Research Article

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Machine Learning-Based Optimization of Green-Synthesized MgO Nanoparticles Using *Cardiospermum halicacabum* for Antibacterial and Reactive Orange 16 Removal

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ABSTRACT

This study aimed to develop multifunctional magnesium oxide nanoparticles (MgO NPs) through a sustainable synthesis route using Cardiospermu*m* halicacabum leaf extract and to evaluate their antibacterial and wastewater-treatment potential. The effects of magnesium nitrate concentration, extract concentration, reaction temperature, and reaction time on MgO yield were optimized using a Taguchi L27 design and ANOVA. The novelty lies in integrating Taguchi optimization with comparative artificial neural network (ANN) and support vector regression (SVR) modelling to optimize and predict plant-mediated MgO production. The optimized nanoparticles were characterized using UV–visible spectroscopy, FTIR, XRD, and SEM–EDX and evaluated for antibacterial activity and hydroxylamine-enhanced Reactive Orange 16 removal. Extract concentration was the dominant synthesis parameter, contributing 54.02% to yield variation. The optimum conditions of 0.10 M precursor, 100 g L^{-1} extract, 65 °C, and 75 min produced 0.13913 ± 0.00035 g of MgO, with only 0.09% deviation from the Taguchi prediction. The ANN and SVR models achieved cross-validated R^2 values of 0.9828 and 0.9999, respectively, confirming the superior predictive performance of SVR. Characterization verified the formation of crystalline cubic-periclase MgO. The nanoparticles exhibited concentration-dependent antibacterial activity. The MgO/NaClO/hydroxylamine system achieved 96.8% Reactive Orange 16 removal within 30 min, with an apparent rate constant of 0.117 min^{-1}. These findings demonstrate the practical potential of green-synthesized MgO nanoparticles for rapid treatment of dye-bearing wastewater. Further studies should investigate catalyst recyclability, degradation-product toxicity, mineralization efficiency, reaction mechanisms, and performance in actual textile effluents.

Keywords: Green synthesis; Sustainability; Optimization; ANN; Reactive orange 16.

1. INTRODUCTION

The continuous discharge of synthetic dyes from textile, printing, leather, and chemical industries has become one of the major environmental concerns because of high stability, toxicity, and resistance to conventional wastewater treatment methods. Among azo dyes, Reactive Orange 16 (RO16) is widely used due to its excellent dyeing properties; however, its complex aromatic structure and azo bonds make it highly persistent in aquatic environments, posing significant ecological and human health risks. Development of sustainable, highly efficient, and environmentally benign technologies for RO16 removal has attracted considerable research interest.

Adsorption is an effective approach for dye removal because of its simplicity, low energy requirement, and high efficiency. Activated biochar derived from *Sterculia foetida* shells has demonstrated effective removal of Acid Blue 158 dye, indicating the potential of sustainable biomass-derived adsorbents for synthetic dye treatment (Yennam *et al.* 2024). Various bio-based adsorbents have demonstrated promising RO16 removal capacities, including cross-linked chitosan-genipin/SiO_2 (57.1 mg g^{-1}), CTS-BADGE/NS (97.8 mg g^{-1}), and CS-EPH/NSi bionanocomposites (110.2 mg g^{-1}), while selenium-doped mesoporous biochar achieved 538 mg g^{-1} through π–π interactions, pore filling, and hydrogen bonding (Wu *et al.* 2024a); (Abdulhameed *et al.* 2024); (Wu *et al.* 2024b); (Dos Reis

et al. 2023). However, adsorption primarily transfers dye molecules from the aqueous phase to the adsorbent, highlighting the need for complementary advanced oxidation and photocatalytic processes for effective degradation.

Semiconductor nanoparticles have emerged as promising photocatalysts for persistent organic pollutants because of their high surface area, catalytic activity, and reactive oxygen species generation. Ce-substituted Mn–Zn ferrite nanoparticles achieved 97.25% Congo Red and 98.42% RO16 degradation under visible light within 120 min, while green-synthesized CuO nanoparticles and oyster shell-derived nHAp/TiO_2/GO nanocomposites achieved 96.37% Congo Red and nearly 98% methylene blue degradation, respectively (Dinesh *et al.* 2022); (Boddu *et al.* 2025); (Vanitha *et al.* 2023). These findings demonstrate the potential of metal oxide nanomaterials for sustainable wastewater remediation

Among semiconductor oxides, ZnO nanoparticles have attracted considerable attention because of their wide band gap, high electron mobility, chemical stability, low toxicity, and low cost. Plant-mediated synthesis further improves their environmental compatibility by using phytochemicals as natural reducing, stabilizing, and capping agents. Garcinia cambogia-mediated ZnO nanoparticles demonstrated efficient degradation of cationic and anionic dyes with antibacterial activity, while Prosopis glandulosa-derived ZnO achieved 95.24% methylene blue removal with an adsorption capacity of 88.5 mg g^{-1} (Sasi *et al.* 2022). These studies highlight the potential of green-synthesized ZnO nanomaterials for integrated adsorption and photocatalytic applications.

In addition to catalytic degradation, multifunctional nanomaterials possessing antimicrobial properties have become increasingly attractive for integrated environmental remediation. Organo-montmorillonite/silver nanocomposites simultaneously achieved complete antibacterial inhibition against Escherichia coli and Staphylococcus aureus while effectively removing textile dyes (Sadeghianmaryan *et al.* 2022). Fungus-mediated Ag–Fe bimetallic nanoparticles exhibited efficient methylene blue removal together with strong antibacterial activity and enhanced seed germination, demonstrating multifunctional environmental applications (Patel *et al.* 2025). Furthermore, green-synthesized silver nanoparticles have shown remarkable anticancer activity by inducing apoptosis and suppressing cell proliferation (Kotteeswaran *et al.* 2024), highlighting the broad biomedical potential of biologically synthesized nanomaterials.

Recent advances have also demonstrated the importance of integrating artificial intelligence (AI) with nanomaterial synthesis and environmental applications. Machine learning algorithms have significantly improved process optimization, prediction accuracy, and experimental efficiency. XGBoost coupled with a genetic algorithm successfully optimized Nano-ZnO synthesis, producing nanoparticles with high yield, large specific surface area, and crystallite sizes below 20 nm while achieving a prediction accuracy of $R^2 = 0.956$ (Guo *et al.* 2026). Artificial neural networks (ANNs) have accurately predicted Cu(II) adsorption using nano zero-valent aluminum, outperforming conventional regression models with extremely low prediction errors (Sadek *et al.* 2023). Similarly, ANN, support vector regression (SVR), and random forest models successfully optimized membrane performance for water treatment applications (Mohammad *et al.* 2025). These findings indicate that machine learning has become a valuable tool for optimizing synthesis parameters and predicting nanoparticle performance.

However, limited studies have combined plant-mediated MgO nanoparticle synthesis with statistical optimization and machine-learning-assisted modelling for enhanced catalytic removal of Reactive Orange 16. The novelty of this study lies in integrating the *Cardiospermum halicacabum*-mediated green synthesis of magnesium oxide nanoparticles with Taguchi L27–ANOVA optimization and comparative ANN–SVR modelling. Unlike conventional synthesis approaches, the proposed method uses plant-derived phytochemicals as natural complexing and stabilizing agents, thereby reducing the need for hazardous chemicals. The optimized MgO nanoparticles were further applied in hydroxylamine-enhanced catalytic oxidation of Reactive Orange 16, establishing a sustainable and multifunctional approach that combines data-driven nanoparticle production with rapid treatment of dye-contaminated wastewater.

