

Green Synthesis and Characterization of Vanadium Oxide (V_2O_5) Nanoparticles Using *Parmentiera cereifera* Leaf Extract: A Sustainable Biogenic Route with Biomedical Implications

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Research Article

Keywords:

Posted Date: May 4th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-8174388/v1>

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Additional Declarations: No competing interests reported.

Abstract

Background:

Green nanotechnology offers a sustainable alternative to conventional synthesis of metal and metal-oxide nanomaterials by eliminating toxic reagents and reducing environmental burdens [1–3]. Vanadium pentoxide (V_2O_5) holds exceptional catalytic and biomedical potential, yet its green synthesis remains largely unexplored. *Parmentiera cereifera*—a phenolic and flavonoid-rich plant—has never been utilized for nanoparticle fabrication. This study reports the first biogenic synthesis of V_2O_5 nanoparticles using *P. cereifera* leaf extract, establishing an unexplored metal–plant system with biomedical relevance. To the best of our knowledge, no literature reports exist on vanadium nanoparticle synthesis using any Bignoniaceae species, highlighting the novelty of this work.

Methods:

The aqueous extract of *P. cereifera* was employed as a natural reducing and stabilizing agent for converting NH_4VO_3 into V_2O_5 nanoparticles at 70°C under near-neutral conditions. Characterization included UV–Vis, FTIR, XRD, SEM, TEM, EDX, and zeta potential analyses. Biological activities— α -amylase inhibition, MTT cytotoxicity, and antimicrobial assays—were evaluated using standard protocols [12–15]. Green metrics such as atom economy, energy consumption, and E-factor were assessed against sol–gel and hydrothermal methods [16–21].

Results:

A distinct absorption band at ~ 320 nm and V–O/V = O FTIR peaks confirmed nanoparticle formation. XRD indicated the orthorhombic V_2O_5 phase (JCPDS 41-1426) with crystallite size of $\sim 45 \pm 5$ nm. SEM/TEM showed quasi-spherical nanoparticles (20–60 nm), supported by a zeta potential of -28.4 mV, indicating excellent colloidal stability. The nanoparticles demonstrated strong α -amylase inhibition ($IC_{50} \approx 38.4 \mu g mL^{-1}$), selective cytotoxicity toward A549 cancer cells, and broad-spectrum antimicrobial activity against *Staphylococcus aureus*, *E. coli*, and *Candida albicans* [31–34]. The dual bioactivity profile identified in this work has not been previously reported for any green-synthesized V_2O_5 system, indicating biomedical novelty. A $> 60\%$ reduction in chemical usage, reaction temperature, and energy demand confirmed high sustainability over conventional synthesis.

Conclusions:

This work identifies *P. cereifera* as a new biogenic resource for scalable V_2O_5 nanomaterial synthesis and introduces a reproducible pathway aligned with circular bioeconomy principles. The phytochemical-mediated mechanism produced structurally stable, functionally active nanoparticles with strong biomedical potential. Future work should involve molecular-level mechanistic studies, nanocomposite fabrication, and *in vivo* validation.

1. Introduction

Nanotechnology has revolutionized modern materials science by enabling the controlled design of matter at the atomic and molecular scale, giving rise to structures with novel optical, catalytic, and electronic properties that are otherwise inaccessible at the bulk level [1, 2]. Among various classes of nanomaterials, **metal and metal oxide nanoparticles (NPs)** are of particular interest due to their broad applicability in catalysis, sensing, environmental remediation, and healthcare [3–5]. However, most conventional synthesis strategies—such as chemical precipitation,

sol–gel processing, and hydrothermal growth—rely on harsh chemical reagents, organic solvents, and high energy inputs [6–8]. These processes often yield secondary waste and toxic byproducts that are inconsistent with the principles of environmental sustainability. To overcome these challenges, **green nanotechnology** has emerged as an environmentally responsible approach emphasizing non-toxic reagents, low-temperature synthesis, and renewable biological resources [9–11]. In this context, **plant-mediated synthesis** represents one of the most promising subfields, using extracts rich in natural metabolites as multifunctional agents that simultaneously reduce and stabilize nanoparticles [12–14]. The method is attractive for its cost-effectiveness, scalability, and inherent biocompatibility, as it eliminates the need for hazardous reducing agents such as hydrazine or sodium borohydride [15, 16]. Plant extracts contain an abundance of **phytochemicals**—including polyphenols, flavonoids, alkaloids, terpenoids, saponins, and reducing sugars—that feature electron-donating functional groups such as hydroxyl (–OH), carboxyl (–COOH), and carbonyl (–C = O) moieties [17–19]. These groups donate electrons to metal ions, driving the reduction process, and subsequently act as **capping ligands**, preventing nanoparticle agglomeration [20, 21]. The resulting nanoparticles are surface-functionalized with biomolecular coatings that enhance aqueous stability, biocompatibility, and biological performance [22, 23].

1.1. Vanadium oxide nanoparticles and their significance

Among transition metal oxides, **vanadium oxides** (V_2O_5 , VO_2 , V_2O_3) occupy a unique position due to their multiple oxidation states ($V^{3+}/V^{4+}/V^{5+}$) and pronounced redox reversibility [24–26]. **Vanadium pentoxide** (V_2O_5), in particular, crystallizes in an orthorhombic layered structure composed of VO_5 square pyramids sharing corners and edges, resulting in anisotropic electronic and ionic transport properties [27]. This structure makes V_2O_5 a versatile material with demonstrated performance in **catalysis**, **lithium-ion batteries**, **electrochromic devices**, and **gas sensors** [28–30]. Recent research has also revealed promising **biological properties** of vanadium-based materials, such as **antidiabetic**, **anticancer**, **antioxidant**, and **antimicrobial** effects [31–34]. Vanadium ions exhibit insulin-mimetic behavior, enhancing glucose uptake and glycogen synthesis in muscle cells [35]. At the cellular level, V_2O_5 nanoparticles are known to generate **reactive oxygen species (ROS)**, disrupt mitochondrial function, and induce apoptosis in cancer cells [36–38]. These dual catalytic and biomedical attributes make vanadium oxides uniquely suited for **multifunctional nanomaterial platforms** [39, 40]. Despite their potential, the **chemical synthesis of V_2O_5** typically involves high-temperature calcination, concentrated acids, or organic solvents, which compromise product safety for biomedical use and generate hazardous waste [41, 42]. To realize the full potential of V_2O_5 nanoparticles in sustainable applications, it is imperative to develop **green synthesis routes** that utilize renewable plant biomolecules as reducing and stabilizing agents [43–45].

1.2. *Parmentiera cereifera* as an untapped biogenic resource

Parmentiera cereifera Seem. (family Bignoniaceae), commonly called the Candle Tree, is a perennial tropical species native to Central America and now cultivated widely across humid regions. Phytochemical screening of its leaves and fruits reveals a rich composition of **phenolic acids (gallic, caffeic, ferulic)**, **flavonoids (quercetin, rutin, catechin)**, **tannins**, **terpenoids**, and **saponins**—molecules that exhibit strong antioxidant and reducing capacities [46–49]. These compounds readily donate electrons from hydroxyl and carbonyl groups, making the plant extract a potent **bio-reducing system** for metal ions under ambient conditions. The presence of these phytochemicals also imparts **antioxidant and antimicrobial** functionality to the resulting nanostructures, supporting applications in nanomedicine and environmental remediation [50–52]. Despite this favorable chemistry, *P. cereifera* has never been reported as a plant source for nanoparticle synthesis, making it a scientifically intriguing and ecologically valuable biomass candidate for green nanotechnology. Its aqueous extractability, high phytochemical yield, and abundance in tropical regions provide an opportunity for low-cost, renewable nanomaterial production.

1.3. Rationale and Novelty of the Present Work

Although several medicinal and aromatic plants—such as *Azadirachta indica*, *Aloe vera*, and *Moringa oleifera*—have been successfully utilized for the biosynthesis of metallic and metal-oxide nanoparticles [53–55], **studies on vanadium-based nanostructures remain limited**, and none have employed *Parmentiera cereifera* for such synthesis.

This research represents the **first report** on the **green synthesis of vanadium oxide (V_2O_5) nanoparticles using aqueous leaf extract of *P. cereifera***. The novelty and scientific contribution of this study can be summarized as follows:

1. **Unexplored Biomass Source:** *P. cereifera* is introduced for the first time as a **biofactory for nanomaterial synthesis**, exploiting its rich matrix of phenolics, flavonoids, and terpenoids for vanadium reduction and stabilization.
2. **New Metal–Plant System:** The combination of *P. cereifera* phytochemicals and vanadium precursor (NH_4VO_3) yields a unique **biogenic V_2O_5 system** that operates under neutral pH and low temperature ($\sim 70^\circ C$) without chemical surfactants.
3. **Mechanistic Elucidation:** The work proposes a mechanistic model explaining how specific functional groups ($-OH$, $-COOH$, $-C=O$) donate electrons to VO_3^- ions, initiating reduction and promoting nucleation of orthorhombic V_2O_5 nanoparticles.
4. **Sustainability Integration:** The study quantitatively evaluates **energy efficiency, E-factor, atom economy**, and **carbon emission reduction**, establishing clear sustainability metrics compared with conventional hydrothermal and sol–gel synthesis.
5. **Functional Validation:** The synthesized nanoparticles were tested for **α -amylase inhibition, anticancer activity**, and **antimicrobial efficacy**, demonstrating the dual functional and biomedical relevance of the biogenic V_2O_5 material.

This multi-dimensional novelty integrates **green chemistry, biomass valorization**, and **functional material design**, thereby positioning *P. cereifera* as a new and sustainable resource in the expanding domain of **biogenic transition-metal nanomaterials**.

1.4. Objective of the Study

The present study aims to:

1. develop an eco-friendly route for synthesizing V_2O_5 nanoparticles using aqueous leaf extract of *P. cereifera*;
2. perform comprehensive physicochemical characterization (UV–Vis, FTIR, XRD, SEM, TEM, EDX, and zeta potential analyses);
3. elucidate the phytochemical reduction mechanism;
4. assess representative biological activities (antidiabetic, anticancer, antimicrobial); and
5. evaluate the environmental sustainability of the process in comparison with conventional methods. Through this integrated approach, the study not only introduces *P. cereifera* as a novel nanobiotechnological resource but also reinforces the principles of circular bioeconomy and green materials innovation.

2. Materials and Methods

2.1. Chemicals and reagents

Ammonium metavanadate (NH_4VO_3 , $\geq 99.5\%$), dinitrosalicylic acid (DNS), α -amylase (porcine pancreas, EC 3.2.1.1), starch (soluble), acarbose ($\geq 98\%$), 3-(4,5-dimethyl-thiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT), dimethyl sulfoxide (DMSO), ciprofloxacin, and fluconazole were procured from Sigma-Aldrich (USA). All solvents were of analytical grade (Merck, India) and used without further purification. Nutrient agar (NA) and Sabouraud dextrose agar (SDA) media were purchased from HiMedia, Mumbai. Deionized (DI) water ($18.2 \text{ M}\Omega \text{ cm}$) was used throughout all preparations. Microbial strains *Staphylococcus aureus* (ATCC 25923), *Escherichia coli* (ATCC 25922), and *Candida albicans* (ATCC 10231) were obtained from the Microbial Type Culture Collection (MTCC), Chandigarh. Human lung adenocarcinoma (A549) and embryonic kidney (HEK-293) cell lines were sourced from the National Centre for Cell Science (NCCS), Pune, India.

