



Synthesis Parameter-driven Performance of Green CeO₂ Nanoparticles: Antioxidant Efficiency and Corrosion Resistance of Mild Steel

G. Alagarsamy¹, P. Berlin Push², G. Vinoth³, Jayshree Majumdar^{4,5}, Amuthakkannan Rajakannu^{6*} and S. Velmurugan⁷

¹Department of Mechanical Engineering, Grace College of Engineering, Thoothukudi, TN, India

²Department of Mechanical Engineering, Noorul Islam Centre for Higher Education, Kanyakumari, TN, India

³Department of Physics, Academy of Maritime Education and Training (AMET) Deemed to be University, Kanathur, Chennai, TN, India

⁴Department of Food Technology, Guru Nanak Institute of Technology, Kolkata, WB, India

⁵Department of Agriculture and Food Engineering, Indian Institute of Technology Kharagpur, WB, India

^{6*}Department of Mechanical and Industrial Engineering, College of Engineering, National University of Science and Technology, Sultanate of Oman

⁷Department of Mechanical Engineering, Vel Tech High Tech Dr. Rangarajan Dr. Sakunthala Engineering College, Trivallur, TN, India

Received: 30.04.2026 Accepted: 25.05.2026 Published: 30.06.2026

*kannan.maya1986@gmail.com



ABSTRACT

Cerium oxide (CeO₂) nanoparticles were successfully synthesized via a green synthesis route using *Tinospora cordifolia* leaf extract as a natural reducing, capping, and stabilizing agent. The synthesized nanoparticles were evaluated for their antioxidant activity and corrosion inhibition performance toward mild steel in acidic media. X-ray diffraction (XRD) analysis confirmed the formation of nanocrystalline CeO₂ with a cubic fluorite crystal structure, while Fourier transform infrared (FTIR) spectroscopy revealed the presence of phytochemical functional groups responsible for nanoparticle stabilization and surface functionalization. Morphological analysis indicated clustered nanoparticle structures composed of nanoscale crystallites, whereas dynamic light scattering (DLS) measurements showed larger hydrodynamic diameters due to particle aggregation in aqueous suspension. The influence of synthesis parameters, including pH, temperature, reaction time, and extract concentration, on nanoparticle formation and stability was also investigated. The corrosion inhibition performance of the synthesized CeO₂ nanoparticles was assessed using potentiodynamic polarization (PDP), electrochemical impedance spectroscopy (EIS), and gravimetric weight-loss measurements. The nanoparticles exhibited concentration-dependent inhibition behavior, achieving a maximum corrosion protection efficiency of 82.5%. EIS results revealed enlarged Nyquist semicircles and increased charge transfer resistance, confirming the formation of a protective surface film on mild steel. Weight-loss studies demonstrated inhibition efficiencies of 23.5% after 24 h and 64.7% after 48 h of immersion. Furthermore, DPPH and ABTS radical scavenging assays confirmed significant antioxidant activity, with the methanolic extract exhibiting superior performance. The results demonstrate that *T. cordifolia*-mediated CeO₂ nanoparticles possess effective antioxidant and mixed-type corrosion inhibition properties through adsorption-driven surface interactions, highlighting their potential as sustainable multifunctional materials for corrosion protection applications.

Keywords: Electrochemical impedance spectroscopy; Potentiodynamic polarization; Adsorption; Charge transfer; Antioxidant.

1. INTRODUCTION

Recent advancements in nanomaterials have highlighted the significant potential of green-synthesized nanoparticles for multifunctional biomedical, environmental, and anticorrosion applications. Plant-mediated synthesis routes provide eco-friendly and cost-effective alternatives while introducing bioactive surface functionalities that enhance nanoparticle performance, leading to strong antioxidant, antibacterial, and photocatalytic activity due to improved crystalline structure and surface reactivity (Jayaseelan *et al.* 2024). Similarly, biofunctionalized CeO₂ nanoparticles synthesized via green routes exhibit improved band gap

and enhanced physicochemical properties, emphasizing the importance of phytochemical-assisted synthesis (Mylarappa *et al.* 2026).

Cerium oxide (CeO₂) nanoparticles have attracted significant attention due to their unique redox cycling ability (Ce³⁺/Ce⁴⁺), oxygen vacancy formation, and catalytic properties, making them highly effective for corrosion protection. The incorporation of functionalized CeO₂ nanoparticles into polymer coatings significantly improves corrosion resistance by forming dense barrier layers, reducing charge transfer reactions, and enhancing mechanical stability through passive film formation (Xavier, 2021). Additionally, CeO₂-based conductive

polymer coatings demonstrate excellent self-healing and anticorrosion efficiency due to controlled inhibitor release and nanoparticle-induced passivation, achieving protection efficiencies as high as ~99.95% (Khokher and Lata, 2024).

Advanced nanofiller engineering and hybridization strategies have further improved coating performance. Functionalized CeO₂ nanocomposites prepared through electrodeposition exhibit enhanced protective behavior, supported by electrochemical and structural analyses (Ngo *et al.* 2020). Similarly, silane-modified and PANI-coated CeO₂ nanoparticles incorporated into waterborne epoxy coatings demonstrate improved impedance stability, adhesion strength, and reduced water permeability (Xiao *et al.* 2024). Furthermore, plant-derived CeO₂ nanoparticles exhibit multifunctional properties, including antibacterial, antioxidant, anticancer, and corrosion inhibition efficiency up to 95.44% (Muthulakshmi *et al.* 2026).

Beyond corrosion protection, CeO₂-based nanomaterials play a crucial role in catalysis and biomedical applications. CeO₂-modified catalysts enhance hydrocarbon production and deoxygenation processes in biomass conversion, reducing corrosive oxygenated compounds (Kaewpengkrow *et al.* 2014). Functionalized CeO₂ nanoparticles also exhibit superior antioxidant and antimicrobial performance due to enhanced redox activity and oxygen vacancy concentration (Liu *et al.* 2026). Moreover, CeO₂-based nanozymes enable simultaneous antibacterial activity and tissue regeneration through controlled redox modulation, promoting wound healing and reducing oxidative stress (Pang *et al.* 2025).

Natural plant extracts such as *Tinospora cordifolia* have been extensively explored as sustainable corrosion inhibitors and nanoparticle synthesis agents. These extracts demonstrate high corrosion inhibition efficiency (up to ~92%) through adsorption-driven mechanisms following Langmuir isotherm behavior and mixed-type inhibition (Royani *et al.* 2025). Methanolic extracts of *Tinospora cordifolia* significantly enhanced the corrosion resistance of carbon steel through adsorption-driven mechanisms, with electrochemical studies indicating increased charge transfer resistance and inhibition efficiency up to 85.94%, along with improved surface smoothness due to protective film formation (Royani *et al.* 2023). In acidic environments, the extract exhibited superior anticorrosion performance with inhibition efficiencies exceeding 90%, where electrochemical and statistical analyses confirmed mixed-type inhibition behavior governed by Langmuir adsorption isotherm and stable barrier layer formation on mild steel (Thomas *et al.* 2021). Similarly, the extract

demonstrated inhibition efficiency up to 87.18% via electrochemical methods, acting as a mixed-type inhibitor, while SEM analyses confirmed reduced surface degradation and enhanced surface protection through adsorption mechanisms (Saxena *et al.* 2021).

Despite the growing number of studies on *Tinospora cordifolia*-mediated nanoparticle synthesis, the multifunctional potential of green-synthesized CeO₂ nanoparticles for simultaneous antioxidant and corrosion inhibition applications remains insufficiently explored. Previous investigations have primarily focused on Mg(OH)₂ nanoparticles exhibiting antioxidant, antibacterial, anti-inflammatory, and enzyme inhibition properties (Rajkumar *et al.* 2024), bimetallic Ag–Cu nanoparticles with antibacterial and anticancer activities (Soundarya *et al.* 2025), and CuO nanoparticles with enhanced antimicrobial activity influenced by extract concentration (Anitha *et al.* 2022). Similarly, green-synthesized Al₂O₃@g-C₃N₄ nanocomposites have demonstrated excellent photocatalytic efficiency for wastewater treatment applications (Rajasekaran *et al.* 2025). However, limited information is available regarding the dual functionality of *Tinospora cordifolia*-derived CeO₂ nanoparticles as both antioxidant agents and corrosion inhibitors. Therefore, the present study focuses on the green synthesis of CeO₂ nanoparticles using *Tinospora cordifolia* leaf extract and systematically investigates their structural characteristics, antioxidant activity, and corrosion inhibition performance toward mild steel in acidic media. This work provides new insights into the development of sustainable, multifunctional CeO₂-based nanomaterials for corrosion protection and related industrial applications.

This research presents a sustainable phytochemical-assisted method for synthesizing Cerium oxide (CeO₂) nanoparticles with *Tinospora cordifolia* leaf extract, showcasing a distinctive amalgamation of green nanotechnology with dual-functional efficacy in antioxidant activity and corrosion inhibition. This study reveals a direct mechanistic relationship between the adjustment of synthesis parameters (pH, temperature, reaction duration, and extract concentration) and the resultant physicochemical qualities, aggregation behavior, and functional efficiency, in contrast to conventional methods. A significant innovation involves clarifying the adsorption-induced creation of a protective film on mild steel, substantiated by integrated electrochemical (PDP, EIS) and gravimetric investigations, resulting in a high inhibition efficiency of 82.5%. The study emphasizes the synergistic effect of phytochemical capping in improving radical scavenging activity and corrosion resistance, providing a cohesive approach for the development of eco-friendly, multifunctional nanomaterials for harsh acidic conditions.