2. MATERIALS AND METHODOLOGY

2.1 Materials and Reagents

Fresh *Cardiospermum halicacabum* leaves were obtained from Anthiyur, Erode, Tamil Nadu during April and May 2026. Magnesium nitrate hexahydrate [$Mg(NO_3)_2 \cdot 6H_2O$] was employed as the magnesium precursor, while Reactive Orange 16 served as the target dye. Sodium hydroxide (NaOH), Hydroxylamine hydrochloride ($NH_2OH \cdot HCl$), ethanol, hydrochloric acid (HCl), and other necessary analytical-grade reagents were purchased from Star Scientific Enterprises, Erode, Tamil Nadu, India. All substances were utilized directly without further purification. Distilled water was used for preparing the leaf extract, precursor solution, and dye samples. Before each experiment, the glassware was thoroughly cleaned with dilute hydrochloric acid, repeatedly rinsed using distilled water and completely dried.

2.2 Preparation of *Cardiospermum halicacabum* Leaf Extract

The *Cardiospermum halicacabum* leaves was collected from Anthiyur, Tamil Nadu, India, between April and May 2026. The samples were repeatedly rinsed with distilled water to remove dust and surface impurities and shade-dried at ambient temperature for ten days. Dried leaves were converted into fine powder using a GM300 Retsch electric grinder. For aqueous extraction, 10.0 g of leaf powder was mixed with 100 mL of DI water and heated at 85 °C for 10 min with continuous magnetic stirring (Kavitha *et al.* 2021). After cooling, the mixture was centrifuged at 10,000 rpm. The supernatant was vacuum-filtered through Whatman No. 1 filter paper. The prepared extract was stored at 4 °C until further use.

2.3 Green Synthesis of Magnesium Oxide Nanoparticles

Magnesium oxide nanoparticles were prepared using *Cardiospermum halicacabum* leaf extract as a natural complexing and stabilizing medium. A 0.1 M magnesium nitrate solution was produced by dissolving 2.56 g of $Mg(NO_3)_2{\cdot}6H_2O$ in 100 mL of DIW. The prepared leaf extract was introduced dropwise into the precursor solution under constant magnetic stirring at 700 rpm and 62 °C for 1 h (Sahith *et al.* 2025). Sodium hydroxide solution was added to promote magnesium hydroxide precipitation. The development of a whitish suspension indicated particle formation. Phytochemicals present in the extract facilitated nucleation, restricted particle growth, and stabilized the resulting structures. The proposed transformations are:

Dissociation of magnesium nitrate hexahydrate:

$$Mg(NO_3)_2 \cdot 6H_2O \rightarrow Mg^{2+} + 2NO_3 + 6H_2O \quad \ldots (1)$$

Formation of magnesium hydroxide:

$$Mg^{2+} + 2OH^- \rightarrow Mg(OH)_2 \quad \ldots (2)$$

Thermal conversion into magnesium oxide:

$$Mg(OH)_2 \xrightarrow{\Delta} MgO + H_2O \quad \ldots (3)$$

The precipitate was separated by centrifugation and washed using distilled water and ethanol. It was subsequently vacuum-filtered through a 0.22 µm membrane and dried at 60 °C for 12 h (Amale *et al.* 2026). The dried material was calcined at 500 °C for 3 h to obtain MgO NPs. Finally, the prepared nanoparticles were stored in a light-protected container at room temperature until analysis.

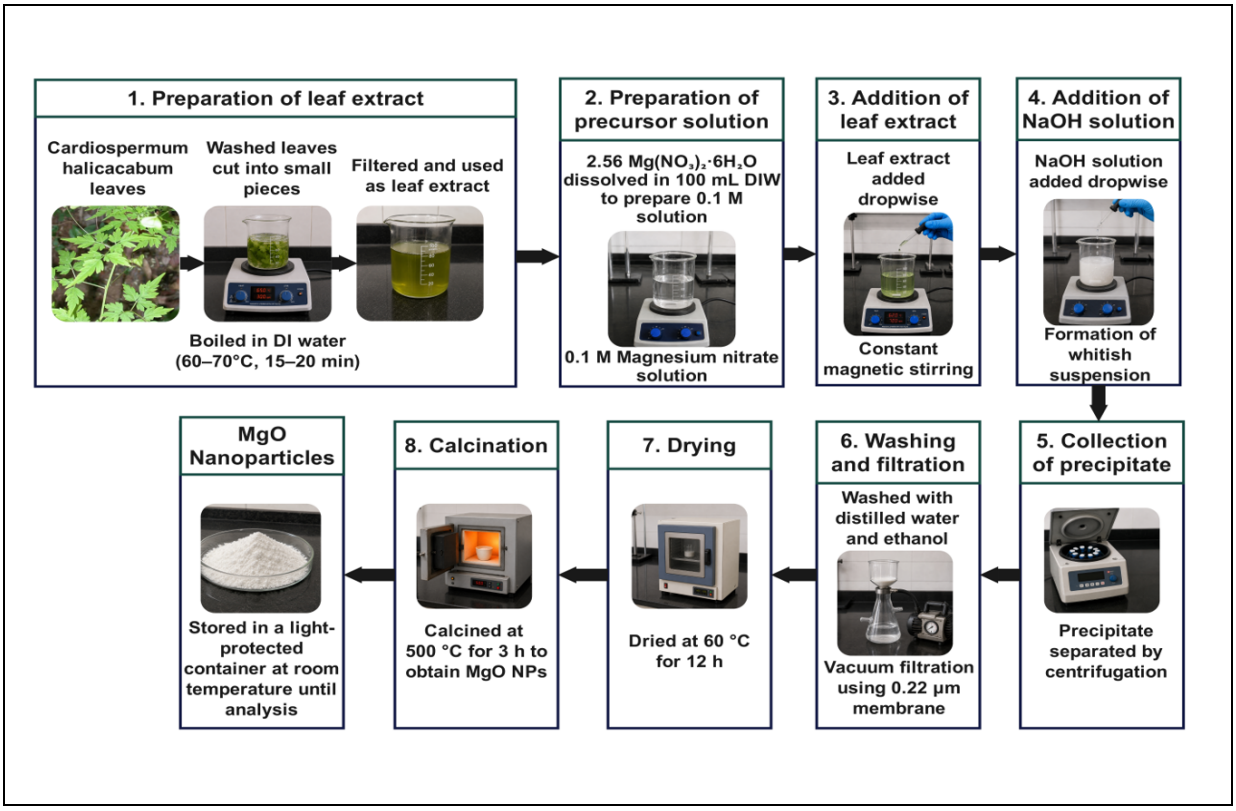


Fig. 1: Green synthesis pathway of MgO nanoparticles

2.4 Taguchi L27 Optimization on the Synthesis of MgO Nanoparticles

A Taguchi L27 orthogonal array was constructed in Minitab to maximize the yield of magnesium oxide nanoparticles (MgO NPs) produced using *Cardiospermum halicacabum* leaf extract. The resulting design comprised 27 experimental combinations. The investigated variables were $Mg(NO_3)_2 \cdot 6H_2O$ concentration (A), leaf-extract concentration (B), reaction temperature (C), and reaction duration (D). The selected factors and levels are presented in Table 1.

