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A Concise Overview of Recent Developments and Uses in Nano-Silica and Nanoparticles Encased in Silica

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Abstract

Nano-silica and silica-coated nanoparticles have gained significant attention lately due to their exceptional chemical and physical properties, including a high surface area-to-volume ratio, adjustable porosity, thermal and chemical stability, biocompatibility, and ease of surface modification. These characteristics make them versatile materials applicable in various scientific and industrial sectors. Their ability to control particle size, shape, and surface traits allows them to be effectively utilized in catalysis, drug delivery, biosensing, and environmental remediation. Silica nanoparticles are particularly valued for their chemical inertness, low toxicity, and capacity for functionalization with organic or inorganic molecules, enabling the creation of multifunctional hybrid materials. Their porous structure and biocompatibility enable efficient drug carrier systems for controlled release and targeted therapies. Furthermore, silica serves as a solid support for active metal sites, enhancing catalytic efficiency and selectivity. Silica-based nanoparticles are beneficial for environmental applications, such as dye removal from polluted water, heavy metal adsorption, and contaminant degradation. Silica-coated metal nanoparticles merge the protective advantages of silica shells with the desired optical, electrical, and magnetic properties of metals, thereby enhancing the nanoparticles' lifespan and functionality while improving dispersion and preventing agglomeration. Recent advances in synthesis techniques, such as sol-gel processes, microemulsion technologies, and surface grafting, allow for better control over the size, thickness, and efficacy of silica coatings. This review discusses the primary applications of nano-silica, recent innovations in silica-coated nanoparticle technology, and its growing potential in biomedicine, environmental sustainability, catalysis, and sensing.

Keywords: Nano-silica, silica-coated nanoparticles, biocompatibility, catalysis, biomedical applications.

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INTRODUCTION

Nanoparticles, ranging from 1 to 100 nm, display optical, catalytic, electronic, and magnetic properties that are size-dependent and markedly different from those of bulk materials. This unique characteristic facilitates their extensive use in various fields, including medicine, electronics, environmental engineering, and agriculture [1].

Among the diverse range of nanomaterials, silica nanoparticles (SiO_2 NPs) are particularly favored due to their substantial surface area, adjustable porosity, biocompatibility, chemical inertness, and hydrophilic properties [2]. These attributes render SiO_2 particularly suitable for applications in drug delivery, adsorption, catalysis, bioimaging, and sensing.

Despite the wealth of literature available, several challenges remain. A significant number of prior studies tend to offer descriptive insights rather than analytical evaluations, often lacking a thorough comparison of synthesis methods, coating techniques, and performance in applications. Furthermore, the impact of critical parameters—such as coating thickness, porosity, and surface chemistry—on the functional characteristics of SiO_2-based materials is frequently not addressed in depth in the majority of existing reviews [3–5].

There is a notable absence of a comprehensive and critical assessment that links synthesis parameters to structure and application performance for SiO_2 and silica-coated metal nanoparticles. This article aims to provide:A comparative and critical examination of synthesis methods and an assessment of the effects of coating thickness on optical and magnetic properties.

CHARACTERISTICS AND COMPOSITE APPLICATIONS OF SILICON DIOXIDE (SIO_2)

The combination of silica with metals (e.g., Au, Ag, Fe_3O_4) results in core–shell systems that exhibit enhanced optical or magnetic functionality while benefiting from the protective, stabilizing nature of the silica shell Silicon dioxide exists in amorphous and crystalline forms and is recognized for its thermal stability, electrical insulation, and biological compatibility [6]. Mesoporous silica nanoparticles (MSNs) offer high pore volume and surface area (>800 m²/g), enabling drug delivery (mesoporous structures providing high loading capacity)and enhanced catalytic performance [7].

SiO_2 forms stable composites with TiO_2, Fe_3O_4, Au, Ag, and polymers, leading to improved dispersibility, enhanced electron transport, and reduced aggregation. TiO_2–SiO_2 composites, for instance, demonstrate superior photocatalytic degradation due to improved charge separation [8].

SYNTHESIS AND FUNCTIONALIZATION OF NANO-SILICA

A range of synthesis methods is utilized to produce nano-silica, each varying in aspects such as particle size regulation, cost-effectiveness, scalability, and environmental compatibility. Nano-silica can be synthesized through physical, chemical, and biological pathways and the major synthesis routes of SiO_2 Nanoparticles is shown in Figure1. A critical comparison is presented in Table 1.

