

Phytogenic NiO Nanoparticles Derived from *Syzygium cumini* Seeds for Efficient Photocatalytic Dye Degradation and Antimicrobial Applications

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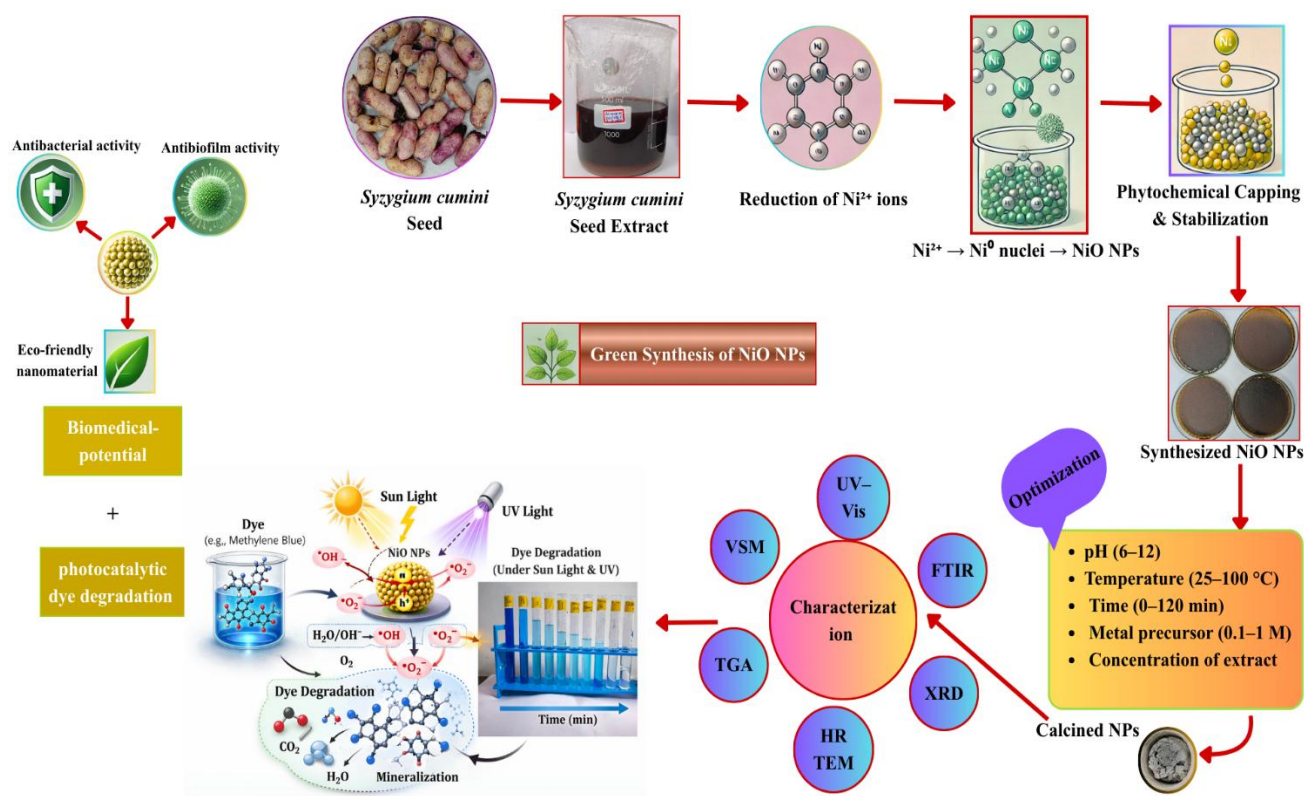
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Phytogenic NiO Nanoparticles Derived from *Syzygium cumini* Seeds for Efficient Photocatalytic Dye Degradation and Antimicrobial Applications

Abstract

Although integrated optimization and multifunctional validation are still lacking, green production of metal oxide nanoparticles presents a viable substitute for traditional techniques. This work describes an environmentally friendly production of NiO nanoparticles utilizing seed extract from *Syzygium cumini*, which was followed by a thorough physicochemical, photocatalytic, and biological assessment. In order to achieve stable nanostructures, key parameters such as precursor concentration, extract volume, pH, temperature, and reaction time were tuned during the preparation of the nanoparticles using a phytochemical-mediated reduction method. Nanoparticle production was validated by UV-Vis spectroscopy, which showed a distinctive absorption peak at 330 nm. A crystalline cubic NiO phase was discovered by XRD analysis, and well-dispersed spherical particles with an average size of 15–25 nm were observed by HRTEM. TGA showed excellent thermal stability, VSM verified weak ferromagnetic behavior, and FTIR revealed phytochemical-mediated capping. According to pseudo-first-order kinetics, photocatalytic tests employing methylene blue demonstrated 78% degradation under natural sunshine and 91% degradation under UV irradiation in 90 minutes, with preserved activity throughout five reuse cycles. In terms of biology, the NiO NPs demonstrated concentration-dependent antibacterial activity at MIC levels of $\geq 70\%$ growth inhibition, up to 78% antibiofilm inhibition, and inhibition zones as large as 27 mm for *E. Coli* and 23 mm for *S. aureus*. They also shown significant antioxidant activity. Overall, the multifunctional performance of *S. cumini*-mediated NiO nanoparticles shows promise for antibacterial surface applications and sustainable wastewater remediation.

Keywords: Nickel oxide nanoparticles; *Syzygium cumini*; Green synthesis; Antibacterial activity; Antibiofilm property; Photocatalytic.



Graphical Abstract of Green synthesis, optimization, characterization, and biomedical evaluation of NiO nanoparticles derived from *Syzygium cumini* seed extract.

Introduction

Scalable, cost-effective, and environmentally friendly methods for creating metal oxide nanoparticles are becoming more and more necessary due to the quick development of nanotechnology. Traditional physicochemical methods frequently produce hazardous byproducts due to their use of toxic chemicals, high temperatures, and energy-intensive procedures. As a result, green synthesis—which uses biomolecules produced from plants as natural reducing and stabilizing agents under mild reaction conditions—has become a viable substitute [1]. The high concentration of polyphenols and metal-chelating chemicals in seed extracts makes them particularly appealing among the several plant-based methods. The seeds of *Syzygium cumini*, sometimes known as jamun, are an understudied source of phytochemicals that are high in anthocyanins, tannins, gallic acid, ellagic acid, and flavonoids [2]. In addition to providing surface capping that improves the durability and biological functioning of nanoparticles, these biomolecules serve as electron donors during metal ion

reduction. Additionally, their inherent antioxidant and antibacterial qualities point to possible synergistic benefits when included into nanomaterial systems [3].

Because of their strong surface reactivity, catalytic efficiency, redox potential, thermal resilience, and magnetic behavior, nickel oxide (NiO) nanoparticles are becoming more and more popular. Because of these characteristics, NiO can be used in biomedical materials, antimicrobial coatings, and wastewater cleanup [4]. However, rigorous synthesis optimization is rarely combined with thorough structural, thermal, magnetic, photocatalytic, and biological validation in papers on green-synthesized NiO nanoparticles. Specifically, there is still little research on the application of *S. cumini* seed extract. Thus, the goal of this research is to create an environmentally friendly, optimal synthesis of NiO nanoparticles utilizing seed extract from *S. cumini* and to directly link their multifunctional performance to their physicochemical characteristics [5,6]. To verify nanoparticle production and crystallinity, structural and morphological characterization was carried out using UV-Vis, FTIR, XRD, and HRTEM. Thermal stability and breakdown behavior were assessed using thermogravimetric analysis (TGA), which is essential for determining durability in catalytic and biological operating settings. Magnetic characteristics that are important for possible magnetic recovery, catalyst recyclability, and functional surface applications were examined using vibrating sample magnetometry (VSM).

The functional performance of the optimized NiO nanoparticles was further assessed through photocatalytic degradation of methylene blue under UV and natural sunlight irradiation, along with antibacterial, antibiofilm, antioxidant, MIC, and MBC evaluations. Through the integration of sophisticated characterisation, synthesis optimization, and multifunctional testing, this study offers a thorough framework that connects structural features to biological and environmental applicability.

2. Materials and Methods

2.1 Materials

HiMedia Laboratories (Mumbai, India) supplied ethanol, crystal violet, nickel nitrate hexahydrate [$\text{Ni}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$, AR grade], and all microbiological medium. Every reagent used was analytical grade and didn't require any additional purification. All studies were conducted using distilled water. The Microbiology Laboratory at the Bharth Institute of Higher Education and Research, Chennai-73, provided the bacterial strains *Escherichia coli* (ATCC

25922) and *Staphylococcus aureus* (ATCC 25923). In May and June of 2025, fresh fruits of *Syzygium cumini*, often known as jamun, were gathered from Thiruvancherry village in Tamil Nadu, India (Latitude: 12.814° N). To prepare the extract, the seeds were separated, cleaned, and allowed to dry in the shade.

2.2 Preparation of *Syzygium cumini* (Jamun) Seed Extract

Fresh *S. cumini* fruits, handpicked at peak ripeness, were collected locally and taxonomically authenticated by the Department of Botany, Bharath Institute of Higher Education and Research, Chennai, India. The seeds were separated, thoroughly washed with distilled water, and shade-dried for 5–7 days. The dried seeds (10 g) were powdered using a mechanical grinder and mixed with 100 mL of distilled water. The mixture was heated at 60 °C for 20 minutes, cooled to room temperature, and filtered using Whatman No. 1 filter paper. The clear filtrate was centrifuged at 5000 rpm for 10 minutes to remove residual particulates, and the supernatant was stored at 4 °C until use as both a reducing and stabilizing agent [7].

2.3 Green Synthesis of Nickel Oxide (NiO) Nanoparticles

To standardize the conditions for efficient nanoparticle formation, the *Syzygium cumini* seed extract was subjected to controlled optimization experiments. A fixed volume of 100 mL of the prepared seed extract was placed in a conical flask and maintained at 50 °C under continuous stirring. A nickel precursor solution was prepared by dissolving 0.375 g of metal salt in 100 mL of distilled water, and the solution was transferred into a 50 mL burette for controlled addition. The precursor was introduced dropwise into the extract at a constant rate of one drop every 5 seconds. Throughout the addition process, the onset and progression of colour change were carefully monitored and recorded, along with the corresponding burette volume and reaction time. These observations were used to determine the optimal precursor addition rate and extract–metal interaction time for efficient NiO nanoparticle formation [8].

2.3 Optimization of Green Synthesis Parameters

A series of controlled experiments were performed to determine the optimum conditions for NiO nanoparticle formation. Each parameter was varied individually while the others were kept constant.

2.3.1 Optimization of pH

The reaction pH was adjusted between 5–11 using 0.1 M NaOH or 0.1 M HCl. The extract and precursor mixture was prepared at each pH and monitored for color change and absorbance intensity to identify the optimal pH for nanoparticle formation.

2.3.2 Optimization of Temperature

To evaluate the influence of temperature, the reaction mixture was incubated at 25, 40, 60, 80, and 100 °C. The mixture was maintained for a fixed duration while monitoring the visual color change and UV–Vis absorbance.