The combination of these factor and levels generated 27 experimental runs. The recovered dry mass of MgO nanoparticles after washing, drying, and calcination was selected as the response (Y). The complete experimental matrix and corresponding yield values are presented in Table 2.

Table 1. Factors and levels used in the Taguchi L27 design

Code	Synthesis Factor	Unit	Level 1	Level 2	Level 3
A	$Mg(NO_3)_2 \cdot 6H_2O$ concentration	M	0.05	0.10	0.15
B	*C. halicacabum* extract concentration	g L^{-1}	50	100	150
C	Reaction temperature	°C	50	65	80
D	Reaction time	min	45	60	75

Table 2. Taguchi L27 experimental matrix and MgO nanoparticle dry yield

Run	$Mg(NO_3)_2 \cdot 6H_2O$ (M)	Extract (g L^{-1})	Temperature (°C)	Time (min)	MgO dry yield (g)
1	0.05	50	50	45	0.0748
2	0.1	50	50	45	0.0873
3	0.15	50	50	45	0.0809
4	0.05	100	65	60	0.1196
5	0.1	100	65	60	0.1324
6	0.15	100	65	60	0.1258
7	0.05	150	80	75	0.1087
8	0.1	150	80	75	0.1212
9	0.15	150	80	75	0.1149
10	0.05	50	65	75	0.1018
11	0.1	50	65	75	0.1145
12	0.15	50	65	75	0.1077
13	0.05	100	80	45	0.1039
14	0.1	100	80	45	0.1162
15	0.15	100	80	45	0.1098
16	0.05	150	50	60	0.0976
17	0.1	150	50	60	0.1104
18	0.15	150	50	60	0.1038
19	0.05	50	80	60	0.0869
20	0.1	50	80	60	0.0995
21	0.15	50	80	60	0.0931
22	0.05	100	50	75	0.1146
23	0.1	100	50	75	0.1275
24	0.15	100	50	75	0.1207
25	0.05	150	65	45	0.1015
26	0.1	150	65	45	0.1141
27	0.15	150	65	45	0.1079

Analysis of variance was applied to determine the statistical contribution and significance of all synthesis parameters. Signal-to-noise ratio was calculated by the "larger-is-better" criterion because nanoparticle yield was intended to be maximized (Chowdhury *et al.* 2026):

$$S/N = -10\log_{10}\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{Y_i^2}\right] \quad \ldots (4)$$

Main-effect plots, factor rankings, percentage contributions, and interaction trends were examined to identify the parameter combination producing the highest MgO NP yield.

2.5 Confirmation Tests

The optimum factor levels obtained from the Taguchi analysis were verified experimentally. MgO NPs were synthesized under the predicted operating conditions, and their measured dry yield was compared with the estimated response. Model reliability was assessed from the percentage deviation between the predicted and experimental results:

$$\text{Deviation}(\%) = \frac{|Y_{\text{exp}} - Y_{\text{pred}}|}{Y_{\text{exp}}} \times 100 \quad \ldots (5)$$

A low deviation indicated satisfactory agreement and confirmed the suitability of the optimized synthesis conditions.

2.6 ANN and SVR Modeling

Artificial neural network (ANN) and support vector regression (SVR) models were developed to describe the nonlinear relationship between the four synthesis variables and MgO NP yield.

Before model development, the variables were normalized between 0 and 1 using:

$$x_i = \frac{X - X_{\min}}{X_{\max} - X_{\min}} \quad \ldots (6)$$

where x_i shows the normalized value, X is the original observation, and $X_{\min}$ and $X_{\max}$ represent its minimum and maximum limits. The ANN architecture was selected by varying the number of hidden neurons and choosing the configuration with minimum prediction error and maximum determination coefficient.

The ANN employed a feed-forward multilayer perceptron consisting of four input neurons, a hidden layer, and one output neuron (Alanazi *et al.* 2025). During forward propagation, the weighted input values were transferred through the hidden layer and transformed using an activation function to generate the predicted MgO nanoparticle yield. The prediction error was determined from the difference between the experimental and predicted yields. During backpropagation, the network weights and biases were iteratively adjusted to minimize this prediction error. The ANN architecture was selected by varying the number of hidden neurons and choosing the configuration with the minimum prediction error and maximum coefficient of determination.

The same experimental inputs and responses were used to construct the SVR model. SVR maps the input variables into a higher-dimensional feature space and constructs a regression function within an ε-insensitive error margin. A kernel function was employed to represent the nonlinear relationships between the synthesis parameters and MgO nanoparticle yield. Only observations outside the ε-insensitive region, known as support vectors, contributed directly to the final regression function. The regularization parameter C, kernel parameter, and ε value were tuned through cross-validation to balance prediction accuracy and model generalization.

Cross-validation was employed for both ANN and SVR models to reduce dependence on a single training–testing division and assess their ability to predict unseen observations. ANN and SVR accuracy was compared using mean squared error (MSE) and the coefficient of determination (R2) (Lateef *et al.* 2022):

$$\text{MSE} = \frac{1}{n}\sum_{i=1}^{n}\left(Y_{i,\text{exp}} - Y_{i,\text{pred}}\right)^2 \quad \ldots (7)$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(Y_{i,\text{exp}} - Y_{i,\text{pred}}\right)^2}{\sum_{i=1}^{n}\left(Y_{i,\text{exp}} - \bar{Y}_{\text{exp}}\right)^2} \quad \ldots (8)$$

The model exhibiting the lowest MSE and highest R^2 was considered more reliable for predicting MgO nanoparticle yield.

2.7 Characterization of Green-synthesized MgO Nanoparticles

2.7.1 Optical Analysis by UV–visible Spectroscopy

The absorption properties of prepared magnesium oxide nanoparticles were examined using UV–visible spectroscopy (Dhanaraj *et al.* 2024). The resulting spectrum was also employed to estimate their optical bandgap. Measurements were recorded from 200 to 600 nm with a Thermo Scientific EVOLUTION 260 BIO spectrophotometer. Quartz cuvettes were used for sample analysis, and distilled water served as the blank reference.

2.7.2 Fourier-transform Infrared Spectral Analysis

The chemical bonds and surface functional groups associated with *Cardiospermum halicacabum* leaf extract and the green-synthesized magnesium oxide nanoparticles were evaluated before and after calcination

at 500 °C for 3 h. FTIR spectra were acquired using a Shimadzu IRAffinity-1S instrument over a wavenumber range of 4000–500 cm^{-1}.

2.7.3 Crystalline Structure Analysis by X-ray Diffraction

The phase purity, crystal structure, and average crystallite size of green-synthesized magnesium oxide nanoparticles were determined by X-ray diffraction. Patterns were recorded by a Philips X'Pert diffractometer with Cu Kα radiation (λ = 1.5406 Å) and operated at 20 mA (Prajudtasri *et al.* 2025). Diffraction intensities were collected across a 2θ interval of 20–80° to verify MgO crystallinity and detect any secondary crystalline phases.

2.7.4 Morphological and Elemental Examination by SEM–EDX

Surface morphology, shape, particle dimensions, and elemental distribution of purified magnesium oxide nanoparticles were investigated by scanning electron microscopy coupled with EDX. SEM micrographs were obtained at scale bars of 2 µm, 1 µm, and 500 nm.