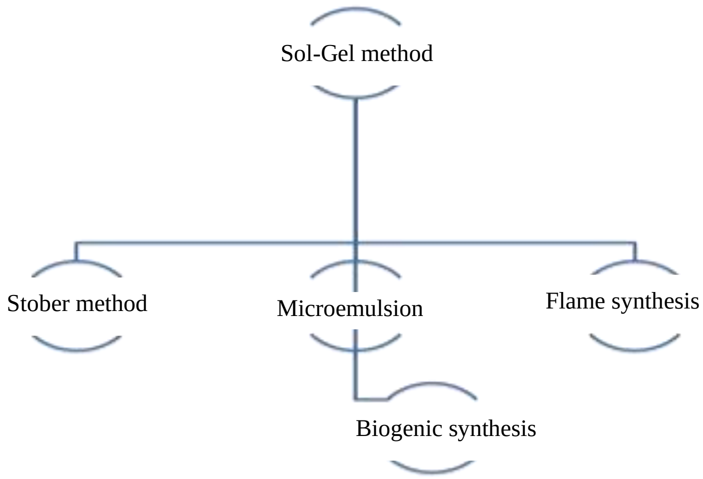

Figure 1. Major synthesis routes of SiO_2 nanoparticles.

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Table 1. Comparison of major Sio_2 synthesis techniques.

Method	Size	Advantages	Limitations	Scalability
Sol–gel [9]	20–200 nm	Tunable porosity	Slow, pH dependent	Moderate
Stöber [10]	50–500 nm	Monodisperse spheres	Limited <20 nm	High
Microemulsion [11]	5–50 nm	Excellent nanoscale control	Low yield, expensive surfactants	Low
Flame synthesis [12]	10–100 nm	Industrial-scale purity	Poor monodispersity	Very High
Biogenic [13]	20–80 nm	Eco-friendly	Poor reproducibility	Low–Moderate

Functionalization Strategies

Silane coupling agents (for instance, APTES, MPTMS) facilitate the incorporation of amine, thiol, or carboxyl groups for subsequent conjugation. Polymer coatings such as PEG improve biocompatibility and inhibit protein adsorption. The integration of metal oxides (TiO_2, Fe_3O_4) enhances photocatalytic and magnetic properties [14–16].

Critical Insight

Despite the well-established nature of functionalization strategies, achieving consistent shell thickness and reproducible surface chemistry poses significant challenges, especially during the scaling process.

SURFACE MODIFICATION AND SILICA COATING STRATEGIES

Silica coating plays a vital role in enhancing the stability, dispersibility, and functional efficacy of metal nanoparticles for various applications, including catalysis, biomedicine, sensing, and water treatment. The effectiveness of silica encapsulation is significantly influenced by the surface chemistry of the nanoparticles and the technique utilized for silica growth.

Metal nanoparticles may have better surface adhesion when coated with silica, a well-known way to make things more stable, biocompatible, and functional. The process usually starts with making silica nanoparticles in an alkaline water solution. Thicker silica shells are later made by breaking down and condensing tetraethyl orthosilicate (TEOS), which is a common silicon alkoxide precursor [17].

Strategies for Surface Functionalization

To achieve efficient silica coating, it is essential to maintain precise control over the interfacial characteristics of the metal nanoparticles. Surface functionalization is critical for ensuring appropriate nucleation and uniform silica growth.

Key Strategies Encompass

Utilization of small molecules, synthetic polymers, or biopolymers that introduce reactive groups (e.g., –OH, $–NH_2$, –COOH) to facilitate silica deposition.Ligand-exchange methods, particularly for hydrophobic nanoparticles (e.g., oleylamine-capped particles), where hydrophobic ligands are substituted with silica-compatible groups such as methoxypoly(ethylene glycol) silane (mPEG-silane) or 3-aminopropyltriethoxysilane (APTES).

Surface activation through mild oxidation or pH modification to promote silica condensation on the nanoparticle surface.Pre-coating with intermediate layers (e.g., PVP, citrate, or polydopamine) to enhance adhesion and enable uniform shell formation.

