oil-removal and environmental remediation [12].



Catalytic Activity

- A 2025 study on Fe_3O_4-SiO_2/Co–Cr–B magnetic core–shell catalysts presents detailed catalytic performance metrics (hydrogen generation rate, activation energy) for hydrogen generation and compares these core–shell systems to other non-noble metal catalysts. The Fe_3O_4 (inorganic core) delivers enhanced stability, magnetic separability, and dispersion of active catalytic sites, resulting in a fourfold improvement in hydrogen evolution kinetics compared to previous systems [16].
- Studies on Au-AuPd core–shell nanoparticles show catalytic activity enhancements due to the inorganic gold core in selective hydrogenation and nitrogen reduction, providing quantitative comparisons (e.g., mass activity increases under plasmonic excitation and dark conditions) [17].
- A rod-like ZnO/lignin nanosphere composites are obtained using co-assembly, followed by changing the addition time of LNSs to control their sizes. The composites demonstrate good performance in visible-light photocatalysis test [18].

SiO_2-CuO core–shell nanoparticles used in photocatalytic superhydrophobic coatings showcase powerful catalytic degradation of dyes like Rhodamine B and methylene blue, leveraging the semiconductor properties of CuO for enhanced photoactivity [19]. Core–shell heterophase catalysts with superhydrophobic surfaces enable synergistic integration of high catalytic activity and water repellency, offering improved performance in electrochemical energy conversion systems.

Different Cores

For hydrophobic core–shell nanoparticles, silica (SiO_2) is one of the most widely utilized core materials owing to its chemical stability, non-toxicity, low cost, optical transparency, and ease of synthesis through methods such as the Stöber process, which enables precise control over particle sizes ranging from tens to hundreds of nanometers. The silica core serves as a robust mechanical backbone that enhances the structural integrity and durability of the nanoparticle while providing a high surface area for the deposition of functional hydrophobic shells. Additionally, silica particles can act as versatile carriers capable of encapsulating dyes, drugs, catalysts, and other active agents within their porous or hollow structures. In superhydrophobic systems, the silica core plays a crucial role in generating nanoscale surface roughness, which is essential for trapping air pockets and reducing liquid–solid contact. When the silica surface is further modified with low-surface-energy materials such as fluorinated silanes, alkylsilanes, or polydimethylsiloxane (PDMS), a hydrophobic shell is formed that significantly enhances water repellency. The synergistic combination of silica-induced roughness and hydrophobic surface chemistry results in transparent, mechanically stable, and highly water-repellent coatings, making silica-based hydrophobic core–shell nanoparticles particularly attractive for self-cleaning glass, anti-fouling surfaces, optical devices, and protective coatings.

Magnetic nanoparticles, particularly magnetite (Fe_3O_4) and maghemite (γ-Fe_2O_3), are widely employed as core materials in hydrophobic core–shell nanoparticles due to their unique ability to respond to external magnetic fields. This magnetic responsiveness enables precise control over particle movement, positioning, and recovery, making them highly attractive for reusable and sustainable applications. The magnetic core facilitates easy separation and recyclability of nanoparticles from aqueous environments using a simple magnetic field, eliminating the need for complex filtration or centrifugation processes. Furthermore, iron oxide nanoparticles possess intrinsic catalytic activity and can participate in Fenton and Fenton-like reactions for the degradation of organic pollutants, thereby combining remediation and recovery capabilities within a single platform. To impart hydrophobicity and improve environmental stability, the magnetic cores are commonly encapsulated within silica or polymer shells, which are subsequently functionalized with low-surface-energy molecules such as fluorosilanes, alkylsilanes, or PDMS. The resulting hydrophobic core–shell structures exhibit excellent water repellency while retaining magnetic functionality, allowing them to selectively adsorb oils and organic contaminants from water and then be rapidly collected and reused through magnetic separation. Consequently, magnetic hydrophobic core–shell nanoparticles have found extensive applications in oil–water separation, wastewater treatment, environmental remediation, and recyclable catalytic systems.

