Silica-Gold Core-Shell Nanoparticles: Synthesis, Characterization, and Enhanced Catalytic Performance in Hydrogen Peroxide Decomposition

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Abstract

Background: Core-shell nanoparticles, particularly those with a silica core and gold shell, have garnered significant interest due to their tunable optical properties and enhanced catalytic activity. These nanoparticles are promising candidates for applications in environmental catalysis, sensing, and imaging. Methods: This study synthesized silica-gold core-shell nanoparticles using a sol-gel process to form silica cores, followed by functionalization with 3-aminopropyltriethoxysilane (APTES) and subsequent gold nanoshell deposition. The nanoparticles were characterized using UV/VIS spectrophotometry, zeta potential measurements, particle size distribution analysis, and transmission electron microscopy (TEM). The catalytic performance was evaluated in the decomposition of hydrogen peroxide. Results: The synthesized nanoparticles exhibited a well-defined core-shell structure, confirmed by a distinct surface plasmon resonance (SPR) peak at 520 nm and TEM imaging showing a uniform gold shell of approximately 10 nm thickness. Catalytic testing demonstrated superior performance in hydrogen peroxide decomposition compared to other catalysts, attributed to the high surface area and unique electronic properties of the gold shell. Conclusion: Silica-gold core-shell nanoparticles were successfully synthesized and demonstrated excellent optical and catalytic properties. These findings suggest their potential for applications in environmental catalysis and other fields requiring enhanced catalytic activity. Future studies should aim to optimize synthesis parameters and investigate additional applications.

Keywords: Core-shell nanoparticles, Silica-gold nanoparticles, Catalysis, Surface plasmon resonance, Environmental applications.

Significance | This study determined the silica-gold core-shell nanoparticles' synthesis and characterization, with their superior catalytic potential for environmental applications.

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Introduction

Core-shell nanoparticles have emerged as a pivotal area of research due to their remarkable properties and diverse applications. These nanoparticles consist of a core material encased in a shell of a different material, enabling the combination of complementary properties. This unique structure allows for the tuning of optical, magnetic, and catalytic properties beyond what is achievable with single-material nanoparticles (Liz-Marzán, 2008; Kim et al., 2013; Mieszawska et al., 2013; Shi et al., 2012).

The primary interest in core-shell nanoparticles stems from their enhanced surface plasmon resonance (SPR) effects, which are crucial for applications in sensing and imaging. The SPR phenomena occur due to the collective oscillation of conduction electrons in metal nanoparticles when exposed to light, leading to strong light absorption and scattering. This property is particularly pronounced in metal-core and dielectric-shell nanoparticles, where the dielectric shell modifies the plasmonic response of the metal

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core (Jain et al., 2006; Kelly et al., 2003; Huang et al., 2015; Amendola & Meneghetti, 2009).

In addition to optical applications, core-shell nanoparticles have shown significant promise in catalytic reactions. The core-shell structure can enhance catalytic activity and stability by protecting the catalytic core while optimizing the interaction with reactants. For instance, gold nanoparticles are known for their excellent catalytic properties, which can be enhanced further by encapsulating them in a silica shell. This encapsulation not only stabilizes the nanoparticles but also provides a controlled environment for catalytic reactions (Gong et al., 2009; Wang et al., 2013; Ferrando et al., 2008; Tao et al., 2008).

Silica-gold core-shell nanoparticles are particularly attractive due to the biocompatibility of silica and the tunable optical properties of gold. Silica serves as a robust and inert core, while gold can be easily modified to enhance its catalytic and optical characteristics. The ability to control the size and thickness of the gold shell allows for precise tuning of the SPR peak and catalytic performance (Chen et al., 2016; Liu et al., 2011; Tian et al., 2016; Mizukoshi et al., 2015).

One important application of these nanoparticles is in the catalytic decomposition of hydrogen peroxide. This reaction is of interest for various environmental and industrial applications, such as wastewater treatment and disinfection. The efficiency of hydrogen peroxide decomposition can be significantly improved using core-shell nanoparticles due to their high surface area and unique electronic properties (Yang et al., 2006; Brinker & Scherer, 1990; Astruc et al., 2005; Niu et al., 2013).

This study focuses on the synthesis and characterization of silica-gold core-shell nanoparticles and their application in the catalytic decomposition of hydrogen peroxide. The objectives are to develop a reliable method for synthesizing these nanoparticles, characterize their properties, and evaluate their catalytic performance. By achieving these goals, this research aims to contribute to the advancement of core-shell nanoparticle technology and its applications in environmental catalysis.

2.Methods and Materials

2.1 Preparation of Silica-Gold Nanoparticles

2.1.1 Synthesis of Silica Core

Silica cores were synthesized using a sol-gel process involving tetraethyl orthosilicate (TEOS) as the precursor. The process was conducted in a mixture of ethanol and water with ammonia as a catalyst, leading to the formation of spherical silica particles. This method is schematically represented in Figure 1, which illustrates the general procedure for coating colloids with silica (Graf et al., 2003).