These functionalization processes ensure robust interfacial bonding, enhance stability during silica growth, and provide improved control over shell thickness.

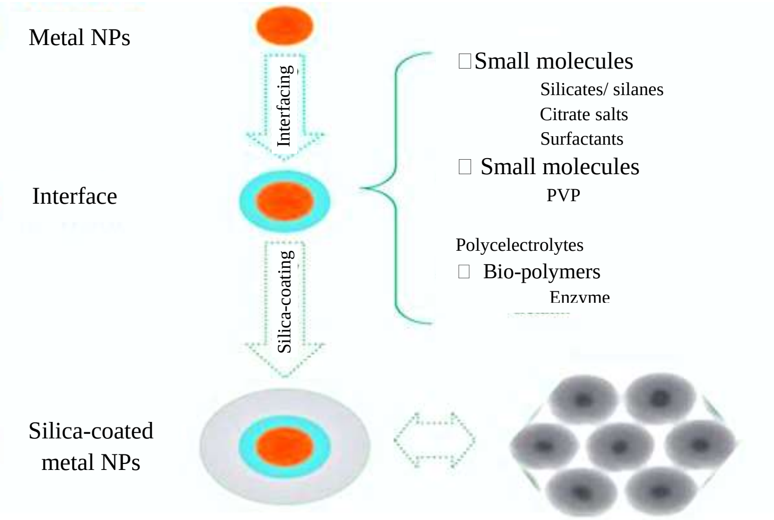

Figure 2. Silica-Coating techniques [18].

Silica Coating Methods

Figure 2 shows the key steps in converting bare metal nanoparticles into hybrid nanostructures coated uniformly with silica. A range of well-established techniques is used to deposit silica onto metal nanoparticle surfaces. The most widely adopted approaches are described below.

- *Stöber Process:* The Stöber process represents a traditional sol–gel technique that is widely employed for the coating of metal nanoparticles, especially those that are citrate-capped, such as Au, Ag, Co, and Fe_3O_4. In this procedure, tetraethyl orthosilicate (TEOS) is subjected to controlled hydrolysis and condensation within an ethanol–water–ammonia environment, resulting in the formation of uniform silica shells encasing the nanoparticles. This method allows for meticulous regulation of shell thickness and particle monodispersity, yielding coatings that typically vary from 10 to over 100 nm, contingent upon the concentration of TEOS and the duration of the reaction [19].
- *Hydrolysis/Polycondensation Approach:* This technique commences the growth of silica by means of TEOS hydrolysis on the surfaces of ligand-functionalized nanoparticles. It is particularly advantageous for the creation of thin silica layers measuring between 5 and 20 nm. Ongoing polycondensation leads to the development of thicker silica shells exceeding 40 nm, which exhibit enhanced durability, chemical resistance, and prolonged colloidal stability. This method is extensively utilized in biomedical and catalytic fields where both protective and functional attributes are essential [20].
- *Layer-by-Layer (LbL) Silica Deposition:* The Layer-by-Layer approach entails the sequential application of silica and/or polymer intermediate layers. Its primary benefits encompass: Enhanced dispersion of nanoparticles, minimized aggregation, and adjustable shell thickness through multiple deposition cycles. The capability to integrate functional layers (such as dyes, drugs, peptides, catalysts) provides exceptional versatility for the design of multifunctional hybrid nanostructures, which are employed in drug delivery, imaging, catalysis, and surface-enhanced Raman scattering (SERS) enhancement.

Thin vs Thick Silica Coatings – Effects and Comparisons

The application of silica coatings on metal nanoparticles is essential for controlling their stability, optical characteristics, biocompatibility, and overall functional efficacy. The thickness of the silica layer significantly affects the physicochemical properties and the appropriateness of the nanoparticles for various uses. Tables 2–4 present a comprehensive comparison of thin versus thick silica coatings, detailing their respective benefits, drawbacks, and relevance in cutting-edge nanotechnology applications.

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APPLICATIONS OF NANO-SILICA AND COATED NANO-SILICA

Nano-silica (SiO_2) and its coated forms have amazing physical and chemical properties, such as a large surface area, adjustable porosity and better resistance to heat and chemicals. These attributes have resulted in widespread applications across several domains. This section examines the principal uses of nano-silica, accompanied by pertinent references. Figure3. Shows the application map of SiO_2-based nanomaterials.