2. MATERIALS AND METHODOLOGY

2.1 Preparation of CeO₂ Nanoparticles

The leaves of *Tinospora cordifolia* were collected from the Anthiyur forest region in Tamil Nadu, India, meticulously washed with distilled water to eliminate sticking impurities, and subsequently air-dried under ambient conditions. Aqueous extracts were made using boiling 50 g of chopped leaves in 200 mL of deionized water for 50 minutes and filtration through filter paper; the filtrate was stored at 5 °C and used as a dual-function reducing and capping medium. Soxhlet extraction was eschewed in favor of a gentle aqueous digesting method to uphold eco-friendly processing and avert damage to delicate phytoconstituents. For nanoparticle synthesis, 50 mL of the extract was magnetically agitated at about 1800 rpm at 32 °C, after which an aqueous solution of cerium precursor (0.5 M cerium nitrate hexahydrate) was added dropwise under continuous agitation. The pH of the reaction was

modified to around 9 to facilitate the hydrolysis of Ce³⁺ ions into hydroxide intermediates, which then undergo condensation and dehydration to produce Cerium dioxide nuclei. Bioactive chemicals, including polyphenols and flavonoids, in the extract promoted nucleation while inhibiting excessive particle development and agglomeration via surface stabilization (Matussin and Khan, 2025). The reaction mixture was stirred for 48 hours to ensure complete precursor conversion. Precipitate was isolated using centrifugation, thoroughly rinsed with deionized water to eliminate residual ions, and then subsequently dried at ambient temperature for 24 hours. To ensure reproducibility, the nanoparticle synthesis was independently repeated three times under identical experimental conditions. The reported results represent the mean values obtained from repeated measurements, and experimental variability was estimated using the standard deviation. Phase purity and successful nanoparticle synthesis were verified using X-ray diffraction, Fourier transform infrared spectroscopy, and energy-dispersive X-ray studies.

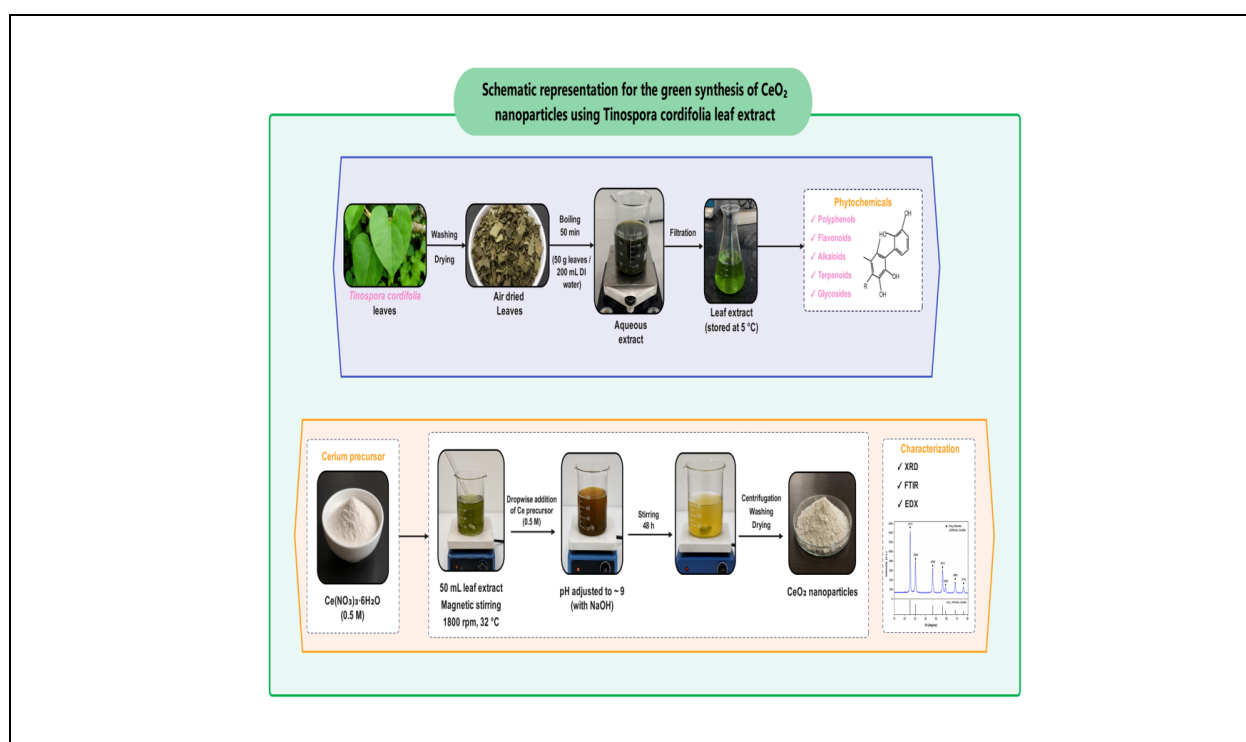


Fig. 1: Schematic diagram of the preparation of CeO₂ nanoparticles

2.1.1 Optimization of Synthesis Parameters

The critical synthesis variables were methodically optimized by obtaining UV–Vis spectra within the 200–800 nm range and tracking the absorbance at $\lambda_{\text{max}} = 295$ nm (A₂₉₅) as the principal response metric. The absorption feature detected below 300 nm is ascribed to band-edge transitions and ligand-to-metal charge transfer processes linked to Cerium dioxide, potentially overlapping with $\pi \rightarrow \pi^*$ transitions

of residual phytoconstituents from *Tinospora cordifolia* extract adsorbed on the nanoparticle surface. A₂₉₅ served as a comparative metric for process optimization, while the synthesis of phase-pure CeO₂ nanoparticles was corroborated using X-ray diffraction,

The crystallite size of the produced cerium dioxide nanoparticles was determined using the Debye–Scherrer equation (1):

$$D = \frac{K\lambda}{\beta \cos \theta} \quad \dots (1)$$

In this context, D signifies crystallite size (nm), K indicates the form factor (about 0.9), λ specifies the X-ray wavelength (CuK α =0.15406 nm), β refers to the whole width at half maximum in radians, and θ represents the Bragg diffraction angle.

The crystallinity index was determined using Equation (2). The diffraction pattern indicates that the material exhibits distinct nanocrystalline properties, with phase identification accurately determined by peak indexing instead of complete Rietveld refinement.

$$\text{Crystallinity (\%)} = \frac{A_c}{A_c + A_a} \times 100 \quad \dots (2)$$

Where cap A. sub c represents the integrated crystalline peak area and cap A. sub a represents the amorphous area. The amorphous content was determined from the remaining fraction of the total diffraction area (Muduli and Ranjan Sahoo, 2023).

Fourier transform infrared spectroscopy and energy-dispersive X-ray spectroscopy. The optimized synthesis conditions were selected based on the highest absorbance intensity observed at $\lambda_{\text{max}} = 295$ nm, indicating enhanced nanoparticle formation and colloidal stability. These conditions were further validated through XRD, FTIR, and EDX analyses, which confirmed the successful synthesis of phase-pure CeO₂ nanoparticles with the desired structural and compositional characteristics.

2.1.1.1 Effect of Metal Precursor Concentration

Increasing the concentration of the cerium precursor from 0.1 to 0.4 M resulted in a continuous rise in absorbance at 295 nm, indicating enhanced hydrolysis-condensation activity and a greater formation of scattered cerium dioxide nuclei. The A₂₉₅ intensity increased from roughly 1.3 a.u. at 0.1 M to around 2.4 a.u. at 0.5 M, signifying enhanced nucleation efficiency with elevated precursor concentration. According to this tendency, a concentration of 0.5 M cerium salt was determined to be the best condition and was utilized for subsequent experimental investigations and bulk nanoparticle manufacturing.

2.1.1.2 Effect of Plant Extract Ratio

The volume of *Tinospora cordifolia* extract (2–8 mL in a constant reaction system) significantly influenced the UV–Vis response. The maximum absorbance at 295 nm (~2.6 a.u.) was noted at 2 mL, while a gradual decrease to ~1.0 a.u. occurred with an increase in extract volume to 8 mL. This tendency indicates that a minimal extract quantity suffices for sufficient phytochemicals to achieve efficient reduction and stabilization, but an excessive extract diminish the availability of effective precursors and encourage excessive complexation of metal ions, thus obstructing uniform nucleation. Thus, an optimal extract volume of 2 mL was chosen for further synthesis, with proportionate scaling implemented for larger batch preparations of cerium dioxide nanoparticles.