2.8 Antimicrobial Performance of Green-synthesized MgO Nanoparticles

2.8.1 Microorganisms

The antimicrobial potential of magnesium oxide nanoparticles prepared using *Cardiospermum halicacabum* leaf extract was investigated against selected bacterial strains. The bacterial panel included Gram-positive species *Staphylococcus aureus* ATCC 25923and *Bacillus subtilis* ATCC 6633, together with the *Escherichia coli* ATCC 25922 and Gram-negative species *Pseudomonas aeruginosa* ATCC 27853 (Karthick *et al.* 2026).

2.8.2 Disc-diffusion Assessment of Antibacterial Activity

Antibacterial performance of magnesium oxide nanoparticles synthesized using *Cardiospermum halicacabum* leaf extract was evaluated against four bacterial strains using the Kirby–Bauer disc-diffusion method (Huang *et al.* 2023). Each bacterial suspension was adjusted to the 0.5 McFarland standard, corresponding to approximately 1.5×10^8 CFU mL^{-1}. Mueller–Hinton agar plates containing 20 mL of medium were uniformly inoculated with the respective bacterial cultures. Sterile 5 mm filter-paper discs were loaded with MgO nanoparticle suspensions at concentrations of 0.05, 0.25, 0.50, 1.00, 2.00, 5.00, and 10.00 mg mL^{-1} and placed on the inoculated agar. The prepared plates were maintained at 4 °C for 30 min and subsequently incubated at 36 °C for 24 h. Antibacterial effectiveness was quantified by measuring the diameter of the inhibition zone surrounding each disc. All experiments were performed in triplicate (n = 3), and inhibition-zone diameters were expressed as mean ± standard deviation. Statistical differences among MgO nanoparticle concentrations were evaluated using one-way analysis of variance (ANOVA), followed by Tukey's post-hoc multiple-comparison test. Differences were considered statistically significant at $p < 0.05$.

2.9 Catalytic Degradation of Reactive Orange 16 Using MgO Nanoparticles

Reactive Orange 16 removal was investigated using green-synthesized magnesium oxide nanoparticles in the presence and absence of hydroxylamine (Hussain *et al.* 2026). A 20 mg L^{-1} dye solution was transferred into a 250 mL beaker and agitated in the dark for 30 min to establish equilibrium. Subsequently, 5 mg of MgO nanoparticles were introduced. Separate experiments were performed using H_2O_2 and NaClO as oxidizing agents, both with and without 2 M hydroxylamine hydrochloride. The reaction pH was maintained at the experimentally selected value (Rao *et al.* 2025). Aliquots of 2 mL were withdrawn, and residual dye absorbance was measured at the maximum absorption wavelength of Reactive Orange 16, approximately 493 nm. Dye-removal efficiency was calculated using eqn (9) (Kaur and Pal, 2026):

$$R(\%) = \frac{C_0 - C_t}{C_0} \times 100 = \frac{A_0 - A_t}{A_0} \times 100 \qquad \dots (9)$$

3. RESULTS AND DISCUSSION

3.1 Green Formation of MgO Nanoparticles

Table 3. Response table for the mean of dry yield MgO nanoparticle at different factor levels

Level	$Mg(NO_3)_2 \cdot 6H_2O$ Concentration (M)	Extract Concentration (g L^{-1})	Reaction Temperature (°C)	Reaction Time (min)
1	0.10104	0.09406	0.10196	0.09960
2	0.11368	0.11894	0.11392	0.10768
3	0.10718	0.10890	0.10602	0.11462
Delta	0.01263	0.02489	0.01197	0.01502
Rank	3	1	4	2

Magnesium oxide nanoparticles were produced through a sustainable route using Cardiospermum halicacabum leaf extract as a natural complexing and stabilizing medium. Gradual introduction of the extract into the $Mg(NO_3)_2 \cdot 6H_2O$ solution, followed by alkaline precipitation, changed the initially transparent mixture into a whitish suspension, indicating magnesium hydroxide formation (Fig. 2). Phytochemicals in the extract supported nucleation and restricted excessive particle aggregation by interacting with magnesium ions. Subsequent drying and calcination at 500 °C converted the precipitated $Mg(OH)_2$ into crystalline MgO nanoparticles. The final white powder confirmed

successful thermal transformation, while further verification was obtained from UV–visible, FTIR, XRD, and SEM–EDX analyses.

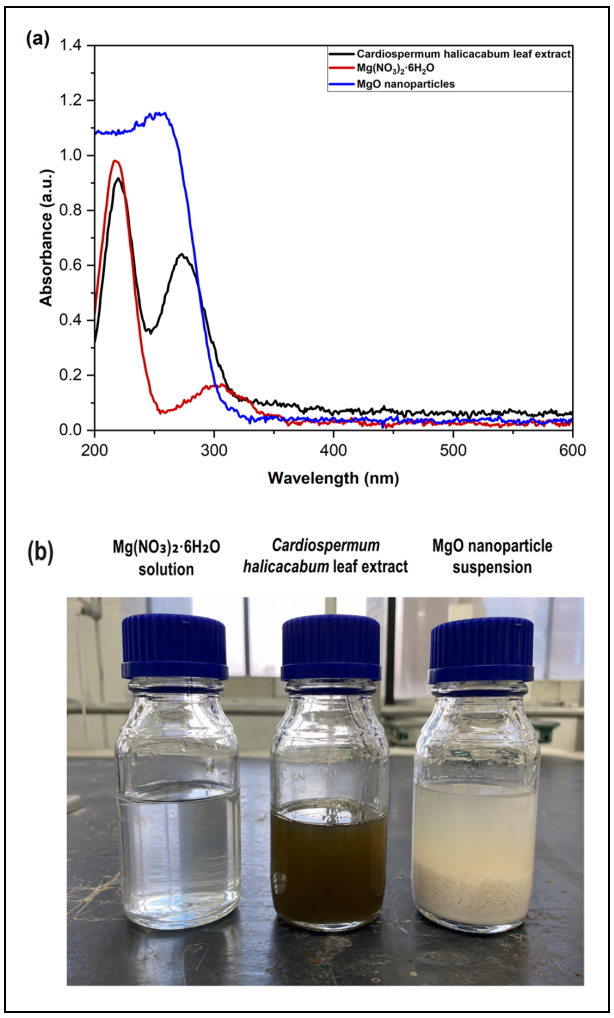


Fig. 2: UV–visible characterization of green-synthesized MgONPs: (a) spectra of MgONPs, $Mg(NO_3)_2 \cdot 6H_2O$, and *Cardiospermum halicacabum* leaf extract and (b) visual confirmation of MgONP biosynthesis

3.2 Taguchi L27 Analysis and ANOVA

The dry yield MgO nanoparticle varied from 0.0748 to 0.1324 g across the Taguchi L27 experiments. The highest observed yield of 0.1324 g was obtained at 0.10 M $Mg(NO_3)_2 \cdot 6H_2O$, 100 g L^{-1} extract, 65 °C, and 60 min.

The response table for means (Table 3) indicated that, extract concentration had the largest effect, followed by reaction time, precursor concentration, and temperature. The highest mean responses were obtained at A2, B2, C2, and D3.