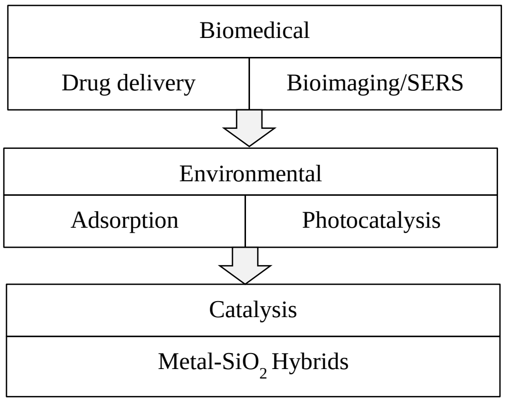

Figure 3. Application map of sio_2-based nanomaterials.

Construction and Cement Composites

The performance of cementitious materials is significantly improved by nano-silica through various mechanisms. Enhanced mechanical strength and durability: The interaction between nano-silica and calcium hydroxide (CH) produces additional calcium-silicate-hydrate (C-S-H) gel, leading to a denser microstructure and improved compressive strength and durability of concrete [25].

Table 2. Thin Vs thick silica coating on metal nanoparticles.

S. No.	**Thin Coating (5–20 nm)**	**Thick Coating (>40 nm)**
	Metal core with thin SiO_2 shell	Metal core with thick SiO_2 shel
1	Optical enhancement	High stability
2	High SERS signal	Lower enhancement
3	Lower protection	Strong oxidation resistance

Table 3. Comparison of thin vs. thick silica coatings on core–shell nanoparticles.

Coating Thickness	**Advantages**	**Limitations**	**Applications**
Thin Shell (≈5–20 nm)	Strong optical enhancement; significantly boosts SERS activity; maintains magnetic saturation	Lower chemical protection; higher probability of metal-core leakage	SERS substrates; biosensing platforms; photothermal imaging
Thick Shell (>40–50 nm)	Excellent structural stability; strong oxidation resistance; improved uniformity and biocompatibility	Reduced optical intensity; weakened magnetic response	Drug delivery; catalysis; wastewater treatment

Table 4. Thin vs thick shell comparison.

Parameter	**Thin Shell**	**Thick Shell**	**References**
SERS signal	High	Low	[21]
Oxidation resistance	Moderate	High	[22]
Magnetic response	Strong	Reduced	[23]
Drug delivery use	Limited	Excellent	[24]

Decreased permeability and improved crack resistance: Nano-silica refines the pore structure by filling microvoids, which limits the penetration of water, chloride ions, and other aggressive agents, thereby enhancing long-term performance [26].

Biomedical Applications

In biomedicine, functionalized silica nanoparticles are extensively utilized due to their biocompatibility, adjustable surface chemistry, and ease of functionalization. Drug delivery systems: Mesoporous silica nanoparticles (MSNs) are capable of encapsulating substantial drug loads and facilitating controlled, stimuli-responsive release profiles [27]. Bioimaging and sensing: Dye-doped fluorescent silica nanoparticles act as stable probes for high-resolution cellular imaging and biosensing applications [28]. Antimicrobial coatings: Silica coated with Ag or ZnO nanoparticles shows enhanced antibacterial properties and effectively minimizes the risk of infection in medical devices [29].

Environmental Remediation

Silica-based nanomaterials provide environmentally friendly solutions for pollution control. Heavy metal adsorption: Functionalized silica nanoparticles with thiol or amine groups effectively adsorb Pb^{2+}, Cd^{2+}, Hg^{2+}, and other hazardous metals from contaminated water [30]. Photocatalytic degradation: SiO_2–TiO_2 composites are capable of degrading organic pollutants under UV/visible light, offering sustainable pathways for water purification [31].

Antibacterial Activity

The TiO_2-PTMSPA composite (MF-TSSM) exhibits a wide range of antibacterial properties. Inhibition zones for Klebsiella pneumoniae range from 9 to 23 mm (10 to 80 µg/mL), whereas Pseudomonas aeruginosa shows inhibition zones of 10 to 14 mm. This antibacterial activity is attributed to the generation of reactive oxygen species and electrostatic interactions that result in damage to the cell membrane [32].