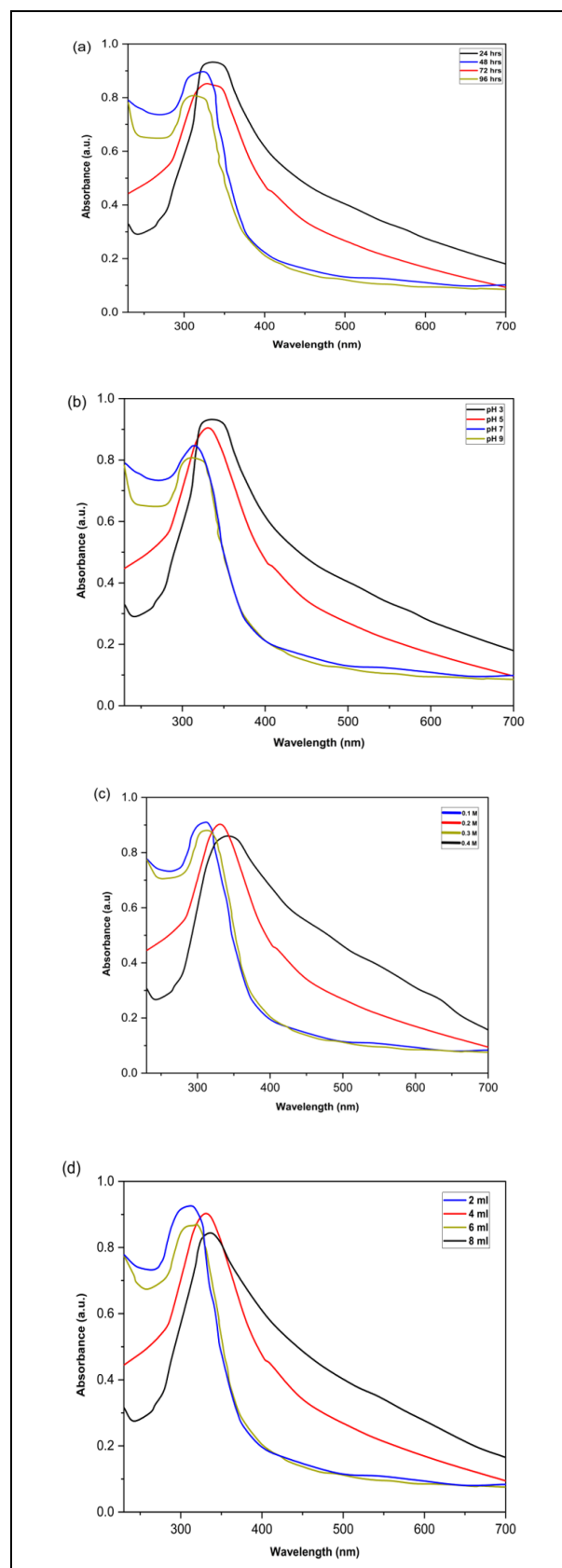


Fig. 2: Optical spectra under synthesis variations of (a) effect of time (b) effect of pH (c) effect of plant ratio and (d) effect of metal precursor

2.1.1.3 Effect of pH

The impact of pH solution (3–9) on the synthesis system demonstrated that the maximum absorbance at 295 nm (~2.4 a.u.) was observed in acidic conditions (pH 3), followed by a gradual decrease with increasing alkalinity, ultimately reaching ~1.0 a.u. at pH 9. The synthesis of cerium dioxide necessitates alkaline conditions to promote the hydrolysis of cerium ions into hydroxide intermediates, which subsequently condense into oxide nuclei. In acidic conditions, the detected UV response is predominantly affected by soluble metal–ligand complexes and phytochemical chromophores from *Tinospora cordifolia*, rather than actual nanoparticle production. Considering the chemical requirements for hydrolysis and colloidal stability, a pH of approximately 7 was determined to be the ideal setting. At elevated pH levels (~9), swift precipitation and particle aggregation decrease the concentration of well-dispersed species, resulting in reduced absorbance intensity.

2.1.1.4 Effect of Time

The impact of reaction duration (24–90 h) on nanoparticle formation was assessed via absorbance measurements at 295 nm, revealing peak intensity (~2.1 a.u.) at 24 h, a minor decline at 48 h (~1.9 a.u.), and a substantial reduction at prolonged durations (90 h, ~0.6 a.u.). The reduction in optical sensitivity over extended reaction time is due to particle development, agglomeration, and subsequent sedimentation, which decrease the concentration of well-dispersed, optically active species in the medium. Despite the maximum reaction being observed at 24 hours, a duration of 48 hours was chosen for bulk synthesis to guarantee complete precursor conversion and uniform yield of Cerium dioxide nanoparticles stabilized by *Tinospora cordifolia* extract. To ensure reproducibility, each optimization experiment was conducted in triplicate under identical conditions. The reported absorbance values represent the mean of three independent measurements, and the corresponding standard deviations were calculated to assess experimental variability and measurement reliability.

2.1.2 Characterization of CeO₂ NPs

The phase identification of cerium dioxide nanoparticles was conducted using powder X-ray diffraction utilizing an X'Pert PRO (Malvern Panalytical, Netherlands) with Cu K α radiation. The surface morphology and elemental composition were analyzed using an SU8010 SEM with an EDX detector. Functional group analysis was conducted by FTIR spectroscopy within the 400–4000 cm⁻¹ range utilizing a PerkinElmer FTIR spectrophotometer. The particle size distribution and dispersion stability in a colloidal medium were assessed using dynamic light scattering utilizing a Litesizer (Anton Paar, Austria).

2.1.3 Antioxidant Activity Assays

2.1.3.1 DPPH Assay

The antioxidant effectiveness of *Tinospora cordifolia* extract and its derived cerium dioxide nanoparticles, produced using methanol, ethyl acetate, and acetone solvents, was evaluated via the DPPH free radical scavenging assay. Different amounts of each extract (10–100 ppm) were combined with a methanolic DPPH solution and incubated under regulated circumstances, following which absorbance was measured at 517 nm by a UV-vis spectrophotometer. The radical scavenging efficiency was subsequently assessed by computing the percentage inhibition derived from the decrease in absorbance (Bhukya *et al.* 2026).

$$\text{DPPH Scavenging (\%)} = \left[\frac{A_{\text{control}} - A_{\text{sample}}}{A_{\text{control}}} \right] \times 100 \dots (3)$$

The control absorbance (A control) refers to the DPPH solution tested without Cerium dioxide nanoparticles, whereas the sample absorbance (A sample) indicates the measurement for the DPPH solution with the nanoparticles present. The IC₅₀ value, defined as the concentration of extract required to inhibit 50% of DPPH free radicals, was determined from the dose-response curve and expressed in $\mu\text{g/mL}$ for each extract and its corresponding cerium dioxide nanoparticles.

2.1.3.2 ABTS Assay

The antioxidant efficacy of *Tinospora cordifolia* extracts and their associated Cerium dioxide nanoparticles, synthesized using methanol, distilled water, and acetone, was assessed via the ABTS radical cation decolorization experiment. Various amounts of each extract (10–100 ppm) were reacted with potassium persulfate to produce ABTS⁺ radicals, which were subsequently mixed with the test solutions; the reduction in absorbance was recorded at 734 nm after a designated incubation period. The degree of radical scavenging was measured by calculating the percentage inhibition derived from the decrease in absorbance intensity.

$$\text{ABTS Inhibition (\%)} = \left[\frac{A_{\text{control}} - A_{\text{sample}}}{A_{\text{control}}} \right] \times 100 \dots (4)$$

A control represents the absorbance of the ABTS solution measured without Cerium dioxide nanoparticles, while A sample indicates the absorbance of the ABTS solution measured in the presence of the nanoparticles. Similarly, the IC₅₀ value for ABTS radical scavenging was calculated from the percentage inhibition plot against concentration for all extracts and cerium dioxide nanoparticles.

2.1.4 Anticorrosion Activity

The anticorrosion efficacy of cerium dioxide nanoparticles, produced with *Tinospora cordifolia* extract, was evaluated in a 0.5 M hydrochloric acid environment at ambient temperatures (298 ± 2 K). Electrochemical investigations were performed using a standard three-electrode configuration with mild steel as the working electrode (exposed area: 1 cm^2), a saturated calomel electrode as the reference, and platinum as the counter electrode. Before experimentation, the working electrode surface was mechanically polished, cleaned, degreased, and let to stabilize at open-circuit potential for 30 minutes. Electrochemical impedance spectroscopy was conducted at open circuit potential using a 10 mV sinusoidal signal across a frequency spectrum of 100 kHz to 0.01 Hz, followed by potentiodynamic polarization scans within ± 250 mV of open circuit potential at a scan rate of 1 mV s^{-1} . Gravimetric analysis was conducted by comparing the mass loss of specimens immersed in uncontrolled acid with those in solutions containing the extract-based inhibitor, from which the inhibition efficiency was then estimated. All experiments were conducted in triplicate, and the results were presented as mean values accompanied by their respective standard deviations. A previous study reported that the cerium oxide (CeO_2) nanoparticles integrated with h-BN-PANI-based nanofillers significantly enhanced the anticorrosion performance of waterborne epoxy coatings through improved interfacial compatibility. Electrochemical impedance spectroscopy (EIS) revealed higher charge transfer resistance and low-frequency impedance, confirming the formation of a dense protective barrier (Yao *et al.* 2026).

The synergistic interaction between cerium dioxide nanoparticles and bioactive compounds from *Tinospora cordifolia* creates a stable interfacial layer that improves surface coverage and facilitates the formation of a homogeneous protective film on mild steel. Unlike an unprotected surface, where metal dissolution and oxygen reduction occur freely, the modified interface demonstrates heightened charge-transfer resistance and significantly inhibits both anodic and cathodic reactions, thereby validating the mixed-mode inhibition behavior identified in electrochemical investigations. The phytochemical compounds serve as effective capping agents that promote adsorption onto the metal surface, enhance film integrity, and improve the longevity of corrosion protection in acidic conditions.