2.3.3 Optimization of Reaction Time

The reaction mixture was allowed to proceed for different durations (20, 40, 60, 120, and 180 min). Samples were withdrawn at each time point and analyzed to determine the minimum time required for complete nanoparticle formation.

2.3.4 Optimization of Precursor Concentration

Nickel nitrate solutions of varying concentrations (100, 200, 300, 400, and 500 mM) were prepared. Each concentration was reacted with the fixed extract volume under identical conditions to evaluate its effect on nanoparticle formation.

2.3.5 Optimization of Extract Volume

Different volumes of seed extract (1.0, 1.5, 2.0, 2.5, and 3.0 mL) were added dropwise into the reaction mixture. The influence of phytochemical availability on reduction efficiency and colloidal stability was assessed.

2.3.6 Calcination of Synthesized Nanoparticles

After completing the optimized synthesis, the reaction mixture was cooled to room temperature and centrifuged at 8000 rpm for 10 minutes. The obtained pellet was washed three times with distilled water and twice with ethanol to remove unreacted residues. The dried material was then calcined at 400 °C for 2 hours using a controlled heating ramp of 5 °C/min, ensuring the conversion of precursor intermediates into crystalline NiO nanoparticles.

2.4 Characterization Techniques

2.4.1. UV–Visible Spectroscopy

The UV-1800, Genesys 180, Thermo Fisher Scientific, USA, UV-visible spectrophotometer was used to record the optical absorption profile of the produced NiO nanoparticles. Quartz cuvettes with a 1 cm optical path length were used for measurements in the 200–800 nm wavelength range. To prevent saturation effects, the samples were suitably diluted with deionized water before analysis. Deionized water was used as a reference for baseline correction. In accordance with accepted practices documented in the literature, the acquired spectra were utilized to evaluate the optical properties of the nanoparticles [9]. Optimization studies were performed by varying precursor concentration, plant extract volume, pH, reaction time, and temperature. The absorbance profile of each condition was recorded between 200–800 nm using a UV–Vis spectrophotometer to determine the optimal parameters for NiO nanoparticle formation.

2.4.2. Fourier Transform Infrared Spectroscopy (FTIR)

A Nicolet Summit LITE FTIR spectrometer (Thermo Fisher Scientific, USA) was used to record FTIR spectra in the 4000–400 cm^{-1} range using the KBr pellet method. Using normal interpretation procedures, the spectra were utilized to determine the phytochemical functional groups from *S. cumini* seed extract that are responsible for stabilizing nanoparticles and reducing metal ions [10].

2.4.3. X-Ray Diffraction (XRD)

Using an XRD diffractometer (PANalytical X'Pert PRO, Netherlands) fitted with Cu-K α radiation ($\lambda = 1.5406 \text{ \AA}$), the crystalline structure of NiO nanoparticles was investigated. At a scan rate of 2°/min, diffraction patterns were gathered throughout a 2 θ range of 10°–80°. The Debye-Scherrer equation was used to determine the crystallite size (D), and the standard JCPDS card for NiO (JCPDS No. 47-1049) was used to index the peaks [11].

2.4.4. High-Resolution Transmission Electron Microscopy (HRTEM)

This HRTEM (JEOL JEM-2100, Japan) was used to examine morphological characteristics and lattice configurations at 200 kV. Particle size, shape, and dispersion were

revealed by the micrographs, and the polycrystalline nature of the nanoparticles was validated by Selected Area Electron Diffraction (SAED) patterns. Lattice fringe measurements based on known imaging principles were performed using digital microscopy software [12].

2.4.5. Thermogravimetric Analysis (TGA)

A TA Instruments TGA Q50 (USA) was used to assess the thermal stability and breakdown behavior of NiO nanoparticles. The samples were heated in a nitrogen environment (50 mL/min) from 30 to 800°C at a rate of 10°C/min. According to comparable green-synthesis investigations, the TGA curves revealed details about moisture loss, the breakdown of organic residues from plant extract, and the stability of the metal oxide phase [13].

2.4.6. Vibrating Sample Magnetometry (VSM)

A Lakeshore 7407 Vibrating Sample Magnetometer (USA) was used to examine the magnetic characteristics. At ambient temperature, hysteresis loops were captured when a magnetic field of -10 to +10,000 Oe was applied. To evaluate the appropriateness of NiO nanoparticles for biomedical applications, including magnetic carrier systems, parameters such as coercivity (H_c), remanent magnetization (M_r), and saturation magnetization (M_s) were retrieved [14].

2.5 Biological Assays

2.5.1 Antibacterial Activity

Two common human pathogenic bacteria, *E. coli* (Gram-negative) and *S. aureus* (Gram-positive), were used to test the antibacterial activity of the produced NiO nanoparticles. In accordance with CLSI recommendations, the agar well diffusion method was used to conduct the assay [15]. Overnight growth of fresh bacterial cultures in nutrient broth was followed by adjustment to the 0.5 McFarland standard (1×10^8 CFU/mL). Sterile cotton swabs were used to evenly inoculate sterile Mueller–Hinton agar plates. 50 μ L of NiO nanoparticle suspensions at concentrations of 50, 100, 150, 200, and 250 μ g/mL were added to each well after 8 mm diameter wells were aseptically punched. The control was DMSO, a solvent free of nanoparticles. Following a 24-hour incubation period at 37 ± 1 °C, inhibitory zone diameters were measured with a digital Vernier caliper.

2.5.2. Minimum Inhibitory Concentration (MIC) and Minimum Bactericidal Concentration (MBC)

The broth microdilution test on 96-well microtiter plates was used to estimate the MIC values of NiO nanoparticles in accordance with CLSI guidelines [16]. NiO nanoparticles were serially diluted two times in Mueller-Hinton broth to achieve final concentrations between 0.078 and 10 µg/mL. 100 µL of a standardized bacterial inoculum (1×10^2 CFU/mL) was added to each well. A microplate reader (Robonik Readwell Touch ELISA reader, India) was used to measure turbidity at 600 nm after microplates were incubated for 24 hours at 37 °C. Ten microliters from wells with no discernible growth were spread out on sterile nutrient agar plates and cultured for twenty-four hours at 37 °C in order to determine MBC. The MBC was the lowest concentration that did not exhibit colony formation.

2.5.3. Biofilm Inhibition Assay

The crystal violet (CV) microtiter plate assay, which is frequently used to assess antibiofilm characteristics, was employed to quantify biofilm inhibition. In short, NiO nanoparticles at concentrations ranging from 1/16 MIC to 2 MIC were applied to 96-well plates together with bacterial suspensions (1×10^6 CFU/mL). Planktonic cells were removed from the wells by gently washing them with phosphate-buffered saline (PBS, pH 7.4) after they had been incubated for 24 hours at 37 °C. After 15 minutes of staining with 0.1% crystal violet, the adherent biofilm was washed and dissolved in 95% ethanol. A microplate reader was used to detect absorbance at 595 nm. The percentage of biofilm inhibition was computed in comparison to the untreated control wells.

2.5.4. DPPH Antioxidant Assay

The antioxidant activity of NiO nanoparticles was assessed using the 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging experiment [23]. NiO nanoparticle suspensions of 20, 40, 60, 80, and 100 µg/mL were combined with a freshly made DPPH solution (0.1 mM in methanol). To prevent photodegradation, the mixture was incubated for 30 minutes at room temperature (25 °C) in the dark. Using a UV-Vis spectrophotometer (Shimadzu UV-1800, Japan), absorbance was measured at 517 nm. The positive control was ascorbic acid (20–100 µg/mL), while the blank was a DPPH solution devoid of material [17].

2.6 Photocatalytic Degradation of Organic Dye

2.6.1 Preparation of Pollutant Solution

Methylene blue (MB) was selected as a representative cationic dye due to its widespread occurrence in textile and pharmaceutical effluents. A primary stock solution (100 mg L^{-1}) was prepared by dissolving analytical-grade methylene blue in deionized water. Working solutions of 10 mg L^{-1} were freshly prepared prior to each experiment by appropriate dilution. All glassware was thoroughly rinsed with distilled water to avoid contamination.

2.6.2 Photocatalytic Activity Evaluation

The degradation of methylene blue (MB) under UV and ambient sunlight irradiation was used to assess the photocatalytic activity of the green-synthesised NiO nanoparticles. A freshly made methylene blue solution (1 ppm) was made with distilled water. Five milliliters of the dye solution were put into sterile glass test tubes for every experiment. In order to examine the impact of catalyst loading on photocatalytic effectiveness, NiO nanoparticles were added in different doses, ranging from $10 \text{ }\mu\text{g}$ to $0.078 \text{ }\mu\text{g}$ per milliliter of dye solution. The same experimental setup was used for a control sample that included simply MB solution devoid of nanoparticles. To create adsorption–desorption equilibrium between the dye molecules and the catalyst surface, the reaction solutions were magnetically agitated for 30 minutes in the dark before irradiation. A 125 W mercury lamp that emitted light at 365 nm was used to irradiate the samples for UV-driven tests. To guarantee consistent illumination, a gap of 10 to 15 cm was kept between the lamp and the samples. The tests were carried out with constant stirring at room temperature ($25 \pm 2 \text{ }^{\circ}\text{C}$). The samples used in sunshine-driven tests were exposed to direct sunlight under clear skies from 11:00 AM to 2:00 PM. Throughout the trial, the average ambient temperature was between 30 and 40 $^{\circ}\text{C}$, and the average light intensity was between 90,000 and 100,000 lux. With regular intervals of 20 minutes, the total irradiation time reached 120 minutes. To eliminate the catalyst particles, aliquots were taken at prearranged intervals and centrifuged for five minutes at 8000 rpm. A UV-visible spectrophotometer was used to measure the absorbance of the clear supernatant in the 400–800 nm wavelength range. By measuring the absorbance at 664 nm, which corresponds to the typical maximum absorption wavelength (λ_{max}) of methylene blue (MB), the residual concentration of MB was ascertained. Using the following formula, the photocatalytic degradation efficiency (%) was determined:

$$\text{Degradation efficiency (\%)} = \frac{A_0 - A_t}{A_0} \times 100$$

where:

- A_0 is the initial dye concentration after dark adsorption equilibrium,
- A_t is the dye concentration at irradiation time t .

2.6.3 Kinetic Analysis

The degradation kinetics were analyzed assuming pseudo-first-order reaction behavior, described by the Langmuir–Hinshelwood model:

$$\ln \left(\frac{C_0}{C_t} \right) = kt$$

where:

- k represents the apparent rate constant (min^{-1}),
- t is irradiation time.

The rate constant was determined from the slope of the linear plot of $\ln(C_0/C_t)$ versus time.

2.6.4 Catalyst Reusability Study

To assess operational stability, the wasted NiO nanoparticles were collected by centrifugation at the end of each cycle, thoroughly cleaned with distilled water and ethanol, and then dried for four hours at 60°C . Up to five successive cycles were performed using the recovered catalyst, all of which were carried out under exacting experimental conditions. To evaluate performance retention, the degradation efficiency was measured at the end of each cycle.