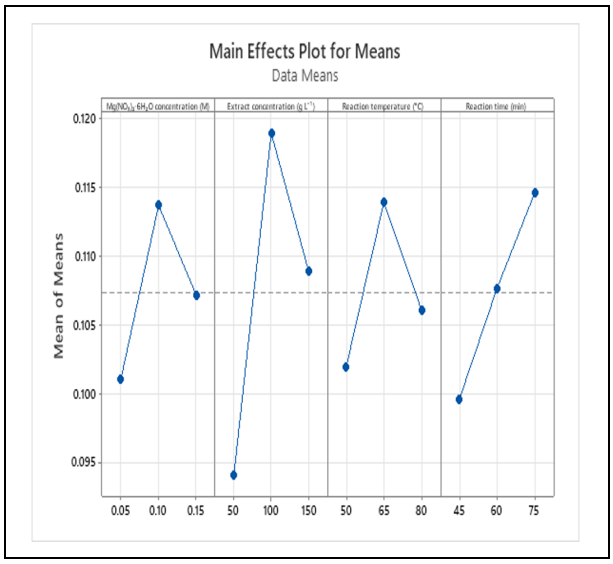


Fig. 3: Main-effect plot for the mean of dry yield MgO nanoparticle obtained from the Taguchi L27 design

The main-effects plot for means (Fig. 3) showed that yield increased when precursor concentration, extract concentration, and temperature were raised from Level 1 to Level 2, but decreased at Level 3. Reaction time produced a progressive increase in yield from 45 to 75 min.

Table 4. Response table for signal-to-noise ratios of MgO nanoparticle yield

Level	$Mg(NO_3)_2 \cdot 6H_2O$ Concentration (M)	Extract Concentration (g L^{-1})	Reaction Temperature (°C)	Reaction Time (min)
1	-19.99	-20.61	-19.96	-20.13
2	-18.95	-18.52	-18.90	-19.44
3	-19.47	-19.28	-19.54	-18.83
Delta	1.04	2.09	1.06	1.30
Rank	4	1	3	2

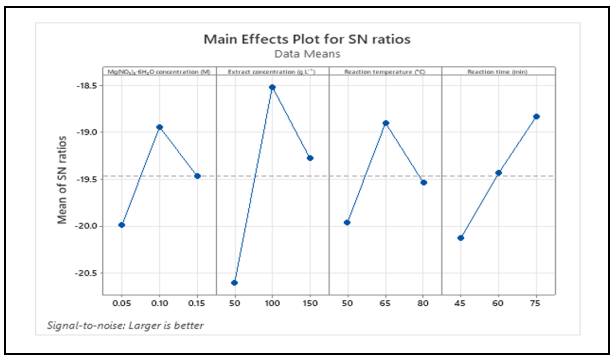


Fig. 4: Main-effect plot for S/N of MgO nanoparticle dry yield

The S/N-ratio response table (Table 4) ranked extract concentration as the most influential factor, followed by reaction time, temperature, and precursor concentration. The largest S/N ratios occurred at A2B2C2D3.

As shown in Fig. 4, the optimum synthesis condition was 0.10 M $Mg(NO_3)_2 \cdot 6H_2O$, 100 g L^{-1} extract, 65 °C, and 75 min. The corresponding Taguchi-predicted yield was 0.13926 g.

ANOVA results (Table 5) confirmed that all four synthesis factors were statistically significant ($p<0.001$). Extract concentration exhibited the highest contribution of 54.02%, followed by reaction time at 19.47%, precursor concentration at 13.75%, and temperature at 12.76%. Therefore, extract concentration was the dominant parameter controlling MgO nanoparticle production.

Table 5. ANOVA results for the Taguchi L27 optimization of MgO nanoparticle dry yield

Source	DF	Sequential SS	Contribution (%)	Adjusted SS	Adjusted MS	F-value	p-value
$Mg(NO_3)_2 \cdot 6H_2O$ concentration (M)	2	0.000718	13.75	0.000718	0.000359	22,909.82	<0.001
Extract concentration (g L^{-1})	2	0.002822	54.02	0.002822	0.001411	89,996.60	<0.001
Reaction temperature (°C)	2	0.000666	12.76	0.000666	0.000333	21,252.83	<0.001
Reaction time (min)	2	0.001017	19.47	0.001017	0.000509	32,445.57	<0.001
Residual error	18	<0.000001	0.01	<0.000001	<0.000001	—	—
Total	26	0.005225	100.00	—	—	—	

3.3 Confirmation Tests

A confirmation experiment was conducted at the Taguchi-optimized condition of 0.10 M $Mg(NO_3)_2 \cdot 6H_2O$, 100 g L^{-1} *C. halicacabum* extract, 65 °C, and 75 min. The three confirmation runs produced MgO yields of 0.1388, 0.1395, and 0.1391 g, respectively. The mean experimental yield was 0.13913±0.00035 g, which was close to the Taguchi-predicted value of 0.13926 g. The deviation between the predicted and experimental yields was only 0.09%, confirming the reliability of the Taguchi optimization.

3.4 ANN and SVR Prediction

ANN and SVR models were constructed to predict MgO nanoparticle yield from precursor concentration, extract concentration, reaction temperature, and reaction duration (Ahmad *et al.* 2023). The ANN and SVR models produced cross-validated R^2 values of 0.9828 and 0.9999, respectively, demonstrating excellent predictive performance. The prediction errors were further evaluated using RMSE and MAE. The ANN model produced RMSE and MAE values of 0.00182 and 0.00155 g, respectively, whereas the SVR model achieved substantially lower values of 0.00014 and 0.00011 g, respectively. These lower error values confirm the closer agreement of the SVR predictions with the experimental MgO nanoparticle yields and demonstrate its superior predictive accuracy.

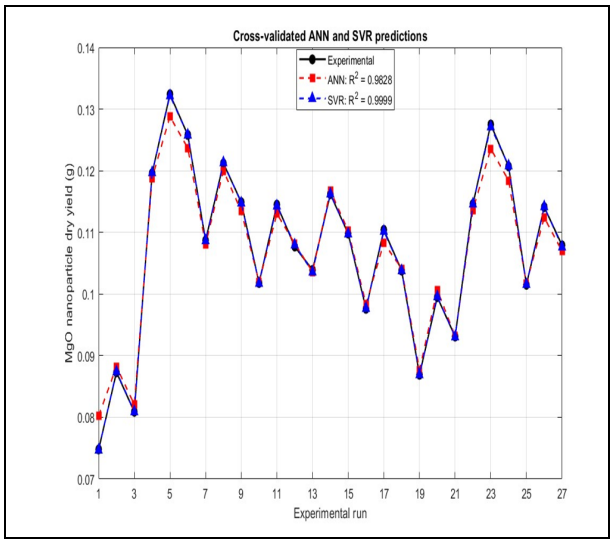


Fig. 5: Experimental and cross-validated ANN and SVR predicted MgO nanoparticle yields for Taguchi L27 runs

Both models closely followed the experimental yield pattern. However, the SVR predictions showed closer agreement with the observed values than the ANN predictions.