Mild steel is prone to severe corrosion in an acidic solution (0.5 M HCl) because the aggressive ions, namely chloride (Cl^-) and hydrogen ions (H^+), along with dissolved oxygen (O_2), promote the anodic dissolution of mild steel and the cathodic oxygen reduction reactions. The addition of *Tinospora cordifolia* mediated green-synthesized CeO_2 nanoparticles to the system dramatically modifies the corrosion characteristics via an

adsorption process. The phytochemicals in the extract serve as capping and stabilizing agents, which promote the adherence of CeO_2 nanoparticles to the mild steel surface. This results in the development of a compact, uniform and tenacious CeO_2 -phytochemical protective layer. This protective layer shields the active sites, retards the mobility of corrosive ions and increases the stability of the interface. This results in an increase in charge transfer resistance and a significant reduction in both anodic and cathodic reactions. This establishes a mixed-type mode of inhibition, where the inhibitor simultaneously inhibits the anodic and cathodic reactions, thus enhancing the corrosion resistance and lifespan of mild steel in the acidic environment.

3. RESULTS AND DISCUSSION

3.1 UV Spectra

The UV-visible absorption spectra of *Tinospora cordifolia* extract and synthesized Cerium dioxide nanoparticles exhibited a characteristic absorption band around 369 nm, which is attributed to ligand-to-metal charge transfer transitions ($\text{O}^{2-} \rightarrow \text{Ce}^{4+}$) commonly associated with CeO_2 nanostructures. This transition occurs because electrons are transferred from the oxygen 2p valence band to the cerium 4f conduction band, which is an intrinsic electronic property of the CeO_2 fluorite crystal structure, confirming the formation of cerium oxide nanoparticles. The distinct absorption band observed in the nanoparticle spectrum, absent in the bare plant extract, indicates successful nucleation and growth of CeO_2 nanocrystals. The absence of significant spectral shifts suggests that the phytochemicals primarily function as reducing, stabilizing, and capping agents during nanoparticle synthesis. The bioactive phytochemicals present in *Tinospora cordifolia*, such as flavonoids and terpenoids, donate electrons to Ce^{4+} ions, facilitating their reduction and subsequent nucleation and growth into CeO_2 nanocrystals, while simultaneously coating the nanoparticle surface to prevent agglomeration. The observed absorption feature provides preliminary evidence for the formation of CeO_2 nanoparticles; however, UV-Vis spectroscopy alone is insufficient for definitive phase identification. Therefore, the successful synthesis and structural characteristics of the nanoparticles were further confirmed using complementary techniques, including X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), and electron microscopy analyses.

3.1.1 Powder X-ray Diffraction

The powder X-ray diffraction profile of the synthesized cerium dioxide nanoparticles (Fig. 4) displays several prominent reflections with significant peak broadening, signifying nanoscale crystallinity. The primary diffraction maxima identified at $2\theta = 30.07^\circ$, 32.55° , and 48.06° correspond to the (111), (200), and

(220) planes of fluorite cubic CeO_2 , in agreement with standard JCPDS data (card no. 81-1544), confirming successful phase formation. Supplementary weak reflections at elevated angles, such as the (400) plane at approximately 68.9° , further corroborate the tetragonal structure. The expanded peaks and diminished intensity of higher-order planes result from small crystallite sizes, lattice distortions, and defects produced during green synthesis. Quantitative examination reveals around 65.17% crystalline and 24.8% amorphous material, indicating partial structural disorder. The degree of crystallinity was estimated from the XRD diffraction pattern by calculating the ratio of the integrated area of the crystalline peaks to the total diffraction area (crystalline and amorphous contributions).

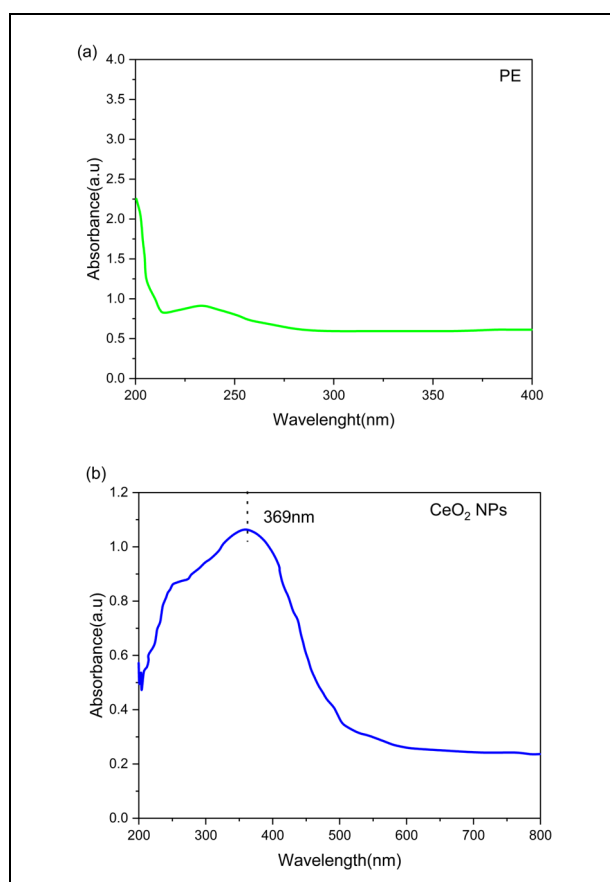


Fig. 3: (a) UV–Vis spectra of plant extract and (b) CeO_2 nanoparticles

The mean crystallite size of the synthesized nanoparticles was ascertained to be approximately 18.3 nm.

3.1.2 Fourier Transform Infrared Spectroscopy

The FTIR spectra of *Tinospora cordifolia* extract and the synthesized CeO_2 nanoparticles (Figs. 5 and 6) confirm the phytochemical-assisted formation and stabilization of the nanoparticles. A broad absorption band at $3335\text{--}3485\text{ cm}^{-1}$ corresponds to O–H stretching

vibrations of phenolic and alcoholic groups, indicating the presence of biomolecules acting as capping agents on the nanoparticle surface. Peaks observed at $2542\text{--}2449\text{ cm}^{-1}$ are associated with aliphatic C–H stretching, suggesting residual organic constituents from the plant extract. The bands near 1540 and 1373 cm^{-1} are attributed to C=O, C–N, and C=C functional groups of flavonoids and proteinaceous compounds involved in nanoparticle stabilization. Distinct absorption bands in the $1130\text{--}839\text{ cm}^{-1}$ region correspond to Ce–O stretching vibrations, confirming the formation of the CeO_2 lattice. The enhanced intensity of these metal–oxygen bands compared to the pure extract further validates the successful synthesis of nanocrystalline cerium oxide, in agreement with previous reports (Li *et al.* 2023).

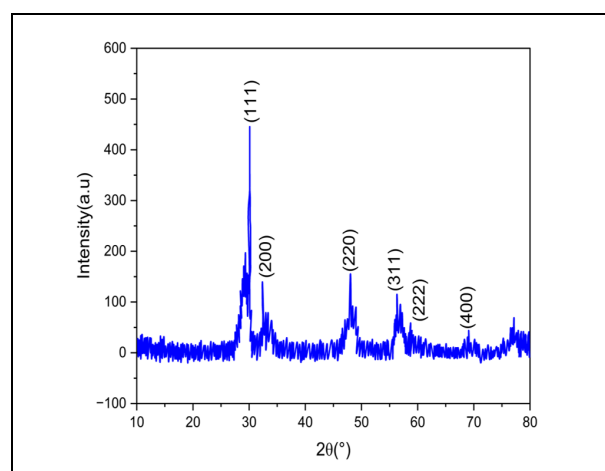


Fig. 4: XRD pattern of synthesized CeO_2 nanoparticles

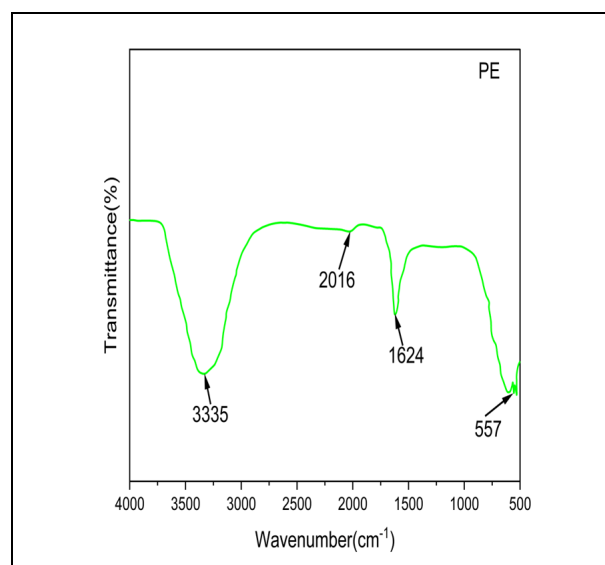


Fig. 5: FTIR analysis of *Tinospora* leaf extract

3.1.3 Scanning Electron Microscope

Scanning electron microscopy was utilized to examine the surface morphology of produced cerium

dioxide nanoparticles, as illustrated in Fig. 7. The micrographs obtained at an accelerating voltage of approximately 5 kV offer improved depth and spatial resolution for precise surface inspection. A working distance of roughly 8.8 mm was preserved to enhance image focus and depth of field, indicating the distance between the sample surface and the detector system. Imaging was conducted with a secondary electron detector, facilitating precise monitoring of surface roughness and particle dispersion. The 5 μm scale bar signifies that the detected features range from micro- to nanoscale dimensions, corroborated by additional investigations. The instruments were operated at high-vacuum settings to limit contamination and mitigate charging effects, hence enhancing image clarity. Morphological study indicates that the nanoparticles display variable geometries, encompassing angular and faceted structures, frequently forming aggregated clusters on a textured substrate. The observed aggregation behavior may influence corrosion performance by affecting nanoparticle dispersion and surface coverage. Excessive aggregation can reduce the effectiveness of the protective barrier, whereas improved dispersion promotes enhanced corrosion resistance. The existence of distinct crystalline structures and sharp-edged facets indicates partial crystallinity and validates the development of organized nanoscale domains. The observed aggregation behavior is expected to influence the corrosion protection efficiency of CeO_2 nanoparticles. Moderate aggregation may increase the effective particle size; however, uniformly distributed nanoparticle clusters can contribute to the formation of a more compact protective layer that restricts the diffusion of corrosive species. In contrast, excessive aggregation may reduce the available active surface area and generate localized defects, thereby lowering the barrier performance. Therefore, the degree of nanoparticle aggregation plays a significant role in determining the overall corrosion resistance of the developed system. Earlier research demonstrated that, the CeO_2 -based microcapsules prepared by emulsion polymerization improved self-healing and anticorrosion performance of epoxy coatings under harsh conditions. SEM analysis confirmed uniform spherical morphology, while electrochemical tests indicated increased impedance and reduced corrosion product formation. The enhanced protection is attributed to adsorption-driven surface interactions and passive layer formation by CeO_2 nanoparticles (Liu *et al.* 2022).

