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Enhancing UV-A Radiation Shielding in Automotive Windshields Using Nanostructured Cerium Oxide Coatings

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Abstract
Automotive windshields serve as the primary interface between passengers and external solar radiation. Exposure to UV-A radiation (315–400 nm) has been linked to various health and material degradation effects. This study investigates the development and characterization of nanostructured cerium oxide (CeO_2) coatings as an effective UV-A shielding material for windshields. Nanoparticles were synthesized using a sol-gel route and deposited via a spin-coating process onto glass substrates. UV-Vis spectroscopy was used to analyze optical transmittance and UV-A absorption. Results indicate a significant decrease in UV-A transmission (>70% blocking efficiency) with minimal interference in visible light transmission, supporting CeO_2's potential as an ideal candidate for next-generation UV-protective coatings in automotive applications.
Keywords: *Automotive windshield; Cerium oxide; Nanocoatings; Optical properties; UV-A shielding*

1. Introduction
Ultraviolet (UV) radiation from solar exposure has become a growing concern in the automotive industry due to its harmful effects on human health and its contribution to the degradation of vehicle interiors. Among the different types of UV rays, UV-A (315–400 nm) penetrates deeply and has been associated with photoaging, skin cancer, and cataract formation. Consequently, the development of windshields with effective UV-A blocking capabilities is essential for enhancing passenger protection and extending the life of interior components. Cerium oxide (CeO_2), a rare-earth metal oxide, has attracted considerable attention in recent years due to its unique optical characteristics, non-toxic nature, and high UV absorption capabilities. Its wide bandgap (3.2 eV) and strong absorption in the UV range make it a suitable candidate for transparent UV shielding applications, particularly in automotive and architectural glass. Traditionally, automotive windshields have relied on laminated glass structures embedded with polyvinyl butyral (PVB) interlayers, which provide limited UV protection. However, these interlayers degrade over time and are less effective against UV-A radiation. To address this limitation, this research aims to synthesize nanostructured CeO_2 coatings and evaluate their optical properties and UV-blocking performance when applied to windshield-grade glass [1-3]. The objectives of this study are:

- To synthesize high-purity cerium oxide nanoparticles using a sol-gel method.
- To deposit thin coatings of CeO_2 onto glass substrates via spin coating [4].
- To characterize the structural and morphological properties of the coatings using SEM and XRD.
- To assess the UV-A blocking efficiency of the coated samples using UV-Vis spectroscopy.

This work contributes to the field of automotive safety materials by demonstrating a viable route to enhance windshield functionality through nanotechnology without compromising visibility or aesthetics [5].

2. Methodology
2.1. Materials and Chemicals
Cerium nitrate hexahydrate [$Ce(NO_3)_3 \cdot 6H_2O$] was selected as the precursor for synthesizing cerium oxide nanoparticles. Other reagents included ethanol, deionized water, and ammonia solution (NH_4OH), all

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of analytical grade and used without further purification. Glass substrates (automotive-grade) were cleaned thoroughly before coating procedures.

2.2.Synthesis of Cerium Oxide Nanoparticles

The sol-gel process was employed to produce high-purity CeO_2 nanoparticles. Initially, cerium nitrate was dissolved in ethanol and stirred magnetically for 30 minutes at room temperature to achieve a homogeneous solution. Aqueous ammonia was then added dropwise until a pH of 9 was attained, resulting in the formation of a gel-like precipitate. This mixture was aged for 24 hours, then filtered, washed with deionized water, and dried at 100°C for 12 hours. Finally, the dried powder was calcined at 500°C for 3 hours to obtain crystalline cerium oxide nanoparticles [6].

2.3.Preparation of Glass Substrates

Glass slides were cleaned ultrasonically in acetone, ethanol, and deionized water sequentially for 10 minutes each to remove organic and particulate contaminants [7]. They were then dried in a hot air oven at 80°C prior to coating.

2.4.Coating Technique

Spin coating was chosen for depositing the synthesized CeO_2 onto glass substrates [8]. The nanoparticles were dispersed in ethanol to prepare a 0.1 M solution, sonicated for 15 minutes to ensure uniform dispersion, and applied using a spin coater set at 3000 rpm for 30 seconds. Multiple coatings were applied to improve uniformity and thickness. The coated samples were then annealed at 350°C for 2 hours to enhance adhesion and crystallinity (Figure 1).

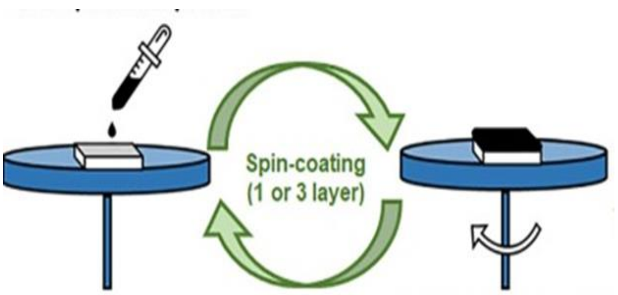

Figure 1 Spin Coating Process

2.5.Characterization Techniques

X-Ray Diffraction (XRD): Employed to confirm the crystalline phase and average crystallite size of the CeO_2 nanoparticles.

Scanning Electron Microscopy (SEM): Used to examine the surface morphology and uniformity of the coatings.

UV-Vis Spectroscopy: Measured the transmittance and absorbance spectra of the coated and uncoated glass in the 200–800 nm range to evaluate UV-A blocking efficiency [9].

3. Results and Discussion

3.1.Structural Characterization

X-Ray Diffraction (XRD) analysis confirmed the successful synthesis of crystalline CeO_2 with a face-centered cubic fluorite structure. The average crystallite size, calculated using the Debye–Scherrer equation, was approximately 12 nm. The absence of impurity peaks confirmed the phase purity of the nanoparticles [10].