Metal nanoparticles, including gold (Au), silver (Ag), copper (Cu), platinum (Pt), and palladium (Pd), are extensively utilized as core materials in hydrophobic core–shell nanoparticles due to their exceptional plasmonic, catalytic, and electronic properties. Noble metal cores such as Au and Ag exhibit localized surface plasmon resonance (LSPR), which enhances light absorption, electromagnetic field confinement, and Raman signal amplification, making them highly valuable in optical sensing and spectroscopy applications. Meanwhile, Pt and Pd nanoparticles serve as highly efficient catalysts for a wide range of chemical transformations, including hydrogenation, oxidation, and environmental remediation reactions, owing to their high surface activity and catalytic selectivity. Metal cores also contribute superior electrical conductivity, enabling enhanced performance in electromagnetic interference (EMI) shielding, electrochemical devices, and sensor platforms. To improve durability, prevent oxidation or aggregation, and impart water repellency, these metallic cores are often encapsulated within silica or polymer shells that are subsequently modified with hydrophobic agents such as fluorosilanes, alkylsilanes, or hydrophobic polymers. The resulting hydrophobic core–shell nanoparticles combine the intrinsic optical, catalytic, and electronic functionalities of the metal core with the anti-wetting and anti-fouling characteristics of the shell. Such multifunctional architectures have been widely employed in surface-enhanced Raman scattering (SERS) substrates, biosensors, catalytic coatings, anti-corrosion surfaces, and self-cleaning materials, where both the advanced functionality of the metallic core and the protective hydrophobic shell are essential for long-term performance and reliability.

Metal oxide nanoparticles, including titanium dioxide (TiO_2), zinc oxide (ZnO), cerium oxide (CeO_2), and aluminum oxide (Al_2O_3), are among the most widely utilized core materials in hydrophobic core–shell nanoparticles owing to their abundance, chemical stability, high surface area, and diverse functional properties. Each metal oxide offers unique advantages that extend beyond simple structural support. TiO_2 is renowned for its strong photocatalytic activity and UV-blocking capability, making it highly effective in self-cleaning and environmental remediation applications. ZnO exhibits antibacterial, UV-absorbing, and piezoelectric properties, enabling its use in antimicrobial coatings, sensors, and energy-harvesting devices. CeO_2 possesses excellent oxygen storage capacity and reversible redox behavior, which are valuable in catalytic and antioxidant applications, while Al_2O_3 contributes exceptional mechanical strength, hardness, and abrasion resistance, enhancing coating durability. In hydrophobic core–shell systems, these metal oxide cores provide intrinsic micro- and nanoscale surface roughness that is essential for achieving superhydrophobicity. Subsequent surface modification with low-surface-energy compounds such as fluorosilanes, alkylsilanes, or stearic acid creates a hydrophobic shell that significantly reduces surface wettability. The synergistic combination of hierarchical roughness from the metal oxide core and the hydrophobic surface chemistry results in robust, UV-resistant, self-cleaning, anti-icing, and antibacterial coatings. Consequently, metal oxide-based hydrophobic core–shell nanoparticles have found extensive applications in outdoor protective coatings, architectural materials, solar panels, biomedical surfaces, and environmental protection technologies where long-term durability and multifunctionality are required.

Carbon-based inorganic nanoparticles, such as carbon black, carbon nanotubes (CNTs), and graphene oxide (GO), are increasingly employed as core materials in hydrophobic core–shell nanoparticles due to their excellent electrical conductivity, lightweight nature, chemical stability, and high aspect ratio. These carbonaceous cores impart multifunctional properties that are highly desirable in advanced coatings and electronic materials. Their intrinsic conductivity enables the fabrication of anti-static surfaces, electromagnetic interference (EMI) shielding materials, and sensitive electronic devices, while their exceptional mechanical properties contribute to improved strength, toughness, and crack resistance of composite coatings. Additionally, carbon-based materials exhibit high thermal stability and thermal conductivity, making them suitable for applications operating under elevated temperatures or harsh environmental conditions. To achieve hydrophobicity and improve environmental durability, the carbon cores are commonly encapsulated with shells composed of silica (SiO_2), polydimethylsiloxane (PDMS), fluorosilanes, or other low-surface-energy materials. These hydrophobic shells not only protect the conductive carbon core from environmental degradation but also introduce surface roughness and water repellency, resulting in robust superhydrophobic coatings. The combination of electrical conductivity, mechanical reinforcement, thermal stability, and hydrophobicity enables carbon-based core–shell nanoparticles to be utilized in corrosion-resistant coatings, self-cleaning conductive surfaces, flexible electronics, wearable sensors, energy devices, and multifunctional smart coatings where both conductivity and water repellency are essential for long-term performance.