3.1.4 Dynamic Light Scattering

Fig.9 illustrates particle size properties of cerium dioxide nanoparticles derived from dynamic light scattering study. The examination of cumulants yields Z-hydrodynamic diameter with polydispersity of 0.6079 and an instrument-reported range of 71.17%. The PDI surpassing 0.5, along with the micrometer-scale average size, validates the existence of a highly polydisperse

system characterized by aggregated structures rather than a uniformly scattered nanocolloid. Distributions based on both intensity and volume demonstrate that substantial particle clusters markedly affect the scattering response, characteristic of aggregation-prone suspensions. This behavior endorses an adsorption-driven corrosion inhibition mechanism, wherein clustered nanoparticles, supported by *Tinospora cordifolia* phytochemicals, promote improvement of adherent and dense protective layer on mild steel surface.

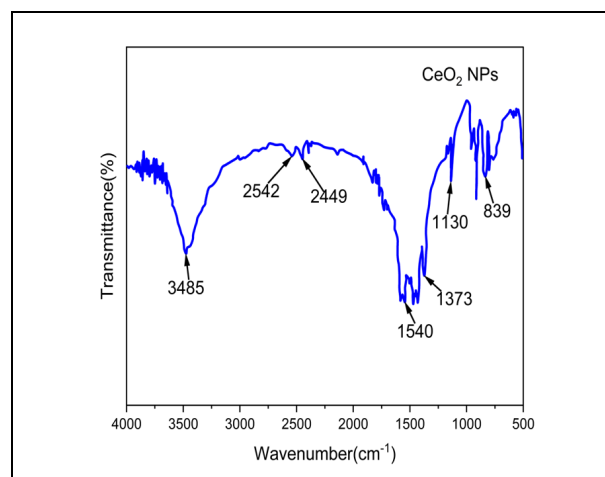


Fig. 6: FTIR analysis of synthesized CeO_2 NPs

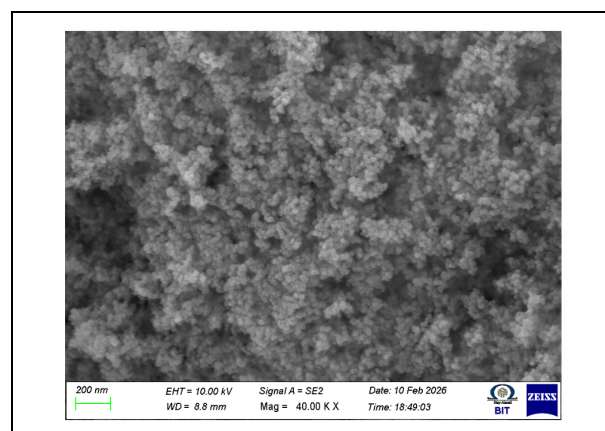


Fig. 7: SEM micrograph of synthesized nanoparticles

The variation in DLS measurements is expected, as this technique measures the hydrodynamic size of particle clusters in suspension rather than individual crystallites; in this system, the recorded dimensions primarily reflect micrometer-scale agglomerates formed from primary Cerium dioxide nanocrystals.

The aggregation behavior demonstrated by DLS significantly affects the corrosion inhibition efficacy of cerium dioxide nanoparticles. The presence of micrometer-scale agglomerates signifies inadequate dispersion in solution; nonetheless, this trait does not

compromise protective efficacy but rather improves layer development on the metal surface. The synergistic impact of nanoparticle aggregation and phytochemical capping from *Tinospora cordifolia* facilitates the formation of a dense, homogeneous, and highly adherent barrier layer upon adsorption onto mild steel. This aggregation-assisted layer enhances surface covering, diminishes exposed electrochemically active areas, and restricts the admission of chloride ions. Electrochemical investigations, encompassing impedance and polarization tests, substantiate this behavior by demonstrating diminished corrosion current density and elevated charge transfer resistance, so affirming enhanced inhibitory efficacy in the presence of these nanoparticles.

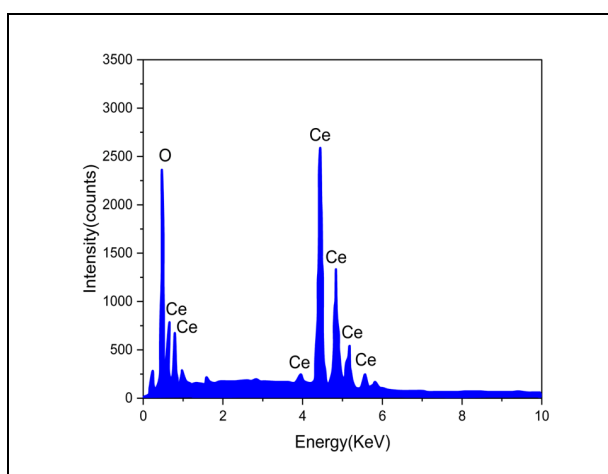


Fig. 8: EDX profile of synthesized nanoparticles

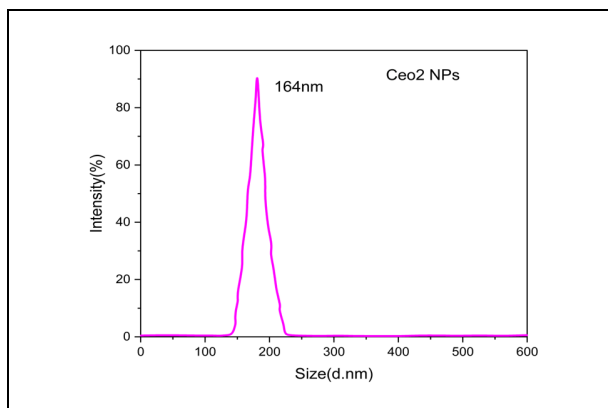


Fig. 9: DLS size distribution of synthesized nanoparticles

3.1.5 Zeta Potential

Zeta potential profile displays singular, relatively narrow peak near 0 mV, showing minimal electrostatic repulsion and pronounced tendency for particle aggregation at aqueous conditions. The observation corresponds by micrometer-scale hydrodynamic dimensions derived from DLS analysis, indicating that colloidal stability is influenced not by

charge effects but by steric hindrance from surface-attached phytochemicals. In the production process, bioactive chemicals from *Tinospora cordifolia* adhere to the surface of Cerium dioxide nanoparticles, offering steric stability that facilitates partial dispersion and improves interfacial contacts, advantageous for corrosion prevention and antioxidant activity.

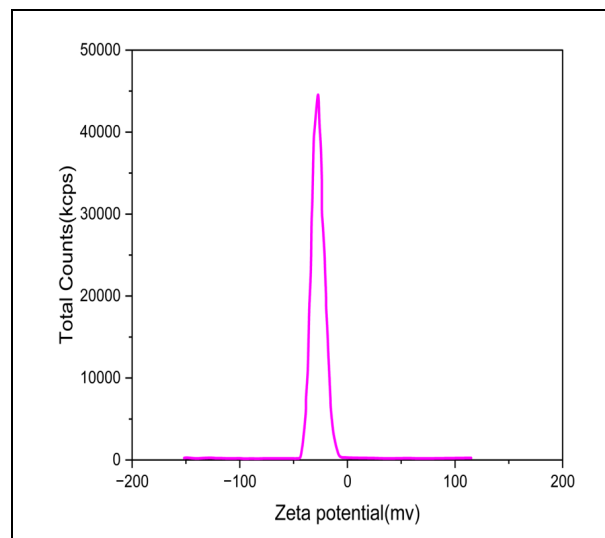


Fig. 10: Zeta potential of synthesized nanoparticles

3.2 Antioxidant Activity

Following synthesis and thorough characterisation of cerium dioxide nanoparticles, their antioxidant efficacy was analysed by ABTS and DPPH radical scavenging assays. The analytical approaches were extensively utilized to measure free radical neutralization efficiency, crucial for prospective applications in biomedical and environmental remediation sectors.