Catalysis

Nano-silica serves as an exceptional support material in heterogeneous catalysis, owing to its high surface area and thermal stability. Metal-supported catalysis: Silica nanostructures loaded with Pd or Pt significantly enhance hydrogenation and oxidation reactions, which are extensively utilized in industrial applications [33]. Acid–base catalysis: Silica that is functionalized with sulfonic acid accelerates esterification and alkylation reactions, thereby improving both efficiency and selectivity [34].

Electronics and Coatings

Silica nanoparticles are crucial in the development of contemporary electronic and optical devices. Dielectric materials: The addition of nano-silica to hybrid polyimide films diminishes leakage currents, thereby enhancing the performance of microelectronic components [35]. Anti-reflective coatings: Porous silica layers improve transmittance in solar cells, resulting in enhanced photovoltaic efficiency [36].

Agricultural Applications

Silica nanoparticles provide sustainable alternatives to traditional agrochemicals. Protection against fungal infections: Mesoporous silica nanoparticles (MSNs) that carry proteins, nucleotides, or antifungal agents offer protection to maize and other crops from fungal pathogens, thereby improving germination rates [37,38]. Improved water absorption: Nano-silica facilitates enhanced water uptake in plants, supporting better growth during drought conditions [39]. Structural reinforcement: Silica nanoparticles contribute to increased rigidity in plants, enhancing their resistance to environmental stressors [40].

Energy Storage Applications

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Nano-silica is increasingly being recognized in the realm of advanced energy storage technologies. Lithium-ion batteries: The use of Si/SiO_2 composite anodes enhances cycle stability by restricting volume expansion throughout the charging and discharging processes. Supercapacitors: Mesoporous silica enhances electrolyte accessibility in carbon-based electrodes, resulting in elevated capacitance and superior electrochemical performance [41].

RESEARCH FUTURES

In order to address current limitations and propel the field forward, forthcoming investigations into silica nanomaterials should concentrate on the following strategic avenues:

Development of Green and Sustainable Synthesis Methods

There exists a significant demand for environmentally sustainable and scalable synthesis pathways for silica nanoparticles utilizing bio-based, waste-derived, or low-impact precursors. Such methodologies will minimize environmental impact and production expenses while enhancing commercial feasibility. A recent review illustrates the practicality of employing green synthesis techniques to fabricate silica nanoparticles that are appropriate for a variety of applications [42]

Design of Smart and Stimuli-Responsive Silica Coatings

Silica nanoparticles of the next generation should integrate stimuli-responsive features — for instance, coatings that respond to pH, redox states, temperature, light, or enzymatic stimuli — to facilitate controlled release, targeted delivery, or adaptive functionality. Recent advancements in polymer-modified mesoporous silica nanoparticles (MSNs) indicate potential for regulated drug delivery in response to external or internal stimuli [43]. Moreover, the incorporation of bio-inspired surface functionalization can enhance the biocompatibility, stability, and multifunctionality of silica nanostructures.

Comprehensive Lifecycle and Environmental Impact Assessment

As the application of silica nanoparticles broadens, thorough investigations into their environmental behavior, biodegradation, and long-term ecological consequences become crucial. This encompasses lifecycle assessment (LCA), recyclability protocols, and analysis of degradation products — particularly for coated or composite nanomaterials. Although specific LCA studies on nano-silica are presently scarce, related reviews on nanoparticle green synthesis and environmental nanotechnology underscore this as a pressing necessity.[44]

CONCLUSION

Silica nanoparticles and silica-coated metal nanostructures exhibit exceptional versatility in biomedical, catalytic, and environmental fields, attributed to their adjustable porosity, thermal stability, and potential for surface functionalization. Notwithstanding significant advancements, considerable obstacles persist in achieving uniformity of the shell, scalable production methods, and reliable performance in applications. Quantitative analyses indicate that the thickness of the coating has a profound effect on optical, catalytic, and magnetic properties, highlighting the critical need for optimization of structure–property relationships. Future investigations should focus on environmentally friendly synthesis methods, improved uniformity of coatings, and comprehensive long-term toxicity evaluations, in addition to the integration of large-scale systems for practical applications. By addressing these deficiencies, the progression towards next-generation silica-based nanomaterials with enhanced efficiency, safety, and market potential can be expedited.

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