Table 6. Confirmation of the Taguchi-optimized MgO nanoparticle synthesis condition

Result	Value
Optimum condition	0.10 M, 100 g L^{-1}, 65 °C and 75 min
Taguchi-predicted yield	0.13926 g
Confirmation run 1	0.1388 g
Confirmation run 2	0.1395 g
Confirmation run 3	0.1391 g
Mean confirmation yield	(0.13913±0.00035) g
Prediction deviation	0.09%

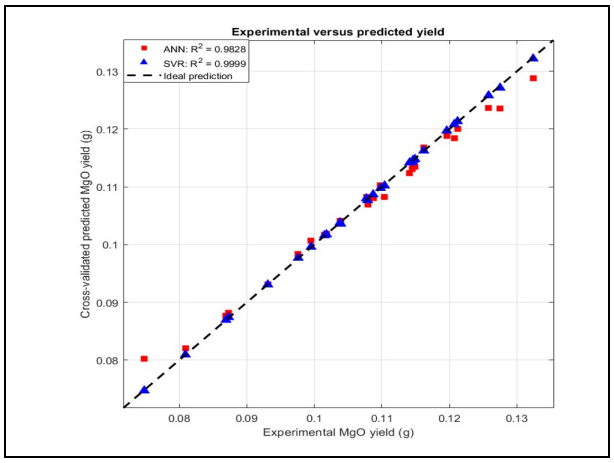


Fig. 6: Experimental versus cross-validated ANN and SVR predicted MgO nanoparticle yields

The SVR points were positioned close to the ideal prediction line, confirming its superior prediction accuracy. At the optimum condition, ANN and SVR predicted yields of 0.13385 and 0.13919 g, respectively. The SVR result differed from the Taguchi prediction by only 0.05%.

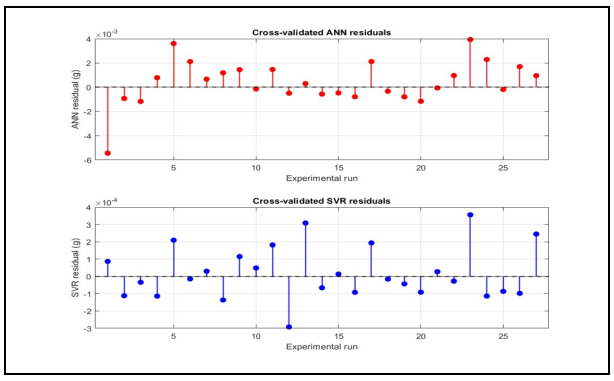


Fig. 7: Cross-validated residual distributions of the ANN and SVR models for MgO nanoparticle-yield prediction

The SVR residuals were smaller and more closely distributed around zero than the ANN residuals. Therefore, SVR was selected as the more reliable model for predicting MgO nanoparticle yield.

3.5 Characterization of MgO Nanoparticles

3.5.1 UV–visible Absorption Analysis

Optical responses of *Cardiospermum halicacabum* leaf extract and optimized magnesium oxide nanoparticles were examined between 200 and 600 nm. The plant extract displayed absorption bands near 220 and 273 nm, which can be associated with electronic transitions of phenolic and other phytochemical constituents. These compounds may assist magnesium-ion complexation, particle nucleation, and surface stabilization during green synthesis. The MgO nanoparticle spectrum exhibited a characteristic absorption edge around 305 nm, supporting the formation of nanoscale magnesium oxide. Changes in absorption intensity and band position between the extract and MgO sample further indicated the participation of plant-derived functional groups in nanoparticle development. Minor displacement of the MgO absorption edge may arise from variations in crystallite dimensions, morphology, surface defects, agglomeration, and preparation conditions. The MgO nanoparticle spectrum exhibited a characteristic absorption edge around 305 nm, supporting the formation of nanoscale MgO. A similar absorption peak at 294 nm and an optical band gap of 4.52 eV were reported for green-synthesized MgO nanoparticles, indicating that the observed optical response is consistent with previously reported MgO nanostructures (Kiran *et al.* 2023).

3.5.2 FTIR Investigation of Surface Functional Groups

FTIR spectra of *Cardiospermum halicacabum* leaf extract and magnesium oxide nanoparticles before and after calcination were recorded between 4000 and 500 cm^{-1}. This analysis identified the biomolecular groups involved in magnesium-ion complexation, nanoparticle nucleation, and surface stabilization. As illustrated in Fig. 8, leaf extract showed broad band near 3294 cm^{-1}, assigned to O–H stretching in phenolic and alcohols compounds. The signal at approximately 2925 cm^{-1} originated from aliphatic C–H stretching. Absorption around 1602 cm^{-1} was associated with carbonyl stretching and aromatic vibrations of plant-derived constituents. The bands near 1384 and 1050 cm^{-1} corresponded to C–N and C–O stretching, respectively. Several of these organic signals remained in the uncalcined nanoparticles, confirming phytochemical attachment to their surfaces. After calcination at 500 °C, their intensities decreased substantially because of organic-material decomposition. Meanwhile, a prominent absorption region between approximately 615 and 548 cm^{-1} appeared, corresponding to Mg–O lattice vibrations and supporting MgO nanoparticle formation.

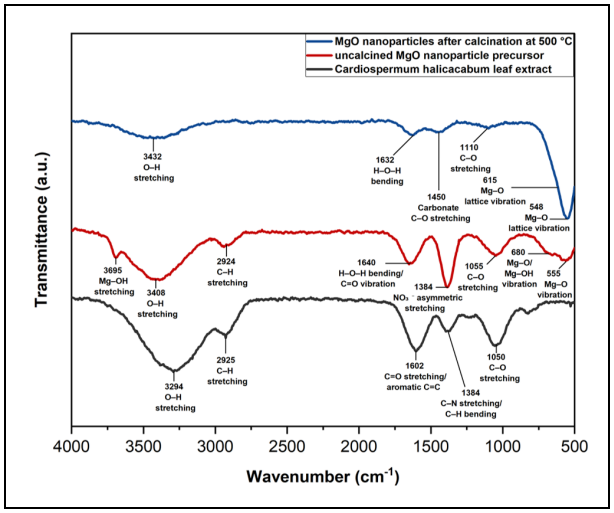


Fig. 8: FTIR spectra of *Cardiospermum halicacabum* leaf extract, uncalcined MgO nanoparticle precursor, and MgO nanoparticles after calcination at 500 °C

The formation of magnesium oxide nanoparticles was supported by characteristic absorption bands appearing within 500–620 cm^{-1}, particularly near 548 and 615 cm^{-1}, which were assigned to Mg–O lattice vibrations. These signals became more prominent after calcination, confirming the conversion of the magnesium hydroxide precursor into MgO. Compared with the plant-extract spectrum, the uncalcined nanoparticle sample showed shifted bands near 3408, 1640, 1384, and 1055 cm^{1}. These spectral changes indicate that biomolecules in the leaf extract participated in magnesium-ion complexation, nucleation, and particle stabilization. Most organic absorption bands weakened or disappeared following calcination because the attached plant-derived compounds underwent thermal decomposition. These Mg–O vibrational bands are comparable to the 541–552 cm^{-1} region reported for green-synthesized MgO nanoparticles from plant peel extracts, further confirming successful conversion of the precursor into crystalline MgO (Badilli *et al.* 2026).

Table 7. FTIR peak assignments of leaf extract and MgO nanoparticles

Sample	Peak (cm^{-1})	Assignment	Interpretation
Leaf extract	3294	O–H stretching	Phenolic and alcoholic compounds
Leaf extract	2925	Aliphatic C–H stretching	Plant-derived organic constituents
Leaf extract	1602	C=O stretching/aromatic vibrations	Carbonyl-containing phytochemicals
Leaf extract	1384	C–N stretching	Nitrogen-containing biomolecules
Leaf extract	1050	C–O stretching	Alcohols, phenols and polysaccharides
Uncalcined MgO precursor	3408	O–H stretching	Surface hydroxyl groups and attached phytochemicals
Uncalcined MgO precursor	1640	C=O/aromatic vibrations	Phytochemical interaction with Mg^{2+} ions
Uncalcined MgO precursor	1384	C–N stretching	Residual plant-derived compounds
Uncalcined MgO precursor	1055	C–O stretching	Surface-bound organic constituents
Calcined MgO NPs	615 and 548	Mg–O lattice vibrations	Formation of crystalline MgO

The principal FTIR absorption bands and their corresponding functional-group assignments are summarized in Table 7. The shifts observed in the uncalcined precursor indicate phytochemical involvement in Mg^{2+} complexation and particle stabilization, whereas the prominent Mg–O bands after calcination confirm MgO formation.