Ceramic nanoparticles, including zirconium dioxide (ZrO_2), silicon carbide (SiC), and aluminum nitride (AlN), are widely employed as core materials in hydrophobic core–shell nanoparticles due to their exceptional hardness, thermal resistance, and chemical inertness. These ceramic cores provide outstanding mechanical durability, making them particularly effective in applications where coatings are exposed to abrasion, erosion, or harsh operating environments. ZrO_2 is valued for its high fracture toughness and wear resistance, SiC offers excellent hardness and thermal conductivity, while AlN combines superior thermal conductivity with electrical insulation, making it attractive for advanced engineering applications. The inherent thermal stability of these ceramics enables their use in aerospace, automotive, marine, and high-temperature industrial systems where conventional materials may degrade. When coated with hydrophobic shell layers such as fluorosilanes, alkylsilanes, PDMS, or hydrophobic polymer coatings, the resulting core–shell nanoparticles exhibit both extreme durability and strong water repellency. The ceramic core provides structural integrity and resistance to mechanical and thermal stress, while the hydrophobic shell minimizes

water adhesion, corrosion, contamination, and biofouling. Consequently, ceramic-based hydrophobic core–shell nanoparticles have emerged as promising materials for robust anti-corrosion, anti-fouling, anti-icing, and self-cleaning coatings that can maintain their performance under extreme environmental and operational conditions.

Polymeric materials such as polystyrene (PS), poly(methyl methacrylate) (PMMA), polyurethane (PU), polyacrylonitrile (PAN), polyethylene (PE), and polylactic acid (PLA) are widely employed as core materials in hydrophobic core–shell nanoparticles due to their lightweight nature, mechanical flexibility, tunable size, and versatile surface chemistry. These polymers can be synthesized with controlled nano- or microscale dimensions, contributing to the hierarchical surface roughness required for superhydrophobicity while reducing the overall weight of the material. Their abundant functional groups enable facile surface modification and strong interfacial bonding with inorganic shells such as silica, titania, or zinc oxide, which further enhance durability and functionality. Unlike rigid inorganic cores, polymeric cores provide flexibility and resistance to cracking, making them particularly suitable for coatings on fabrics, plastics, and other deformable substrates. Certain polymers, such as PMMA and PS, also offer excellent optical transparency, enabling the fabrication of transparent superhydrophobic coatings for windows, displays, and optical devices. Furthermore, biodegradable polymers such as PLA provide environmentally friendly alternatives for sustainable coatings and biomedical applications. When combined with functional shells, polymeric core–shell structures can exhibit additional properties including photocatalytic activity, antibacterial behavior, abrasion resistance, electromagnetic interference shielding, and oil–water separation capability. Consequently, polymer-based hydrophobic core–shell nanoparticles have found widespread applications in self-cleaning textiles, transparent protective coatings, biomedical interfaces, marine coatings, packaging materials, and separation membranes.

