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Introduction to Core-shell Nanomaterials

Core-shell nanomaterials have emerged as a transformative class of materials, offering tailored functionalities by combining two or more distinct components into a single nanoscale structure. These materials consist of a core, which serves as the central framework, and a shell that encapsulates it, modifying and enhancing its physical, chemical, and functional properties. The precise engineering of core-shell structures allows for unprecedented control over stability, reactivity, and selectivity, making them indispensable in a wide range of applications spanning energy, environment, and medicine. The concept of core-shell architectures has its roots in classical colloidal chemistry, where early studies focused on coating particles with thin layers to alter surface properties [1]. Over time, advances in synthesis techniques and nanofabrication methods have enabled the design of highly sophisticated core-shell structures with tailored compositions, morphologies, and functionalities. The ability to integrate multiple materials into a single entity has given rise to novel phenomena, including synergistic electronic interactions, enhanced mechanical strength, and controlled surface chemistry, leading to superior performance compared to their single-component counterparts.

In modern research and industrial applications, core-shell nanomaterials play a pivotal role in addressing global challenges. In the energy sector, they are revolutionizing battery technology, fuel cells, and photocatalytic energy conversion by enhancing charge transport and stability. In environmental science, they contribute to pollution remediation, water purification, and catalytic processes aimed at sustainable development. In medicine, core-shell structures are redefining drug delivery, biosensing, and imaging by providing controlled release mechanisms and biocompatibility. Their versatility extends to emerging fields such as flexible electronics, wearable sensors, and next-generation computing, where their unique properties enable groundbreaking innovations. The continuous evolution of core-shell nanomaterials reflects the dynamic progress in materials science and nanotechnology. With ongoing advancements in synthesis techniques, characterization tools, and computational modeling, the potential for developing new architectures with unprecedented functionalities continues to expand. Understanding the fundamental

principles governing these structures is essential for unlocking their full potential and harnessing their benefits across diverse scientific and technological domains.

1.1 Basic Concept of Core-shell Structures

Core-shell nanomaterials are defined as composite structures where one material (the core) is encapsulated by another (the shell), forming a hierarchical architecture with distinct physicochemical properties. The core can be metallic, ceramic, polymeric, or carbon-based, while the shell can be composed of materials such as oxides, polymers, metals, or even organic molecules. This structural arrangement allows for precise control over surface chemistry, reactivity, and stability, leading to tailored properties that cannot be achieved with homogeneous nanomaterials. Core-shell nanomaterials represent a fundamental advancement in the field of nanoscience, providing an innovative means of tailoring material properties at the nanoscale. The ability to selectively engineer the core and shell with different compositions, morphologies, and interfacial properties has led to a broad spectrum of applications across scientific and industrial domains. The importance of core-shell nanomaterials stems from their ability to combine the advantages of both core and shell materials while mitigating their individual limitations. The shell can act as a protective barrier, preventing core degradation, oxidation, or unwanted interactions with the external environment [2]. Conversely, it can also enhance the surface properties of the core, improving its solubility, biocompatibility, or catalytic efficiency. Additionally, core-shell structures enable controlled release mechanisms in drug delivery, selective adsorption in environmental remediation, and enhanced charge transfer in energy conversion technologies. Their ability to be fine-tuned for specific functions makes them indispensable in scientific research and technological advancements.

Compared to single-component nanomaterials, core-shell structures offer several critical advantages that make them superior in functionality and applicability. The most significant benefits include enhanced stability, tunable properties, multifunctionality, and improved performance across various applications [3]. One of the primary challenges with conventional nanomaterials is their inherent instability, particularly in reactive environments. Metal nanoparticles, for instance, often suffer from oxidation, aggregation, or dissolution, which severely limits their practical use. The shell in core-shell nanomaterials serves as a protective layer, shielding the core from environmental degradation and improving its long-term stability. This feature is particularly important in catalysis, where nanoparticles need to maintain their structural integrity under harsh reaction conditions. Another crucial advantage is the tunability of physical and chemical properties. By modifying the shell composition, thickness, or structure, researchers can control surface interactions, optical absorption, and electronic conductivity [4]. This tunability is highly beneficial in optical and electronic applications, where the core-shell architecture enables fine control over plasmonic resonance, bandgap engineering, and charge transport mechanisms. For example, in quantum dot-based solar cells, core-shell designs improve light absorption efficiency while minimizing energy loss through recombination.

Core-shell nanomaterials also offer multifunctionality, allowing for the integration of complementary properties within a single material. This synergy is particularly evident in biomedical applications, where a magnetic core can be combined with a biocompatible shell for targeted drug delivery and imaging. Similarly, catalytic nanoparticles can be encapsulated within porous shells to enhance selectivity and reaction rates while minimizing unwanted side reactions. This multifunctional capability extends their utility in diverse fields, ranging from biosensing to environmental remediation. Additionally, core-shell structures enable enhanced dispersion and processability compared to single-component nanomaterials. Many nanoparticles tend to aggregate due to high surface energy, limiting their uniformity and application potential [5]. The presence of a stabilizing shell improves colloidal stability, ensuring better dispersion in solvents, polymers, and other matrices. This property is particularly advantageous in nanocomposite manufacturing and coating technologies, where uniform distribution of nanomaterials is essential for performance optimization.

1.2 Historical Development of Core-shell Materials

The concept of core-shell materials has evolved significantly over time, from early observations in colloidal chemistry to sophisticated nanoscale engineering in modern materials science. The development of core-shell structures has been driven by the need to manipulate material properties at the microscopic and nanoscopic levels, enabling advancements in catalysis, optics, energy storage, and biomedicine. The history of core-shell materials is intertwined with progress in surface chemistry, thin-film deposition, and nanofabrication techniques, each contributing to the precision and functionality of these hybrid architectures. The continuous refinement of synthesis methods, along with the growing understanding of interfacial interactions, has led to the emergence of highly customized core-shell systems designed for specific applications [2].

The foundation of core-shell materials can be traced back to the early studies in colloidal chemistry during the late 19th and early 20th centuries. Researchers investigating colloidal suspensions observed the formation of layered structures where one material surrounded another, often due to differences in surface energy and chemical affinity. These early discoveries laid the groundwork for the controlled synthesis of heterogeneous particles, where distinct compositions could be maintained in a single entity. One of the earliest practical demonstrations of core-shell structures was in the form of gold-coated colloidal particles, which were explored for their optical properties in stained glass and early colorimetric assays. The phenomenon of surface plasmon resonance, observed in these materials, highlighted the impact of shell layers on the optical behavior of metallic cores [6]. These findings spurred further investigations into how core-shell structures could be systematically engineered to achieve desirable optical, electronic, and chemical properties.

By the mid-20th century, advances in coating and thin-film technologies provided new pathways for constructing core-shell materials with greater precision. Techniques such as electrochemical deposition, sol-gel processing, and chemical vapor deposition (CVD) enabled researchers to deposit uniform layers of materials

onto various substrates [7]. These methods were initially applied to macroscopic materials but were later adapted for nanoscale applications as interest in nanotechnology grew. The development of metal-oxide coatings marked a significant step in core-shell material research, as oxide shells provided stability and passivation to reactive metallic cores. This was particularly important for applications in catalysis and corrosion resistance, where the controlled exposure of active sites could be achieved through selective shell design. Additionally, polymer coatings were introduced to enhance dispersibility and biocompatibility, paving the way for biomedical applications of core-shell nanoparticles [8]. As deposition techniques improved, multilayer core-shell structures emerged, where multiple shell layers could be stacked to achieve enhanced functionality. This advancement was particularly useful in optical coatings, where interference effects could be manipulated to control reflectivity and absorption across different wavelengths. The evolution of these technologies set the stage for modern nanofabrication approaches, enabling the production of tailored core-shell architectures for a wide range of applications.

The rise of nanotechnology in the late 20th and early 21st centuries revolutionized the design and synthesis of core-shell materials. The ability to manipulate materials at the atomic and molecular levels allowed for unprecedented control over core and shell properties, leading to materials with precisely engineered functionalities. Breakthroughs in chemical synthesis, such as the Stöber method for silica coating and seed-mediated growth for metal nanoparticles, provided reliable approaches for constructing uniform core-shell structures [9]. These methods enabled the fine-tuning of shell thickness, composition, and crystallinity, ensuring optimal performance in specific applications. Additionally, self-assembly techniques facilitated the spontaneous organization of nanoscale components into core-shell architectures, leveraging molecular interactions to achieve controlled morphologies. At the same time, advancements in physical deposition techniques, including atomic layer deposition (ALD) and pulsed laser deposition, allowed for conformal coating of nanomaterials with atomic precision [10]. These techniques were particularly valuable in electronic and catalytic applications, where nanoscale uniformity is crucial for performance optimization. The integration of computational modeling further accelerated the development of core-shell materials, enabling the prediction of interfacial behavior and guiding experimental design.