2.7 Statistical Analysis

All experiments were performed in triplicate ($n = 3$), and results are expressed as mean $\pm$ standard deviation (SD). Statistical comparisons between groups were analyzed using one-way ANOVA followed by Tukey's post-hoc test, with significance set at $p < 0.05$. Graphs and curve-fitting (including optimization plots) were generated using OriginPro 2022. MIC/MBC

values were interpreted based on visible growth inhibition and regrowth confirmation, without additional statistical testing.

Results and Discussion

3.1 UV–Visible Spectroscopy

Using UV-visible spectroscopy in the 200–800 nm range, the optical properties of the metal precursor, *Syzygium cumini* seed extract, and the produced NiO nanoparticles (NiO NPs) were assessed. The overlay spectrum (Fig. 1) makes it easy to see how each of the three components behaves optically. The *Syzygium cumini* seed extract showed a broad absorption band between 270 and 330 nm, which is attributed to the presence of polyphenols, flavonoids, tannins, and other antioxidant-rich phytochemicals. According to numerous reports, these biomolecules function as natural stabilizing and reducing agents during the creation of nanoparticles [18]. As is typical of Ni²⁺ ionic transitions, the metal precursor solution exhibited a significant absorbance below 250 nm, followed by a sharp drop. A baseline for monitoring the creation of nanoparticles is provided by this noticeable departure from the spectrum of the seed extract.

The spectrum of the produced NiO NPs showed a clear absorption shoulder at $\approx$ 320–350 nm after the seed extract was added to the nickel precursor, indicating that the nanoparticle production process was successful. The intrinsic band-gap transitions of NiO, which are generally reported within the 300–380 nm range, correspond to this absorption area, which is well-documented for NiO nanoparticles [19]. The creation of nanoscale NiO and the reduction of Ni²⁺ ions are shown by the small bathochromic (red) shift in comparison to the seed extract signals. The involvement of phytoconstituents in the creation of nanoparticles is further demonstrated by a discernible drop in absorbance intensity when compared to the pure extract, indicating their function as capping agents and electron donors. This optical behavior is consistent with the method of green synthesis, in which the biomolecules help to stabilize and reduce the nanoparticles. Overall, the UV–Vis spectral characteristics provide compelling evidence that was used to successfully biosynthesize NiO nanoparticles. *cumini* seed extract, exhibiting distinctive absorbance patterns in line with previously documented green-synthesised NiO NPs [20].

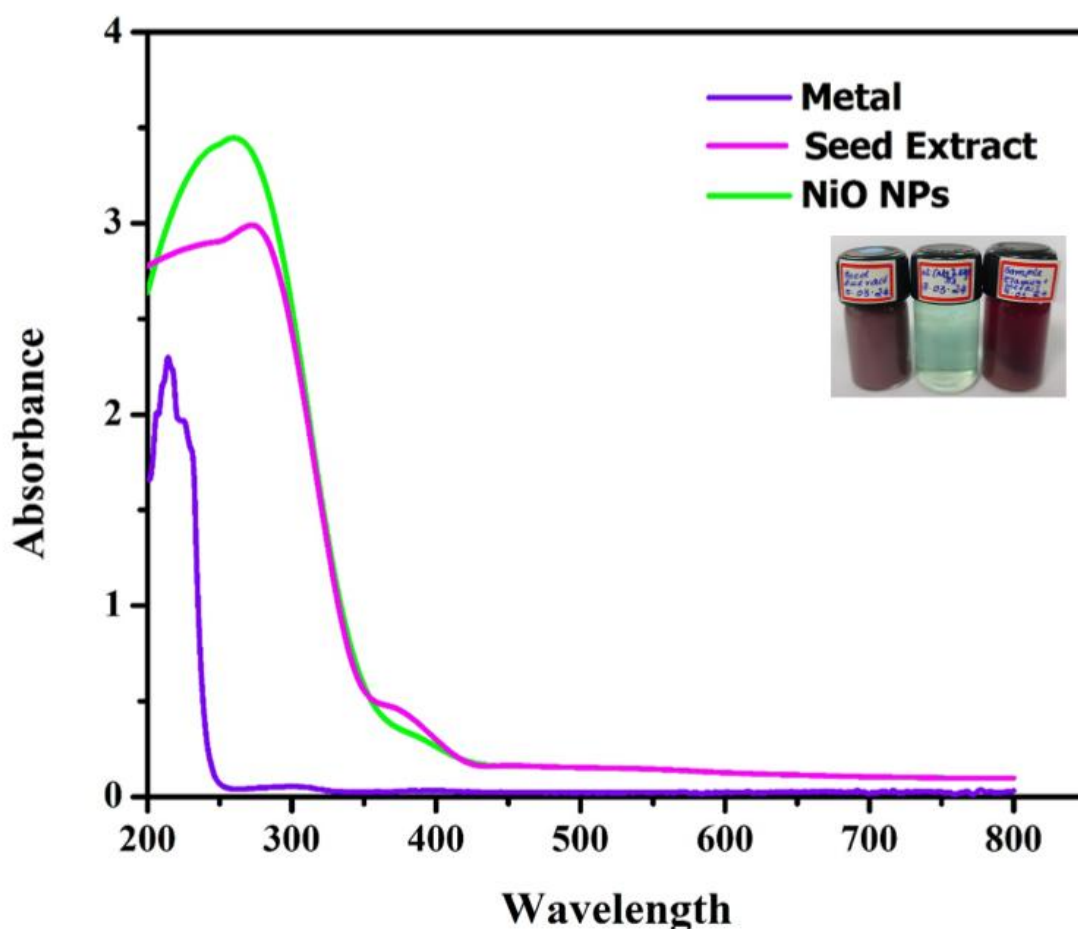


Figure 1. UV–Vis absorption spectra of metal ion solution, *Syzygium cumini* seed extract, and biosynthesized NiO nanoparticles.

3.2 Optimization of NiO Nanoparticle Synthesis

The concentration of the precursor greatly affected how the NiO nanoparticles began to form and expand. As the Ni (NO₃)₂ concentration increased from 100 to 500 mM, the solution gradually turned darker, and the absorbance rose, peaking around 310–330 nm, a sign of more nanoparticles forming (Fig. 2a). The 400 mM and 500 mM treatments glowed with the greatest intensity, indicating a surge in particle presence and more effective metallic ion reduction. At 500 mM, the peak broadened slightly, hinting at the beginning of clumping. Consequently, they determined that 400 mM was the best precursor concentration for creating consistent and uniformly sized NiO NPs.

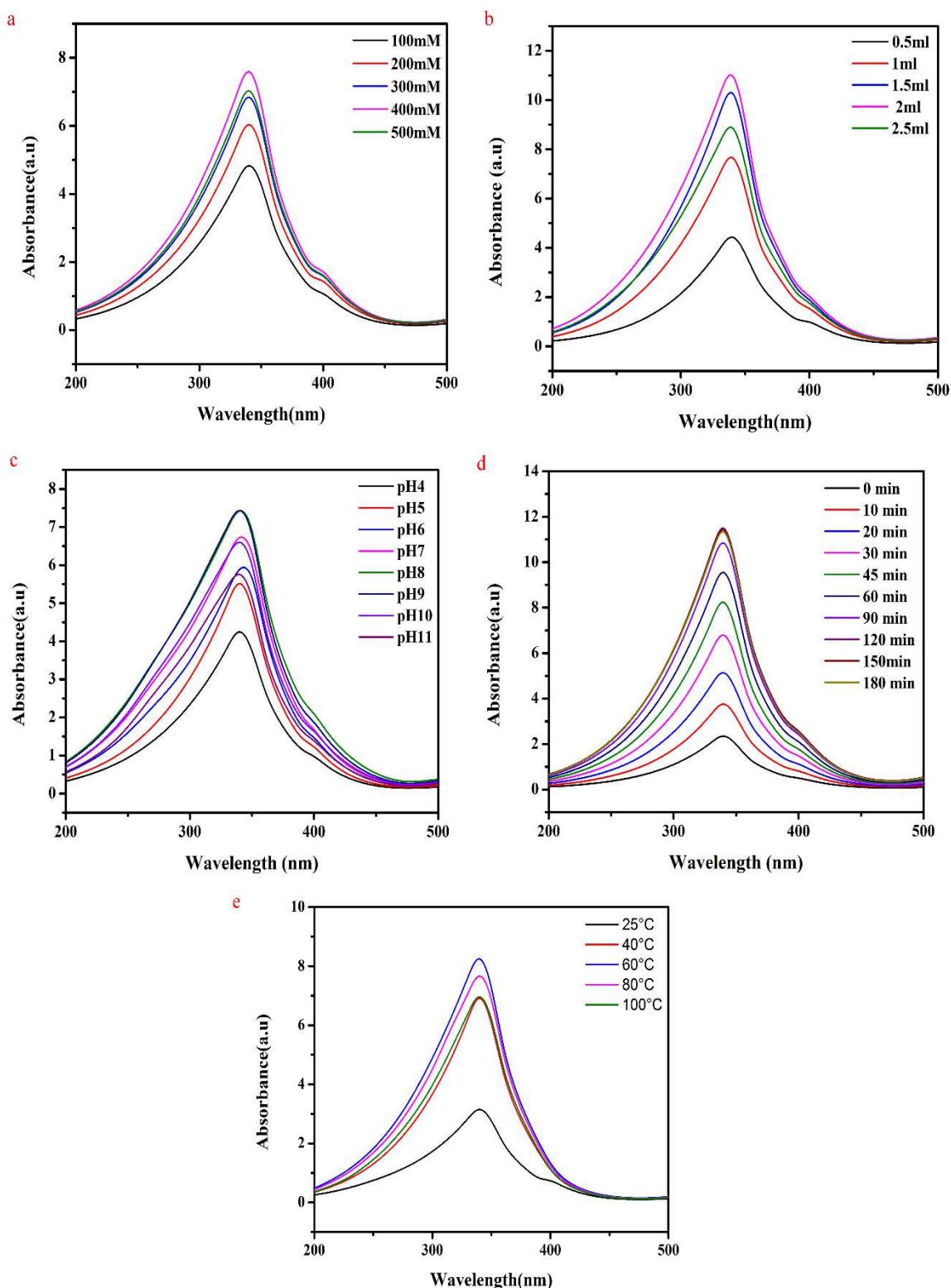


Figure 2. UV–Vis optimization of NiO NP synthesis showing the effects of (a) precursor concentration, (b) extract volume, (c) pH, (d) reaction time, and (e) temperature on nanoparticle formation.

A higher phytochemical availability, promoted by varying the seed extract volume (0.5–2.5 mL), led to a more efficient reduction. As the absorbance intensity grew steadily, the peak reached its highest point at 2.0 mL, which suggested the perfect balance between the reducing agent and metal ions. The peak dipped slightly at 2.5 mL, possibly indicating that an overabundance of biomolecules was present, which could hinder the process. Consequently, the optimal volume for efficient synthesis was determined to be 2.0 mL of extract, as illustrated in Fig. 2b. Nanoparticle stability and how they interacted with light were heavily dependent on the reaction's pH. Acidic conditions (pH 4–6) produced lower absorbance, indicating slow reduction kinetics and incomplete nucleation. Neutral to alkaline environments (pH 7–10) displayed sharper and higher peaks, confirming enhanced reduction due to deprotonated phytochemicals. At pH 11, the peak intensity decreased, likely due to excessive OH⁻ leading to premature precipitation (Fig. 2c). The best-defined plasmon peak occurred at pH 9, suggesting optimal stabilization and growth under mildly alkaline conditions.