3.5.3 Crystalline-phase Evaluation by X-ray Diffraction

XRD analysis were conducted to verify the structure and crystalline phase of the green-synthesized magnesium oxide nanoparticles and to estimate their average crystallite size. Fig. 8 presents the pattern of MgO nanoparticles prepared by *Cardiospermum halicacabum* leaf extract. Distinct reflections observed at approximately 36.91°, 42.88°, 62.27°, 74.64°, and 78.58° corresponded to the (111), (200), (220), (311), and (222) crystallographic planes, respectively. These reflections confirmed the formation of the face-centred cubic periclase structure of MgO and agreed with the ICDD reference pattern PDF 45-0946, which displayed corresponding reflections at 36.94°, 42.92°, 62.30°, 74.69°, and 78.63°. The absence of prominent secondary-phase reflections indicated the effective conversion of the precursor into crystalline MgO during calcination. No intense peaks associated with residual $Mg(OH)_2$ or $Mg(NO_3)_2{\cdot}6H_2O$ were detected, indicating successful precursor conversion and satisfactory phase purity after calcination. These reflections closely match those reported at 36.94°, 42.86°, 62.30°, 74.70°, and 78.62° for green-synthesized MgO nanoparticles, confirming the same phase-pure cubic periclase structure (Muhaymin *et al.* 2024).

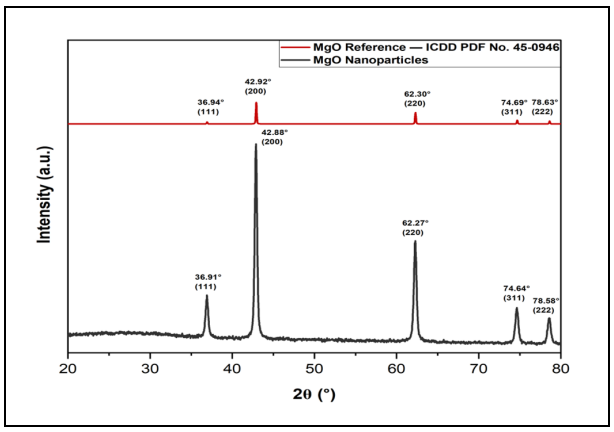
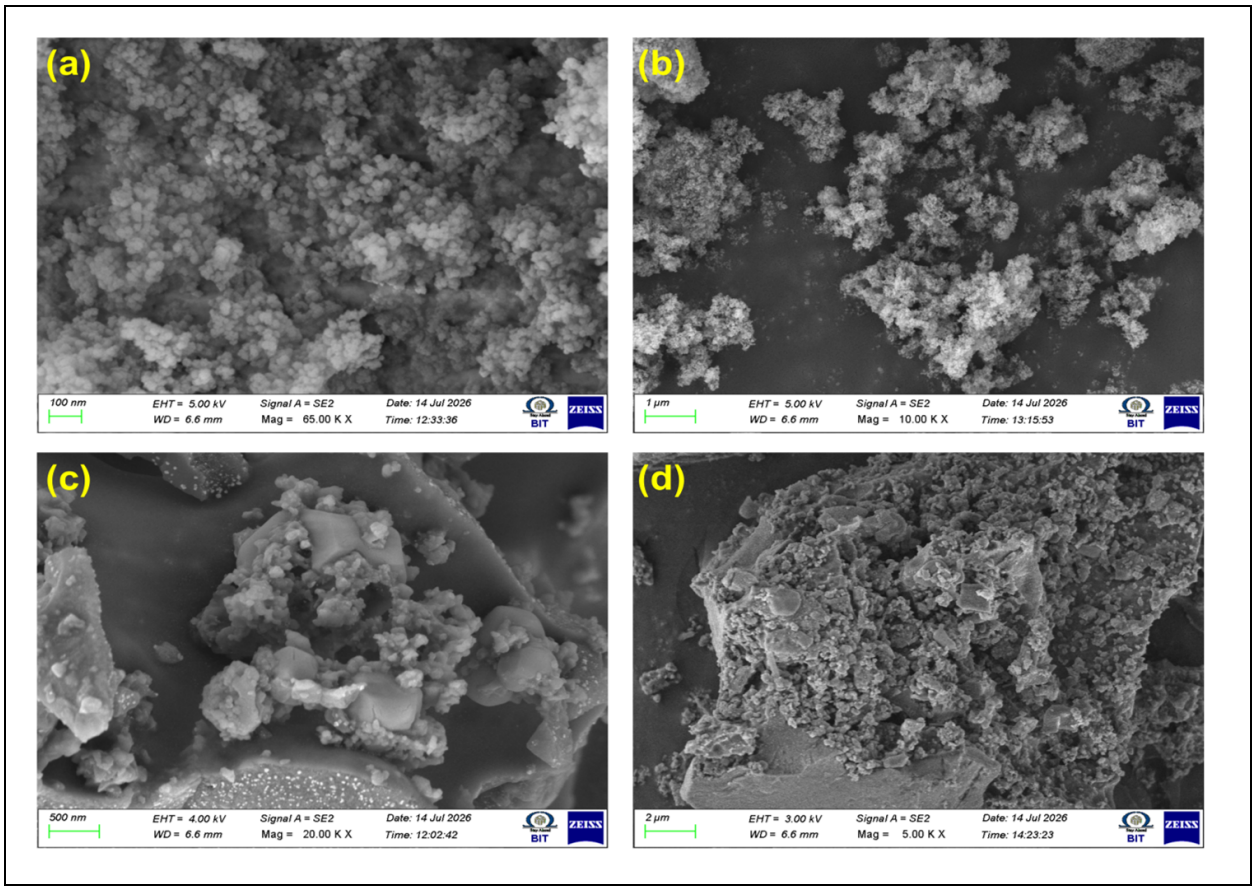