As synthesis methods became more sophisticated, the complexity of core-shell architectures evolved beyond simple core-shell designs into multi-shell and hybrid structures. These advanced architectures were developed to address specific functional requirements in emerging technologies. One notable advancement was the introduction of yolk-shell structures, where a hollow space exists between the core and shell. These materials provided enhanced reactivity and transport properties, making them particularly valuable in energy storage and catalysis. Similarly, asymmetric core-shell structures were designed to achieve directional interactions, enabling applications in targeted drug delivery and directional light emission [11]. Another key development was the emergence of multifunctional core-shell systems, where different material properties could be integrated within a single nanostructure. For example, magnetic-plasmonic core-shell nanoparticles combined

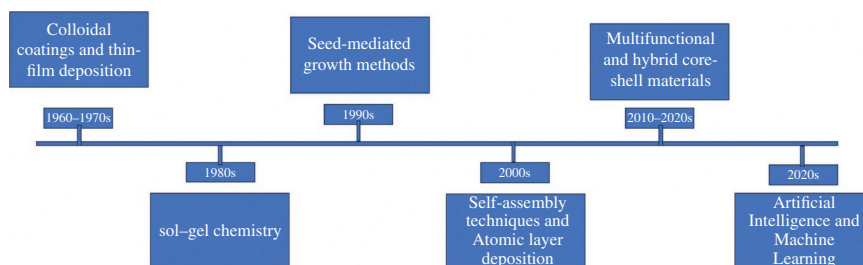


Figure 1.1 This timeline illustrates key milestones in the evolution of core-shell materials, from early colloidal coatings and sol-gel chemistry to advanced self-assembly techniques and AI-driven design.

optical and magnetic functionalities, allowing for dual-mode imaging and therapeutic applications. Similarly, semiconductor-metal core-shell systems were designed for enhanced photocatalytic activity, leveraging synergistic effects at the core-shell interface [12]. The continued evolution of core-shell architectures has been driven by the need for materials with tunable, application-specific properties. By leveraging interfacial engineering and hybrid material design, researchers have expanded the capabilities of core-shell structures, enabling their use in increasingly diverse and complex technological applications.

The development of core-shell materials has been marked by several key milestones, each representing a significant leap in scientific understanding and technological application. Figure 1.1 shows the historical development of core-shell materials from the early methods to ongoing researches.

1960s–1970s: Early studies on colloidal coatings and thin-film deposition laid the foundation for controlled core-shell synthesis.

1980s: The development of sol-gel chemistry enabled the formation of silica-coated nanoparticles, a breakthrough for biomedical and catalytic applications.

1990s: Seed-mediated growth methods were introduced for metal nanostructures, leading to precise control over size and morphology in plasmonic materials.

2000s: Advances in self-assembly techniques and ALD allowed for the fabrication of complex multilayer and hollow-core architectures.

2010s: The rise of multifunctional and hybrid core-shell materials led to breakthroughs in energy storage, targeted drug delivery, and high-performance coatings.

2020s and Beyond: Ongoing research focuses on the integration of artificial intelligence and machine learning to design next-generation core-shell materials with optimized properties for emerging applications.

The historical progression of core-shell materials demonstrates the convergence of chemistry, physics, and materials science in developing highly engineered nanostructures. As new fabrication techniques and theoretical insights continue to emerge, core-shell architectures are expected to play a crucial role in the advancement of nanotechnology, enabling innovations in fields ranging from renewable energy to personalized medicine.

1.3 Unique Properties of Core-shell Structures

Core-shell nanomaterials exhibit a wide range of unique properties that arise from their distinct architecture, where a core material is encapsulated within a shell of a different composition. This structural arrangement allows for the combination of diverse material properties, leading to enhanced functionality beyond what is achievable with single-component nanomaterials. By carefully selecting the core and shell materials, researchers can design nanostructures with tailored optical, electronic, magnetic, mechanical, and catalytic characteristics, making them highly versatile for applications in energy storage, environmental remediation, and biomedicine. The presence of a shell provides additional stability to the core, preventing degradation, oxidation, or unwanted interactions with the surrounding environment. This is particularly crucial for materials that are prone to chemical instability, such as metal nanoparticles, which require protective shells to maintain their reactivity and longevity [13]. Furthermore, the interface between the core and shell plays a significant role in determining the overall behavior of the nanomaterial, as it influences charge transfer, surface interactions, and structural integrity. Core-shell structures also enable precise control over surface chemistry, allowing for selective functionalization with biomolecules, catalysts, or other active species. This ability to manipulate surface properties without altering the core's intrinsic characteristics is valuable in applications such as targeted drug delivery, where surface modifications can enhance biocompatibility while preserving the therapeutic properties of the core. Additionally, the tunability of optical, electronic, and magnetic properties through core-shell engineering has opened new possibilities in fields such as plasmonics, spintronics, and quantum dot solar cells [14]. By integrating multiple functionalities within a single nanostructure, core-shell materials provide a platform for designing advanced materials with superior performance and multifunctionality. Their adaptability and tunable nature have made them a cornerstone of modern nanotechnology, driving innovations in a wide range of scientific and industrial fields. The unique properties of core-shell structures shown in Figure 1.2,

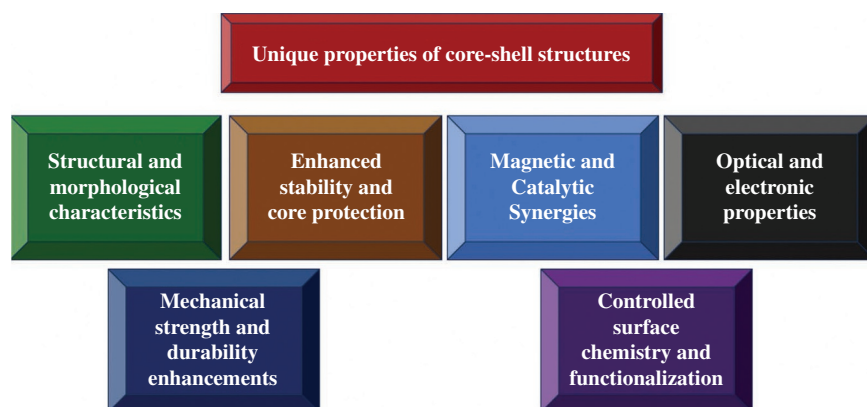


Figure 1.2 Unique properties of core-shell structures including structural stability, enhanced protection, magnetic and catalytic synergies, optical and electronic properties, mechanical strength, and controlled surface chemistry.

such as enhanced stability, catalytic synergies, and controlled surface functionalization, play a crucial role in various advanced applications.

1.3.1 Structural and Morphological Characteristics

The structural and morphological characteristics of core-shell nanomaterials are fundamental to their unique properties and functional advantages. The interplay between core and shell materials governs the overall physical and chemical behavior, influencing stability, reactivity, and application-specific performance. Core-shell nanomaterials exhibit well-defined geometries, which can be precisely engineered through controlled synthesis methods such as sol-gel processing, templated growth, and ALD [15]. Their morphology varies from spherical and cubic to rod-like, hollow, or hierarchical structures, depending on the synthesis conditions and the material system employed. The structural and morphological characteristics of core-shell nanomaterials critically influence their physicochemical properties, determining their stability, reactivity, electronic behavior, and mechanical performance. The architecture of a core-shell nanostructure is defined by the size, shape, and composition of both the core and the shell, as well as the interfacial interactions between them. The ability to manipulate these parameters enables precise control over the material's functionality, making core-shell structures highly versatile for diverse applications [16]. One of the primary structural advantages of core-shell nanomaterials is their ability to exhibit synergistic properties that arise from the combination of core and shell materials. For instance, in plasmonic nanoparticles, the shell can modify the localized surface plasmon resonance (LSPR) of the core by altering the dielectric environment, leading to tunable optical absorption and scattering properties. This principle is extensively utilized in surface-enhanced Raman spectroscopy (SERS) and biosensing applications. Similarly, in quantum dots (QDs), the shell passivates surface defects in the core, reducing non-radiative recombination and enhancing photoluminescence efficiency, which is crucial for applications in optoelectronic devices and bioimaging.