3.2.1 DPPH Evaluation

The DPPH scavenging efficacy of *Tinospora cordifolia* extracts derived from acetone, ethyl acetate, and methanol (Fig. 11a,b) demonstrated a concentration-dependent response, with IC_{50} values. Methanolic extracts exhibited significant antioxidant activity across the investigated doses, demonstrating their superior capacity to extract polar hydrogen-donating chemicals among the solvents. Acetone extracts demonstrated significant scavenging efficacy, while ethyl acetate extracts showed relatively diminished activity, indicating a restricted extraction of potent antioxidant compounds. The identified trend of diminishing inhibition with lower concentration was uniform across datasets, and the solvent efficacy adhered to the hierarchy: methanol > acetone > ethyl acetate. This constant polarity-dependent response underscores the essential importance of solvent selection in optimizing extraction efficiency and validates methanol as the most effective medium for

isolating DPPH-active phytochemicals. Several studies have reported that, silver-loaded CeO₂ nanoparticles synthesized by hydrothermal methods demonstrated enhanced antioxidant activity and inhibition of melanin. Structural characterization confirmed stable nanostructures, while DPPH and ABTS assays validated strong radical scavenging behavior. The study highlights potential applications in dermatological treatments (Ghorbani *et al.* 2025). The IC₅₀ value, defined as the concentration of extract required to inhibit 50% of DPPH free radicals, was determined from the dose-response curve and expressed in µg/mL for each extract and their corresponding cerium dioxide nanoparticles. Green synthesized CeO₂ nanoparticles using *Oroxylum indicum* exhibited an IC₅₀ value of 20.8 µg/mL in DPPH assay, which was lower than the reference ascorbic acid (33.2 µg/mL), confirming their antioxidant compatibility (Mim *et al.* 2024).

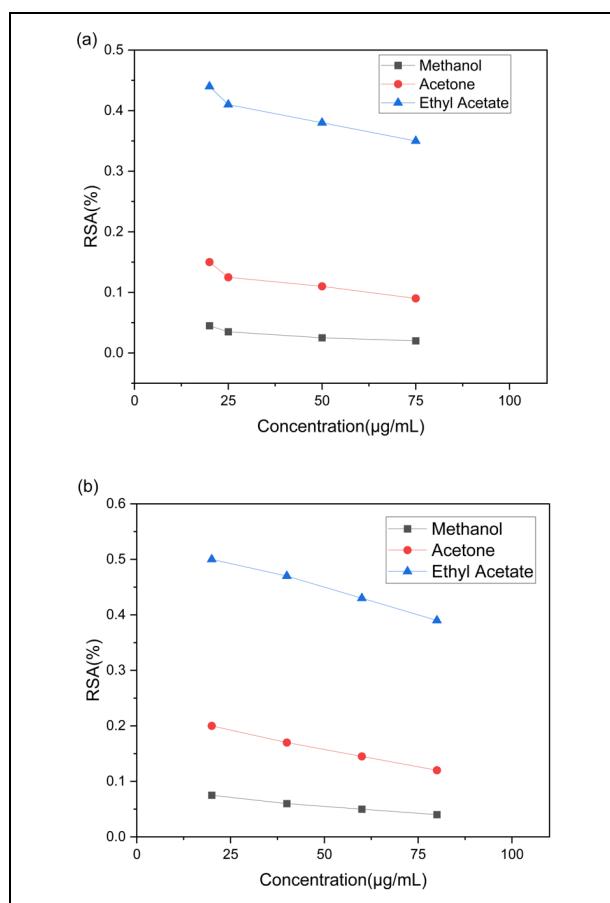


Fig. 11: (a) DPPH activity of plant extract and (b) nanoparticles

3.2.2 ABTS Evaluation

Antioxidant efficacy of *Tinospora cordifolia*, extracted with methanol, acetone, and distilled water were assessed using DPPH and ABTS assays, demonstrating a distinct concentration-dependent response. Aqueous extracts exhibited superior

scavenging efficacy in the DPPH system at all investigated doses, whereas methanol and acetone extracts displayed relatively diminished activity. A steady reduction in inhibition was noted with dilution, validating a conventional dose-response relationship. Conversely, ABTS assay results demonstrated that acetone extracts exhibited significantly greater radical neutralization capacity compared to their aqueous and methanolic equivalents. The changes underscore the significant impact of solvent polarity and assay technique on antioxidant assessment, indicating that extraction efficiency and measured activity are contingent upon both the solvent's chemical properties and the specific free radical system utilized. Prior investigations reported ABTS radical scavenging assay confirmed the strong antioxidant activity of the FA-CS-LG-CeO₂-TP nanocomposite, attributed to enhanced redox cycling of Ce³⁺/Ce⁴⁺ and polyphenol-mediated free radical neutralization (Sathiyaseelan *et al.* 2026). Similarly, the IC₅₀ value for ABTS radical scavenging was calculated from the percentage inhibition plot against concentration for all extracts and cerium dioxide nanoparticles.

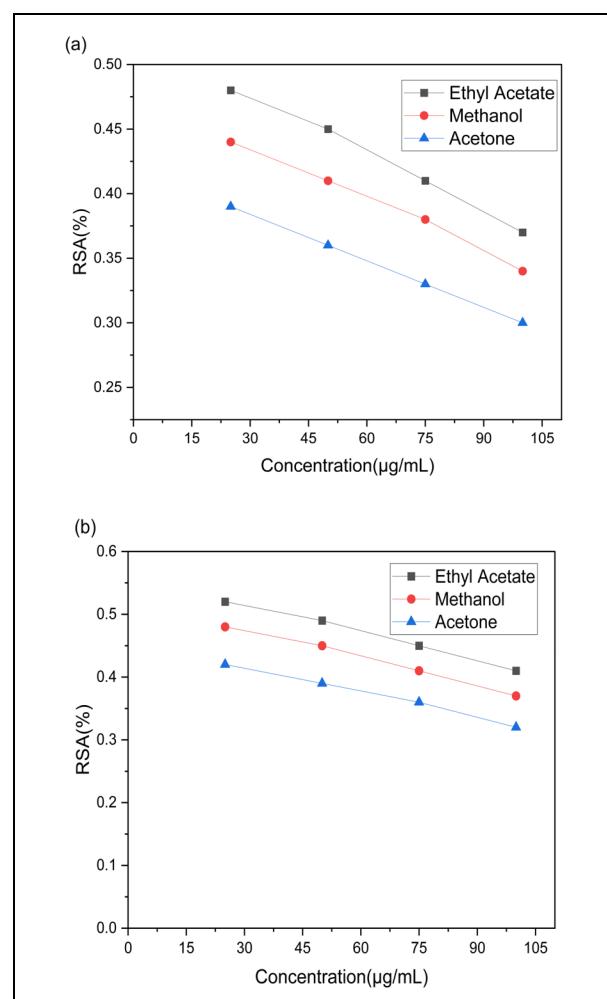


Fig. 12: (a) ABTS activity of plant extract and (b) nanoparticles

3.3 Anticorrosive Activity

3.3.1 Electrochemical Impedance Spectroscopy

Electrochemical impedance spectroscopy (EIS) were non-invasive analytical method employed to investigate interfacial processes at the electrode-electrolyte interface using a low-amplitude AC signal throughout a wide frequency range. Impedance data elucidate aspects like charge transfer resistance, double-layer capacitance, and mass transport effects, all of which are intricately linked to corrosion processes and inhibitor efficacy. In corrosion systems, an raise at charge transfer resistance, together with alterations at capacitive behavior, often indicates formation of protective layer on metal surface. Consequently, EIS was extensively used to evaluate both mechanisms and efficacy of corrosion inhibitors at harsh conditions. This study utilized Nyquist and Bode representations (Figs. 13a,b) to assess the corrosion prevention efficacy of Cerium dioxide nanoparticles and *Tinospora cordifolia* extract on mild steel. According to previous reports, green-synthesized CeO₂ nanoparticles incorporated into dual-function microcapsules exhibited self-healing and corrosion inhibition behavior by controlled release mechanisms. EIS results confirmed improved impedance response, demonstrating strong barrier formation and corrosion resistance in aggressive environments (Yin *et al.* 2025). The obtained EIS data were analyzed by fitting to an equivalent circuit model $R_s(QdlR_{ct})$, where R_s denotes the solution resistance, R_{ct} represents the charge transfer resistance, and Qdl is the constant phase element (CPE) used in place of ideal capacitance to account for surface heterogeneity. The circuit fitting was performed using ZSimpWin software, and the chi-square (χ^2) values were less than 0.01, confirming excellent agreement between experimental and fitted data. The fitted parameters are summarized in Tables 1 and 2.