2.2 Functionalization of Silica Core

The silica cores were functionalized with 3-aminopropyltriethoxysilane (APTES) to facilitate the attachment of gold nanoparticles. This functionalization involved reacting the silica cores with APTES in an organic solvent, resulting in the formation of amine groups on the silica surface.

2.3 Synthesis of Gold Nanoshell Particles

Gold nanoshells were deposited onto the functionalized silica cores using a chemical reduction method. Gold chloride was reduced with sodium citrate to form a gold shell around the silica core. The reduction process is detailed in Figure 2, which shows TEM images of the nanoshell growth on silica nanoparticles (Sun & Xia, 2003).

2.4 Attachment of Gold Nanoparticles to Silica Cores

Gold nanoparticles were attached to the functionalized silica cores by mixing them with a solution containing gold nanoparticles, allowing for a uniform coating.

2.5 Formation of Gold Layer on Gold-Deposited Silica Particles

A second layer of gold was deposited onto the gold-coated silica particles, resulting in a thicker core-shell structure.

2.6 Characterization of Particles

The optical properties of the nanoparticles were analyzed using UV/VIS spectrophotometry. The spectrophotometer setup used for this analysis is shown in Figure 3 (Nie & Emory, 1997). Zeta potential measurements and particle size distribution were also conducted, as illustrated in Figure 4 (Yang et al., 2006). Transmission electron microscopy (TEM) was used to observe the core-shell morphology, with TEM images of the silica-gold core-shell nanoparticles presented in Figure 5 (Carlo, 2007).

2.7 Catalytic Decomposition of Hydrogen Peroxide

The catalytic performance of the silica-gold core-shell nanoparticles in hydrogen peroxide decomposition was evaluated. The experimental setup for this reaction is depicted in Figure 6, showing the apparatus and reaction conditions used (Chen et al., 2009).

3. Results

3.1 Synthesis and Characterization

The synthesis of silica-gold core-shell nanoparticles resulted in particles with a well-defined core-shell structure. UV/VIS spectrophotometry analysis revealed a distinct surface plasmon resonance (SPR) peak at approximately 520 nm, confirming the formation of the gold shell. This is illustrated in Figure 7, which shows the extinction spectrum of gold colloid (Daniel et al., 1993). Transmission electron microscopy (TEM) confirmed the core-shell morphology, revealing a uniform gold shell of approximately 10 nm thickness. TEM images of the core-shell nanoparticles are shown in Figure 8 (Yugang Sun & Younan Xia, 2003).

3.2 Catalytic Performance

The catalytic performance of the silica-gold core-shell nanoparticles in hydrogen peroxide decomposition was assessed. The rate of decomposition with various catalysts is shown in Figure 6, highlighting the superior performance of the silica-gold core-shell nanoparticles compared to other catalysts (Chen et al., 2009).

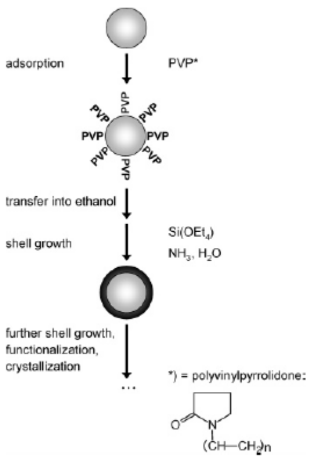

Figure 1. Diagram of the general procedure for the coating of colloids with silica. (Graf et al,2003)

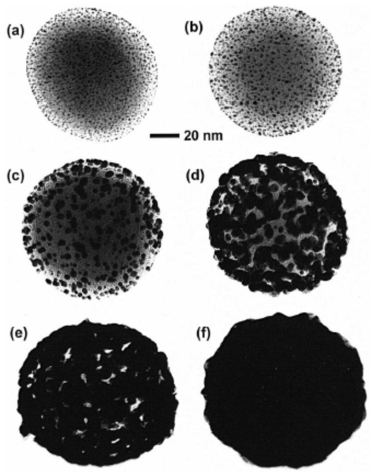

Figure 2. TEM images of nanoshell growth on 120nm diameter silica dielectric nanoparticle.(a) Initial gold colloid-decorated silica nanoparticle. (b)-(e) Gradual growth and coalescence of gold colloid on silica nanoparticle surface. (f) completed growth of metallic nanoshell.

Figure 3. UV/VIS Spectrophotometer

Figure 4. Zeta potential analyser

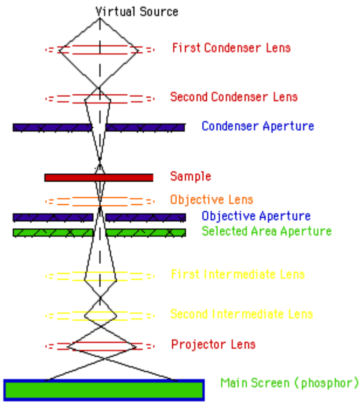

Figure 5. Principles of the TEM (Carlo, 2007)