Morphology plays a crucial role in determining charge transport and carrier dynamics in electronic and energy applications. For example, in core-shell nanowires used in photovoltaic devices, a well-ordered shell with a uniform thickness can facilitate efficient charge separation while minimizing recombination losses at the core-shell interface. The structural integrity of the shell is particularly important in lithium-ion battery anodes, where it acts as a buffer layer, accommodating volume expansion and preventing mechanical degradation of high-capacity anode materials such as silicon [17]. The interfacial structure between the core and shell also significantly affects catalytic activity. In core-shell catalysts, lattice strain at the interface modifies the electronic structure of active sites, often leading to enhanced catalytic efficiency. For example, in Pt-based core-shell electrocatalysts for fuel cells, the shell can alter the d-band center of the core, optimizing the adsorption energy of reactants and improving catalytic turnover rates. Additionally, the porous morphology of certain core-shell structures enhances mass transport of reactants and products, further boosting catalytic performance [18].

The interfacial compatibility between the core and shell is a crucial factor, as lattice mismatch, strain effects, and interfacial bonding dictate the overall stability and

mechanical integrity of the structure. In many cases, the core-shell architecture enables the confinement of charge carriers, phonons, or spin interactions within a specific region, leading to enhanced electronic, optical, and magnetic behaviors. The shell material can also introduce strain-induced effects that modify the energy band structure of the core, thereby tuning electronic states and optical responses. Furthermore, precise control over shell thickness at the nanometer scale allows for gradual modification of physical properties, such as light absorption in plasmonic nanostructures or exciton confinement in semiconductor QDs [19]. The morphological features of core-shell nanomaterials also play a crucial role in catalytic applications, where high surface area and porous shell structures facilitate reactant diffusion while protecting the active core from deactivation. Similarly, in biomedical applications, the shell morphology dictates cellular uptake, biocompatibility, and controlled release kinetics of drug-loaded nanocarriers. By tailoring the core-shell interface and overall morphology, scientists can fine-tune the properties of these nanostructures for specific technological applications, making them indispensable in fields ranging from energy storage and environmental sensing to nanomedicine and optoelectronics. Thus, the structural and morphological characteristics of core-shell nanomaterials are not merely descriptive features but are deeply connected to their functional attributes. By precisely engineering the size, shape, and interface of core-shell structures, researchers can tailor their optical, electronic, catalytic, and mechanical properties to meet the specific demands of advanced applications in nanotechnology.

1.3.2 Enhanced Stability and Core Protection

The core-shell architecture is fundamentally designed to enhance the stability and protect the core material from degradation, oxidation, dissolution, or unwanted interactions with the surrounding environment. The shell serves as a physical and chemical barrier, significantly extending the functional lifespan of the core material while maintaining or even improving its intrinsic properties. The degree of stability enhancement depends on factors such as shell composition, thickness, crystallinity, and interfacial bonding with the core [20]. One of the most significant advantages of core-shell nanomaterials is their role in preventing oxidation and corrosion, particularly in metallic and semiconductor nanoparticles. For example, noble metal cores such as silver and copper are prone to oxidation in ambient conditions, leading to loss of conductivity and plasmonic properties. Encapsulating these cores with inert shells like silica (SiO_2), alumina (Al_2O_3), or carbon effectively prevents oxidative degradation by forming a diffusion barrier that inhibits oxygen and moisture penetration [21]. Similarly, in semiconductor QDs, passivating the core with a higher-bandgap shell such as ZnS over CdSe QDs significantly improves photostability by preventing surface oxidation and non-radiative recombination at defect sites. The core-shell structure also enhances thermal stability by providing structural rigidity and reducing thermal-induced sintering or coalescence. This is particularly relevant in catalytic applications where metal nanoparticles experience high-temperature conditions. For instance, in Pt-based catalysts for fuel cells, the presence of a protective shell such as TiO_2 or ZrO_2 prevents nanoparticle aggregation

and deactivation under thermal stress. The shell can also act as a thermal buffer, redistributing heat more efficiently and reducing localized overheating effects that could destabilize the core.

In addition to chemical and thermal stability, core-shell materials improve colloidal stability in liquid-phase applications. Bare nanoparticles tend to agglomerate due to van der Waals attractions or uncontrolled surface interactions, which reduces their dispersibility and functional performance. Coating these nanoparticles with stabilizing shells such as polyethylene glycol (PEG), silica, or polymers introduces electrostatic or steric repulsion, thereby preventing aggregation and maintaining a stable dispersion over extended periods [22]. This is particularly important in biomedical and catalytic applications, where maintaining uniform particle distribution is crucial for consistent performance. Core-shell structures also play a pivotal role in electrochemical stability, particularly in energy storage and conversion devices. In lithium-ion batteries, transition metal oxide nanoparticles used as cathodes suffer from structural degradation due to continuous lithium intercalation and deintercalation. Coating these cathodes with protective layers such as Li_3PO_4 or Al_2O_3 prevents unwanted side reactions with the electrolyte and mitigates phase transitions that lead to capacity fading [23]. Similarly, in electrocatalysts for water splitting, core-shell architectures reduce leaching of active metal sites, thereby extending the durability of the catalyst under harsh electrochemical conditions.

The core-shell interface is another critical factor in stability enhancement. Strong interfacial adhesion ensures mechanical robustness, preventing shell delamination or collapse under operational conditions. The degree of lattice mismatch between core and shell materials influences the overall stability, with well-matched interfaces leading to improved stress distribution and reduced defect formation. For instance, epitaxially grown shells in semiconductor heterostructures provide better structural coherence, minimizing strain-induced defects that could otherwise compromise electronic and optical performance [24]. Thus, enhanced stability and core protection in core-shell nanomaterials are achieved through a combination of chemical passivation, physical shielding, electrostatic stabilization, and interfacial engineering. These attributes make core-shell structures indispensable in advanced applications where long-term reliability, resistance to environmental factors, and preservation of functional properties are paramount.

1.3.3 Controlled Surface Chemistry and Functionalization

The surface chemistry of core-shell nanomaterials plays a crucial role in determining their interfacial interactions, stability, and functional performance across various applications. Controlled surface chemistry and functionalization allow precise tuning of properties such as solubility, catalytic activity, biocompatibility, and selective binding, making core-shell structures highly versatile for targeted applications in catalysis, sensing, drug delivery, and energy storage [25]. The ability to engineer surface characteristics through the composition and modification of the shell provides a fundamental advantage over conventional single-component nanomaterials.

One of the key aspects of surface chemistry control in core-shell nanostructures is the selective functionalization of the shell with chemical groups that impart desired

surface properties. For instance, in biomedical applications, the outer shell of nanoparticles is often modified with hydrophilic polymers, such as PEG, to enhance biocompatibility and prevent nonspecific protein adsorption [26]. Similarly, the functionalization of silica-coated nanoparticles with amino ($-\text{NH}_2$), carboxyl ($-\text{COOH}$), or thiol ($-\text{SH}$) groups enables selective conjugation with biomolecules, facilitating applications in targeted drug delivery, bioimaging, and biosensing [27]. The ability to modify the surface charge and hydrophobicity of core-shell nanomaterials is also critical for dispersion stability and controlled interactions with surrounding environments. For example, in colloidal systems, electrostatic or steric stabilization through functionalization prevents nanoparticle aggregation. The use of surfactants, polyelectrolytes, or zwitterionic coatings can regulate the zeta potential of the shell, ensuring stable dispersions in aqueous or organic media. This approach is particularly beneficial in catalytic applications where maintaining high surface area and accessibility to reactants is crucial.

In catalysis, controlled surface chemistry of core-shell nanomaterials directly influences reaction kinetics and selectivity. The shell can be engineered to create specific active sites or enhance mass transport by incorporating functional groups that regulate adsorption–desorption dynamics. For instance, in core-shell structured catalysts with noble metal cores (e.g., Pt, Pd) and transition metal oxide shells (e.g., TiO_2 , CeO_2), the shell can introduce oxygen vacancies that promote catalytic activity through charge transfer effects. Similarly, in enzyme-mimicking nanozymes, surface functionalization of the shell with ligands or co-catalysts can enhance catalytic efficiency by optimizing substrate affinity and reaction pathways [28].