Hybrid organic cores have emerged as a versatile class of building blocks for designing core–shell based superhydrophobic materials. Unlike purely inorganic cores such as silica or metal oxides, hybrid organic cores are composed of polymers, biopolymers, or organic–inorganic hybrids, which offer unique advantages in terms of lightweight nature, flexibility, and chemical tunability. Polystyrene (PS), polymethyl methacrylate (PMMA), and polyurethane (PU) are the most widely used polymeric cores due to their ease of synthesis, low density, and compatibility with surface modification. When coated with inorganic shells such as silica, titania, or zinc oxide and subsequently functionalized with hydrophobic agents like polydimethylsiloxane (PDMS), fluorosilanes, or stearic acid, these particles exhibit enhanced nanoscale roughness combined with low-surface-energy chemistry. As a result, hybrid organic core–shell particles demonstrate robust superhydrophobicity while retaining mechanical flexibility, making them suitable for applications in textiles, packaging films, and protective coatings. In addition, biopolymer cores such as chitosan, starch, or cellulose provide the added benefits of biodegradability and biocompatibility, thereby expanding their use into eco-friendly coatings, biomedical devices, and drug delivery carriers. Conducting polymers like polyaniline and polypyrrole, when employed as cores, impart electrical conductivity alongside water repellence, enabling multifunctional applications in anticorrosion coatings, sensing, and electromagnetic interference shielding. Moreover, organically modified silicates (ORMOSILs) and polymer–silica hybrids combine the toughness of organic networks with the chemical stability of silica, resulting in hybrid cores with superior thermal and chemical resistance. The multifunctionality of hybrid organic cores arises from the synergy between the core, which imparts bulk properties such as flexibility, conductivity, or biodegradability, and the shell, which governs surface roughness and hydrophobicity. However, challenges such as limited thermal stability, wear resistance under abrasion, and scalability of synthesis methods must be addressed for practical deployment. Future research on hybrid organic cores is expected to focus on eco-friendly formulations, self-healing shells, and multifunctional systems that integrate superhydrophobicity with optical, electrical, or magnetic responses for advanced applications in flexible electronics, marine coatings, and sustainable materials.

Enhanced Properties and Performance

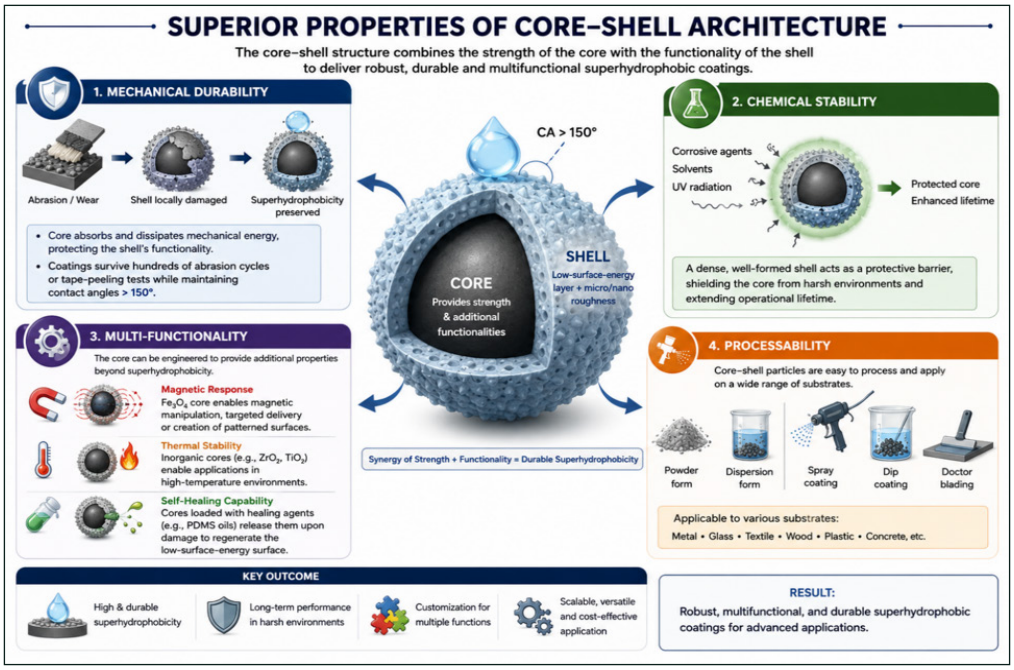
The core-shell architecture imparts a suite of superior properties:

- Mechanical Durability: This is the most significant

advantage. Under abrasion or wear, the shell may be locally damaged. However, the superhydrophobic functionality is preserved because the low-surface-energy material is not just a superficial layer but is an integral part of the shell surrounding the durable core. The core absorbs and dissipates mechanical energy, protecting the shell's functionality. Studies have shown coatings surviving hundreds of abrasion cycles or tape-peeling tests while maintaining contact angles above 150°.