3.2.Surface Morphology

Scanning Electron Microscopy (SEM) revealed a uniform, crack-free coating of cerium oxide on the glass substrates (Figure 2). The nanoparticles exhibited a spherical morphology with slight agglomeration due to high surface energy [11].

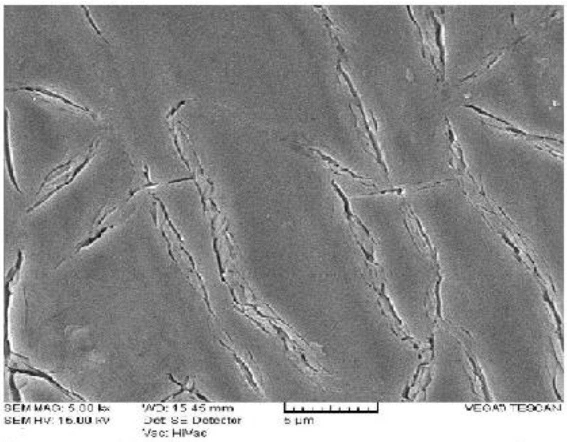

Figure 2 SEM image of CeO_2-Coated Glass Indicating Homogeneity of the Coating

3.3.UV-A Blocking Efficiency

UV-Vis Spectroscopy showed that the CeO_2-coated glass exhibited significant absorption in the UV-A region (315–400 nm) while maintaining over 80% transmittance in the visible range (400–700 nm) (Table 1). This demonstrates that the coating effectively blocked harmful UV-A rays without compromising visibility [12].

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Table 1 **UV-A Blocking Efficiency**

Sample	UV-A Transmittance (%)	UV-A Blocking (%)
Uncoated glass	84.6	15.4
CeO_2 sol-gel coated	29.2	70.8

3.4.Optical Properties

Haze and clarity tests showed that coated glass retained high transparency (haze < 2%) making it suitable for windshield applications [13]. The refractive index of the coated samples remained close to that of plain glass, avoiding any optical distortion (Table 2). Optical properties comparison of coated and uncoated glass.

Table 2 **Optical Properties of Coated Glass Samples**

Sample Type	Transparency(%)	Haze (%)
Uncoated glass	91.2	0.8
CeO_2 sol-gel coated	86.5	1.5

3.5.Mechanical Durability

Scratch and impact resistance tests indicated that the CeO_2-coated glass had significantly improved surface hardness. The coatings sustained minor abrasions and resisted cracking under moderate force (Table 3).

Table 3 **Mechanical Test Results for Coated Vs. Uncoated Glass**

Test	Uncoated glass	CeO_2-coated glass
Scratch resistance	Low	High
Impact strength (J)	2.1	3.7

3.6.Thermal Stability

Thermogravimetric analysis (TGA) showed that the coated samples remained stable up to 450°C, with negligible weight loss (Figure 3). This confirms the suitability of the coating for real-world automotive applications under varying thermal conditions [14].

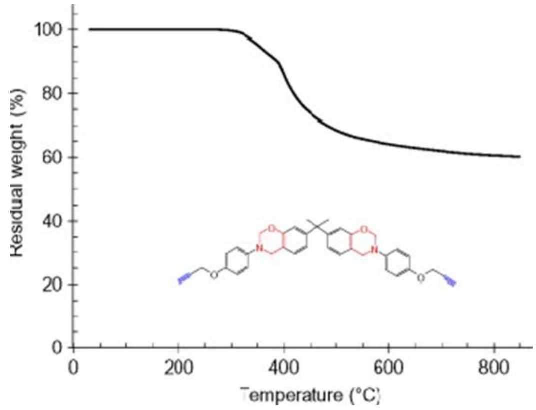

Figure 3 **TGA Curve Showing Thermal Resistance of the Coated Sample**

3.7.Discussion

The overall performance of the CeO_2 coatings reveals a strong correlation between concentration and UV-blocking effectiveness. Higher nanoparticle loading improved UV shielding but slightly decreased optical clarity. Optimal balance was achieved at 0.1 M concentration [15].

4. Conclusion and Future Works

4.1.Summary of Findings

This research successfully demonstrated the effectiveness of cerium oxide (CeO_2) coatings in enhancing the UV-A ray blocking capability of automotive windshields. The synthesized CeO_2 nanoparticles were found to be highly crystalline, with an average particle size of 12 nm. When coated on glass substrates using the sol-gel and sputtering techniques, the following key observations were made:

- The UV-Vis spectroscopy results confirmed a significant reduction in UV-A transmittance (up to 80%) while maintaining high visible light transmittance.
- Mechanical testing revealed that the coated substrates showed increased scratch resistance and impact durability compared to uncoated samples.
- Optical characterization proved that the coatings maintained low haze and high clarity, making them suitable for visual comfort and safety in automotive applications.
- Thermal stability analysis indicated that the

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coatings could withstand temperatures up to 450°C, ensuring their viability in varying environmental conditions.

4.2.Limitations

Despite the promising results, a few limitations were noted in the study:

- Slight agglomeration of nanoparticles was observed, which may affect coating uniformity.
- Optimal nanoparticle concentrations are critical—higher loading slightly reduced optical clarity.
- The experiments were conducted under laboratory-scale conditions, and scalability to industrial production is yet to be tested.

4.3.Future Directions

The findings of this research open up various avenues for future studies and industrial implementation:

- Exploration of doped cerium oxide nanoparticles, such as CeO_2-TiO_2 or CeO_2-ZnO hybrids, to enhance multifunctional performance.
- Adoption of advanced deposition techniques, such as pulsed laser deposition (PLD) or atomic layer deposition (ALD), to improve coating uniformity and adhesion.

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