In electrochemical applications, surface functionalization of core-shell materials is employed to improve ion transport, electronic conductivity, and chemical stability. For lithium-ion batteries, carbon-coated transition metal oxides enhance electrical conductivity while preventing electrolyte decomposition at the electrode surface. In supercapacitors, functionalized shells with nitrogen- or sulfur-doped carbon frameworks increase pseudocapacitive behavior, leading to higher energy storage capacity [29]. In fuel cells, surface modification of core-shell electrocatalysts with organic ligands or heteroatoms optimizes charge transfer kinetics, improving catalytic efficiency for oxygen reduction or hydrogen evolution reactions (HER) [30].

Surface chemistry control is also critical in environmental applications, particularly in pollutant removal and water purification. Functionalized core-shell nanoparticles can be designed with selective adsorption sites for heavy metal ions, organic pollutants, or toxic gases. For example, silica-coated magnetic nanoparticles functionalized with thiol ($-\text{SH}$) groups exhibit high affinity for mercury removal from water, while core-shell metal-organic frameworks (MOFs) with functionalized ligands provide tunable adsorption capacities for volatile organic compounds (VOCs) [31].

The engineering of surface chemistry extends beyond simple functionalization to include dynamic and stimuli-responsive coatings. In smart drug delivery systems, pH-sensitive or thermo-responsive polymeric shells can modulate drug release behavior, ensuring site-specific and controlled therapeutic action. Similarly, in adaptive optical materials, surface-modified core-shell nanoparticles respond to external stimuli such as light, electric fields, or magnetic fields, enabling tunable

optical and electronic properties [32]. Thus, controlled surface chemistry and functionalization of core-shell nanomaterials provide a powerful tool for tailoring material properties to specific applications. By precisely engineering the shell composition, functional groups, and interfacial interactions, researchers can optimize performance in catalysis, energy storage, biomedical applications, and environmental remediation, demonstrating the profound impact of surface chemistry in nanotechnology.

1.3.4 Tunable Optical and Electronic Properties

Core-shell nanomaterials exhibit highly tunable optical and electronic properties due to their unique structural configurations, which allow precise control over quantum confinement effects, charge transport dynamics, and light-matter interactions. These properties arise from the interplay between the core and shell materials, their relative band structures, and interfacial effects that influence charge separation, recombination, and energy transfer mechanisms. By engineering the composition, thickness, and morphology of the shell, researchers can modulate these properties to achieve tailored functionalities for applications in optoelectronics, photovoltaics, photocatalysis, and quantum dot-based technologies.

One of the most significant optical features of core-shell nanomaterials is the ability to tune their absorption and emission spectra through quantum size effects. In semiconductor core-shell QDs, the bandgap energy can be precisely controlled by varying the core size or introducing a shell with a higher or lower bandgap [14]. For example, CdSe/ZnS QDs exhibit enhanced photoluminescence efficiency and stability due to the ZnS shell, which passivates surface trap states and reduces non-radiative recombination [33]. This property makes them highly useful for applications in bio-imaging, light-emitting diodes (LEDs), and display technologies. Beyond quantum confinement, the optical properties of core-shell materials are strongly influenced by plasmonic interactions, especially in metal-core/dielectric-shell structures. In noble metal-based core-shell systems, such as Au@SiO₂ or Ag@TiO₂, LSPR effects can be tuned by modifying the core size, shell thickness, and dielectric environment. The presence of a shell alters the electromagnetic field distribution around the metal core, enabling precise spectral tuning of plasmonic absorption for applications in surface-enhanced Raman scattering (SERS), optical sensors, and photothermal therapy [34]. These tunable plasmonic features also enhance light absorption in solar cells and photocatalysts, improving their efficiency by facilitating hot-electron transfer processes. The electronic properties of core-shell nanomaterials are governed by band alignment at the core-shell interface, which dictates charge separation and carrier transport behavior. In heterostructured semiconductor core-shell materials, such as TiO₂@CdS or ZnO@CdSe, type I, type II, or quasi-type II band alignments can be engineered to optimize charge carrier dynamics. Type II heterojunctions, where the conduction and valence band edges of the core and shell are staggered, promote efficient spatial separation of electrons and holes, reducing recombination losses and enhancing photocatalytic or photovoltaic performance. This design principle is widely applied in artificial photosynthesis, perovskite solar cells, and photodetectors.

Another crucial factor in tuning electronic properties is the modulation of carrier mobility and conductivity through shell engineering. In core-shell nanowires and nanotubes, a conductive shell material can serve as an efficient charge transport layer, reducing interfacial resistance and improving electrical performance [35]. For example, Si@C core-shell nanowires exhibit enhanced lithium-ion transport in battery anodes due to the conductive carbon shell, which mitigates volume expansion and prevents capacity degradation [36]. Similarly, in transparent conducting electrodes, metal-oxide core-shell structures like Ag@ITO or Cu@ZnO provide high electrical conductivity while maintaining optical transparency, making them ideal for next-generation flexible electronics and displays. Core-shell nanomaterials also enable tunable nonlinear optical (NLO) responses and photonic applications by leveraging interfacial effects. In metal–semiconductor hybrid structures, such as Au@TiO₂ or Pt@CdS, strong plasmon–exciton coupling can modify the optical response, leading to enhanced two-photon absorption, second-harmonic generation, and other nonlinear effects. These properties are highly valuable for applications in laser technologies, optical limiters, and ultrafast photonic devices.

Furthermore, core-shell architectures can be designed to exhibit dynamic, stimuli-responsive optical and electronic behaviors. Thermochromic, electrochromic, and mechanochromic materials utilize core-shell structures to achieve reversible color changes under external stimuli [37]. For instance, core-shell nanocrystals with phase-change materials in the shell (e.g., GeTe@SiO₂) show tunable infrared reflectivity, which can be applied in smart windows and adaptive thermal coatings. Similarly, ferroelectric core-shell nanoparticles exhibit field-tunable dielectric properties, enabling applications in tunable capacitors and high-frequency electronic components [38]. Thus, the ability to precisely manipulate optical and electronic properties through core-shell nanostructuring has opened new avenues in energy conversion, sensing, optoelectronics, and quantum technologies. By leveraging band engineering, interfacial control, and plasmonic enhancements, core-shell materials provide a highly adaptable platform for next-generation functional materials with superior performance and versatility.

1.3.5 Magnetic and Catalytic Synergies

Core-shell nanomaterials exhibit remarkable magnetic and catalytic properties due to the synergistic effects between the core and shell components. By integrating different functional materials in a hierarchical structure, these nanomaterials achieve enhanced performance compared to their single-component counterparts. The interplay between magnetism and catalysis is particularly valuable in applications such as targeted drug delivery, magnetic separation, environmental remediation, and heterogeneous catalysis. The ability to tune these properties by altering the composition, shell thickness, and interfacial interactions makes core-shell architectures highly versatile for advanced nanotechnology applications. The magnetic properties of core-shell nanomaterials are strongly influenced by factors such as core size, shell composition, interfacial strain, and spin interactions. Magnetic core-shell structures typically consist of a ferromagnetic or superparamagnetic core (e.g., Fe, Fe₃O₄, Co, Ni) encapsulated by a protective shell made of oxides, noble metals, or polymers [39].

The shell serves multiple roles, such as preventing oxidation, reducing magnetic aggregation, and providing functionalization sites for biomedical or catalytic applications. For example, $\text{Fe}_3\text{O}_4@\text{SiO}_2$ nanoparticles retain their superparamagnetic behavior while gaining chemical stability and surface modifiability, making them ideal for magnetically guided drug delivery and bioseparation [40].

Exchange coupling effects at the core-shell interface can also lead to enhanced magnetic anisotropy and coercivity, particularly in structures such as $\text{Fe}@\text{Fe}_3\text{O}_4$ or $\text{Co}@\text{Pt}$. These effects enable precise control over magnetic relaxation dynamics, which is crucial for magnetic hyperthermia treatments in cancer therapy. In magnetic resonance imaging (MRI), core-shell nanostructures such as $\text{Fe}_3\text{O}_4@\text{Au}$ or $\text{Fe}_3\text{O}_4@\text{Dopamine}$ exhibit improved relaxivity, leading to superior contrast enhancement compared to conventional MRI contrast agents. In the field of catalysis, core-shell nanomaterials enhance reaction efficiency through multiple mechanisms, including electronic modulation, active site protection, and surface area optimization [13]. Core-shell catalysts often feature a catalytically active core surrounded by a shell that fine-tunes reactivity while improving stability and selectivity. In metal@metal oxide systems (e.g., $\text{Pt}@\text{CeO}_2$, $\text{Au}@\text{TiO}_2$), the shell regulates charge transfer at the interface, boosting catalytic activity in oxidation and hydrogenation reactions. These effects are particularly beneficial in energy applications such as fuel cells, HER, and CO_2 reduction.