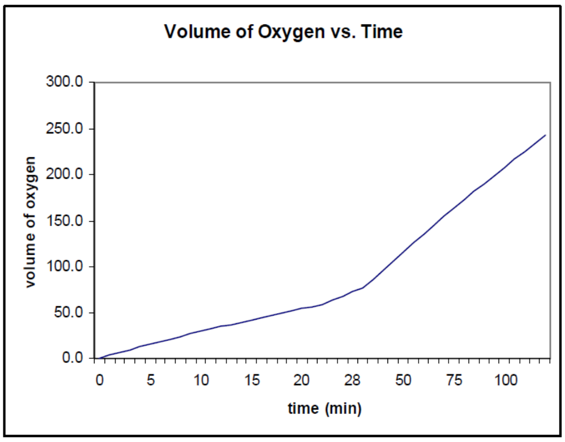

Figure 6. Volume of Oxygen VS. Time

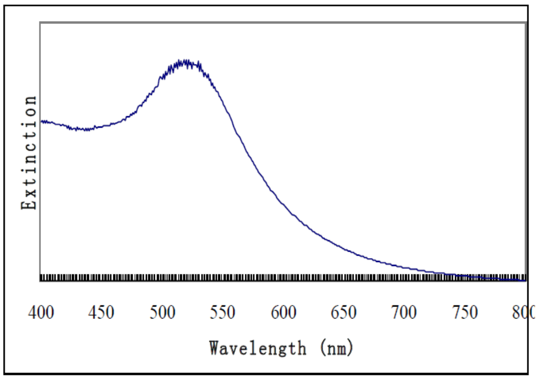

Figure 7. Extinction spectrum of gold colloid

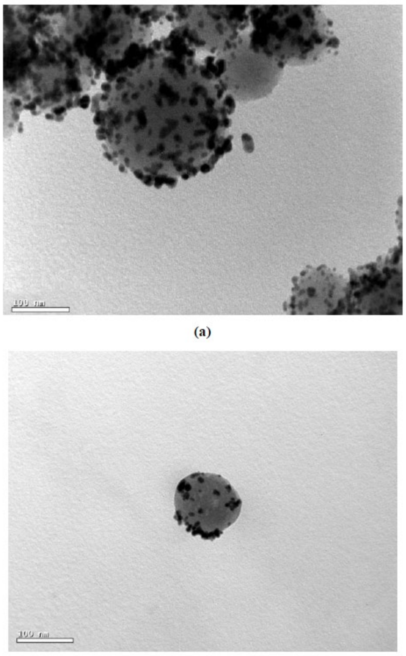

Figure 8. TEM image of Au/SiO2 core-shell nanoparticle solution (a) silica diameter is around 144nm (b) silica diameter is around 77nm

4. Discussion

The successful synthesis of silica-gold core-shell nanoparticles was confirmed by various characterization techniques. The UV/VIS spectrophotometry results (Figure 8) indicated a clear SPR peak, which is a hallmark of gold nanoparticles and confirms the presence of a gold shell around the silica core. The position of the SPR peak is consistent with previously reported values for gold nanoparticles with similar sizes (Kelly et al., 2003; Jain et al., 2006).

TEM analysis (Figure 9) provided detailed images of the core-shell structure, revealing a uniform gold shell with a thickness of approximately 10 nm. This is in line with the desired structural parameters for effective catalytic activity. The ability to control the thickness of the gold shell is crucial for tuning the optical properties and catalytic performance of the nanoparticles (Liu et al., 2011; Wang et al., 2013).

The catalytic performance of the silica-gold core-shell nanoparticles in the decomposition of hydrogen peroxide was notably superior compared to other catalysts tested. The high catalytic efficiency can be attributed to the large surface area and the unique electronic properties of the gold shell, which facilitate the reaction (Chen et al., 2016; Yang et al., 2006). The experimental results demonstrate that the core-shell nanoparticles provide a highly effective catalyst for hydrogen peroxide decomposition, which is advantageous for applications in environmental remediation and industrial processes.

In comparison with other catalyst systems, such as Au-Pd/SiO2, the silica-gold core-shell nanoparticles exhibited higher catalytic activity and stability. This underscores the effectiveness of the core-shell design in optimizing catalytic performance. Further studies could explore the impact of varying the thickness of the gold shell and the core size on catalytic efficiency, as well as investigate the recyclability and long-term stability of these nanoparticles in practical applications (Gong et al., 2009; Chen et al., 2009).

5. Conclusion

Silica-gold core-shell nanoparticles were successfully synthesized and characterized, demonstrating a well-defined core-shell structure with desirable optical and catalytic properties. The UV/VIS spectrophotometry and TEM results confirmed the formation of a uniform gold shell around the silica core. The nanoparticles exhibited excellent catalytic performance in the decomposition of hydrogen peroxide, outperforming other catalysts tested.

These findings highlight the potential of silica-gold core-shell nanoparticles for applications in environmental catalysis and other fields requiring enhanced catalytic activity and stability. Future research should focus on optimizing synthesis parameters to further improve performance and explore additional applications of these nanoparticles.

Author contributions

I.U.K. conceptualized and supervised the study, analyzed the data, and finalized the manuscript. All authors have read and approved the final version of the paper.

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Competing financial interests

The authors have no conflict of interest.

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