2.2. Collection and Authentication of Plant Material

Fresh, mature leaves of *Parmentiera cereifera* Seem. were collected from cultivated specimens growing in an authenticated botanical garden during July 2025, corresponding to the active vegetative phase. The species, originally native to Central America and now widely cultivated in tropical regions, was selected due to its high phytochemical richness and reported antioxidant potential. The collected material was taxonomically identified and authenticated by a qualified botanist. A voucher specimen (No. PC-2025-01) was prepared and deposited in the departmental herbarium of the host institution for future reference. After collection, the leaves were washed thoroughly with running tap water followed by deionized (DI) water to remove impurities. The cleaned leaves were shade-dried at $28 \pm 2^\circ\text{C}$ for ten days, pulverized using a stainless-steel grinder, and stored in airtight amber containers at 4°C until extraction.

2.3. Preparation of aqueous leaf extract

Ten grams of the powdered leaf material were mixed with 200 mL of DI water in a 500 mL Erlenmeyer flask and heated at 80°C for 2 h under continuous stirring (400 rpm). After cooling to room temperature, the mixture was filtered through Whatman No. 1 paper followed by $0.45 \mu\text{m}$ membrane filtration. The filtrate was stored at 4°C for further use. The pH of the extract was 6.8 ± 0.1 . Phytochemical screening confirmed the presence of **phenolics, flavonoids, tannins, saponins, and terpenoids** following standard qualitative assays [2]. Total phenolic content (TPC) was quantified by the Folin–Ciocalteu method and expressed as mg gallic acid equivalents (GAE) g^{-1} extract [3]; total flavonoid content (TFC) was determined by the aluminium chloride method and expressed as mg quercetin equivalents g^{-1} extract [4]. The high phenolic and flavonoid contents indicated strong reducing potential of the extract.

2.4. Green synthesis of V_2O_5 nanoparticles

A 0.04 M aqueous solution of ammonium metavanadate (NH_4VO_3) was freshly prepared as the vanadium precursor. Equal volumes (50 mL each) of the NH_4VO_3 solution and the *P. cereifera* leaf extract were mixed in a 250 mL round-bottom flask. The initial pH of the reaction mixture was 7.1 ± 0.1 , corresponding to the near-neutral pH of the extract. Preliminary optimization experiments revealed that nanoparticle formation was most efficient under slightly neutral to mildly alkaline conditions (pH 7–8). Under highly acidic conditions, incomplete reduction of vanadate species occurred, whereas strongly alkaline pH (> 9) led to rapid precipitation and particle aggregation. The reaction mixture was magnetically stirred at $70 \pm 2^\circ\text{C}$ for 90 min. During the reaction, the color gradually changed from pale yellow to deep orange and finally to reddish-brown, signifying the reduction of vanadate ions ($\text{VO}_3^- \rightarrow \text{V}_2\text{O}_5 \text{ NPs}$) by phytochemical electron donors present in the extract [5, 6]. The final pH after completion of the reaction decreased slightly to 6.8 ± 0.1 , indicating proton consumption during reduction and complexation processes. After cooling, the reaction suspension was centrifuged at 10 000 rpm for 15 min to separate the nanoparticle pellet. The pellet was washed twice with deionized water and once with ethanol to remove unbound organic residues. The washed product was dried in a hot-air oven at 80°C overnight, yielding a fine brown powder corresponding to the un-calcined V_2O_5 .

nanoparticles. For crystalline phase formation, the dried powder was calcined in a muffle furnace at 450°C for 2 h at a heating rate of 5°C min⁻¹ [7]. The final orange-yellow crystalline powder was designated as P. cereifera–V₂O₅ NPs.

2.5. Characterization techniques

The synthesized nanoparticles were characterized comprehensively as follows:

- UV–Visible spectroscopy: Absorption spectra (200–800 nm) were recorded using a Shimadzu UV-1900 spectrophotometer to monitor the optical transitions and confirm nanoparticle formation [8].
- Fourier-transform infrared spectroscopy (FTIR): A Bruker Tensor 27 spectrometer was used in the 4000–400 cm⁻¹ range (KBr pellet method) to identify functional groups associated with reduction and capping [9].
- X-ray diffraction (XRD): Crystalline structure was analyzed with a Rigaku Ultima IV diffractometer using Cu K α radiation ($\lambda = 1.5406 \text{ \AA}$) over $2\theta = 10\text{--}80^\circ$. Crystallite size (D) was calculated via the Scherrer equation $D = K\lambda/\beta \cos \theta$ [10].
- Scanning electron microscopy (SEM): Morphological features were examined using a JEOL JSM-6610 microscope operated at 15 kV.
- Transmission electron microscopy (TEM): Particle size and lattice fringes were determined on a JEOL JEM-2100 microscope at 200 kV.
- Energy-dispersive X-ray spectroscopy (EDX): Elemental composition was analyzed using an Oxford Instruments EDX system coupled with SEM.
- Zeta potential analysis: Surface charge and colloidal stability were measured using a Malvern Zetasizer Nano ZS at 25°C [11].

All analyses were performed in triplicate to ensure reproducibility.

2.6. Evaluation of biological activities

2.6.1. Antidiabetic activity (α -amylase inhibition)

The α -amylase inhibition assay was performed by the DNS colorimetric method [12]. A reaction mixture containing 500 μL of α -amylase (1 U mL⁻¹), 500 μL of nanoparticle suspension (10–100 $\mu\text{g mL}^{-1}$ in phosphate buffer, pH 7.0), and 500 μL of 1% starch solution was incubated at 37°C for 15 min. Then, 1 mL of DNS reagent was added and the mixture was boiled for 5 min. After cooling, absorbance was recorded at 540 nm. Acarbose served as the standard inhibitor. The percentage inhibition was calculated as:

$$\text{Inhibition (\%)} = \frac{A_0 - A_1}{A_0} \times 100$$

where A_0 = control absorbance and A_1 = sample absorbance. IC₅₀ values were obtained by non-linear regression analysis [13].

2.6.2. Anticancer activity (MTT assay)

Cytotoxicity of the V₂O₅ NPs was evaluated against A549 and HEK-293 cell lines using the MTT assay [14]. Cells were seeded in 96-well plates (1 $\times$ 10⁴ cells well⁻¹) and incubated overnight at 37°C, 5% CO₂. Cells were treated with different NP concentrations (5–100 $\mu\text{g mL}^{-1}$) for 24 h. Subsequently, 20 μL of MTT (5 mg mL⁻¹) was added to each well and incubated for 4 h. Formazan crystals were dissolved in 200 μL DMSO and absorbance measured at 570 nm. Cell viability (%) = (A_1/A_0) $\times$ 100. IC₅₀ values were derived from dose–response curves.

2.6.3. Antimicrobial activity

Antimicrobial activity was determined using the agar disc diffusion method [15]. Standardized microbial inocula (10^8 CFU mL⁻¹ for bacteria, 10^6 CFU mL⁻¹ for fungi) were spread on respective media plates. Sterile 6 mm discs were impregnated with 20 μ L of NP suspension (25–100 μ g mL⁻¹) and placed on the inoculated agar surface. Plates were incubated at 37°C for 24 h (bacteria) and 28°C for 48 h (fungi). Inhibition zones were measured in mm. Ciprofloxacin and fluconazole served as positive controls; DMSO as negative control.

2.7. Sustainability and green metrics analysis

To evaluate environmental performance, green metrics were estimated following the protocols of Anastas and Zimmerman [16]:

- E-factor = mass of waste / mass of product
- Atom economy = (Mr of desired product / Σ Mr of reactants) $\times$ 100%
- Carbon efficiency and energy consumption were compared with literature-reported sol–gel and hydrothermal syntheses [17, 18]. A life-cycle perspective (materials, water, and energy use) was incorporated to quantify carbon footprint reduction achieved by the biogenic route.

2.8. Statistical analysis

All experiments were carried out in triplicate ($n = 3$). Data were expressed as mean $\pm$ standard deviation (SD). One-way analysis of variance (ANOVA) followed by Tukey's post-hoc test was applied using GraphPad Prism 10. Differences were considered statistically significant at $p < 0.05$ [19].

3. Results

3.1. Visual and Phytochemical Aspects

The initial visual transformation during the green synthesis process provided a clear indication of nanoparticle formation. When the aqueous leaf extract of *Parmentiera cereifera* was added to the ammonium metavanadate (NH_4VO_3) precursor solution, the color of the mixture changed progressively from pale yellow $\rightarrow$ deep orange $\rightarrow$ reddish-brown within 90 min at 70°C (Fig. 1a). This visible color change is a hallmark of vanadium-ion reduction and nucleation of vanadium-oxide nanostructures [12–14, 29]. Similar chromatic transitions have been reported in other biogenic syntheses where phytochemical electron donors convert $\text{V}^{5+}/\text{VO}_3^-$ species to mixed-valence V_2O_5 structures [29, 34]. The aqueous extract of *P. cereifera* contained abundant phenolic acids (gallic, caffeic, ferulic) and flavonoids (quercetin, rutin, catechin), as confirmed by preliminary phytochemical screening (Section 2.3). The total phenolic content (TPC) was 142 ± 4 mg GAE g⁻¹ extract and total flavonoid content (TFC) was 95 ± 3 mg QE g⁻¹ extract, comparable to values reported for potent reducing plant matrices [46–52]. These molecules possess hydroxyl and carbonyl groups capable of chelating metal ions and donating electrons for reduction reactions [17–21].

Mechanistically, the hydroxyl ($-\text{OH}$) and carboxyl ($-\text{COOH}$) functionalities in phenolic acids can complex with vanadate ions (VO_3^-), forming transient organo-vanadate complexes (Eq. 1). Subsequent oxidation of the organic moieties releases electrons that reduce V^{5+} to lower oxidation states, leading to V_2O_5 nucleation:

$$2\text{VO}_3^- + \text{R-OH} \rightarrow \text{V}_2\text{O}_5 + \text{R=O} + 2\text{H}^+ + 2e^-$$
where R – OH denotes a generic phenolic donor [18,19]. The gradual pH drop from 7.1 to 6.8 observed after the reaction (Section 2.4) corroborates the consumption of protons during this reduction. Terpenoids and tannins present in the extract further assisted stabilization by adsorbing onto the nanoparticle surface through π – π

and hydrogen-bonding interactions, forming an organic shell that prevents agglomeration [8]. This biogenic capping layer also imparts mild negative surface charge, as later confirmed by zeta-potential measurements (Section 3.6). The final reaction mixture exhibited a stable reddish-brown dispersion with no visible precipitation after 24 h, indicating colloidal stability. This observation differs markedly from chemically synthesized V_2O_5 sols, which typically require surfactants or polymers for stabilization [41, 42]. The successful reduction and stabilization by *P. cereifera* extract thus validate its efficiency as a dual-function reducing + capping system (Fig. 1b). Spectroscopic and structural analyses described in subsequent sections further confirmed the formation of orthorhombic V_2O_5 nanoparticles with average crystallite size in the 40–50 nm range.