- Chemical Stability: A dense, well-formed shell can act as a protective barrier, shielding the core from corrosive agents, solvents, or UV radiation, thereby enhancing the coating's operational lifetime in harsh environments.
- Multi-functionality: The core can be tailored to provide additional properties:
  - Magnetic Response: A Fe_3O_4 core allows the coating to be manipulated magnetically, useful for targeted delivery or creating patterned surfaces.
  - Thermal Stability: Inorganic cores like ZrO_2 or TiO_2 enable applications in high-temperature settings.
  - Self-Healing: Cores loaded with healing agents (e.g., PDMS oils) can release them upon damage to regenerate the low-surface-energy surface.

Processability: Core-shell particles are typically synthesized as powders or dispersions that can be easily applied to various substrates (metal, glass, textile, wood) using simple, scalable techniques like spray-coating, dip-coating, or doctor blading.



Applications

Polymeric core materials, including polystyrene (PS), poly(methyl methacrylate) (PMMA), polyurethane (PU), polyacrylonitrile (PAN), polyethylene (PE), and polylactic acid (PLA), are widely utilized in hydrophobic core–shell nanoparticles due to their lightweight nature, mechanical flexibility, tunable size, and versatile surface chemistry. These polymers can be synthesized with controlled dimensions and readily functionalized to facilitate strong interactions with inorganic shells such as silica, titania, or zinc oxide. The polymeric core contributes to micro-scale surface roughness, flexibility, and reduced density, while the shell provides additional functionalities such as abrasion resistance, photocatalytic activity, antibacterial properties, or enhanced durability. Unlike rigid inorganic particles, polymer-based cores can withstand deformation without cracking, making them suitable for flexible coatings and wearable materials. Moreover, transparent polymers such as PMMA and PS enable the fabrication of transparent superhydrophobic surfaces, while biodegradable polymers such as PLA offer environmentally sustainable alternatives. Through appropriate shell engineering and hydrophobic surface modification, polymeric core–shell nanoparticles have been successfully applied in self-cleaning

textiles, transparent coatings, biomedical interfaces, oil–water separation membranes, marine protective coatings, packaging materials, and multifunctional smart surfaces.

Challenges and Future Perspectives

- Despite significant progress, several challenges remain:
- **Scalability**: Many synthesis methods are complex and not cost-effective for large-scale production. The multi-step synthesis of core-shell particles can be complex and expensive compared to simple mixing approaches. Developing cheaper, one-pot, and scalable synthesis methods is crucial for commercialization.
- **Durability**: Superhydrophobic coatings may degrade under abrasion, UV radiation, or chemical attack.
- **Eco-Friendliness**: Fluorinated modifiers, though effective, raise environmental concerns. Research into fluorine-free hydrophobics (e.g., long-chain fatty acids, siloxanes) is growing. The persistence and potential toxicity of fluorinated compounds (PFAS) and some nanoparticles are under increasing scrutiny. Future research must focus on developing eco-friendly, bio-based, and fluorine-free shell materials without compromising performance.
- **Multifunctionality**: Integrating multiple functions (e.g., conductivity, transparency, recyclability) while retaining superhydrophobicity remains a research frontier. Future work will focus on designing "smart" core-shell systems that respond to external stimuli like pH, temperature, or light, allowing for on-demand control of wettability.

Future research should focus on **green synthesis, self-healing coatings, and scalable fabrication routes** for practical deployment.

Conclusion

Core–shell based superhydrophobic materials represent a rapidly advancing field, offering a unique combination of structural robustness and multifunctionality. The ability to tailor both the core and shell components enables broad applications, from environmental remediation to advanced sensing technologies. Overcoming challenges in durability and scalability will be crucial for translating these laboratory advances into industrial and societal impact.

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