One of the most significant advantages of core-shell nanocatalysts is their ability to prevent catalyst deactivation due to sintering, poisoning, or leaching. Noble metal catalysts such as Pt or Pd are prone to aggregation under high-temperature conditions, leading to performance degradation. Encapsulating them with a thermally stable oxide shell, as in $\text{Pt}@\text{ZrO}_2$ or $\text{Pd}@\text{Al}_2\text{O}_3$, prevents nanoparticle migration and maintains catalytic efficiency. Similarly, carbon-shell coatings in $\text{Fe}@\text{C}$ or $\text{Ni}@\text{C}$ catalysts enhance durability while preserving active site accessibility. Magnetic core-shell catalysts offer additional benefits in heterogeneous catalysis, as they enable facile recovery and recyclability using an external magnetic field. This approach is widely used in wastewater treatment, biomass conversion, and industrial chemical synthesis. For example, $\text{Fe}_3\text{O}_4@\text{SiO}_2\text{-Pd}$ nanoparticles function as effective catalysts for Suzuki coupling reactions and can be magnetically separated from reaction mixtures, minimizing catalyst loss and reducing purification costs. Bifunctional core-shell nanostructures that combine magnetic and catalytic properties further expand their applicability. In $\text{Fe}_3\text{O}_4@\text{Au}$ or $\text{Co}@\text{Pd}$ systems, the magnetic core enables external control over the catalyst's position, while the noble metal shell provides high catalytic activity for redox reactions. This synergy is particularly useful in enzymatic mimicry, where magnetically responsive peroxidase-like catalysts (e.g., $\text{Fe}_3\text{O}_4@\text{Pt}$) facilitate reactive oxygen species (ROS) generation for antibacterial and environmental remediation applications. The integration of magnetic and catalytic functionalities in core-shell architectures also plays a vital role in emerging technologies such as artificial photosynthesis, spintronics, and magnetically switchable catalysis [41]. In magneto-plasmonic nanostructures (e.g., $\text{Fe}_3\text{O}_4@\text{Ag}$, $\text{Fe}@\text{Au}$), the interplay between LSPR and magnetic effects enables light-driven catalytic processes with tunable reactivity. These hybrid materials are finding applications in sustainable energy conversion, photocatalytic water splitting, and pollutant degradation.

By leveraging interfacial effects, strain engineering, and composition tuning, core-shell nanomaterials provide an advanced platform for designing multifunctional materials with superior magnetic and catalytic performance. The ability to engineer these properties with precision opens new possibilities for nanotechnology-driven applications in medicine, energy, and environmental sustainability.

1.3.6 Mechanical Strength and Durability Enhancements

Core-shell nanomaterials offer significant improvements in mechanical strength and durability, making them ideal for a wide range of applications where structural integrity and long-term stability are critical. The combination of a strong core material with a protective or functionalized shell provides synergistic effects that enhance the mechanical properties of the composite [42]. By tailoring the composition, thickness, and interface between the core and shell, researchers can achieve materials with superior hardness, toughness, and resistance to wear, corrosion, and fatigue compared to single-component nanomaterials. This enhancement of mechanical properties is particularly useful in industries such as aerospace, automotive, biomedical, and construction, where high-performance materials are essential. The core, typically composed of a material with inherent strength (e.g., metals, ceramics, or carbon-based materials), provides structural support and ensures the material can withstand external forces without failure [43]. The shell, often made of a more flexible or durable material, serves to protect the core from mechanical stress, preventing direct exposure to harsh environmental conditions. In composites such as SiC@TiO₂ or Al₂O₃@Ni, the hard ceramic or metal core is shielded by a tough oxide or polymer shell, which helps absorb and dissipate mechanical energy, reducing the likelihood of fracture under stress.

One of the most significant advantages of core-shell nanomaterials is their ability to improve toughness without compromising strength. The shell can act as a buffer, preventing the propagation of cracks and defects that would typically weaken the material. In systems such as Cu@SiO₂ or Ti@C, the tough shell material imparts energy-dissipating properties, leading to enhanced resistance to crack growth and failure under impact. This is particularly important in high-stress applications, such as structural coatings, armor materials, and lightweight composites used in aerospace engineering. Furthermore, the shell's ability to undergo plastic deformation before fracture can prevent catastrophic failure, a phenomenon that is particularly valuable in load-bearing components [44]. For instance, in core-shell composites like Fe@C or carbon nanotube (CNT) core-shell materials, the shell undergoes deformation under load, which helps to redistribute stresses and prevent brittle fracture [45]. This mechanism can be harnessed in the design of materials for high-impact environments, including automotive crash protection systems and sporting goods, where durability and safety are paramount. In addition to improving mechanical strength, core-shell nanomaterials exhibit enhanced wear and abrasion resistance, a critical factor in industrial applications. Materials such as TiO₂@Al₂O₃ and SiC@SiO₂ show remarkable resistance to surface wear due to the hardness of the shell material, which protects the core from erosion and abrasion. This property is highly beneficial in the manufacture of cutting tools, bearings, and

coatings for machinery that must endure harsh operating conditions. Durability is also enhanced in core-shell nanomaterials through their ability to resist corrosion and environmental degradation. The shell acts as a protective barrier, shielding the core from exposure to corrosive agents, moisture, and high temperatures [46]. For example, in core-shell materials like Zn@Cu or Au@Ag, the shell material prevents oxidation and rust formation on the core, ensuring long-term stability and extending the lifespan of the material. This property is particularly valuable in applications such as marine coatings, medical implants, and electronic devices, where prolonged exposure to aggressive environments can cause material degradation. The ability of core-shell nanomaterials to enhance fatigue resistance is another crucial benefit. In cyclic loading conditions, the core-shell design helps to reduce the initiation and propagation of cracks that would otherwise lead to material failure. This is especially important in applications requiring long-term performance under repeated stress, such as in turbine blades, engine components, and structural elements in bridges and buildings [47]. The shell's ability to absorb and redistribute stress allows the material to withstand many cycles of loading without significant degradation, providing reliability and longevity in critical applications.

Finally, the versatility of core-shell nanomaterials allows for further tuning of mechanical properties through functionalization and surface modification. By introducing functional groups or coating the shell with additional layers of material, the mechanical properties of core-shell nanomaterials can be further enhanced to meet the specific requirements of various applications. This tunability makes core-shell nanomaterials highly adaptable for emerging technologies, such as flexible electronics, wearable devices, and energy storage systems, where both strength and durability are crucial.

1.4 Role in Advancing Nanotechnology

Core-shell nanomaterials are at the forefront of advancing nanotechnology due to their exceptional versatility and unique properties. Their ability to combine the strengths of multiple materials within a single structure enables the tailoring of properties that are essential for a wide range of technological applications. From energy storage to environmental sustainability, biomedicine, and electronics, the incorporation of core-shell structures has led to significant breakthroughs in these fields, pushing the boundaries of what is possible with traditional materials. The functionalization of core-shell nanomaterials allows for precise control over their properties, leading to innovations in various domains that were previously unachievable [48]. The role of core-shell nanomaterials in advancing nanotechnology is closely linked to their adaptability, which makes them indispensable for both current and emerging applications. Their ability to exhibit tunable properties, such as optical, electronic, and mechanical characteristics, is critical for developing next-generation technologies that address challenges across energy, health, and environmental sectors [2]. These materials are also central to the development of sustainable solutions, offering enhanced efficiency, longevity, and performance in a variety of contexts. As research continues to uncover new ways to exploit the