The UV–Vis spectra recorded from 0–180 minutes showed the gradual emergence of NiO NPs. Nucleation and growth continued, as evidenced by the steady increase in the absorbance peak over 120 minutes. The spectra showed no significant change beyond 120 minutes, indicating the reaction was done and nanoparticle formation was complete, as depicted in Fig. 2d. No considerable peak shift was observed, which indicated a steady morphology. Thus, the ideal reaction time was determined to be 120 minutes. A temperature range of 25–100°C had a strong effect on how fast the reaction proceeded, showing significant changes in its kinetics. The absorbance was low at room temperature (25°C), which implied that the reaction hadn't fully completed. The rising temperature boosted the peak intensity, and the most was produced at 60°C, showing how the kinetics were balanced and the nucleation was controlled. At higher temperatures (80–100°C), slight peak broadening suggested the presence of larger or aggregated particles (Fig. 2e). Thus, 60°C was identified as the optimal temperature, ensuring efficient and uniform nanoparticle synthesis [21].

3.3 FTIR Analysis

The phytochemical constituents of the *Syzygium cumini* seed extract involved in the biosynthesis of NiO nanoparticles were inferred from the characteristic absorption bands observed in the FTIR spectrum of the synthesized NiO nanoparticles (Fig. 3). The broad band at 3430 cm⁻¹ corresponds to O–H stretching vibrations of alcohols and phenolic compounds, indicating the presence of polyphenols that may function as reducing and stabilizing agents.

The absorption band at 2925 cm^{-1} is attributed to C–H stretching vibrations of aliphatic chains commonly found in plant-derived biomolecules. Prominent peaks observed at 1592 cm^{-1} and 1469 cm^{-1} are assigned to C=C stretching vibrations of aromatic rings and carboxylate groups, suggesting the involvement of flavonoids and tannins. The bands appearing in the range of $1118\text{--}1061\text{ cm}^{-1}$ correspond to C–O–C and C–O stretching vibrations of polyphenolic compounds. Additionally, weak peaks observed at $862\text{--}882\text{ cm}^{-1}$ are associated with out-of-plane bending vibrations of substituted aromatic rings, indicating the presence of lignin-derived components. Importantly, the formation of NiO nanoparticles was confirmed by the appearance of characteristic metal–oxygen (Ni–O) stretching vibrations below 600 cm^{-1} . Compared to the seed extract, the observed shifts and reduced intensities of the phytochemical-related bands in the NiO nanoparticle spectrum suggest their involvement in the reduction of nickel ions as well as in the capping and stabilization of the nanoparticles. These observations are consistent with previously reported FTIR profiles of NiO nanoparticles synthesized using plant-based extracts [22].

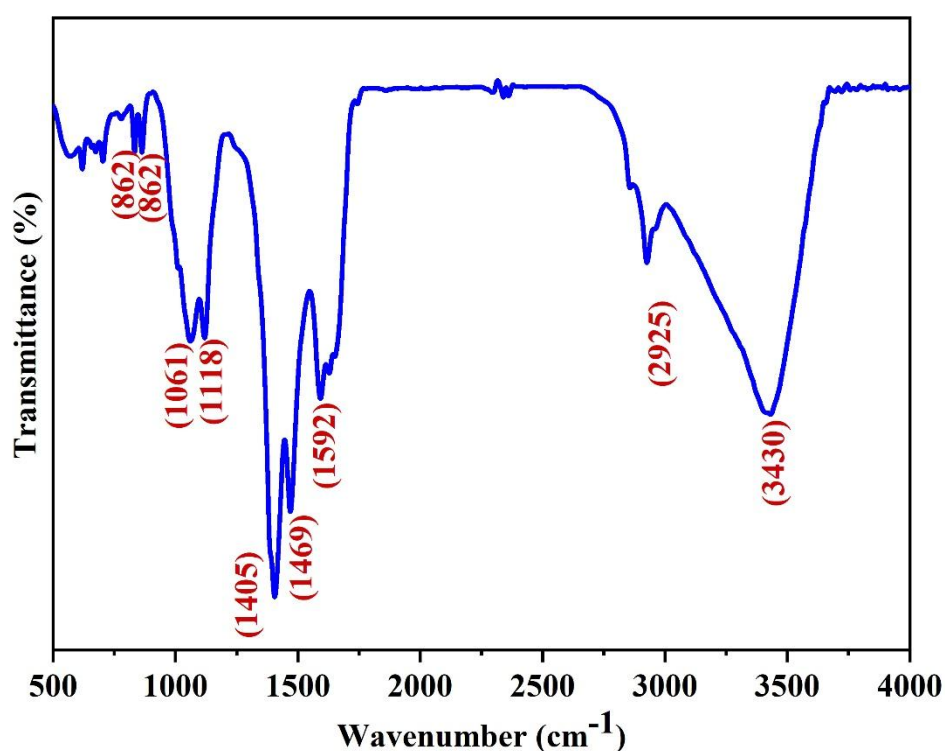


Figure 3 presents the FTIR spectrum, showcasing the green-synthesized NiO nanoparticles' characteristic vibration peaks, confirming functional group interactions,

3.4 XRD Analysis

The (110), (110), (101), (111), and (111) planes, respectively, were represented by the sharp and intense peaks at $2\theta = 18.3^\circ$, 29.4° , 33.0° , 38.4° , and 43.3° in the NiO nanoparticles' XRD diffractogram (Fig. 4). These peaks confirm the creation of crystalline nickel oxide because they match the standard JCPDS card for cubic NiO (JCPDS No. 47-1049) quite well. While the average crystallite size determined using the Debye-Scherrer equation was roughly 15–25 nm, comparable with green-synthesized NiO nanoparticles, the narrow peak widths imply high crystallinity. Persistent substances functioning as surface stabilizers are the cause of little noise or broadness in lower-intensity peaks. The phase purity of the produced nanoparticles is demonstrated by the lack of impurity peaks corresponding to $\text{Ni}(\text{OH})_2$ or Ni metal, indicating that the plant metabolites successfully promoted both reduction and oxidation into NiO. These findings are consistent with earlier research on the creation of NiO nanoparticles mediated by plants [23].

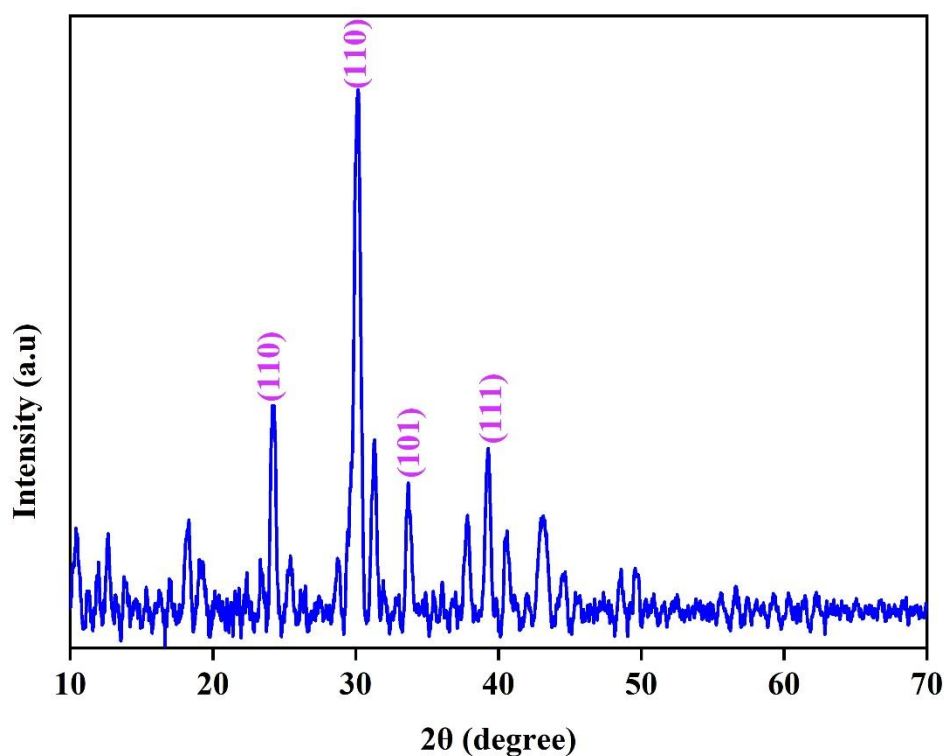


Figure 4. XRD pattern of green-synthesized NiO nanoparticles.

3.5 HRTEM

As is common for plant-mediated metal oxide systems resulting from biomolecule adsorption, the green-synthesised NiO nanoparticles were found to be primarily quasi-spherical with discernible regions of agglomeration using high-resolution transmission electron microscopy (HRTEM) (Fig. 4). Nanoscale domains embedded within an amorphous organic matrix produced from *Syzygium cumini* seed metabolites were visible when the particle size steadily increased across magnifications (100 nm to 5 nm pictures). The production of crystalline NiO was confirmed by the observation of distinct lattice fringes at a higher magnification (5 nm scale). According to the particle size distribution histogram, most synthesized NiO nanoparticles fall within 15–25 nm, averaging about 18–20 nm, which aligns with the consistent features shown in the HRTEM images.