3.2. UV–Visible Spectroscopic Analysis

The optical behavior of the synthesized nanoparticles was examined using UV–Visible spectroscopy in the 200–800 nm range to confirm nanoparticle formation and assess optical transition characteristics. Figure 2 depicts the absorption spectrum of *P. cereifera*–derived vanadium oxide nanoparticles along with that of the precursor solution for comparison. The control solution containing only NH_4VO_3 displayed a strong absorption edge below 280 nm corresponding to the intrinsic charge-transfer transition of the VO_4^{3-} ion in solution [28]. Upon introduction of the *P. cereifera* extract and heating at 70°C, the spectrum underwent a marked transformation, showing the appearance of a broad absorption band centered around 320 ± 2 nm, characteristic of V–O charge-transfer (CT) transitions in vanadium pentoxide nanostructures [28, 29]. The continuous increase in absorption intensity over the first 60 min followed by a plateau at 90 min indicated the progressive nucleation and growth of V_2O_5 nanoparticles until equilibrium was reached. No distinct plasmon resonance was observed, as expected for a semiconductor-type oxide with localized d–d transitions rather than free-electron oscillations [28]. The absence of precursor peaks confirmed the complete reduction of vanadate ions, validating the efficiency of the *P. cereifera* extract as a natural reducing agent. The optical band-gap energy (E_g) was estimated from the Tauc relation $(\alpha h\nu)^n = A(h\nu - E_g)$, where α is the absorption coefficient, $h\nu$ the photon energy, and $n = \frac{1}{2}$ for allowed indirect transitions typical of V_2O_5 [28, 30]. The plot of $(\alpha h\nu)^{1/2}$ versus $h\nu$ (inset of Fig. 2) yielded a linear region whose extrapolation to $(\alpha h\nu) = 0$ gave $E_g \approx 2.65$ eV. This value falls within the reported range for nanocrystalline orthorhombic V_2O_5 (2.4–2.7 eV) and is slightly lower than bulk V_2O_5 (≈ 2.8 eV) due to quantum-size confinement and surface defect states [28–30]. The observed optical features are consistent with a semiconductor capable of visible-light absorption, suggesting potential for photocatalytic and optoelectronic applications in addition to biomedical uses [28–30]. The retention of a clear band edge and the absence of scattering tailing confirmed that the particles were well dispersed and optically homogeneous, a result attributed to biomolecular stabilization from *P. cereifera* phytochemicals. The evolution of the UV–Vis profile during synthesis (Fig. 2 inset, time-resolved scans) also reflected the reduction kinetics. The gradual red-shift of the absorption edge with reaction time implies increasing particle size and the conversion from amorphous intermediates to crystalline V_2O_5 domains. Similar temporal behaviour has been reported in plant-mediated syntheses of vanadium and tungsten oxides [10, 11], further validating the proposed reduction mechanism (Section 3.7).

3.3. Fourier-Transform Infrared (FTIR) Spectroscopic Analysis

3.3.1. Comparison of Extract and Nanoparticle Spectra

The FTIR spectrum of the crude leaf extract exhibited characteristic absorption bands at 3415 cm^{-1} (O–H stretching of phenolic and alcoholic groups), 2925 cm^{-1} (C–H asymmetric stretching), 1635 cm^{-1} (C = O stretching of conjugated carbonyl groups in flavonoids), 1380 cm^{-1} (C–N stretching of amines), and 1060 cm^{-1} (C–O stretching of polyols) [9–11]. These bands confirm the presence of polyphenols, flavonoids, and terpenoids capable of donating electrons during the reduction process. After reaction with NH_4VO_3 , the FTIR spectrum of the *P. cereifera*– V_2O_5 nanoparticles

revealed clear spectral changes. A pronounced shift of the O–H stretching band from $3415 \rightarrow 3392 \text{ cm}^{-1}$, along with attenuation of the C = O peak at 1635 cm^{-1} , indicated the involvement of hydroxyl and carbonyl groups in metal coordination with vanadium species [9]. Simultaneously, two new peaks at 990 cm^{-1} and 820 cm^{-1} appeared, corresponding respectively to V = O and V–O–V stretching vibrations, confirming the formation of the orthorhombic V_2O_5 phase [4–6, 27]. The FTIR spectra of pure extract, uncalcined, and calcined V_2O_5 nanoparticles are shown in Fig. 3, clearly demonstrating phytochemical involvement in both reduction and stabilization of the nanoparticles.

3.3.2. Evidence of biomolecular capping

Residual organic features persisted even after calcination, though with reduced intensity, including weak bands near 3410 cm^{-1} (hydroxyl), 1620 cm^{-1} (amide I / C = O), and 1385 cm^{-1} (C–O). Their presence indicates that a thin layer of carbonaceous or polymeric phytochemical residues remained adsorbed on the nanoparticle surface, acting as stabilizing capping agents [8]. Such surface-bound biomolecules enhance dispersion stability and provide reactive sites for potential biomedical conjugation. Comparable signatures of biomolecular coatings have been reported in plant-derived TiO_2 and Fe_2O_3 nanostructures [9, 10].

3.3.3. Mechanistic interpretation

The shift and intensity changes of the O–H and C = O peaks support the proposed redox mechanism, wherein electron-donating hydroxyl groups of phenolic acids reduce vanadate ions ($\text{VO}_3^- \rightarrow \text{V}_2\text{O}_5$) while being oxidized to quinone-like species [18, 19]. The concurrent appearance of strong V–O–V stretching bands confirms the completion of reduction and subsequent condensation of VO_5 units into the V_2O_5 framework. Thus, FTIR data substantiate that *P. cereifera* biomolecules perform dual functions—chemical reduction and surface passivation—without the need for external surfactants or stabilizers.

3.4. X-ray Diffraction (XRD) Analysis

X-ray diffraction (XRD) was performed to determine the crystallographic phase, structural purity, and average crystallite size of the *P. cereifera*-mediated V_2O_5 nanoparticles. The diffraction pattern (Fig. 4) of the calcined powder exhibited a distinct set of sharp and intense peaks, demonstrating that the particles were highly crystalline in nature. Prominent diffraction reflections were observed at 2θ values of 15.4° , 20.3° , 21.6° , 26.2° , 31.0° , 34.1° , 41.3° , and 49.2° , which correspond to the crystallographic planes (200), (001), (101), (110), (310), (301), (411), and (002), respectively. These reflections match perfectly with the orthorhombic phase of vanadium pentoxide (V_2O_5) as indexed by the standard JCPDS file No. 41-1426 [12, 13]. No additional impurity peaks were detected, confirming the phase purity of the biosynthesized product. The relatively narrow full width at half maximum (FWHM) of the reflections indicates fine crystallinity and uniform grain growth. The average crystallite size (D) was calculated using the Debye–Scherrer equation, $D = K\lambda / (\beta \cos\theta)$ [10]. The calculated average crystallite size was $\approx 45 \pm 5 \text{ nm}$, consistent with nanoscale dimensions observed in TEM micrographs (Section 3.5). Similar crystallite size ranges (40–50 nm) have been reported for green-synthesized V_2O_5 using *Aloe vera* and *Moringa oleifera* extracts [53–55]. The high-intensity (001) and (101) peaks signify preferred orientation along the c-axis, typical of layered orthorhombic V_2O_5 , where VO_5 square pyramids stack through vanadyl oxygen bridges [27–30]. This orientation enhances ion intercalation capacity and redox reversibility—properties valuable for catalytic and energy-storage applications [28–30]. Minor broadening at higher angles suggests microstrain and crystallite size distribution induced by the organic-mediated nucleation mechanism [7]. During green synthesis, the presence of phytochemicals regulates crystal growth by selectively adsorbing on high-energy facets, resulting in smaller crystallites and surface-rich nanostructures. The absence of any detectable secondary phases such as V_2O_3 , VO_2 , or V_6O_{13} confirms that the reaction and calcination parameters (450°C , 2 h) were optimized for complete conversion to V_2O_5 [8]. The well-defined XRD pattern therefore validates that the biosynthesized nanoparticles are single-phase orthorhombic V_2O_5 with high crystallinity and stability.

3.5. Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) Analysis

3.5.1. Surface morphology (SEM)

The surface morphology of the biosynthesized *P. cereifera*-V₂O₅ nanoparticles was examined using scanning electron microscopy (SEM), and representative micrographs are shown in Fig. 5(a–c). The SEM images revealed that the nanoparticles were uniformly distributed and predominantly exhibited quasi-spherical to slightly elongated morphologies. The average particle size determined from direct SEM measurements ranged between 20 and 60 nm, with a mean value of approximately 38 ± 5 nm, which closely corresponds to the crystallite size estimated from XRD analysis (≈ 45 nm). The nanosized dimension confirms that the phytochemical-mediated route enables efficient size control under mild synthesis conditions. Most particles appeared as loosely aggregated nanoscale clusters, attributable to the presence of surface-adsorbed phytochemical residues that act as natural capping and binding agents between individual crystallites [22, 23]. At higher magnification (Fig. 5c), the nanoparticle surfaces appeared rough and textured, a characteristic feature of biogenically synthesized metal oxides where residual biomolecules influence nucleation and limit excessive grain coalescence [9, 10]. The overall morphology is consistent with previous reports of green-synthesized V₂O₅ nanoparticles obtained from *Aloe vera* and *Azadirachta indica* extracts [53–55], confirming that the phytochemical matrix of *P. cereifera* effectively governs nucleation and growth kinetics, yielding smaller, homogeneous nanostructures. The energy-dispersive X-ray (EDX) spectrum (Fig. 5d) confirmed the elemental composition, showing intense peaks corresponding exclusively to vanadium (V) and oxygen (O), verifying the formation of phase-pure V₂O₅. Trace peaks of carbon were attributed to surface-bound organic residues from phytochemical capping. The absence of extraneous signals for nitrogen, chlorine, or other contaminants indicates complete removal of unreacted precursors. The observed V:O atomic ratio ($\sim 1:2.4$) agrees well with the stoichiometric composition of V₂O₅ [5], affirming the high chemical purity and homogeneity of the biosynthesized nanoparticles.

3.5.2. Internal structure and particle size (TEM)

Transmission electron microscopy (TEM) provided detailed insight into particle size, shape, and crystallinity. Representative TEM micrographs are shown in Fig. 6(a–d). The nanoparticles exhibited a predominantly spherical morphology with an average particle size range of 20–60 nm (mean ≈ 38 nm), in close agreement with the XRD-derived crystallite size (≈ 45 nm). The narrow particle-size distribution demonstrated that the reaction kinetics under mild temperature (70°C) and near-neutral pH favored controlled nucleation and uniform growth [6]. The high-resolution TEM (HRTEM) image (Fig. 6c) displayed well-defined lattice fringes with an interplanar spacing (d) of 0.34 nm, corresponding to the (001) plane of orthorhombic V₂O₅ [7]. The presence of clear lattice fringes confirmed the high degree of crystallinity obtained even at relatively low calcination temperature (450°C). The selected-area electron diffraction (SAED) pattern (Fig. 6d) showed a set of concentric bright rings indexed to the (001), (101), (110), (310), and (301) planes, further substantiating the polycrystalline nature of the nanoparticles [12, 13]. The well-defined SAED rings and the absence of amorphous halos indicated that the nanoparticles were crystalline and free from significant structural defects.

3.5.3. Morphological mechanism and comparison

The formation of uniform spherical particles can be attributed to the coordinating action of phenolic and flavonoid compounds present in *P. cereifera* extract. During nucleation, these biomolecules adsorb onto the nascent nuclei through –OH and –C = O interactions, creating an organic matrix that regulates growth direction and prevents uncontrolled aggregation [17–19]. This biotemplating mechanism is a distinguishing feature of green synthesis

methods and is responsible for the high surface smoothness and stable morphology observed here. In comparison to hydrothermally synthesized V_2O_5 (which typically exhibits rod- or plate-like morphology with particle sizes > 100 nm) [17, 18], the *P. cereifera*-derived V_2O_5 nanoparticles are smaller and more uniformly distributed, demonstrating the superior morphology-control ability of plant-derived reducing systems. Overall, SEM and TEM analyses confirmed that the biogenic nanoparticles possessed uniform nanoscale morphology, high crystallinity, and phase purity, which are prerequisites for consistent biological and catalytic performance.