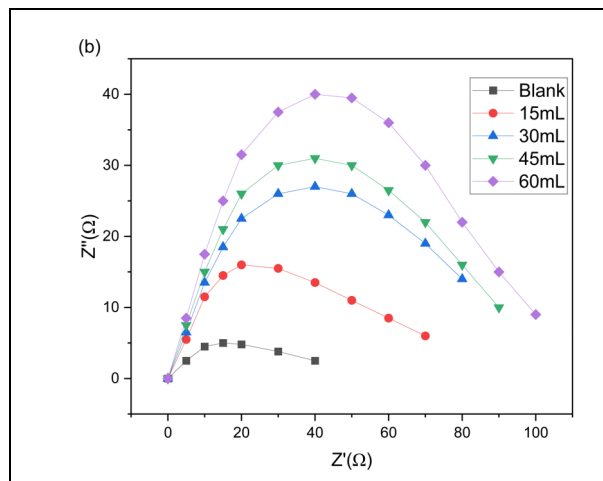
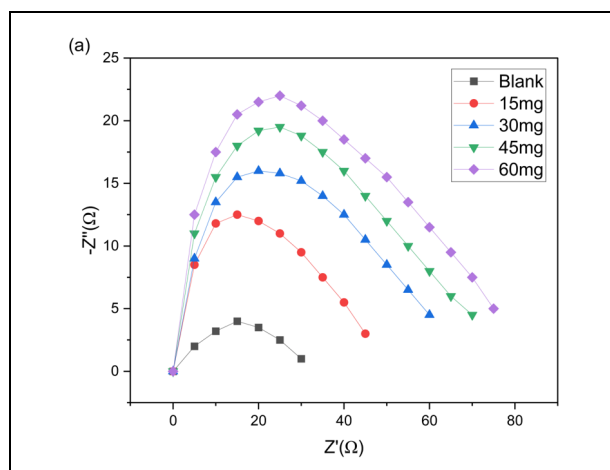


Fig. 13: (a) Nyquist plots for CeO₂ NP concentrations and (b) plant extract concentrations

3.3.2 Nyquist Plot Evaluation

Nyquist plots for CeO₂ at 0.5 M HCl, obtained with and without inhibitors, exhibit diminished capacitive semicircles, signifying a charge-transfer corrosion mechanism at a non-ideal metal–electrolyte interface. The divergence from ideal semicircles is ascribed to surface heterogeneity and suboptimal capacitive performance resulting from the adsorption of inhibitor species. As the inhibitor dosage increases, the semicircle diameter expands, indicating an elevation in charge transfer resistance and a concomitant decrease in corrosion rate. Elevated concentrations of cerium dioxide nanoparticles facilitate the development of a denser, more cohesive protective layer on the steel surface, thereby inhibiting electron transport and improving impedance response up to an ideal concentration (about 60 mg). The augmentation in impedance arc diameter is directly associated with enhanced suppression of both anodic metal dissolution and cathodic hydrogen evolution processes. The adsorption of nanoparticles effectively obstructs active corrosion sites and restricts chloride ion infiltration, hence enhancing corrosion resistance. A comparable trend is noted for *Tinospora cordifolia* extract; however, the somewhat smaller semicircle diameter indicates diminished inhibitory efficacy owing to decreased surface coverage and compromised film integrity in the absence of nanoparticles. The quantitative data (Tables 1 and 2) further substantiate that R_{ct} values escalate with increasing inhibitor concentration, achieving inhibition efficiency of approximately 71% for nanoparticles and 79% for plant extract, hence showing excellent surface adsorption and corrosion mitigation in acidic environments.

Table 1. Impedance analysis with synthesized nanoparticle concentrations

Concentration, mg	Rs, $\Omega \cdot \text{cm}^2$	IE, %	Rct, $\Omega \cdot \text{cm}^2$
Blank	4.20	-	22.80
15	4.40	47.59	43.50
30	4.60	60.82	58.20
45	4.80	66.37	67.80
60	5.00	70.58	77.50

Rs = Solution resistance; Rct = Charge transfer resistance; IE% = Inhibition Efficiency; Qdl = Double layer capacitance; Units: $\Omega \cdot \text{cm}^2$

Table 2. EIS analysis with plant extract concentration

Concentration, mg	Rs, $\Omega \cdot \text{cm}^2$	IE, %	Rct, $\Omega \cdot \text{cm}^2$
Blank	4.10	-	22.20
15	4.30	62.05	58.50
30	5.10	74.34	86.50
45	6.20	76.51	94.50
60	7.10	78.55	113.50

An elevation in inhibitor concentration results in increase at impedance magnitude for Cerium dioxide nanoparticles and *Tinospora cordifolia* extract with maximum values recorded at roughly 40 mg. This transition to elevated phase angles indicates the formation of a more consistent and stable protective layer at the steel–electrolyte interface. The inhibitory mechanism is essentially linked to the creation of an adsorbed, compact, and resistant coating that effectively mitigates corrosion processes instead of merely diminishing material loss.

3.4 Potentiodynamic Polarization

Potentiodynamic polarization were electrochemical approach utilized to examine corrosion kinetics by altering the electrode potential at a specified scan rate while monitoring the resultant current response. The polarization profiles provide critical parameters including corrosion potential (E_{corr}), corrosion current density (I_{corr}), and anodic and cathodic Tafel slopes, which characterize the rates of metal dissolution and reduction reactions for Cerium dioxide nanoparticles and *Tinospora cordifolia* extract. In inhibitor assessment, a decrease in I_{corr} coupled with alterations in E_{corr} indicates enhanced corrosion resistance and elucidates the inhibitory mechanism. Consequently, this technique is frequently employed to estimate corrosion rates and analyze the protective efficacy of inhibitors in harsh environments.

3.4.1 Tafel Curve Analysis

The curves depict the electrochemical response of the system by connecting potential with current density. The characteristics obtained were corrosion current density (I_{corr}), corrosion potential (E_{corr}), and inhibition efficiency for Cerium dioxide nanoparticles and *Tinospora cordifolia* extract. The minimal variance in E_{corr} values indicates that the solutions operate as mixed-type inhibitors, affecting both anodic and cathodic corrosion processes.

3.4.2 Role of Adsorption in Electrochemistry

The corrosion prevention efficacy of *Tinospora cordifolia* extract and biogenic Cerium dioxide nanoparticles were governed by adsorption onto mild steel surface. In acidic conditions, surface protonation generates a partial positive charge, enhancing the attraction of chloride ions and establishing localized negative sites that encourage inhibitor adsorption via electrostatic interactions and donor–acceptor bonding with heteroatoms like oxygen. Potentiodynamic polarization studies indicate a decrease in both anodic and cathodic current densities, with negligible changes in corrosion potential, hence affirming mixed-type inhibitory behavior. The alteration of both anodic and cathodic Tafel slopes signifies that the inhibitors concurrently impede metal breakdown and hydrogen evolution by occupying active surface locations. The nanoparticle approach boosts protection by creating a dense barrier layer that limits ionic movement at the interface. The higher efficacy of nanoparticles relative to plant extract alone is due to improved surface coverage and more robust interfacial blockage enabled by nanoparticle-assisted adsorption.

3.5 Gravimetric Evaluation

3.5.1 Weight Loss Technique

Gravimetric analysis is a widely utilized and dependable method for evaluating metal corrosion rates in the presence of inhibitors like *Tinospora cordifolia* extract and cerium dioxide nanoparticles. This method facilitates direct numerical assessment of material degradation, allowing for the determination of corrosion rate, inhibition efficiency, and surface coverage.

The mass loss of Cerium dioxide nanoparticles diminished from 0.601 g (blank) to 0.460 g at 40 mg after 24 hours, indicating an inhibitory efficiency of 23.5%. After 48 hours, the blank loss of 1.111 g decreased to 0.467 g at the same concentration, resulting in an efficiency of 64.7%. The *Tinospora cordifolia* extract demonstrated a weight reduction of 0.222 g in the uninhibited sample and 0.111 g at a dosage of 40 mg after 24 hours, suggesting enhanced corrosion prevention with higher inhibitor concentrations. *Tinospora cordifolia* extract demonstrated an inhibitory efficacy of

approximately 58.6% at 40 mg after 24 hours. By prolonging the exposure duration to 48 hours, the mass loss diminished from 1.510 g in the unconstrained system to 0.597 g with the extract, resulting in an efficiency of 60.5%. These findings confirm that inhibitory efficacy is concentration- and time-dependent, attributed to progressive surface film stabilization, with CeO₂ nanoparticles outperforming the plant extract at longer exposure durations.

4. CONCLUSION

Biogenic cerium dioxide nanoparticles were successfully synthesized using *Tinospora cordifolia* leaf extract via a sustainable green route, yielding nanocrystalline tetragonal structures with nanoscale crystallite size, stabilized by plant-derived phytochemicals. The nanoparticles demonstrated significant corrosion protection for mild steel in acidic environments, achieving inhibition efficiency of approximately 82.5% from polarization studies and 70.5% from impedance analysis. Gravimetric evaluation further confirmed time-dependent protective behavior, with efficiency increasing from 23.5% at 24 hours to 64.7% at 48 hours. The antioxidant assessment using DPPH and ABTS assays revealed strong radical scavenging activity with concentration-dependent behavior, particularly in methanolic systems, confirming the multifunctional nature of the synthesized nanoparticles. However, practical application is limited by nanoparticle aggregation in aqueous dispersion, which affects long-term dispersion stability and reproducibility. Future studies should focus on surface functionalization to improve colloidal stability, scaling up the green synthesis process, and evaluating in vivo antioxidant activity and performance in real industrial corrosive environments.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

COPYRIGHT

This article is an open-access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).