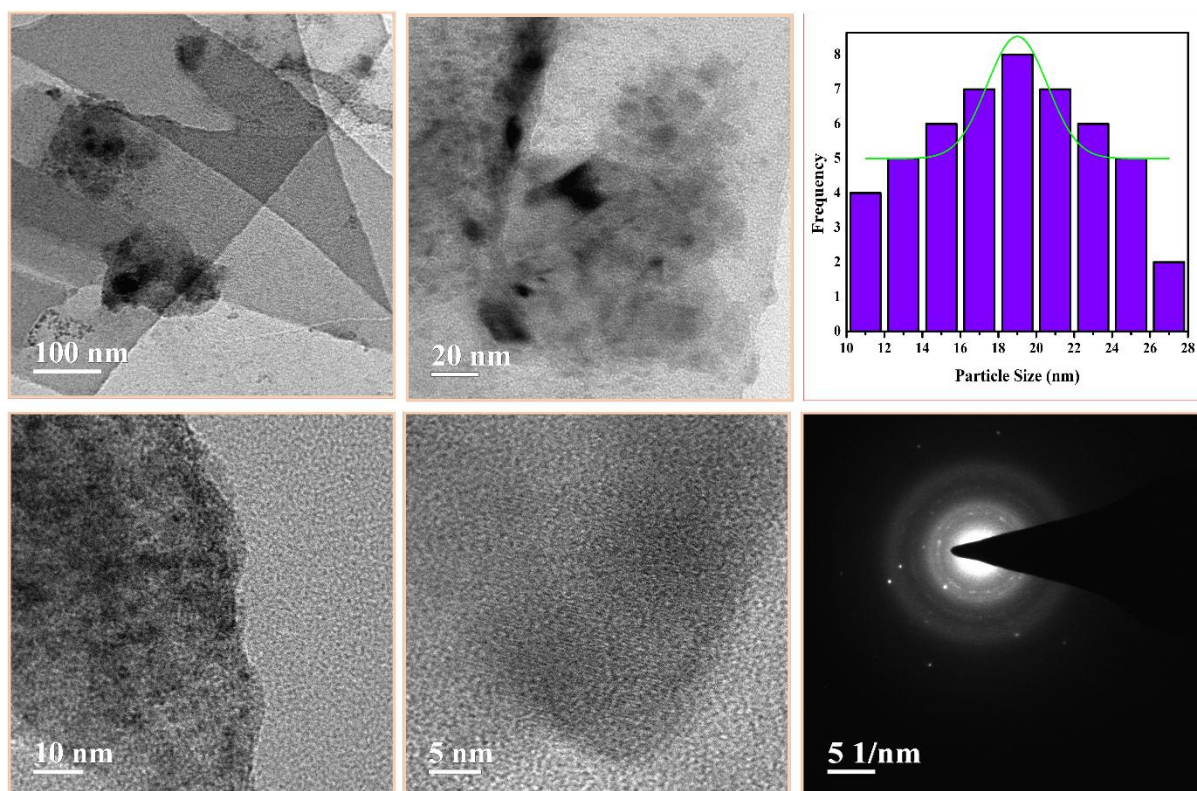


Figure 4. HRTEM micrograph and SAED pattern of NiO nanoparticles confirming crystalline structure.

The (111) plane of cubic NiO is aligned with the measured interplanar spacing (d -spacing = 0.24–0.25 nm), showing that the face-centered cubic (FCC) structure was successfully formed. Bright concentric rings were visible in the SAED pattern, which further supported the idea that NiO nanoparticles are polycrystalline. The (110), (101), and (111)

planes are represented by distinct diffraction rings that match JCPDS NiO standards. Mixed nanocrystalline domains are suggested by the sharp points that are overlaid on the rings. Together, these findings support the creation of well-crystalline NiO nanoparticles, which is in keeping with recent reports of green synthesis employing plant extracts high in polyphenols [24].

3.6 TGA -Analysis

Fig. 5 displays the TGA profiles for the as-prepared (uncalcined) and calcined NiO samples. The uncalcined material showed a three-stage weight loss: a major phytochemical decomposition between 150 and 350 °C (20–27% mass loss; DTG peak 275 °C), a gradual removal of carbonaceous residues up to 500 °C, and a final inorganic residue of 66.0% at 800 °C. With a stable residue of 72.5% above 550 °C and a slight moisture-related loss below 160 °C, the sample that had previously been calcined at 400 °C demonstrated a much lower mass loss upon reheating. The creation of thermally stable NiO and the efficient removal of organic capping agents during calcination are confirmed by the greater final residue of the calcined sample.

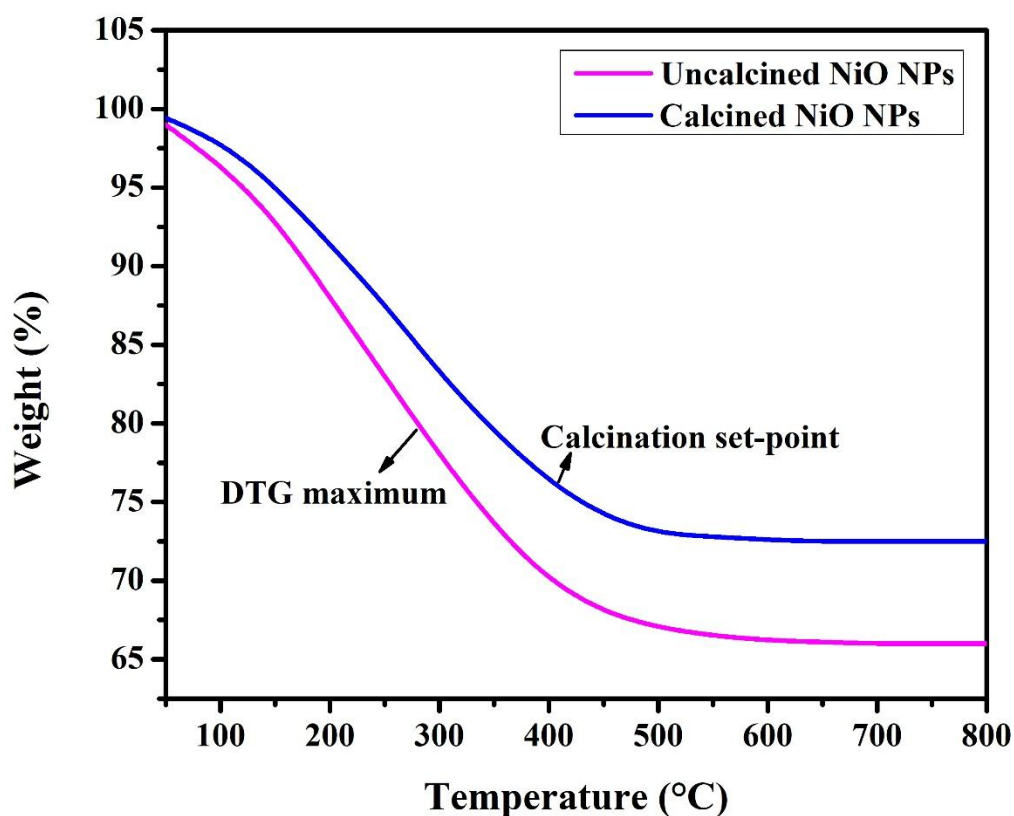


Figure 5 TGA curves of uncalcined and calcined NiO nanoparticles showing weight-loss behavior, DTG maximum, and calcination stability up to 800 °C

It should be noted that no melting event is seen in these TGA curves because the melting temperature of bulk NiO ($\sim 1955\text{ }^{\circ}\text{C}$) is significantly higher than the experimental range (30–800 $^{\circ}\text{C}$). Previous findings on green-synthesized NiO and other metal oxide nanoparticles support the multi-step degradation pattern and the high thermal stability observed in this study [25]. The stabilization plateau above 500 $^{\circ}\text{C}$ further indicates strong binding of phytochemical residues on the NiO surface and efficient oxide formation.

3.7 Vibrating Sample Magnetometry (VSM)

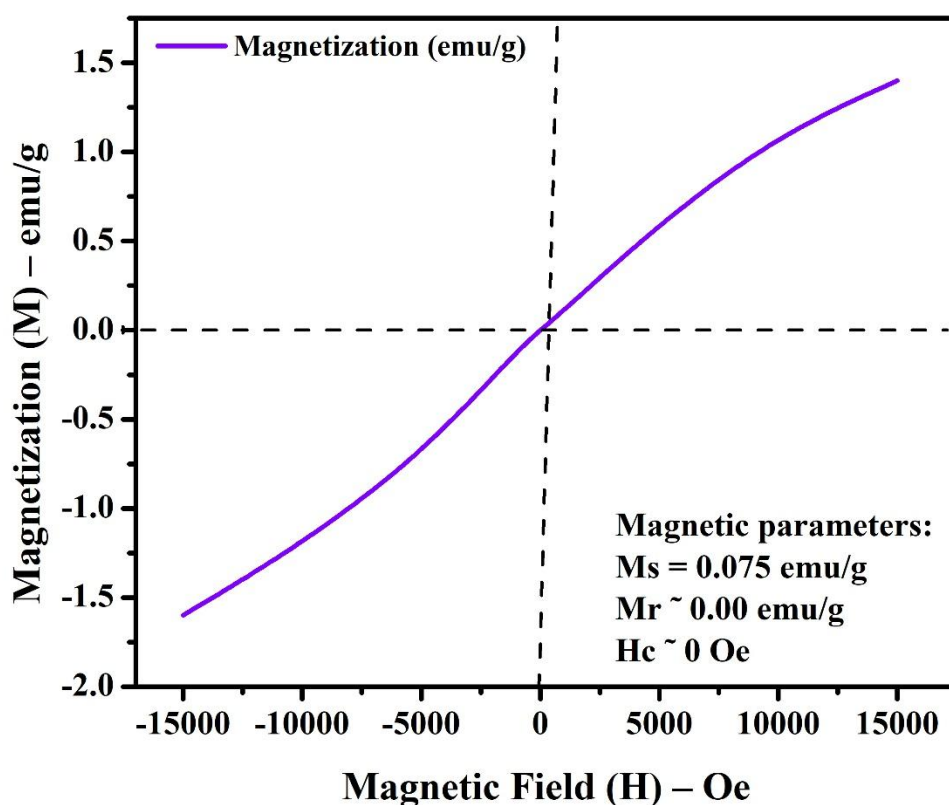


Figure 6: VSM magnetization curve of NiO nanoparticles at room temperature.

Using VSM at ambient temperature, the magnetic characteristics of the produced NiO nanoparticles were evaluated within a magnetic field range of -15,000 to +15,000 Oe (Fig. 6). The M–H curve displays an S-shaped pattern with extremely low magnetization, which is

typical of NiO at the nanoscale. The nanoparticles showed almost zero coercivity ($H_c \approx 0$ Oe), minimal remanence ($M_r \approx 0$ emu/g), and saturation magnetization (M_s) of 0.075 emu/g. Superparamagnetic-like behavior, which is frequently seen in NiO nanoparticles because of size reduction and surface spin effects, is shown by the lack of considerable hysteresis. The green-synthesised NiO nanoparticles have a mild magnetic response and no residual magnetization, which makes them appropriate for biological applications where particle aggregation must be kept to a minimum, according to the VSM profile overall. Because it inhibits unwanted particle aggregation and improves colloidal stability, this magnetic softness is beneficial for medicinal applications like medication delivery and antimicrobial coatings. Recent research has documented similar magnetic behavior for plant-mediated NiO nanoparticles [26].

3.8 Biological Assays

3.8.1 Antibacterial Activity

The antibacterial activity of the biosynthesized NiO nanoparticles was evaluated against *S. aureus* and *E. coli* using the agar well diffusion method, with vancomycin included as a standard antibiotic for comparison. As shown in Fig. 7a, the diameter of the clear inhibition zones increased progressively with increasing nanoparticle concentration, demonstrating a concentration-dependent antibacterial response. These qualitative observations are further supported by the quantitative bar-graph analysis presented in Fig. 7b, which illustrates a steady increase in inhibition zone diameter from 50 to 250 $\mu\text{g mL}^{-1}$ for both bacterial strains. The corresponding numerical values, including standard deviations, are summarized in Table 1. Specifically, the inhibition zones for *S. aureus* increased from 10.25 ± 0.42 mm at 50 $\mu\text{g mL}^{-1}$ to 23.00 ± 0.70 mm at 250 $\mu\text{g mL}^{-1}$, whereas *E. coli* exhibited comparatively larger inhibition zones ranging from 12.20 ± 0.38 mm to 27.00 ± 0.80 mm over the same concentration range. The inhibition zones produced by vancomycin confirmed the antibacterial responsiveness of the tested strains and served as a reference for comparison. The relatively higher susceptibility of *E. coli* toward NiO nanoparticles may be attributed to structural differences between Gram-negative and Gram-positive bacterial cell walls [27].