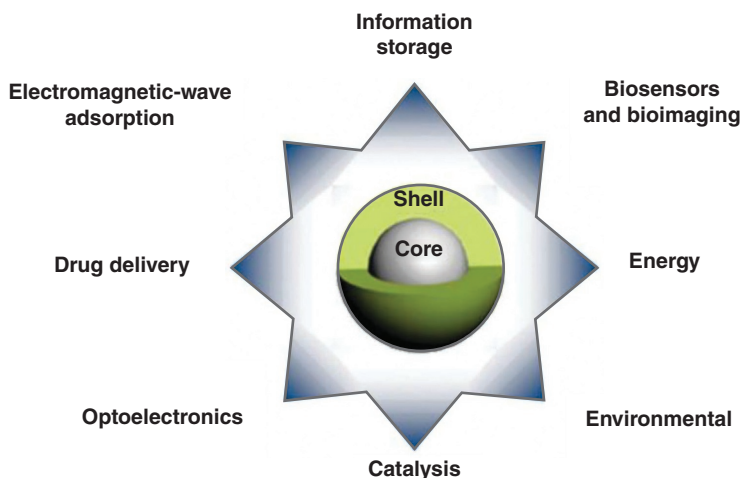


Figure 1.3 Multifunctional roles of core-shell structures in advanced nanotechnology including catalysis, optoelectronics, drug delivery, electromagnetic-wave adsorption, biosensing, energy storage, environmental remediation, and information storage. [13]/with permission of Royal Society of Chemistry.

potential of core-shell nanomaterials, their impact on technological advancement is becoming more profound. From improving the efficiency of energy systems to enabling targeted drug delivery and driving innovations in smart technologies, core-shell materials are playing a pivotal role in shaping the future of nanotechnology. The following subsections explore some of the most important areas where core-shell nanomaterials are contributing to technological advancement. Core-shell structures have gained significant attention due to their versatile applications in advanced nanotechnology, as shown in Figure 1.3, including catalysis, optoelectronics, drug delivery, and energy storage.

1.4.1 Energy Storage and Conversion

Core-shell nanomaterials are revolutionizing energy storage and conversion technologies by offering enhanced performance, stability, and efficiency over traditional materials. These materials are particularly valuable in energy systems that require high energy density, fast charge/discharge cycles, and long-term durability, such as batteries, supercapacitors, and fuel cells. The unique properties of core-shell structures, including their ability to combine dissimilar materials with tailored interfaces, enable the optimization of electrochemical behavior, leading to significant improvements in energy storage and conversion devices. In battery technologies, core-shell nanomaterials are increasingly being used to enhance the performance of anodes and cathodes. For example, in lithium-ion batteries, core-shell particles, such as silicon-based cores coated with carbon or metal oxide shells, help address one of the key challenges in battery design—volume expansion during cycling [49]. Silicon, with its high theoretical capacity for lithium-ion storage, undergoes significant expansion and contraction during charge/discharge cycles, which can

lead to material degradation and capacity loss [50]. By encapsulating the silicon core with a thin, flexible carbon or metal oxide shell, this issue is mitigated, as the shell provides structural integrity, preventing excessive expansion while allowing for high-capacity charge storage. The result is a significant increase in the lifespan and cycling stability of the battery, alongside improved energy density. Similarly, in sodium-ion batteries and other alternative battery technologies, core-shell nanomaterials provide enhanced performance by improving conductivity, reducing internal resistance, and ensuring more efficient ion transfer between the core and shell [51]. The shell material can be engineered to provide a stable and conductive environment for the core material, resulting in a higher rate of charge/discharge and better overall performance. The design of core-shell nanomaterials for energy storage is not limited to batteries; they are also widely used in supercapacitors. In supercapacitors, where high power density and fast charging/discharging are essential, core-shell structures can improve the electrode surface area and increase the charge storage capacity, thus enhancing the overall energy storage efficiency [52].

For energy conversion, core-shell nanomaterials also play a crucial role in optimizing the efficiency of solar cells, fuel cells, and thermoelectric devices. In photovoltaic applications, the use of core-shell nanostructures in materials like QDs or metal-semiconductor hybrids has shown promising results in improving light absorption, charge separation, and charge carrier mobility [53]. The unique optical properties of core-shell structures, which allow for the tuning of absorption wavelengths and enhanced light trapping, contribute to better energy conversion efficiency in solar energy harvesting. The core-shell interface can also facilitate better electron transport and reduce recombination losses, increasing the overall performance of solar cells [54]. In fuel cells, core-shell nanomaterials are employed to enhance catalytic activity and reduce the use of expensive precious metals such as platinum. By designing core-shell catalysts with a noble metal core and a non-noble metal shell, researchers have been able to improve the electrocatalytic performance of the fuel cell while lowering material costs [55]. The shell's role is to facilitate the adsorption of reactants and promote faster reaction kinetics, while the core provides the necessary stability and conductivity to maintain consistent performance over time. Furthermore, core-shell nanomaterials are being explored in thermoelectric devices, where the conversion of heat into electrical energy is a key concern [56]. In these applications, the unique structure of core-shell materials can help optimize the thermal and electrical conductivity properties, allowing for improved thermoelectric efficiency. The core and shell materials can be selected to have complementary properties that enhance heat management and electron mobility, making core-shell nanomaterials ideal candidates for future thermoelectric energy conversion devices.

Overall, the versatility of core-shell nanomaterials in energy storage and conversion applications lies in their ability to combine the best properties of different materials at the nanoscale. By carefully tailoring the core and shell components, it is possible to create materials that address specific challenges in energy efficiency, stability, and performance. As research in this area continues to grow, core-shell nanomaterials are expected to play an increasingly important role in advancing the next generation of energy storage and conversion technologies, contributing to the development of more efficient, sustainable, and high-performance energy systems.

1.4.2 Environmental Applications and Sustainability

Core-shell nanomaterials are increasingly recognized for their potential in environmental applications, particularly in areas related to sustainability, pollution control, and resource management. Their unique properties enable them to address key environmental challenges, including water purification, air quality management, waste treatment, and energy efficiency. The multifunctional nature of core-shell structures allows for the development of materials that not only improve environmental outcomes but also enhance the overall sustainability of industrial processes and everyday technologies. One of the most significant applications of core-shell nanomaterials in environmental protection is in water treatment and purification. Water scarcity and contamination are critical global issues, and the demand for effective water purification technologies is growing [57]. Core-shell materials, especially those with photocatalytic or adsorptive properties, are highly effective in breaking down harmful contaminants such as heavy metals, organic pollutants, and microbial pathogens. For instance, core-shell nanoparticles made of metal oxide cores (e.g., titanium dioxide) with a shell of functionalized carbon or polymer coatings can serve as highly active photocatalysts under UV light. These nanomaterials can degrade organic pollutants and kill bacteria, providing a sustainable approach to water decontamination [58]. The core-shell structure allows for optimal exposure of the catalytic surface, enhancing the material's reactivity and stability, and ensuring long-lasting performance in purification processes. In addition to water treatment, core-shell nanomaterials are gaining attention for their role in air pollution control. Nanocatalysts, composed of a reactive core material surrounded by a protective shell, are used in the catalytic conversion of harmful gases such as carbon monoxide (CO), nitrogen oxides (NO_x), and VOCs [59]. The shell material, often a metal oxide or carbon, acts as a stabilizer, protecting the active core and facilitating the adsorption and transformation of pollutants into less harmful substances. This is particularly beneficial in automotive exhaust systems and industrial applications, where air quality regulations require efficient removal of toxic gases. The enhanced surface area and tunable chemical properties of core-shell nanomaterials make them highly effective in these applications, offering better catalytic efficiency and longer operational lifetimes compared to conventional catalysts.

Another promising application is in the field of environmental remediation and waste treatment. Core-shell nanomaterials can be engineered to capture and degrade hazardous substances, such as heavy metals and pesticides, from contaminated soils or industrial effluents. For example, core-shell nanoparticles with magnetic cores and functionalized shells can be used for the selective removal of toxic metals from wastewater [60]. The magnetic properties of the core allow for easy separation and recycling of the nanoparticles after the cleanup process, ensuring that the materials can be reused, which adds to the sustainability aspect of this technology. Additionally, core-shell materials can be employed to remove oils and hydrocarbons from water and soil, addressing oil spills and other environmental disasters with enhanced efficiency and lower environmental impact [61]. Core-shell nanomaterials are also being explored for energy-efficient environmental solutions, such as the development of energy-efficient coatings for buildings and other infrastructure.

The use of core-shell composites in thermal insulating materials allows for better heat retention and temperature regulation, reducing the need for external energy inputs in heating and cooling systems [62]. These energy-saving applications contribute to the reduction of carbon footprints and energy consumption in both residential and industrial buildings, making them an important component of sustainable construction and urban planning.