REFERENCES

- Anitha, N., Jayarambabu, N., Akshaykranth, A. and Venkatappa, R. T. *Tinospora cordifolia* approached copper oxide nanoparticles using different concentrations for optical and antibacterial applications, *Inorg. Chem. Commun.*, 143, 109786 (2022).
<https://doi.org/10.1016/j.inoche.2022.109786>
- Bhukya, S. N., Velidandi, A., S.M.K, C., Boda, R., Anil Kumar, B., Medikundu, N. R. and Rotte, N. K. A Multifunctional CeO₂/NiO Nanocomposite for Biomedical Applications With Selective Anticancer Activity and Low Eco-Toxicity: In Vitro Studies, *BioNanoSci.*, 16(3), 207(2026).
<https://doi.org/10.1007/s12668-026-02460-5>
- Ghorbani, M., Sepahdoost, N., Vaezi, Z., Kahrizi, D. and Naderi-Manesh, H., Antioxidant effects of silver-ceria nanoparticles on the reduction of melanin in amelanotic melanoma cell biology, *Sci. Rep.*, 15(1), 11177(2025).
<https://doi.org/10.1038/s41598-025-96366-z>
- Jayaseelan, C., Siva, D., Kamaraj, C., Thirugnanasambandam, R., Ganesh, K. V., Subashni, B., Ashokkumar, R. and Saravanan, D., Phytosynthesis of zinc oxide nanoparticles for enhanced antioxidant, antibacterial, and photocatalytic properties: A greener approach to environmental sustainability, *Environ. Res.*, 251, 118770(2024).
<https://doi.org/10.1016/j.envres.2024.118770>
- Kaewpengkrow, P., Atong, D. and Sricharoenchaikul, V., Effect of Pd, Ru, Ni and ceramic supports on selective deoxygenation and hydrogenation of fast pyrolysis *Jatropha* residue vapors, *Renewable Energy*, 65, 92–101 (2014).
<https://doi.org/10.1016/j.renene.2013.07.026>
- Khokher, S. and Lata, S., Benzotriazole loaded polypyrrole/cerium oxide synthesized composite blend within epoxy resin designed as superior coatings against mild steel oxidative corrosion in sodium chloride medium, *J. Mol. Struc.*, 1312, 138525 (2024).
<https://doi.org/10.1016/j.molstruc.2024.138525>
- Li, L., Yao, H., Bi, W., Fu, W. and Wang, N., Anticorrosive coatings made from polydopamine modified graphitic C₃N₄ composites with synergistic anticorrosion effects, *J. Vacuum Sci. Technol. A*: 41(6), 062202(2023).
<https://doi.org/10.1116/6.0002769>
- Liu, S., Xie, H., Cao, Q., Ning, Y., Song, Y., Zhang, C. and Liu, B., Preparation of a novel IPDI/PUF@CeO₂ bi-functional microcapsules and its improvement for the self-healing and anti-corrosion performance in epoxy coatings, *Prog. Org. Coat.*, 169, 106897(2022).
<https://doi.org/10.1016/j.porgcoat.2022.106897>

- Liu, X., Xu, L., Meng, H., Huang, Y., Han, B., Qu, Z., Lyu, Y., Li, S. and Wu, K., Regulating electronic structure of pristine cerium oxide surface/interface for enhanced multienzyme-like activity and antibacterial performance, *Colloids Surf. A: Physicochem. Eng. Aspects*, 736, 139627 (2026). <https://doi.org/10.1016/j.colsurfa.2026.139627>
- Matussin, S. N. and Khan, M. M., A green approach for morphology and size-controlled fabrication of cerium oxide using leaf extract of *Mangifera indica* for photocatalytic activities, *J. Umm Al-Qura Univers. Appl. Sci.*, 11(3), 612–622(2025). <https://doi.org/10.1007/s43994-024-00206-1>
- Mim, J., Sultana, Mst. S., Dhar, P. K., Hasan, Md. K. and Dutta, S. K., Green mediated synthesis of cerium oxide nanoparticles by using *Oroxylum indicum* for evaluation of catalytic and biomedical activity, *RSC Adv.*, 14(35), 25409–25424(2024). <https://doi.org/10.1039/D4RA04132A>
- Muduli, S. and Ranjan Sahoo, T., Green synthesis and characterization of CeO₂ and Ni-doped CeO₂ nanoparticles and its dielectric properties, *Mater. Today: Proce.*, 74, 697–702(2023). <https://doi.org/https://doi.org/10.1016/j.matpr.2022.10.278>
- Muthulakshmi, N., Senthil, M., Archana, B., Mani, A. and Subramanian, R., Biogenic Synthesis of Cerium Oxide Nanoparticles: Characterization, Biological Activities and Their Corrosion Inhibition Properties, *Micros. Res. Tech.*, 89(5), 727–740(2026). <https://doi.org/10.1002/jemt.70109>
- Mylarappa, M., Selvam, C., Ramesh, S., Sanjeevappa, H. K., Govindareddy, P. K. S. and Ramachandregowda, S., Eco-friendly Synthesis of CeO₂ Nanoparticles Using Bee Pollen: Dye Purification, Antioxidant, Antibacterial, Antifungal and Anticancer Properties, *Nanochem. Res.*, 11(1), 86–111(2026). <https://doi.org/10.22036/ncr.2025.512371.1460>
- Ngo, N. K., Shao, S., Conrad, H., Sanders, S. F., D'Souza, F. and Golden, T. D., Synthesis, characterization, and the effects of organo-grafted nanoparticles in nickel coatings for enhanced corrosion protection, *Mater. Today Commun.*, 25, 101628 (2020). <https://doi.org/10.1016/j.mtcomm.2020.101628>
- Pang, Y., Amona, F. M., Chen, X., You, Y., Sha, Z., Liu, Z., Li, J., Liu, Y., Fang, X. and Chen, X., Phytochemical nanozymes reprogram redox for balanced antimicrobial and regenerative therapy in acute and chronic diabetic wounds, *Redox Bio.*, 85, 103718 (2025). <https://doi.org/10.1016/j.redox.2025.103718>
- Rajasekaran, S., Elumalai, A., Sivapriya, J. and Vasanthan, S., Synergistic Design of Al₂O₃@g-C₃N₄ hybrid nanocomposite photocatalyst from *Tinospora cordifolia* Plant extract: A Sustainable Solution for Emerging Organic Pollutants, *Ionics*, 31(9), 9919–9933(2025). <https://doi.org/10.1007/s11581-025-06531-7>
- Rajkumar, M., Presley, S. I. D., Menaa, F., Elbehairi, S. E. I., Alfaifi, M. Y., Shati, A. A., Albalawi, A. E., Althobaiti, N. A., Kirubakaran, D., Govindaraj, P., Meenambigai, K. and Gomathi, T., Biosynthesis and biological activities of magnesium hydroxide nanoparticles using *Tinospora cordifolia* leaf extract, *Bioprocess Biosyst. Eng.*, 47(12), 2111–2129 (2024). <https://doi.org/10.1007/s00449-024-03089-y>
- Royani, A., Aigbodion, V. S., Hanafi, M., Mubarak, N. M., Verma, C., Alfantazi, A. and Manaf, A., Enhancing the corrosion inhibition performance of *Tinospora cordifolia* extract using different fractions of methanol solvent on carbon steel corrosion in a seawater-simulated solution, *Appl. Surf. Sci. Adv.*, 18, 100465(2023). <https://doi.org/10.1016/j.apsadv.2023.100465>
- Royani, A., Hanafi, M., Thakur, A., Zarrouk, A., Mubarak, N. M. and Manaf, A., Electrochemical and computational investigation of *Tinospora cordifolia* fractions as a novel corrosion inhibitor for carbon steel in seawater medium, *Sci. Rep.*, 15(1), 34643(2025). <https://doi.org/10.1038/s41598-025-18572-z>
- Sathiyaseelan, A., You, H. S., Park, S. and Wang, M. H., Postbiotic-assisted synthesis of cerium oxide nanocomposites functionalized with folic acid–chitosan and tea polyphenols for redox-regulated anticancer activity, *Int. J. Bio. Macromol.*, 355, 151422 (2026). <https://doi.org/10.1016/j.ijbiomac.2026.151422>
- Saxena, A., Prasad, D., Thakur, K. K. and Kaur, J., PDP, EIS, and Surface Studies of the Low-Carbon Steel by the Extract of *Tinospora cordifolia*: A Green Approach to the Corrosion Inhibition, *Arab. J. Sci. Eng.*, 46(1), 425–436(2021). <https://doi.org/10.1007/s13369-020-04894-9>
- Soundarya, V., Nagasathya, A., Subashchandhiran, M., Kavitha, T., Karthikeyan, V., Vijay, K., Ranjith, R., Gokul, M. and Karmegam, N., Biosynthesis and Characterization of Bimetallic Ag-Cu Nanoparticles from *Tinospora cordifolia* Aerial Roots and Their Biomedical Applications, *Chem. Select*, 10(39), e02813 (2025). <https://doi.org/10.1002/slct.202502813>
- Thomas, K. V., Thomas, K. J., Rapheal, P. V., Sabu, A. S., Ragi, K. and Johnson, R., *Tinospora cordifolia* extract as an environmentally benign green corrosion inhibitor in acid media: electrochemical, surface morphological, quantum chemical, and statistical investigations, *Mater. Today Sustain.*, 13, 100076(2021). <https://doi.org/10.1016/j.mtsust.2021.100076>
- Xavier, J. R. Superior corrosion protection performance of polypdopamine-intercalated CeO₂/polyurethane nanocomposite coatings on steel in 3.5% NaCl solution, *J. Appl. Electrochem.*, 51(6), 959–975 (2021). <https://doi.org/10.1007/s10800-021-01547-z>

- Xiao, Y., He, X., Wan, T. and Bai, X., Preparation and Corrosion Resistance Analysis of Modified Cerium Oxide/Waterborne Epoxy Composite Coatings, *Surf. Technol.*, 53(14), 96-105 and 189 (2024). <https://doi.org/10.16490/j.cnki.issn.1001-3660.2024.14.008>
- Yao, H., Wang, X., Li, W. and Wang, N., Preparation and modification of polyaniline–boron nitride for enhancing the corrosion resistance of waterborne epoxy coatings, *J. Coat. Technol. Res.*, (2026). <https://doi.org/10.1007/s11998-025-01259-5>
- Yin, C., Zhang, F., Zhang, X., Wang, T. and Zeng, E., Design and Development of Dual-Function Nano-CeO₂-Integrated PUF/Epoxy Microcapsule Systems for Self-Healing and Corrosion-Resistant Epoxy Coatings, *J. Appl. Polym. Sci.*, 142(13), e56654(2025). <https://doi.org/10.1002/app.56654>