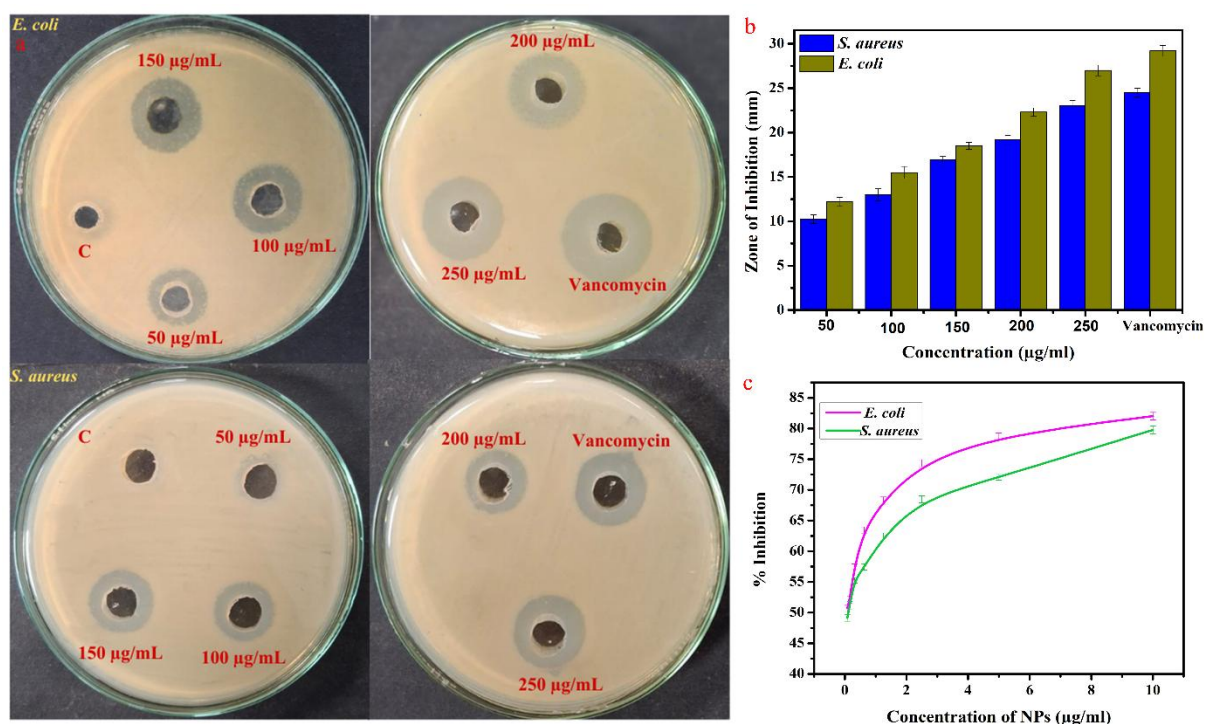


Figure 7. (7a) Agar well diffusion assay showing concentration-dependent antibacterial activity of NiO nanoparticles; (7b) quantitative zone-of-inhibition values (mm ± SD) confirming dose-dependent effects against *S. aureus* and *E. coli*; (7c) MIC analysis of NiO nanoparticles (mean ± SD, n = 3).

Table 1. Antibacterial Activity of Biosynthesized NiO Nanoparticles

S.No	Concentration of NiO NPs (µg/mL)	<i>S. aureus</i> (mm ± SD)	<i>E. coli</i> (mm ± SD)
1	50	10.25 ± 0.42	12.20 ± 0.38
2	100	13.00 ± 0.47	15.50 ± 0.52
3	150	16.90 ± 0.55	18.50 ± 0.60
4	200	19.20 ± 0.63	22.30 ± 0.72
5	250	23.00 ± 0.70	27.00 ± 0.80
6	Vancomycin	21.5± 0.50	29.2± 0.60

The enhanced antibacterial activity relative to the plant extract alone demonstrates that the formation of NiO nanoparticles significantly improved surface reactivity and interaction with bacterial cells. Although specific mechanistic assays (e.g., ROS generation or membrane damage studies) were not conducted, the observed inhibition pattern is consistent with

previously reported antibacterial mechanisms of green-synthesized NiO nanoparticles, which involve surface charge interactions, oxidative stress induction, and phytochemical-assisted membrane disruption. Overall, the results confirm that *Syzygium cumini* seed extract-mediated NiO nanoparticles possess strong and concentration-dependent antibacterial activity, supporting their potential utility as eco-friendly antimicrobial agents. The present study did not include mechanistic assays such as ROS quantification, membrane damage analysis, live/dead imaging, or Ni²⁺ ion release profiling, which could have provided a deeper understanding of the underlying biological effects. Consequently, the exact antibacterial process remains uncertain. However, past research on green-synthesized NiO and other metal oxide nanoparticles points to mechanisms that may entail ROS formation, membrane disruption, and limited metal ion release [28]. Therefore, the inhibition seen in our study is attributed to the interplay of nanoparticle surface traits and phytochemical capping, rather than serving as direct mechanistic evidence.

3.8.2 Minimum Inhibitory Concentration (MIC)

The lowest concentration of biosynthesized NiO nanoparticles that could stop observable bacterial growth after a 24-hour incubation period at 37 °C was found using the MIC assay. At the lowest values (0.156–0.5 µg/mL) in the current investigation, turbidity was seen, suggesting insufficient bacterial suppression. Nonetheless, a dose-dependent rise in inhibition and a progressive decrease in turbidity were noted between 1 and 10 µg/mL, which is in line with the quantitative inhibition pattern depicted in Fig. 7c. *S. aureus* achieved the same amount of inhibition at 5 µg/mL, while *E. coli* showed ≥70% inhibition at 2.5 µg/mL, which was regarded as the MIC threshold.

The maximal inhibitory response for *E. coli* and *S. aureus* at 10 µg/mL was 82% and 79%, respectively, indicating that *E. coli* was marginally more vulnerable to NiO nanoparticles. Similar reports of this difference in sensitivity between Gram-positive and Gram-negative bacteria have been made for various green-synthesised metal oxide nanoparticles [29], where interactions between the nanoparticles are influenced by the architecture of the cellular envelope. The MIC method is a more accurate assessment of antimicrobial potency than agar diffusion assays because it offers a direct contact-based quantitative inhibition measurement. The study's findings unequivocally show that even at low microscale concentrations, the phytochemically encapsulated NiO nanoparticles retain potent inhibitory effect.

3.8.3 Minimum Bactericidal Concentration (MBC)

Aliquots from MIC wells were subcultured onto brand-new nutrient agar plates in order to measure MBC. At concentrations ≤ 5 $\mu\text{g/mL}$, bacterial regrowth was seen, but at 7.5–10 $\mu\text{g/mL}$ for *E. coli* and 10 $\mu\text{g/mL}$ for *S. aureus*, no colony growth was seen. For *E. coli* and *S. aureus*, the MBC was determined to be 7.5 $\mu\text{g/mL}$ and 10 $\mu\text{g/mL}$, respectively (Table 2). In line with previous results on green-synthesized NiO and ZnO nanosystems, the proximity of MIC and MBC values indicates that the NiO nanoparticles exhibit bactericidal activity rather than just bacteriostatic activity [30]. Since MBC gives a fuller view of the dose needed for total bacterial mortality, determining MBC in addition to MIC is essential for assessing the appropriateness of antimicrobial drugs for biomedical applications. Although membrane disruption, surface contact, or oxidative stress have been linked to the bactericidal effects of metal-oxide nanoparticles in other research, these mechanisms cannot be verified here without specific assays (e.g., ROS measurement or ion-release studies). The growth-inhibition and colony-regrowth patterns, which clearly demonstrate the dose-dependent antibacterial activity of NiO nanoparticles, are therefore the only basis for interpreting the current data.

Table 2 The minimum bactericidal concentration of *S. aureus* and *E. coli*.

S. No	Concentration of tin oxide N Ps	Presence of growth in <i>E. coli</i>	Presence of growth in <i>S. aureus</i>
1	10 $\mu\text{g/mL}$	No growth	No growth
2	5 $\mu\text{g/mL}$	No growth	No growth
3	2.5 $\mu\text{g/mL}$	No growth	No growth
4	1.25 $\mu\text{g/mL}$	No growth	No growth
5	0.625 $\mu\text{g/mL}$	No growth	No growth
6	0.312 $\mu\text{g/mL}$	Growth obtained	Growth obtained
7	0.078 $\mu\text{g/mL}$	Growth obtained	Growth obtained

3.8.4 Biofilm Inhibition Assay

Both *S. aureus* and *E. coli* biofilm development was clearly inhibited by the green-synthesised NiO nanoparticles in a concentration-dependent manner (Fig. 9b). NiO NPs disrupt early adhesion and microcolony development, as evidenced by the moderate suppression the NPs caused even at sub-inhibitory levels (1/16–1/4 MIC), with *E. coli* exhibiting 45.2–50.1% inhibition and *S. aureus* demonstrating 43.8–48.7%. Inhibition rose to 58.0% (*E. coli*) and 54.2% (*S. aureus*) at $\frac{1}{2}$ MIC, and then to 66.8% and 63.4% at MIC, respectively, indicating that the extracellular polymeric substances (EPS) were gradually disrupted as the NP concentration rose. *E. coli* and *S. aureus* demonstrated the maximum inhibition at $2\times$ MIC,

with 78.9% and 72.1%, respectively. This was associated with increased nanoparticle interaction with bacterial cell surfaces and EPS, which caused the biofilm matrix to become mechanically unstable. Differences in the structure of the cell envelope, which might affect nanoparticle penetration and surface attachment, may be the cause of the somewhat greater inhibition in *E. coli*. For metal oxide nanoparticles, similar dose-dependent antibiofilm trends have been documented; higher concentrations encourage the production of reactive oxygen species (ROS), disruption of EPS, membrane changes, and suppression of quorum-sensing pathways, all of which contribute to a reduction in biofilm integrity [31]. Overall, the findings support the use of NiO NPs in biomedical and environmental surfaces where biofilm development poses significant issues by confirming that they have high antibiofilm potential even at sub-MIC levels.