In the field of renewable energy, core-shell nanomaterials contribute to environmental sustainability by improving the efficiency and performance of solar energy devices and other renewable technologies. For example, in solar cells, core-shell QDs and nanostructures can enhance light absorption and improve energy conversion efficiency, reducing the overall carbon footprint of energy production [15]. The integration of core-shell materials in solar technologies can also lower the cost of energy production, making renewable sources more competitive with traditional fossil fuels. Beyond direct applications in pollution control and resource management, core-shell nanomaterials contribute to the broader concept of sustainability through their potential in recycling and waste reduction. For instance, in electronic waste (e-waste) recycling, core-shell nanoparticles can be used to selectively extract valuable metals such as gold, silver, and copper from discarded electronic devices [63]. The shell material can be designed to interact with specific metals, ensuring efficient extraction and minimizing the release of hazardous substances. This capability not only supports the recovery of valuable materials but also reduces the environmental burden associated with e-waste disposal. The ability to engineer core-shell nanomaterials with specific functional properties makes them highly suitable for a wide range of environmental applications [2]. By addressing key challenges such as water and air pollution, waste treatment, energy efficiency, and renewable energy development, these materials are paving the way for a more sustainable and environmentally friendly future. As research and development continue, core-shell nanomaterials are expected to play an even more significant role in advancing global sustainability efforts, providing solutions to some of the most pressing environmental issues of our time.

1.4.3 Biomedical Innovations and Drug Delivery

Core-shell nanomaterials are rapidly advancing biomedical applications, particularly in drug delivery, imaging, and therapeutic treatments. The unique structural and chemical properties of core-shell nanoparticles make them ideal candidates for targeted drug delivery, enhanced bioimaging, and the development of new therapeutic modalities [64–66]. These materials can be engineered to offer highly controllable release profiles, biocompatibility, and multifunctionality, positioning them at the forefront of modern medicine. The ability to design core-shell structures with tailored properties enables the development of nanomaterials that can address the complex demands of biomedical applications, improving treatment efficacy and reducing side effects. One of the most significant applications of core-shell nanomaterials in biomedicine is in targeted drug delivery [67]. The core-shell architecture allows for the encapsulation of therapeutic agents within the core, while the shell can be functionalized to provide specific targeting capabilities. For instance,

the shell can be decorated with ligands, antibodies, or peptides that bind selectively to receptors on the surface of target cells or tissues, such as cancer cells or inflamed tissue [68]. This selective targeting reduces the systemic distribution of the drug, thereby minimizing off-target effects and enhancing the therapeutic efficacy of the treatment. The core material can be designed to encapsulate a wide range of therapeutic agents, including small molecules, proteins, RNA, and even gene-editing tools, such as CRISPR [69]. The shell can provide stability and protection to these fragile agents, preventing their premature degradation and ensuring their efficient delivery to the target site.

The controlled release of drugs is another major advantage of core-shell nanomaterials in drug delivery. By altering the composition of the core and shell, the release rate of the encapsulated drug can be precisely regulated, enabling sustained or triggered release depending on the needs of the treatment. For example, the core can be made from a biodegradable polymer that breaks down over time, allowing for the gradual release of the drug. Alternatively, the shell can be responsive to external stimuli, such as pH, temperature, or light, enabling the release of the drug in response to the specific conditions at the disease site [70]. This “smart” drug delivery approach allows for more efficient treatments by ensuring that drugs are delivered only when and where they are needed, improving patient outcomes and reducing the frequency of dosing. Core-shell nanomaterials are also playing a pivotal role in the development of nanocarriers for gene therapy [71]. The core-shell structure can encapsulate genetic material, such as DNA or RNA, and protect it from degradation in the bloodstream, while the shell can be modified to enhance cellular uptake and facilitate endosomal escape. This capability is especially important for the development of non-viral gene delivery systems, which offer a safer alternative to viral vectors that can carry the risk of immune reactions and insertional mutagenesis. Core-shell nanoparticles can also improve the stability of genetic material, providing an effective vehicle for gene-editing tools and therapies [72]. As gene therapies continue to advance, core-shell nanomaterials will play an increasingly vital role in their translation from research to clinical application.

Beyond drug delivery, core-shell nanomaterials are making significant contributions to biomedical imaging and diagnostic applications. The core-shell structure allows for the incorporation of various imaging agents, such as fluorescent dyes, magnetic nanoparticles, or radioisotopes, within the core, while the shell can be designed to enhance the stability and biocompatibility of the particles. These nanoparticles can be used in a variety of imaging modalities, including MRI, computed tomography (CT), positron emission tomography (PET), and fluorescence imaging. By integrating both therapeutic and diagnostic functions into a single nanoparticle (a strategy known as “theranostics”), core-shell nanomaterials enable more precise diagnosis, real-time monitoring of treatment efficacy, and the delivery of targeted therapies. Core-shell nanomaterials are also being explored for their potential in regenerative medicine [73]. The core can be made from biocompatible materials that promote tissue regeneration, while the shell can be functionalized with growth factors, peptides, or biomolecules that stimulate cell proliferation and tissue repair. For instance, core-shell nanoparticles have been used in bone tissue engineering to deliver osteogenic growth factors to sites of bone injury or degeneration.

By combining the regenerative properties of the core with the bioactive molecules on the shell, core-shell nanomaterials can accelerate the healing process and improve the outcomes of tissue repair and regeneration [74]. The development of core-shell nanomaterials for biomedical applications requires careful consideration of factors such as biocompatibility, biodegradability, and toxicity. However, advances in material design and surface functionalization have led to the creation of nanoparticles that are not only effective but also safe for use in medical applications. The versatility and multifunctionality of core-shell nanomaterials provide significant opportunities for improving healthcare outcomes, from more effective drug delivery and gene therapy to enhanced diagnostic imaging and regenerative medicine.

1.4.4 Electronics, Photonics, and Wearable Technologies

Core-shell nanomaterials are making significant strides in the fields of electronics, photonics, and wearable technologies due to their ability to provide enhanced properties such as conductivity, optical response, and mechanical flexibility. Their unique architecture, with a functional core and a shell that can be tailored for specific functions, enables the design of materials with a combination of characteristics that are difficult to achieve with conventional single-component nanomaterials. As a result, core-shell structures are increasingly being explored for applications in flexible electronics, optoelectronics, sensors, and next-generation wearable devices [75]. In electronics, core-shell nanomaterials offer exceptional advantages in the development of high-performance conductors and semiconductors. For example, the core can consist of a material with high electrical conductivity, such as gold, copper, or CNTs, while the shell can be made from a semiconducting or insulating material [76]. This combination allows for the design of nanoparticles that exhibit both high conductivity and tailored electronic properties, making them ideal candidates for use in transistors, integrated circuits, and other electronic components. Additionally, the core-shell structure can be used to enhance the stability of nanomaterials in electronic devices, protecting the conductive core from oxidation or degradation while maintaining efficient charge transport properties.

Core-shell nanomaterials also hold great potential in photonics, particularly in applications such as LEDs, solar cells, and photodetectors [77]. The optical properties of core-shell nanoparticles can be finely tuned by adjusting the composition of the core and shell, allowing for the design of materials with specific absorption and emission characteristics. For example, core-shell QDs are widely used in photonics due to their ability to emit light at precisely controlled wavelengths, which is crucial for applications in displays, lighting, and solar energy conversion [78]. By altering the shell material, the surface states of the core can be controlled, leading to improvements in photoluminescence efficiency, stability, and optical properties. In the field of solar energy, core-shell nanomaterials are being explored for use in next-generation solar cells. The core can be made from a highly efficient light-absorbing material, such as cadmium telluride or silicon, while the shell can be engineered to improve charge separation, enhance stability, and reduce recombination losses [15]. The shell can also protect the core material from environmental degradation, such as moisture and oxidation,

which is a significant challenge in the long-term performance of solar devices. Core-shell structures have the potential to increase the efficiency and durability of photovoltaic devices, making them a promising solution for renewable energy applications. Wearable technologies represent one of the most exciting areas where core-shell nanomaterials are making an impact. As demand grows for lightweight, flexible, and durable devices that can be worn on the body, core-shell nanomaterials offer a unique solution due to their ability to combine strength, flexibility, and conductivity. For example, core-shell nanoparticles can be incorporated into flexible substrates to create stretchable electronics, such as sensors, displays, and communication devices [79]. The shell material can be designed to provide mechanical flexibility, while the core material can impart conductivity and electronic functionality, allowing for the creation of devices that can withstand deformation without compromising performance. This combination of properties is critical for applications in health monitoring, smart clothing, and other wearable technologies.