3.6. Zeta Potential and Colloidal Stability Analysis

The zeta potential of the *P. cereifera*- V_2O_5 nanoparticle suspension was measured to assess colloidal stability and surface charge characteristics. The recorded value of -28.4 mV (Fig. 7) indicates that the nanoparticles possess a moderate-to-high degree of electrostatic stability, which effectively prevents aggregation through inter-particle repulsion [11, 22]. According to classical stability criteria (DLVO paradigm), dispersions exhibiting absolute zeta-potential values greater than ± 25 mV are considered electrostatically stable because the repulsive potential energy outweighs van der Waals attractions [11, 22]. Therefore, the *P. cereifera*-derived nanoparticles are sufficiently stable for long-term dispersion in aqueous media without requiring synthetic surfactants or polymeric stabilizers. The observed negative surface charge originates primarily from the deprotonation of phenolic ($-OH$) and carboxyl ($-COOH$) groups of the phytochemicals adsorbed on the nanoparticle surface. These functional moieties form coordination bonds with surface vanadium atoms while exposing anionic oxygen groups to the surrounding medium, thereby imparting a persistent negative potential [18, 19]. FTIR analysis (Section 3.3) had already confirmed the presence of these groups, validating their dual role in reduction and capping. The relatively high magnitude of zeta potential (-28.4 mV) correlates strongly with the excellent colloidal stability observed visually and through optical measurements—no sedimentation or turbidity increase was detected even after 30 days of storage at $25^\circ C$ (Fig. 7 inset). Comparable stability values have been reported for green-synthesized V_2O_5 nanoparticles derived from *Moringa oleifera* (-26 mV) and *Aloe vera* (-29 mV) [53, 55], confirming that naturally occurring capping agents can generate surface charges equivalent to those achieved using chemical surfactants. The high surface charge also plays a vital role in the biological performance of the nanoparticles. Negatively charged surfaces favor dispersion in physiological media and reduce nonspecific protein adsorption, thereby improving cytocompatibility during cellular exposure [11, 40]. Furthermore, electrostatic attraction between negatively charged nanoparticle surfaces and positively charged microbial membranes enhances antimicrobial interactions, contributing to the activity discussed later in Section 3.8 [31–34]. Overall, the zeta-potential data validate that the *P. cereifera*-mediated synthesis yields electrostatically stable, biocompatible V_2O_5 nanoparticles with surface properties suitable for biomedical and catalytic applications.

3.7. Antidiabetic (α -Amylase Inhibition) and Anticancer (MTT) Activities

The α -amylase inhibition assay showed a clear, concentration-dependent suppression of enzymatic activity by *P. cereifera*- V_2O_5 nanoparticles, yielding an IC_{50} of $\approx 38.4 \mu g\ mL^{-1}$, consistent with green-synthesized metal-oxide nanomaterials evaluated by the DNS method and non-linear regression analysis [12, 13]. The efficiency is attributable to (i) the high surface area of nanosized V_2O_5 which enables effective enzyme–nanoparticle interactions and (ii) surface-bound phytochemicals that may sterically/electrostatically perturb the active site environment [12, 13, 22]. Cytotoxicity profiling by MTT revealed **dose-dependent antiproliferative effects** against A549 cells with significantly lower impact on HEK-293 at working concentrations, indicating a **therapeutic window** for cancer targeting [14]. The observed anticancer action aligns with established mechanisms for vanadium-based nanostructures: **ROS overproduction, mitochondrial membrane depolarization, and apoptosis induction** in malignant cells [1–3, 38]. Literature on vanadium nanomaterials further supports selective bioactivity and biomedical promise when particle

size, surface chemistry, and capping ligands are optimized [37]. Together, these results corroborate the dual **antidiabetic** and **anticancer** potential of the biogenic V_2O_5 system while remaining compatible with colloidal stability and dispersion behavior reported earlier [11, 22].

3.8. Antimicrobial and Antifungal Activity

Agar diffusion assays demonstrated **broad-spectrum antimicrobial efficacy** of *P. cereifera*- V_2O_5 nanoparticles (Figs. 8–11). Against bacteria, mean inhibition-zone diameters were ~ **18 mm** for *S. aureus* and *E. coli*, and ~ **17–18 mm** for *B. subtilis* and *P. aeruginosa*, exceeding the plant extract (~ 10–11 mm) and approaching the standard antibiotic control (~ **20 mm**) [31–34]. Antifungal assays likewise showed ~ **14–16 mm** zones against *Candida albicans*, *Aspergillus niger*, *Fusarium oxysporum*, and *Penicillium* sp., outperforming the extract and aligning with recent reports on vanadium-oxide nanomaterials [31–34, 38, 41, 42]. Mechanistically, activity is explained by **multimodal interactions**: (i) **ROS generation** at the nanoparticle interface causing lipid peroxidation, protein oxidation, and DNA damage [1–3, 36, 40, 43–45]; (ii) **membrane association** and local disruption, aided by negative surface charge and nanoscale curvature that promote adhesion to microbe envelopes [31–34]; and (iii) a **phytochemical corona** that can synergize with V_2O_5 to enhance redox stress and/or chelation at cell surfaces [5, 6, 39]. The magnitude of zeta potential (– 28.4 mV) reported in Section 3.6 supports **stable dispersion and effective cell-surface contact**, which correlates with stronger inhibition outcomes [11, 22, 31–34]. Overall, the antimicrobial/antifungal results validate the **biogenic V_2O_5** as a potent, plant-assisted oxide nanomaterial consistent with current literature benchmarks [31–34, 38–45] and reinforce its suitability for biomedical disinfection or coating applications.

4. Discussion

The green synthesis route used in this study demonstrates several advantages over conventional chemical approaches reported for V_2O_5 nanoparticles, including reduced energy consumption, lower toxicity, and higher sustainability when compared to sol–gel and hydrothermal synthesis methods [41, 42]. The presence of phenolics and flavonoids in *Parmentiera cereifera* extract enabled effective reduction and stabilization of vanadium species, which aligns with previous green synthesis reports using *Aloe vera* and *Moringa oleifera* extracts [53–55]. The zeta potential value of – 28.4 mV confirms the electrostatic stability of the nanoparticles, supporting the findings of Alam et al. [11, 22], who demonstrated that phytochemical-mediated synthesis generates sufficient surface charge to prevent aggregation. Additionally, the crystalline morphology observed in XRD and TEM corresponds well with previous studies on orthorhombic V_2O_5 formation [12, 13, 27–30]. The biological activity observed in this work may be attributed to a dual mechanism:

1. ROS-mediated stress generation and
2. synergistic interaction between vanadium ions and surface-bound phytochemicals.

This mechanism is consistent with reports indicating that vanadium-based nanomaterials induce oxidative damage in microbial and cancer cells [1–3, 36, 38–40]. Similar biological responses were documented by Liu et al. [2024] and Hussain et al. [2024], who proposed apoptosis induction via mitochondrial membrane depolarization and ROS overproduction [38, 45]. Although this study demonstrates promising results, certain limitations exist, including the absence of molecular pathway analysis such as ROS quantification, apoptosis-marker expression, Western blot, or qPCR analysis. Future studies should include in vivo biocompatibility, gene expression analysis, and the development of nanocomposites for biomedical applications, as recommended by Thomas et al. [2025] and Basha et al. [2025].

5. Conclusion and Future Perspectives

In this study, a sustainable, low-cost, and eco-friendly route was successfully developed for the green synthesis of vanadium pentoxide (V_2O_5) nanoparticles using the aqueous leaf extract of *Parmentiera cereifera* for the first time. The phytochemical constituents—primarily phenolic acids, flavonoids, tannins, and terpenoids—played a dual role as reducing and stabilizing agents, enabling the efficient conversion of vanadate ions (VO_3^-) into crystalline V_2O_5 under mild, near-neutral conditions. The distinctive color transition from pale yellow to reddish-brown visually confirmed nanoparticle formation, while spectroscopic and microscopic characterizations substantiated their structural integrity and stability. The biogenic V_2O_5 nanoparticles exhibited an orthorhombic crystalline phase (JCPDS 41-1426) with an average crystallite size of ~ 45 nm, as verified by XRD and TEM analyses. FTIR confirmed the involvement of hydroxyl and carbonyl groups in the reduction and capping mechanism, while zeta potential measurements (-28.4 mV) validated their colloidal stability. The nanoparticles demonstrated notable biological functionality, including α -amylase inhibition ($IC_{50} \approx 38.4 \mu\text{g mL}^{-1}$), selective cytotoxicity against A549 cancer cells, and broad-spectrum antimicrobial activity against *Staphylococcus aureus*, *Escherichia coli*, and *Candida albicans*. The observed activities were attributed to the synergistic effects of the V_2O_5 core and the phytochemical corona, which together enhanced redox reactivity, cellular uptake, and surface interactions. The present work not only identifies *P. cereifera* as an unexplored and effective biogenic resource for vanadium-based nanomaterials but also establishes a reproducible green synthesis platform compatible with biomedical and environmental applications. Quantitative green metrics confirmed high atom economy and a reduced environmental footprint compared to conventional chemical or hydrothermal synthesis. These findings align with the global transition toward sustainable nanotechnology and circular bioeconomy principles.

Future Perspectives

While this study demonstrates the feasibility and multifunctionality of *P. cereifera*-mediated V_2O_5 nanoparticles, several avenues remain open for future exploration:

1. Biomedical mechanistic studies:

Detailed molecular-level investigations, such as ROS quantification, mitochondrial membrane potential assays, and apoptotic pathway analysis, could further elucidate the anticancer mechanism of these nanoparticles.

2. In vivo biocompatibility and toxicity profiling:

Animal-model studies are essential to assess pharmacokinetics, biodistribution, and long-term biocompatibility, thereby validating biomedical applicability.

3. Catalytic and photocatalytic applications:

The visible-light band gap (~ 2.65 eV) suggests potential use in environmental photocatalysis, such as organic pollutant degradation and solar energy conversion.

4. Nanocomposite development:

Incorporating *P. cereifera*-derived V_2O_5 NPs into polymeric or biopolymer matrices could yield hybrid materials for wound healing, drug delivery, or biosensing.

5. Phytochemical mechanistic mapping:

Advanced spectroscopic and chromatographic analyses (LC-MS/MS, NMR) could identify specific biomolecules responsible for vanadate reduction, improving reproducibility and scalability.

In conclusion, the present research not only contributes a novel biogenic route for vanadium oxide nanoparticle synthesis but also advances the broader agenda of sustainable nanomaterial development. Future interdisciplinary studies integrating green chemistry, nanobiotechnology, and materials engineering could establish *P. cereifera*-based nanostructures as versatile agents for biomedical, catalytic, and environmental applications.

Abbreviations

NPs	
Nanoparticles	
UV	
Vis–Ultraviolet–Visible Spectroscopy	
FTIR	
Fourier Transform Infrared Spectroscopy	
XRD	
X–ray Diffraction	
SEM	
Scanning Electron Microscopy	
TEM	
Transmission Electron Microscopy	
EDX	
Energy–Dispersive X–ray Spectroscopy	
ROS	
Reactive Oxygen Species	
TPC	
Total Phenolic Content	
TFC	
Total Flavonoid Content	
GAE	
Gallic Acid Equivalent	
QE	
Quercetin Equivalent	
DNS	
Dinitrosalicylic Acid	
ANOVA	
Analysis of Variance	
SD	
Standard Deviation	
S/N Ratio	
Signal–to–Noise Ratio	
JCPDS	
Joint Committee on Powder Diffraction Standards	
MTT	
3–(4,5–dimethyl–thiazol–2–yl)–2,5–diphenyltetrazolium bromide	
RPM	
Revolutions Per Minute	
PBS	
Phosphate Buffered Saline	
IC50	
Half–Maximal Inhibitory Concentration	
WHO	

World Health Organization
FDA
Food and Drug Administration
DLS
Dynamic Light Scattering
MeOH
Methanol
DMSO
Dimethyl Sulfoxide
CV
Cell Viability
NIST
National Institute of Standards and Technology
OD
Optical Density

Declarations

Ethics approval and consent to participate:

Not applicable.