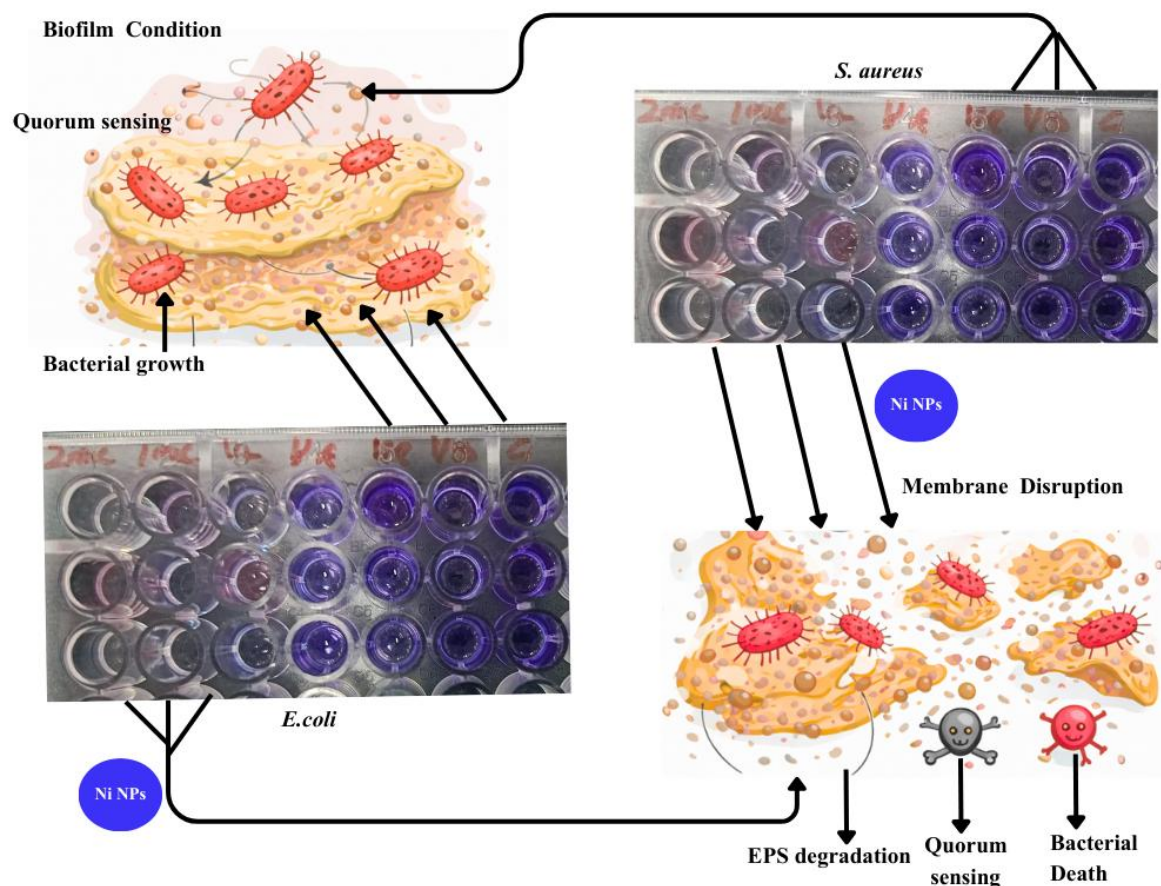


Figure 8. Proposed antibiofilm mechanism of NiO nanoparticles against *E. coli* and *S. aureus*.

Based on the antibiofilm assays and qualitative observations, a plausible mechanism for biofilm inhibition by NiO nanoparticles is proposed (Fig.8), involving disruption of the EPS matrix,

interference with quorum sensing, and subsequent bacterial cell death. The relationship between antimicrobial and antibiofilm activities is closely associated, as the inhibition of planktonic bacterial growth can reduce the initial adhesion and the formation of biofilms [32]. This study demonstrated that NiO nanoparticle concentrations exhibiting substantial antibacterial activity simultaneously hindered biofilm development, implying that compromised bacterial viability diminishes EPS synthesis and disturbs quorum sensing. However, antibiofilm activity did not rely only on bacterial killing, suggesting that NiO nanoparticles might also disrupt biofilm-specific regulatory signals.

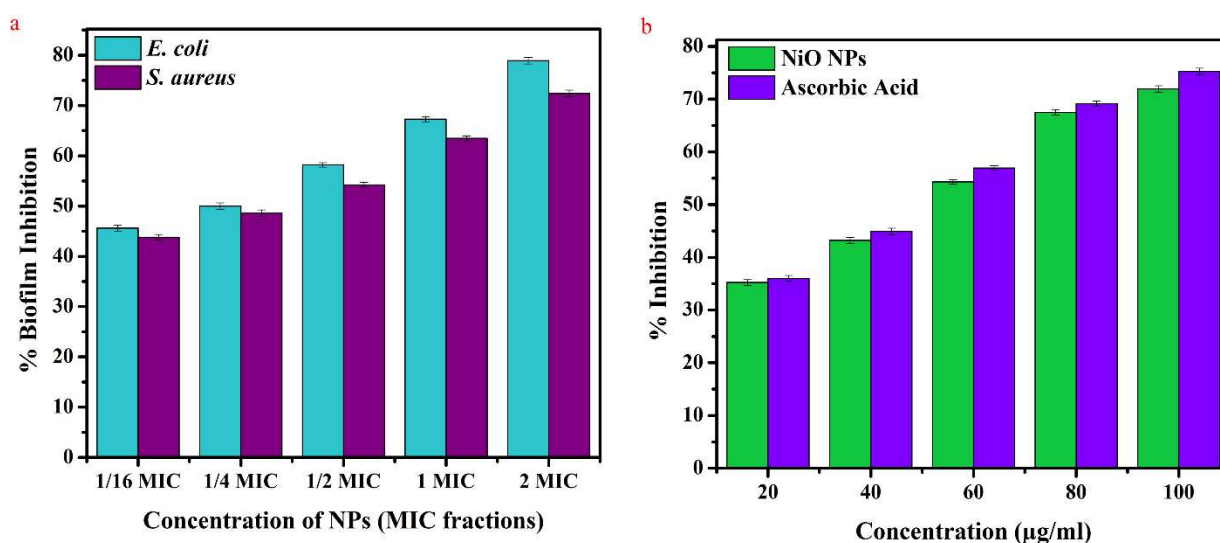


Figure 9. (9a) Biofilm inhibition activity of synthesized NiO nanoparticles against the tested bacterial strains; (9b) DPPH radical scavenging (antioxidant) activity of NiO nanoparticles (mean $\pm$ SD, n = 3).

3.8.5 DPPH Antioxidant Assay

Using the DPPH radical scavenging assay, the antioxidant activity of the green-synthesised NiO nanoparticles was assessed and contrasted with that of ascorbic acid as the reference (Fig. 9b). From 35.4% inhibition at 20 µg/mL to 71.5% at 100 µg/mL, the nanoparticles' scavenging efficiency clearly increased in a dose-dependent manner. As anticipated for a pure molecular antioxidant, ascorbic acid exhibited a similar pattern, displaying somewhat greater levels at each concentration (36.2–74.8%).

Even though NiO NPs' activity was slightly lower than the norm, the difference was still negligible, suggesting that the plant extract's phytochemical coating plays a major role in

electron-donating ability and free-radical neutralization. Increased accessibility of surface-active functional groups that can transfer electrons or hydrogen atoms to stabilize the DPPH radical is suggested by the rising scavenging efficiency with greater NP concentrations. Other green-synthesised metal oxide nanoparticles have been shown to exhibit similar antioxidant properties, with surface-bound polyphenols and flavonoids playing a major role in radical quenching [33]. Furthermore, NiO NPs' high surface-to-volume ratio and nanoscale size may allow for more contact with DPPH molecules, enhancing their capacity to scavenge radicals [34]. All things considered, the findings demonstrate that NiO NPs have robust antioxidant qualities on par with those of conventional antioxidants, underscoring their possible use in environmental and biological systems where oxidative stress is a significant factor.

3.9 Photocatalytic Activity Under UV and Sunlight Irradiation

To gauge how well the green-synthesized *Syzygium cumini*-mediated NiO nanoparticles worked as photocatalysts, researchers watched the breakdown of methylene blue (MB) under both UV and natural sunlight. They tested different amounts of the catalyst, ranging from 0.312 to 10 $\mu\text{g/mL}$. The temporal decrease in MB absorbance at 664 nm under UV exposure is seen in Fig. 10(a). For all catalyst concentrations, a systematic decrease in absorbance was seen as the irradiation period increased, but the control sample just slightly changed. This indicated that the majority of the dye degradation was photocatalytic rather than photolytic [35].

There was a noticeable increase in photocatalytic efficiency that was concentration-dependent. The absorbance decreased more quickly with higher catalyst loading, suggesting better photon absorption and more active surface sites. The greatest degradation efficiency for 10 $\mu\text{g/mL}$ after 120 minutes of UV irradiation was over 90% (Fig. 10b), while lesser concentrations, like 0.312 $\mu\text{g/mL}$, showed about 40–45% degradation. The efficient activation of NiO nanoparticles, which produces electron–hole pairs, is responsible for the increased deterioration under UV radiation. Reactive oxygen species (ROS) such $\bullet\text{OH}$ and $\text{O}_2\bullet^-$ are created when these charge carriers combine with dissolved oxygen and water molecules [36]. These ROS target the chromophoric structure of methylene blue and cause its oxidative destruction.