Core-shell nanomaterials are also being used in the development of sensors for wearable applications. The core can be engineered to have specific interactions with target molecules or environmental conditions, such as temperature, humidity, or pH, while the shell can be functionalized with recognition elements or catalysts that enable sensitive and selective detection. For instance, core-shell nanomaterials have been used in wearable biosensors that monitor glucose levels, detect environmental pollutants, or track physiological parameters such as heart rate and sweat composition [80]. These sensors are essential for personalized healthcare, providing real-time monitoring and data collection that can inform treatment decisions and improve patient outcomes. In the rapidly growing field of optoelectronics, core-shell nanomaterials are being investigated for their potential in applications such as light-emitting devices, photodetectors, and lasers. By manipulating the core-shell architecture, researchers can control the band gap, optical absorption, and emission characteristics of the material, enabling the design of more efficient devices for use in communication systems, imaging, and sensing technologies. For example, core-shell QDs are being explored for use in LEDs, where they offer improved color purity and energy efficiency compared to traditional semiconductor materials [81]. Similarly, in photodetector applications, core-shell structures can be engineered to enhance light absorption and improve the device's sensitivity, paving the way for advancements in optical communication and sensing technologies. Core-shell nanomaterials are also integral to the development of flexible, stretchable, and highly efficient batteries and energy storage devices for wearable technologies [82]. The core-shell structure allows for improved charge storage capacity and cycling stability, which is essential for portable electronics that require long battery life. By designing core-shell electrodes with tailored ion diffusion paths and optimized structural stability, it is possible to increase the efficiency and longevity of wearable energy storage systems. Additionally, the mechanical flexibility of core-shell materials makes them ideal for integration into wearable devices without sacrificing performance, enabling the development of lightweight, long-lasting energy solutions for the growing demand in wearable electronics.

1.4.5 Emerging Fields and Future Prospects

The unique characteristics of core-shell nanomaterials position them as a key technology for emerging fields and future innovations across various domains. As the understanding of these materials deepens and synthesis techniques advance, their potential applications continue to expand, offering exciting possibilities in areas like quantum computing, environmental remediation, and advanced manufacturing. The adaptability of core-shell structures—where the properties of both the core and the shell can be tailored independently—makes them particularly well-suited to meet the demands of cutting-edge technologies in energy, medicine, and beyond. In the field of quantum computing, core-shell nanomaterials are gaining attention for their ability to facilitate quantum state manipulation and enhance coherence times. QDs, for example, can be designed with specific core-shell architectures that control electronic interactions and allow for more stable and efficient qubit operation. The shell can be engineered to reduce electron scattering, which is crucial for maintaining the quantum state over longer periods. Furthermore, core-shell nanomaterials could lead to the development of optically active quantum devices, where the core can absorb and emit light at precisely controlled wavelengths, facilitating the creation of photonic qubits. This application is still in its early stages but holds great promise for the advancement of quantum technologies that will revolutionize computing power. In environmental remediation, core-shell nanomaterials are being explored for their ability to address some of the most pressing challenges related to pollution, resource recovery, and sustainability. Their ability to selectively interact with and remove harmful pollutants, such as heavy metals, organic contaminants, and radioactive substances, makes them ideal candidates for water and soil purification applications. For instance, core-shell nanoparticles with a reactive core (such as iron oxide) and a protective shell (such as carbon or silica) can be used to capture and degrade pollutants through catalytic processes. The shell can also prevent the release of toxic substances from the core, enhancing both the stability and effectiveness of the materials in environmental applications. Additionally, core-shell structures can be designed to be magnetically responsive, facilitating the easy removal of contaminants from water systems.

As advanced manufacturing techniques continue to evolve, core-shell nanomaterials are likely to play an essential role in the fabrication of next-generation devices and components. These materials can be incorporated into additive manufacturing processes, such as 3D printing, to create highly functionalized, multi-material components with specific properties tailored to their intended applications. The ability to integrate different materials into the core and shell of nanoparticles allows for the development of hybrid materials with unprecedented combinations of mechanical, electrical, and thermal properties. For example, core-shell nanomaterials could be used to produce high-strength composites that retain flexibility, enabling the creation of lightweight, durable structures for use in aerospace, automotive, and construction industries. These materials could also be used in the creation of multifunctional coatings for various applications, such as corrosion resistance, self-healing materials, and antifouling surfaces. In energy harvesting and storage, the exploration of core-shell nanomaterials is opening new possibilities for improving the efficiency

and scalability of technologies like solar cells, supercapacitors, and batteries. For solar energy, core-shell materials are being studied for their potential to increase light absorption and improve charge transport efficiency, leading to the development of more efficient solar cells. In energy storage systems, core-shell nanostructures are being developed to enhance the performance of electrodes by optimizing ion diffusion pathways and improving charge/discharge cycles. Additionally, as the demand for flexible and wearable energy devices grows, core-shell materials offer the mechanical flexibility and performance needed for next-generation energy solutions, such as bendable batteries and energy-harvesting textiles.

The medical field is also witnessing breakthroughs in the use of core-shell nanomaterials for personalized medicine and targeted therapies. For example, in drug delivery, core-shell nanoparticles can be engineered to encapsulate drugs in the core, while the shell can be functionalized with targeting ligands to direct the delivery to specific cells or tissues. This approach not only improves the precision and efficacy of treatments but also minimizes side effects by reducing off-target interactions. Furthermore, core-shell nanomaterials can be used in diagnostic applications, such as imaging and biosensing, where the core material provides contrast or detection properties, and the shell can protect the core from degradation or functionalize it for specific interactions with biomarkers. As the field of nanomedicine continues to evolve, core-shell structures will be central to the development of innovative therapies and diagnostic tools that could revolutionize healthcare.

Looking toward the future, core-shell nanomaterials are poised to drive advances in sustainable technologies. As the demand for eco-friendly and renewable technologies increases, the design of core-shell structures with optimized environmental performance will play a significant role in areas such as green energy, sustainable agriculture, and waste management. For instance, core-shell nanoparticles could be designed for efficient light harvesting in bio-photovoltaic systems or to enable sustainable agricultural practices by delivering fertilizers or pesticides in a controlled, environmentally friendly manner. Additionally, the integration of core-shell materials into catalytic processes could pave the way for more efficient industrial applications that reduce energy consumption and waste. The future prospects of core-shell nanomaterials are vast and varied, with their unique properties enabling breakthroughs across a wide range of emerging fields. As research in nanotechnology progresses, the potential for core-shell materials to revolutionize industries—from quantum computing and energy storage to environmental sustainability and personalized medicine—continues to grow. With further advancements in synthesis methods, characterization techniques, and application development, core-shell nanomaterials will undoubtedly continue to play a pivotal role in shaping the next generation of technological innovations.

1.5 Conclusion

Core-shell nanomaterials represent a transformative class of materials that have revolutionized the landscape of nanotechnology. Their unique ability to combine the properties of distinct materials in a single structure offers unprecedented

opportunities across diverse fields such as energy, environment, and medicine. By encapsulating a core material within a shell, these structures enable a level of control over physical, chemical, and electronic properties that single-component nanomaterials cannot match. From enhanced stability and protection of the core to tunable optical and electronic behaviors, the versatility of core-shell architectures positions them at the forefront of scientific research and technological development. The historical evolution of core-shell materials, from early colloidal chemistry concepts to modern advancements in nanotechnology and synthesis methods, has paved the way for their widespread application. Their significance in both industrial and research domains is undeniable, offering solutions to complex challenges in energy storage, energy conversion, environmental sustainability, and medical innovations. By enabling precise control over material properties at the nanoscale, core-shell nanomaterials have also facilitated progress in new fields such as quantum computing, advanced manufacturing, and targeted drug delivery, demonstrating their vast potential for future developments. As the research and development of core-shell nanomaterials continue to advance, the possibilities for their application expand further. Their impact on the future of nanotechnology is profound, driving innovations in fields ranging from flexible electronics and renewable energy to personalized healthcare and environmental remediation. Moving forward, the continued exploration of these materials will undoubtedly lead to even more groundbreaking discoveries, solidifying their place as a cornerstone of modern nanoscience and engineering.

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