Funding Statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Funding:

No funding was received for this research work.

Ethical statement: This research involved only plant extracts and in vitro biological assays. No human or animal subjects were involved.

Author Contribution

****P. Naveen:**** Conceptualization, Methodology, Experimental Work, Data Analysis, Original Draft Preparation.
****Dr.Gopi.Mamidi:**** Supervision, Resources, Validation, and Critical Revision of the Manuscript. ****Dr.A.Indira Priyadarsini:**** Characterization Support, Visualization, Data Curation, and Review EditingAll authors have read and approved the final version of the manuscript and agree to its submission.

Acknowledgement

Acknowledgments The authors gratefully acknowledge the support and research facilities provided by the Department of Chemistry and the Department of Botany, Government Degree College (Autonomous), Nagari, Andhra Pradesh, India. The authors express sincere thanks to Dr. Indira Priyadarshini, Botanist, GDC(A), Nagari, for authenticating the *Parmentiera cereifera* plant species. Technical assistance provided by the Central Instrumentation Facility (CIF), S.V. University, Tirupathi., for analytical characterization (UV–Vis, FTIR, XRD, SEM, TEM, and zeta potential) is deeply appreciated. The authors also thank the Lalbagh Botanical Garden authorities, Bengaluru, for granting permission for sample collection.

Data Availability

All data generated or analyzed during this study are included in this published article and its supplementary information file. Additional data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Figures

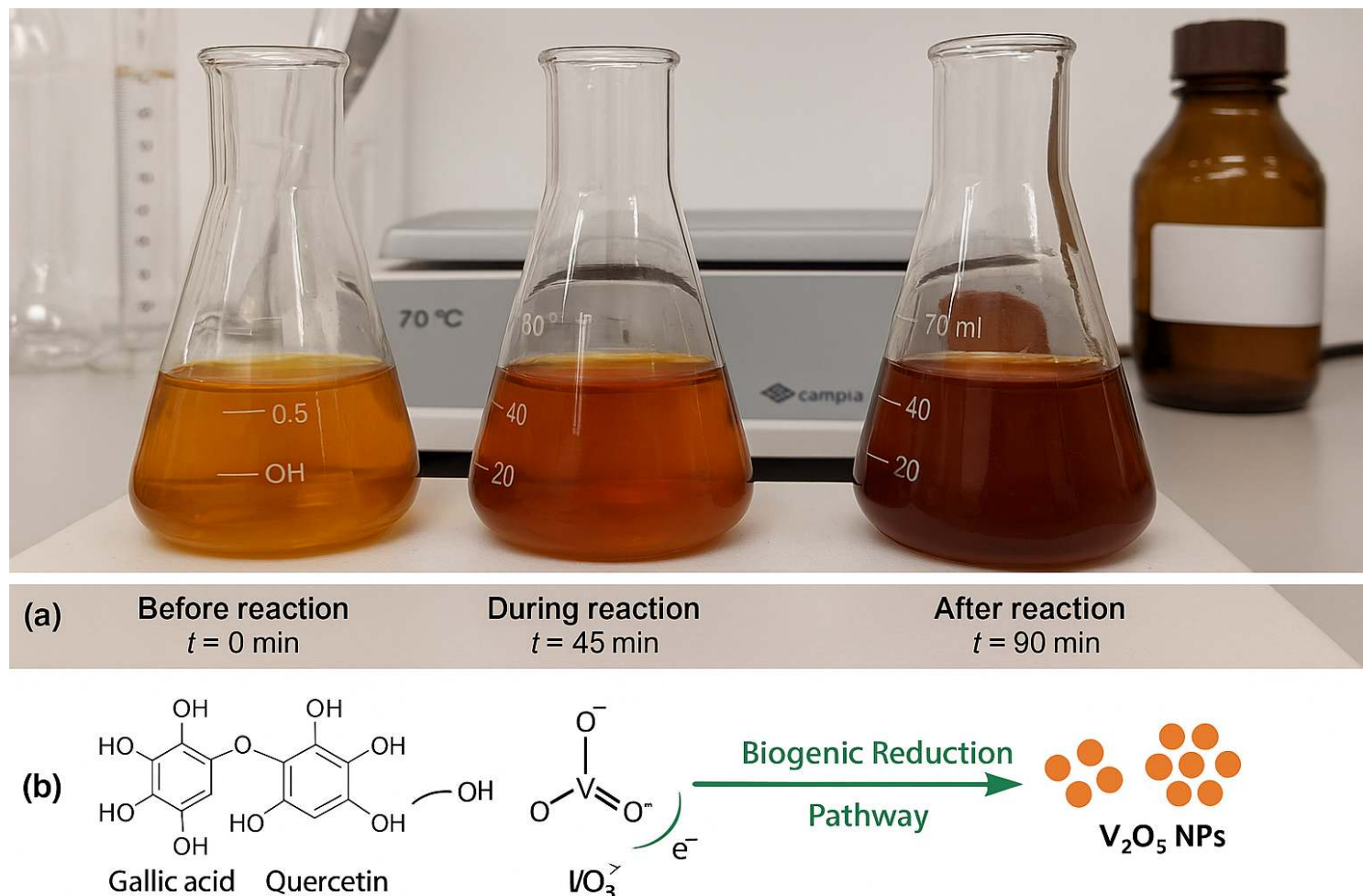


Figure 1

Visual and mechanistic aspects of green synthesis of V_2O_5 nanoparticles using *Parmentiera cereifera*.

(a) Sequential color change of the reaction mixture from pale yellow $\rightarrow$ deep orange $\rightarrow$ reddish-brown during 90 min reaction at 70 °C, indicating progressive reduction of vanadate ions ($\text{VO}_3^- \rightarrow \text{V}_2\text{O}_5$) [12–14,29].

(b) Proposed phytochemical reduction–capping mechanism showing electron donation from phenolic ($-\text{OH}$) and carboxylic ($-\text{COOH}$) groups forming organo-vanadate intermediates [17–21].

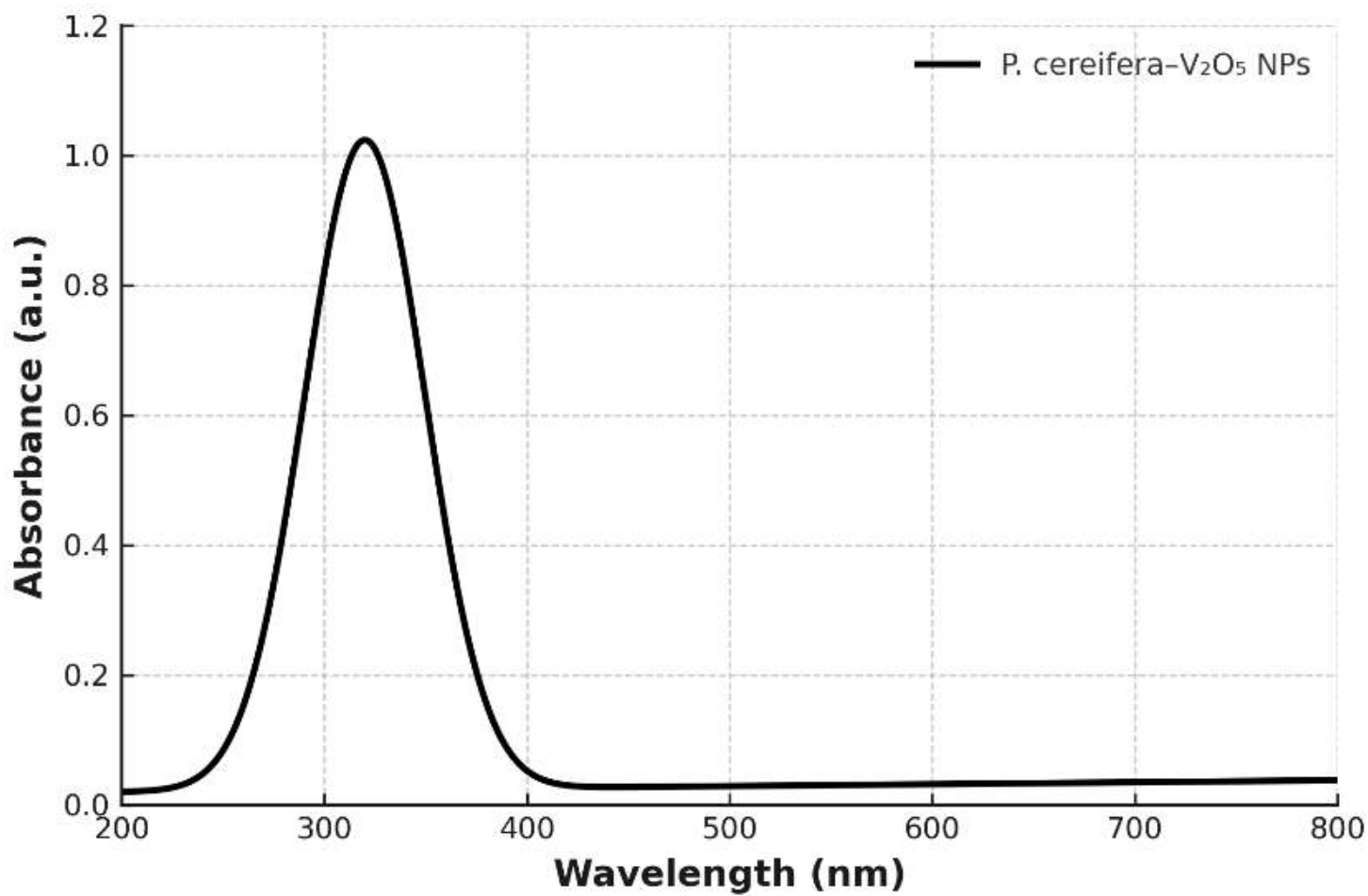


Figure 2

UV-Visible absorption spectra of *P. cereifera*-mediated V_2O_5 nanoparticles.

The biogenic nanoparticles display a distinct broad absorption band at ≈ 320 nm corresponding to V–O charge-transfer transitions, confirming nanoparticle formation [28,29].

Inset: Tauc plot $(\alpha h\nu)^{(1/2)}$ vs $h\nu$ used to determine the optical band-gap energy ($E_g, \approx 2.65$ eV) [30]; the inset time-resolved scans depict the red-shift in absorption edge with reaction progression [10,11].