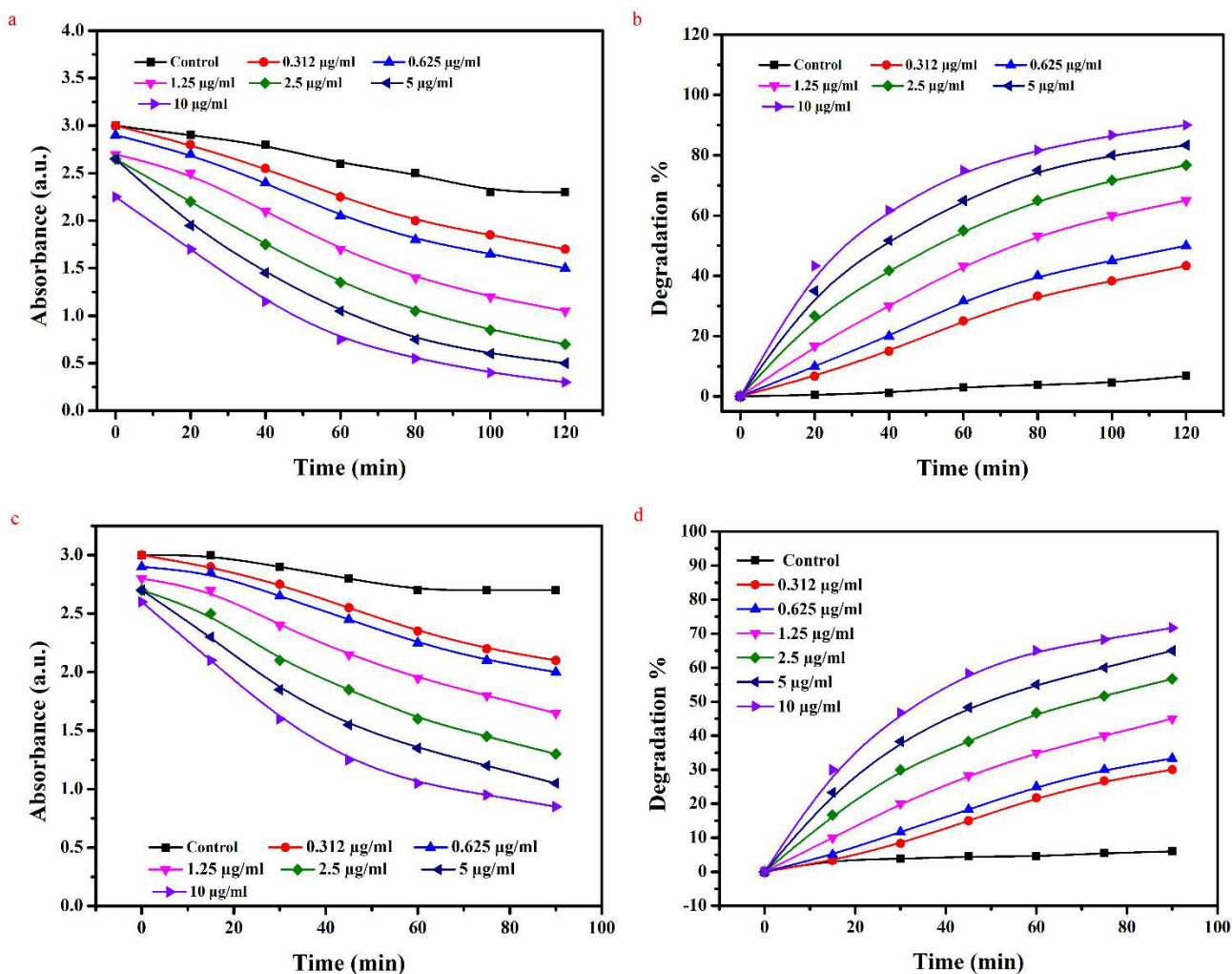


Figure 10. (a,c) Time-dependent absorbance changes of methylene blue under UV and sunlight irradiation, respectively; (b,d) corresponding degradation efficiency (%) showing concentration-dependent photocatalytic activity of NiO nanoparticles.

High surface reactivity and effective charge separation are suggested by the quick degradation that occurs over the first 40 to 60 minutes. After this time, the rate progressively decreased, most likely as a result of partial active site saturation and decreased dye concentration. A similar pattern was seen under natural sunlight (Fig. 10c & d), although the rate of destruction was somewhat slower than under UV irradiation. Over time, the absorbance gradually dropped, and greater catalyst concentrations once more showed better results. After 90 minutes in the sun, the degradation efficiency at 10 $\mu\text{g/mL}$ was roughly 70–75%, but the removal efficiencies at lower doses were only modest (30–50%). Minimal MB self-degradation under sunlight was confirmed by the control sample, which stayed almost unaltered.

Reduced UV portion in the solar spectrum, decreased photon energy in visible light, and variations in natural solar intensity could all be responsible for the comparatively lesser deterioration under sunlight. Because of its broad band gap ($\sim 3.4\text{--}3.8$ eV), NiO reacts to UV light more efficiently. However, the noticeable deterioration in sunlight suggests that the produced nanoparticles have some solar responsiveness, which is beneficial for environmentally friendly repair that is sustainable. The findings unequivocally show that photocatalytic efficiency rises as catalyst concentration does. At larger concentrations, however, the pace of improvement becomes less noticeable, indicating potential light scattering effects or nanoparticle aggregation that could restrict photon penetration [37]. Overall, at all studied concentrations, UV irradiation produced a higher degradation efficiency than sunlight. Compared to sunshine ($\sim 72\text{--}75\%$), the maximal deterioration under UV ($\sim 90\%$) was noticeably higher. Notwithstanding this distinction, the significant deterioration upon exposure to sunlight emphasizes the possible use of these green-synthesised NiO nanoparticles in inexpensive, solar-powered wastewater treatment systems.

3.10 Kinetic Analysis

Utilizing the pseudo-first-order kinetic model developed from the Langmuir–Hinshelwood process, the photocatalytic degradation of methylene blue was assessed. The degradation process adheres to the first-order reaction kinetics depicted in Fig 11 because of the strong linear relationship between the linear plots of $\ln(C_0/C_t)$ and irradiation time (0–120 min) under both UV and sunshine conditions. In contrast to exposure to sunlight, the $\ln(C_0/C_t)$ values increased more steeply with time under UV irradiation, suggesting a higher rate of deterioration [38,39]. According to the slope of the linear regression, UV irradiation had a higher apparent rate constant (k) (0.023 min^{-1}) than sunlight (0.018 min^{-1}). Excellent linear fitting was indicated by the very high correlation coefficients ($R^2 = 0.992$ for UV and $R^2 = 0.987$ for sunshine), which confirmed the applicability of the pseudo-first-order kinetic model. The better oxidative destruction of dye molecules and greater production of reactive oxygen species are the results of more effective excitation of the photocatalyst, which is responsible for the improved performance under UV light. The good linearity and significant rate constant validate the efficient photocatalytic activity of the produced nanoparticles under natural irradiation circumstances, despite the slightly reduced degradation rate under sunshine. With better performance seen under UV irradiation, the kinetic data show that the

photocatalytic degradation process is surface-mediated and regulated by photogenerated charge carriers.

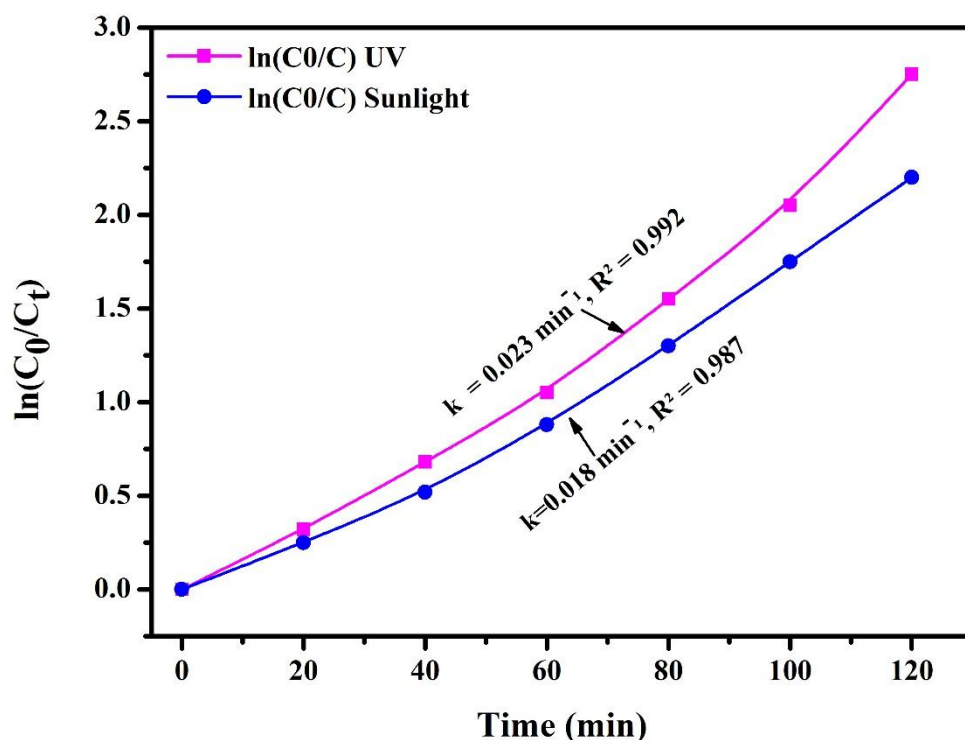


Figure 11. Pseudo-first-order kinetic plots ($\ln(C_0/C_t)$ vs time) for methylene blue degradation under UV and sunlight irradiation (0–120 min).

Catalyst Reusability

The green-synthesized NiO nanoparticles' reusability was assessed throughout five consecutive photocatalytic cycles while being exposed to both UV and ambient sunlight. The degradation efficiency under UV irradiation was 91.8% in the first cycle and lowered marginally to 89.4%, 87.6%, 85.9%, and 83.7% in the second, third, fourth, and fifth cycles, respectively. Likewise, when exposed to sunshine, the degradation efficiency progressively dropped from 78.6% in the initial cycle to 76.8%, 74.9%, 72.5%, and 70.8% following five consecutive cycles. The small decrease in efficiency under both irradiation sources (less than 10% loss after five cycles) could be caused by slight nanoparticle aggregation, partial surface fouling by reaction intermediates, or minimal catalyst loss during centrifugation [40]. Even after repeated use, the comparatively slight drop demonstrates that the NiO nanoparticles retain

a high level of photocatalytic activity and good structural stability. In both UV and sunlight, the catalyst exhibits outstanding operating endurance, underscoring its promise for economical and environmentally friendly wastewater treatment applications.

Conclusion

Using seed extract from *Syzygium cumini* as a biogenic reducing and stabilizing agent, nickel oxide nanoparticles (NiO NPs) were effectively created in an environmentally friendly manner. Crystalline cubic NiO nanoparticles with an average size of 15–25 nm were produced by optimizing the reaction conditions. XRD and HRTEM verified phase purity and nanoscale morphology, while UV-Vis measurement revealed a distinctive absorbance at about 330 nm. The structural resilience was confirmed by VSM, which showed modest ferromagnetic behavior ($M_s = 0.075$ emu/g), and TGA, which showed thermal stability over 500 °C. Strong photocatalytic activity toward the destruction of methylene blue was demonstrated by the produced NiO NPs. In 120 minutes, almost 90% deterioration was attained under UV irradiation, while 70–75% degradation was noted under ambient sunlight. With rate constants of 0.023 min^{-1} (UV) and 0.018 min^{-1} (sunlight), the degradation proceeded according to pseudo-first-order kinetics and showed excellent linear correlation ($R^2 > 0.98$). After five consecutive cycles, reusability investigations showed remarkable operational stability, maintaining over 83% (UV) and 70% (sunlight) efficiency. The nanoparticles demonstrated concentration-dependent antibacterial activity in a biological setting, exhibiting inhibition zones as large as 23 mm for *S. aureus* and 27 mm for *E. coli*. At 5 µg/mL and 2.5 µg/mL, respectively, MIC values were noted, and at 2×MIC, biofilm inhibition was around 78%. At 100 µg/mL, the DPPH assay demonstrated radical scavenging activity of up to ~71%. The combined photocatalytic, antibacterial, antibiofilm, and antioxidant properties of the phytogenic NiO nanoparticles show promise for antimicrobial surface applications and sustainable wastewater remediation. Their translational and industrial viability will be further improved by upcoming studies that include visible-light band gap manipulation, cytotoxicity testing, and pilot-scale wastewater validation.

Plant collection and permissions

Syzygium cumini seeds used in this study were collected from Thiruvancherry village in Tamil Nadu, India (Latitude: 12.814° N). The samples were obtained from publicly

accessible areas without disturbing the local ecosystem. The species is widely cultivated and is not listed as endangered under the Indian Biodiversity Act. All collection procedures complied with relevant local and national biodiversity regulations.

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Declarations

Ethics approval and consent to participate:

Not applicable. This study does not involve human participants or animals.

Clinical trial statement: This study does not involve human participants or clinical trial procedures. Therefore, clinical trial registration is not applicable.

Consent to participate:

Not applicable.

Consent to publication:

All authors have read and approved the final manuscript and consent to its publication.

Competing interests:

The authors declare no competing interests

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Data availability:

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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