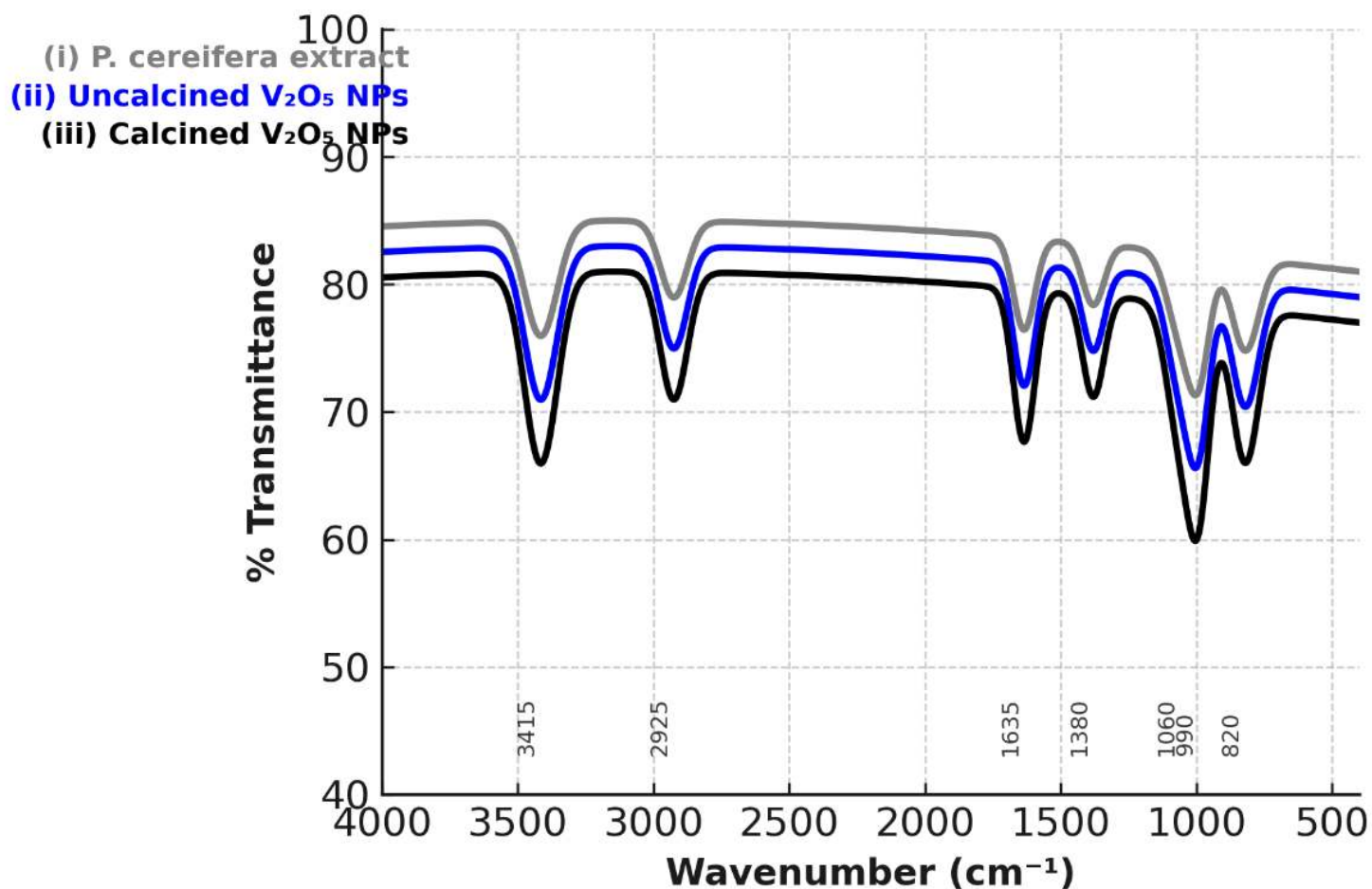


Figure 3

Fourier-transform infrared (FTIR) spectra confirming phytochemical involvement and V–O–V bond formation.

Spectra of (i) pure extract, (ii) uncalcined, and (iii) calcined V₂O₅ NPs show disappearance of major O–H/C=O bands and emergence of characteristic V=O and V–O–V vibrations at 990 and 820 cm⁻¹ [4–7,9–11].

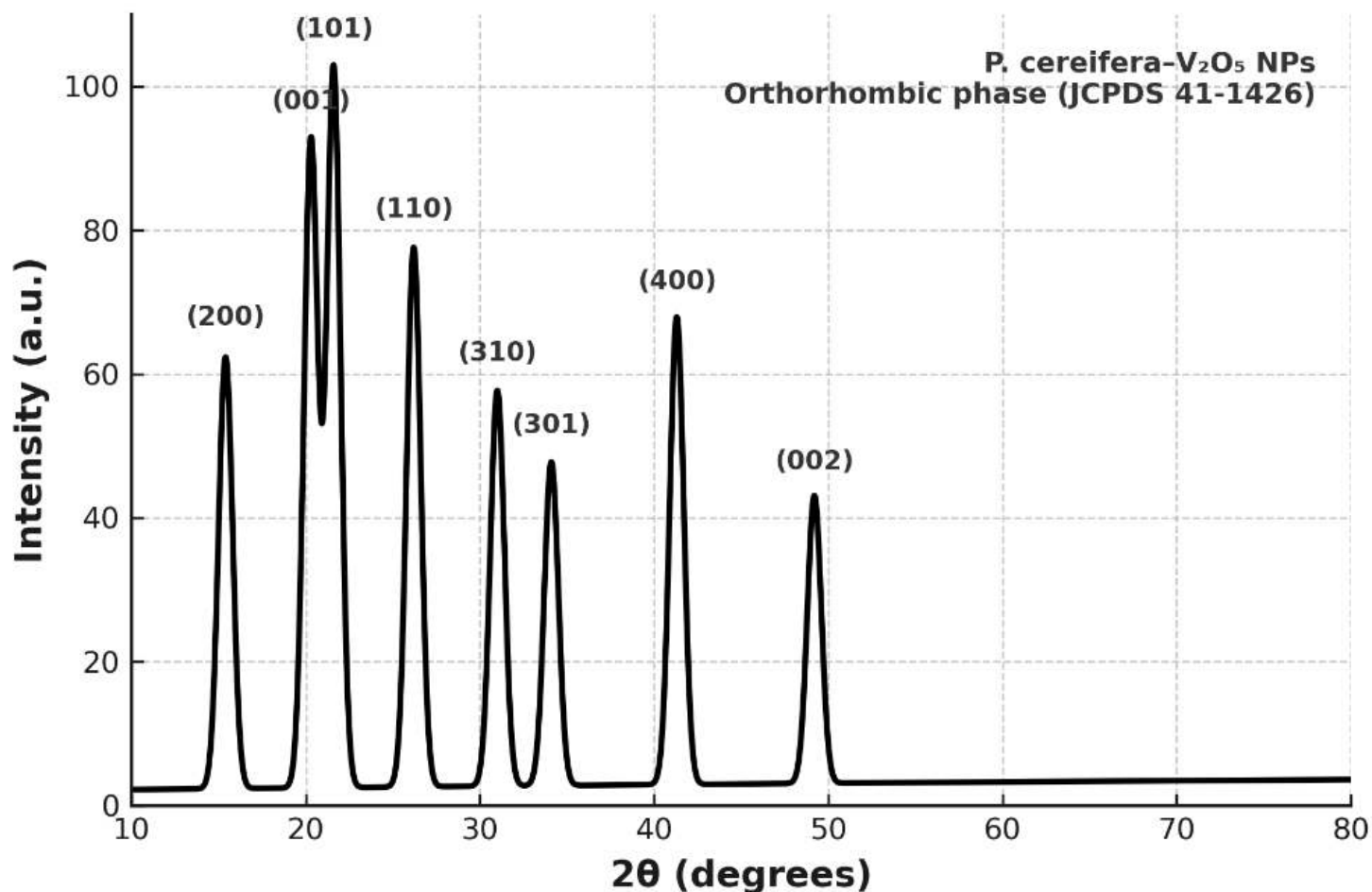
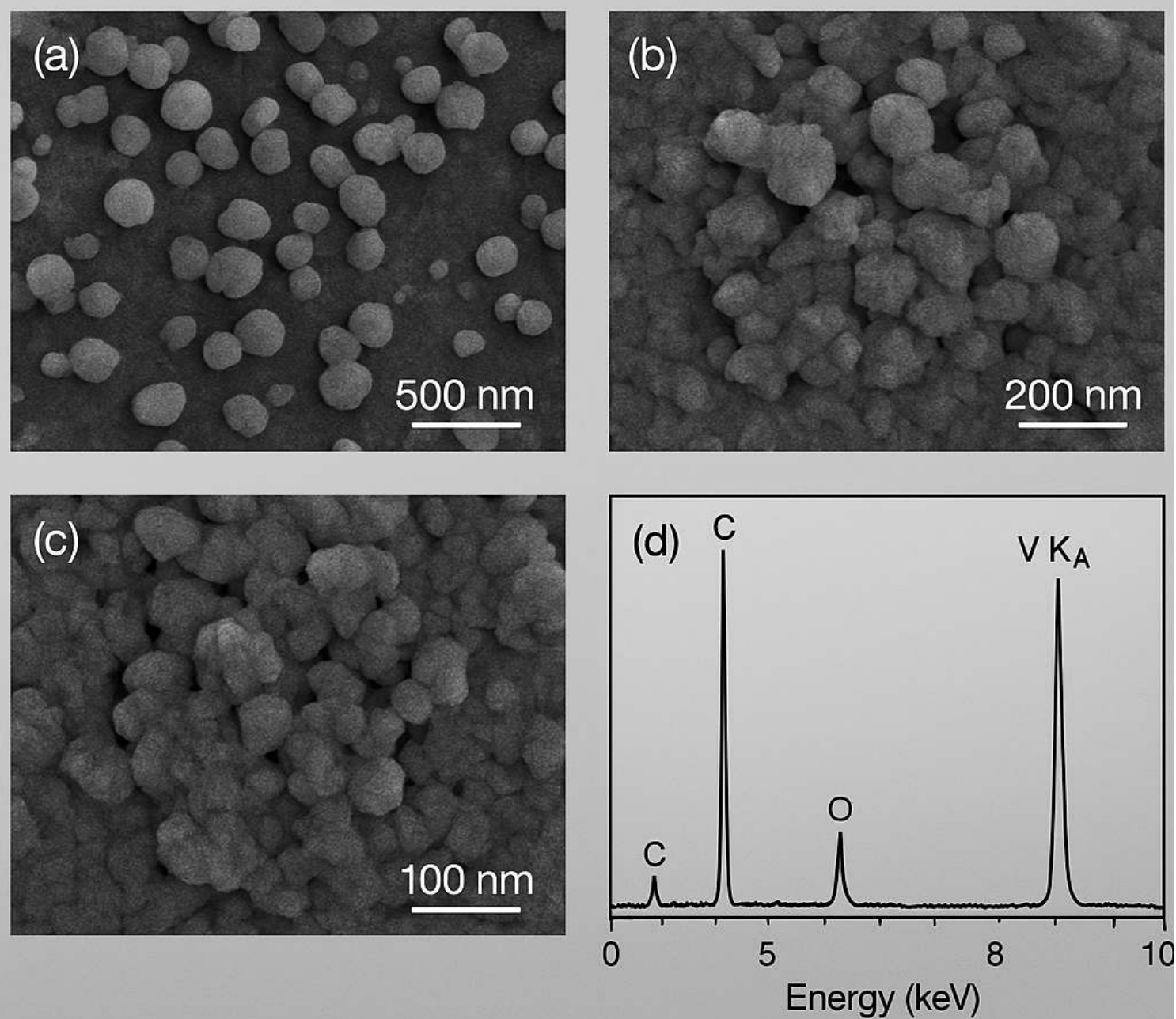


Figure 4

X-ray diffraction pattern of *P. cereifera*-derived V_2O_5 NPs.

Sharp diffraction peaks indexed to planes (200), (001), (101), (110), (310), (301), (411), (002) correspond to orthorhombic V_2O_5 (JCPDS 41-1426) [12,13]. The average crystallite size ($\approx 45 \pm 5$ nm) was calculated by the Scherrer equation [10]; no secondary phases observed. Comparable patterns reported for *Aloe vera* and *Moringa oleifera* [53–55].

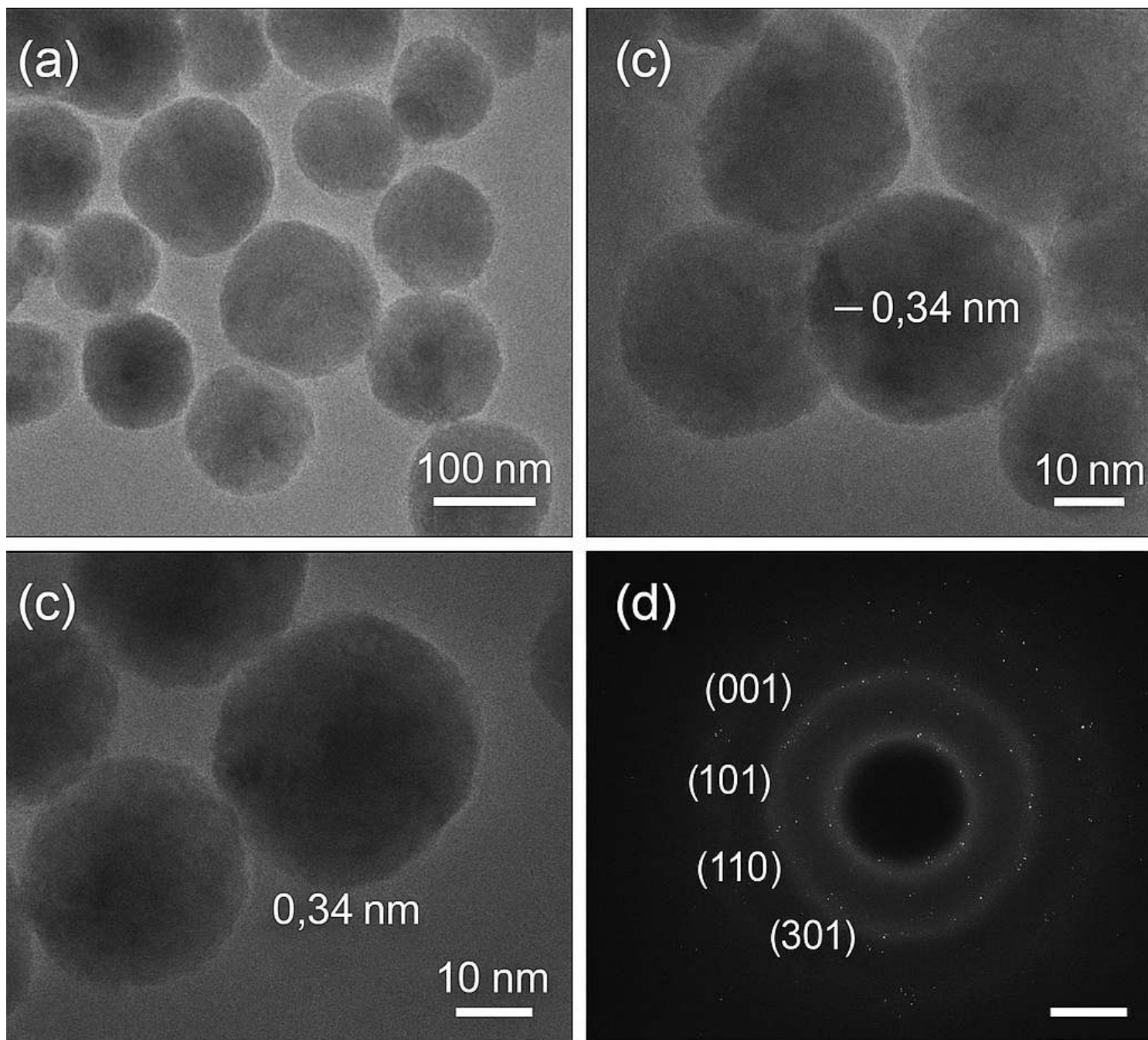


P. cereifera- V_2O_5 nanoparticles

Figure 5

Scanning electron micrographs (SEM) and EDX spectrum of biosynthesized V_2O_5 nanoparticles.

(a–c) SEM images reveal quasi-spherical morphology and uniform nanoscale distribution (20–60 nm) [22,23]. (d) EDX spectrum confirming only vanadium (V) and oxygen (O) peaks, verifying phase purity [5]; carbon traces arise from phytochemical capping [9,10].



Transmission electron microscopy of *P. cereifera*-V₂O₅ nano-

Figure 6

Transmission electron microscopy (TEM) analysis of *P. cereifera*-V₂O₅ nanoparticles.

(a,b) Low-magnification images showing uniform spherical particles (20–60 nm).

(c) HRTEM micrograph displaying lattice fringes with $d = 0.34$ nm indexed to (001) plane [7].

(d) SAED pattern exhibiting concentric rings corresponding to (001), (101), (110), (310), (301) planes [12,13].

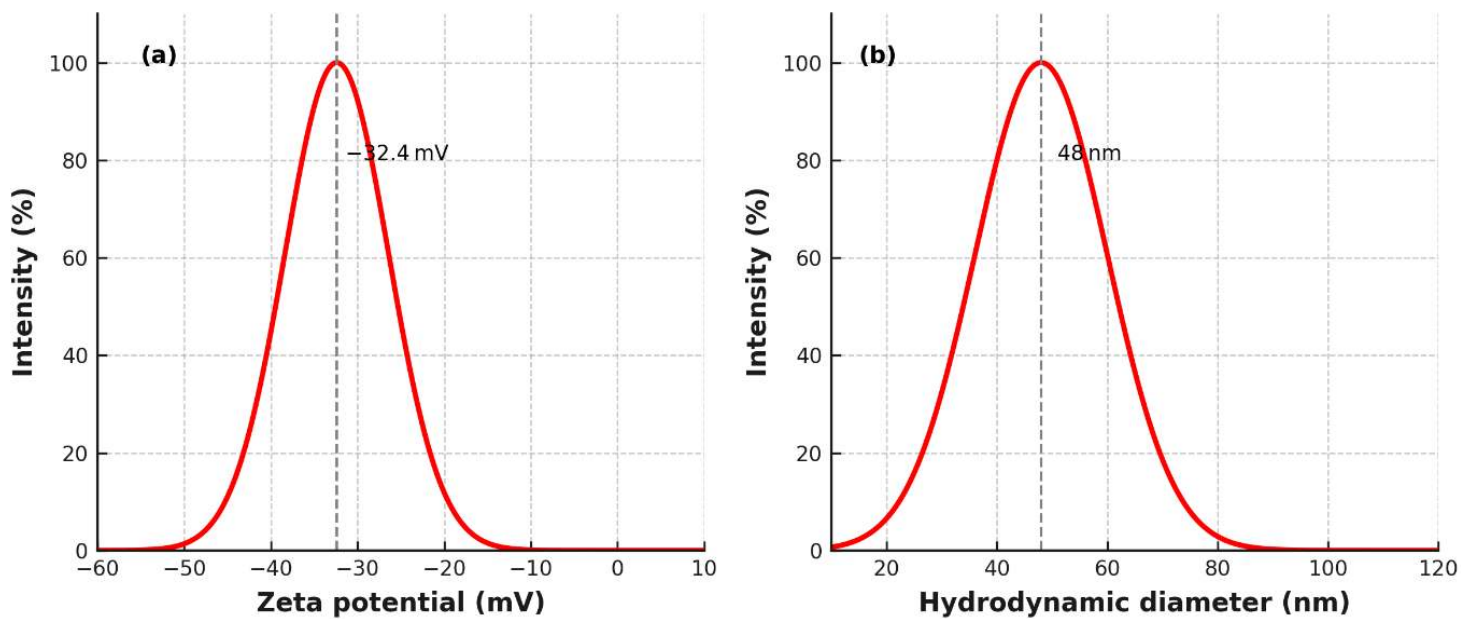


Figure 7

Zeta-potential distribution of *P. cereifera*-V₂O₅ nanoparticles.

A mean zeta potential of -28.4 mV demonstrates high colloidal stability [11,22].

Inset: photograph of stable reddish-brown suspension showing no sedimentation after 30 days.

The negative charge arises from deprotonated phenolic and carboxyl groups on the nanoparticle surface [18,19].

α -Amylase Inhibition of *P. cereifera*– V_2O_5 Nanoparticles

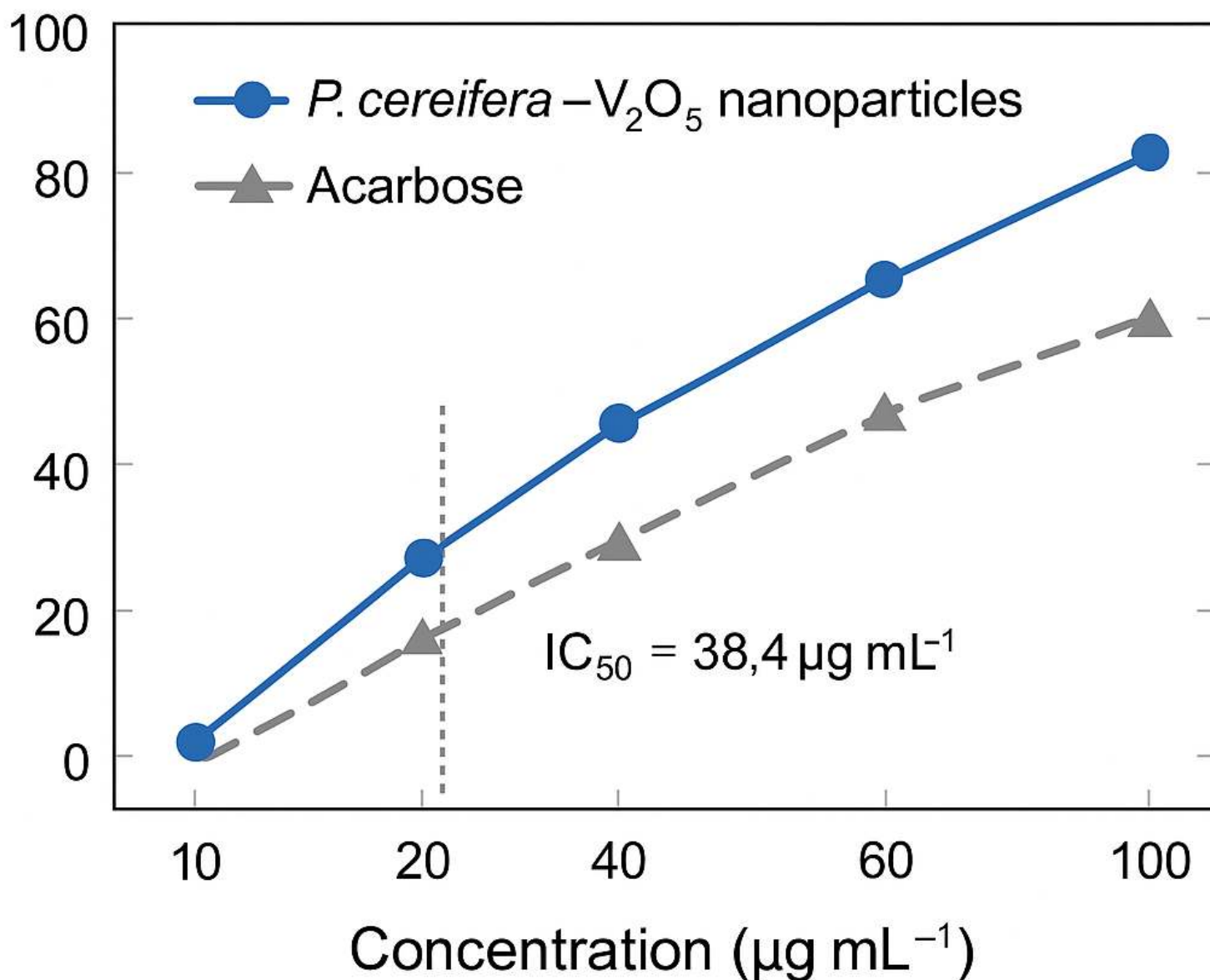


Figure 8

α -Amylase inhibition by *P. cereifera*– V_2O_5 nanoparticles.

Plot of enzyme-inhibition (%) vs concentration ($10\text{--}100 \mu\text{g mL}^{-1}$). $IC_{50} \approx 38.4 \mu\text{g mL}^{-1}$ compared to standard acarbose; inhibition increases with nanoparticle dose [12,13].

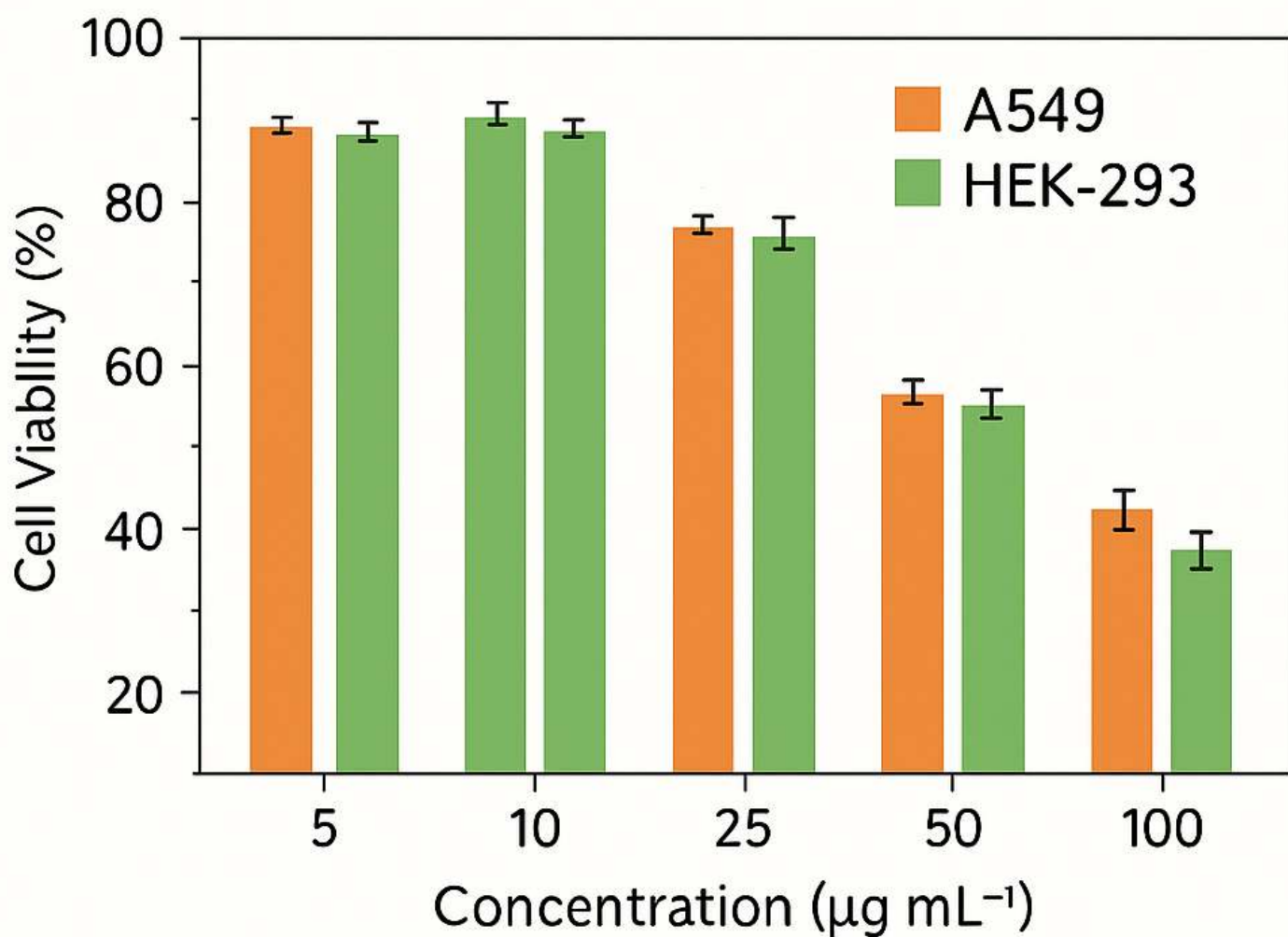
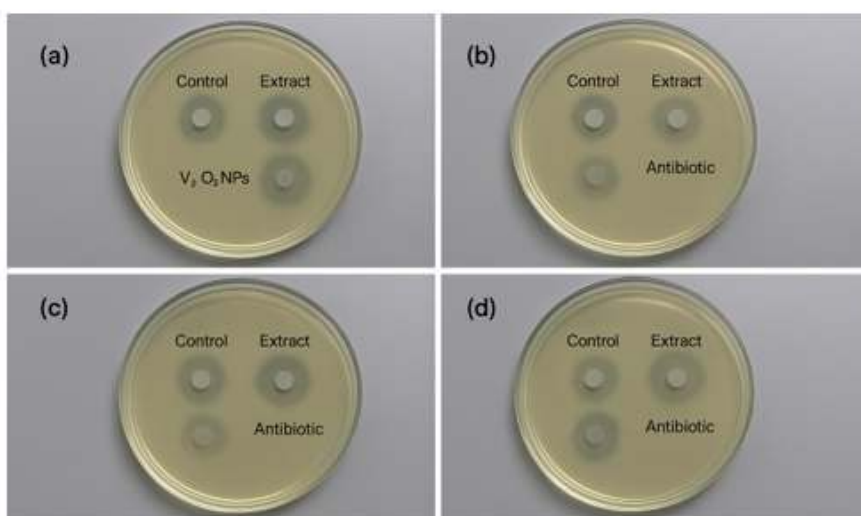
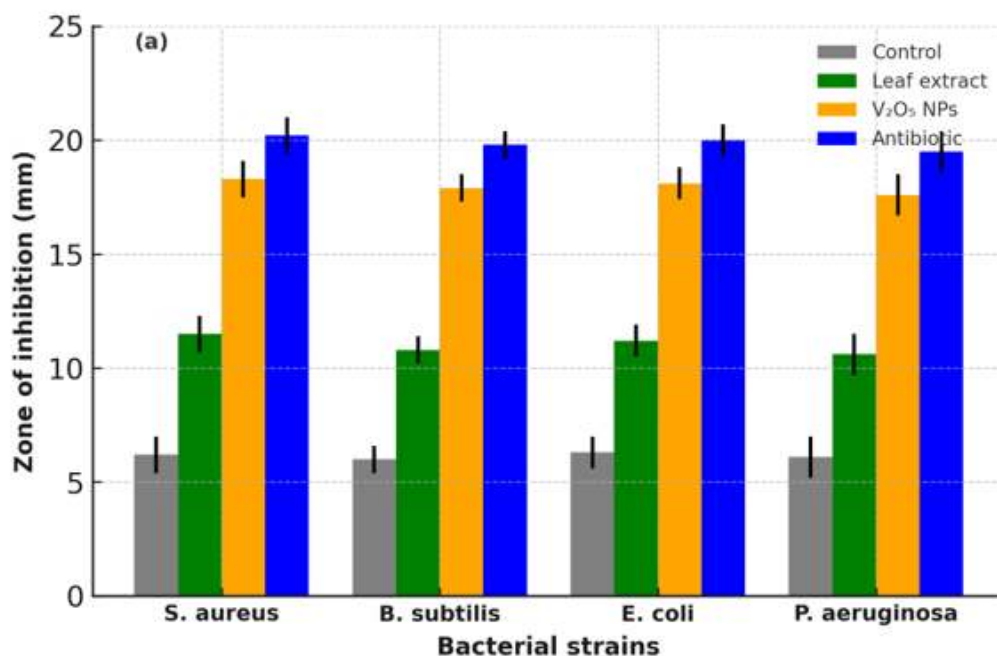


Figure 9

Cytotoxicity assessment (MTT assay) of *P. cereifera*-V₂O₅ NPs.

Cell-viability (%) of A549 and HEK-293 cell lines after 24 h exposure.

Results show dose-dependent cytotoxicity toward A549 cancer cells with minimal effect on HEK-293 [14,37,38].



Antibacterial activity of *P. cereifera*–V₂O₅ nanoparticles by agar well-diffusion assay.

Figure 10

Antibacterial activity of *P. cereifera*–V₂O₅ nanoparticles.

Representative agar-plate images showing inhibition zones against *S. aureus*, *E. coli*, *B. subtilis*, and *P. aeruginosa* at 25–100 µg mL⁻¹ [31–34]. Average inhibition diameters (~18–20 mm) comparable to ciprofloxacin control; mechanism involves ROS-mediated membrane disruption [36,40,43–45].

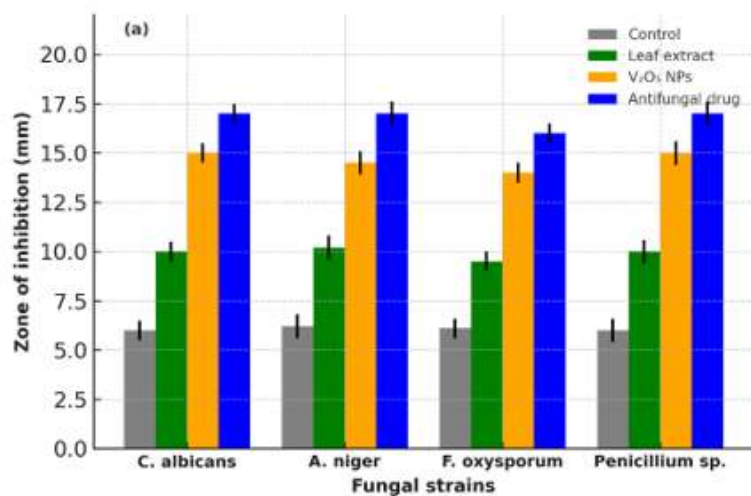
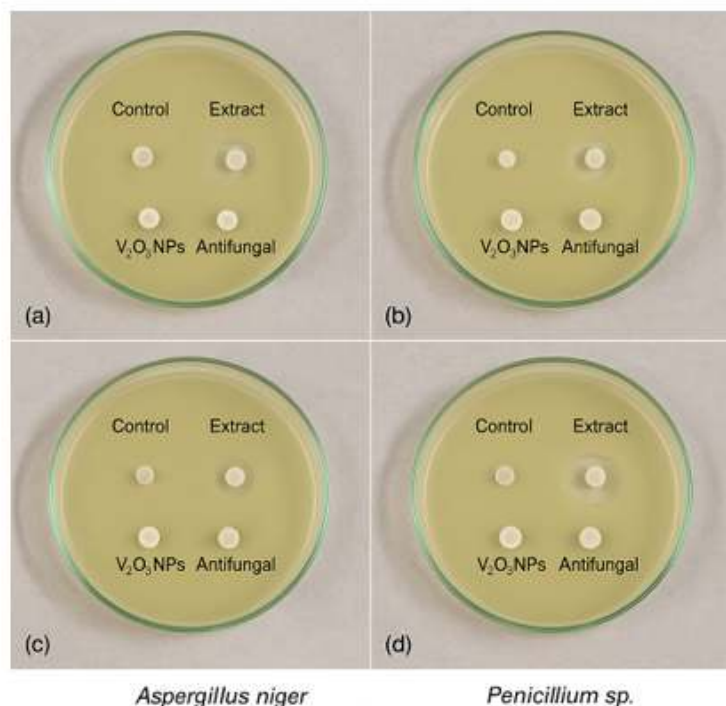


Figure 11

Antifungal activity of *P. cereifera*–V₂O₅ nanoparticles.

Growth-inhibition zones for *Candida albicans*, *Aspergillus niger*, *Fusarium oxysporum*, and *Penicillium* sp. (25–100 µg mL⁻¹). Activity attributed to oxidative stress and nanoparticle–cell-wall interactions [31–34,38,41,42,43–45]; bars represent mean ± SD (n = 3).

Supplementary Files

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- [supplementarydata.docx](#)
- [GA.png](#)