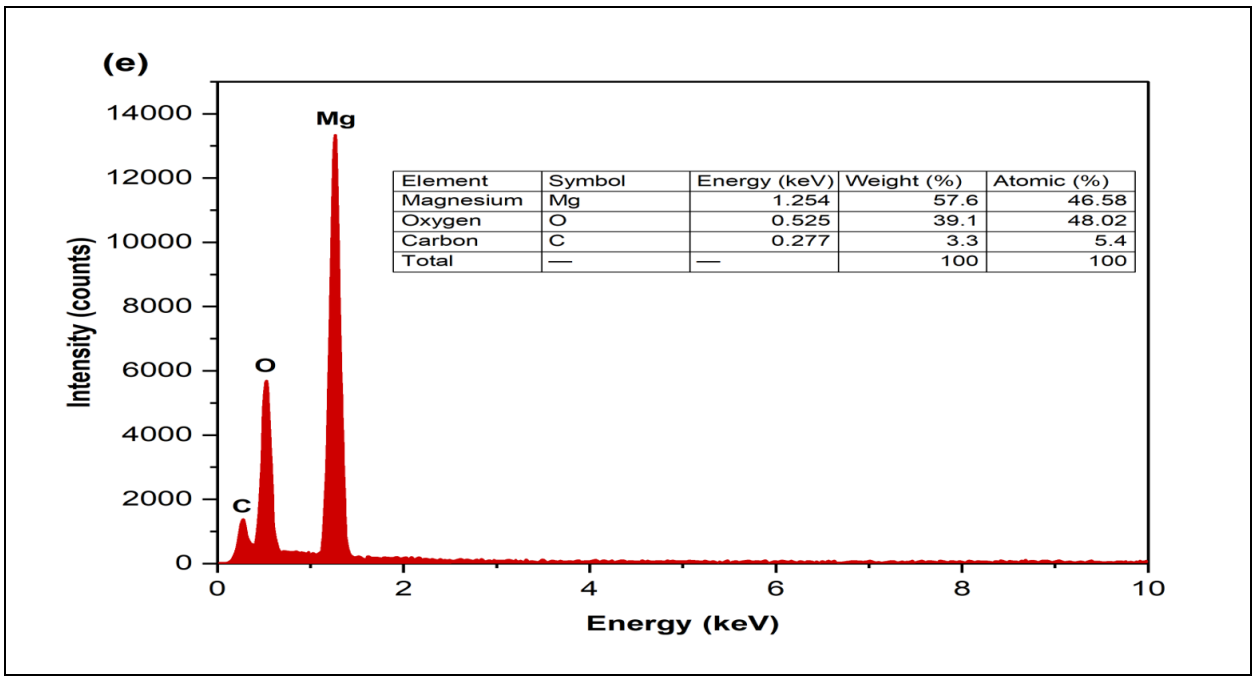
Fig. 9: X-ray diffraction pattern of green-synthesized MgO nanoparticles after calcination at 500 °C

3.5.4 Morphological and Elemental Assessment by SEM–EDX

The elemental composition and morphology of magnesium oxide nanoparticles prepared by aqueous *Cardiospermum halicacabum* leaf extract were examined by SEM–EDX. Micrographs obtained at different magnifications revealed predominantly irregular, granular, and quasi-spherical particles with approximate primary-particle dimensions (Fig. 10). Considerable agglomeration was observed, which was attributed to the high surface energy, van der Waals interactions, and surface hydroxyl groups of the MgO nanoparticles. Precursor concentration, extract dosage, reaction temperature, pH, and phytochemical composition may influence nucleation, particle growth, morphology, and aggregation.

EDX spectroscopy and elemental mapping confirmed magnesium and oxygen as the principal constituents of the prepared nanoparticles. Their measured weight percentages were 57.6% Mg and 39.1% O, supporting MgO formation. A weak carbon signal of 3.3% was also recorded and may originate from residual plant-derived compounds or the carbon adhesive used during sample preparation. No substantial impurity signals were detected, indicating satisfactory elemental purity. These values closely match the 57.25% Mg and 38.99% O reported for green-synthesized MgO nanoparticles by (Seghir *et al.* 2023), further confirming the elemental purity of the prepared nanoparticles.





Element	Symbol	Energy (keV)	Weight (%)	Atomic (%)
Magnesium	Mg	1.254	57.6	46.58
Oxygen	O	0.525	39.1	48.02
Carbon	C	0.277	3.3	5.4
Total	—	—	100	100

Fig. 10: (a-e) SEM micrographs, and EDX spectrum of MgO nanoparticles synthesized using *Cardiospermum halicacabum* leaf extract

The SEM images revealed predominantly irregular, granular, and quasi-spherical MgO nanoparticles with considerable agglomeration. Extensive particle overlap prevented reliable determination of individual particle sizes and particle-size distribution. EDX confirmed Mg and O as the major elements, supporting successful MgO formation and satisfactory elemental purity.

3.6 Antimicrobial Performance

3.6.1 Antibacterial Response

Antibacterial activity of the green-synthesized magnesium oxide nanoparticles was evaluated against the Gram-positive bacteria *Bacillus subtilis* and *Staphylococcus aureus* and the Gram-negative bacteria *Escherichia coli* and *Pseudomonas aeruginosa*. MgO nanoparticle concentrations ranging from 0.05 to 10.00 mg mL^{-1} were investigated (Fig. 11). However, distinct inhibition-zone boundaries could not be identified reliably from the presented photographs. Consequently, the most and least sensitive strains and their inhibition-zone diameters cannot be established from this figure alone. The minimum inhibitory concentrations for *P. aeruginosa* and *E. coli* should be reported only from the corresponding broth-dilution measurements.

Differences in susceptibility may arise from variations in bacterial cell-wall composition and nanoparticle–membrane interactions. MgO nanoparticles can attach to cell surfaces, disturb membrane integrity, and promote leakage of intracellular constituents (Ganvir *et al.* 2026). Their antibacterial performance may additionally involve reactive oxygen species generation, local alkalinity, and Mg^{2+} release. These combined effects can damage cellular proteins, lipids, and nucleic acids, eventually suppressing bacterial growth.

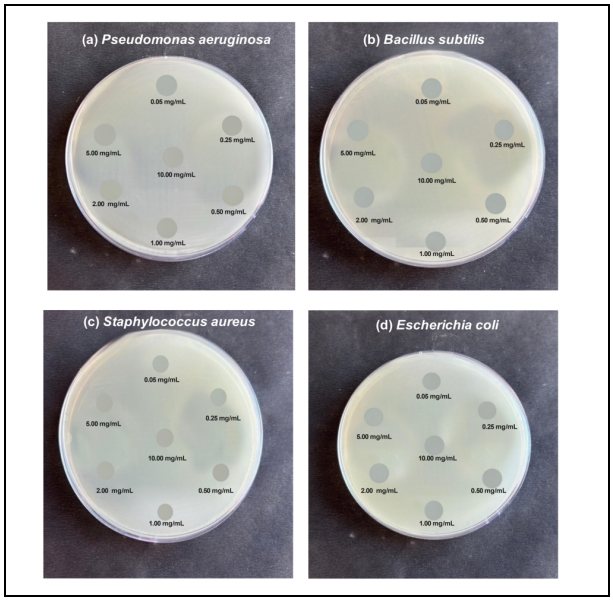


Fig. 11: Antibacterial activity of green-synthesized MgO nanoparticles against (a) *Pseudomonas aeruginosa*, (b) *Bacillus subtilis*, (c) *Staphylococcus aureus* and (d) *Escherichia coli*

The antibacterial behaviour of magnesium oxide nanoparticles is primarily associated with reactive oxygen species generation, including hydroxyl radicals (•OH), superoxide radicals ($O_2^{\bullet-}$), and hydrogen

peroxide (H_2O_2). The reactive species induce oxidative stress, weaken the bacterial cell envelope, raise membrane permeability, and promote leakage of intracellular components. They may also oxidize cellular proteins and damage genetic material, thereby limiting microbial growth. Direct attachment of MgO nanoparticles to the bacterial surface, Mg^{2+} release, and the formation of a locally alkaline environment may further intensify membrane deterioration. Variations in inhibition-zone diameter among the tested strains can be linked to differences in cell-wall structure, surface characteristics, and resistance to oxidative stress. Although these combined processes explain the observed antibacterial response, the relative contribution of each pathway requires further investigation.

3.7 Catalytic Oxidation of Reactive Orange 16

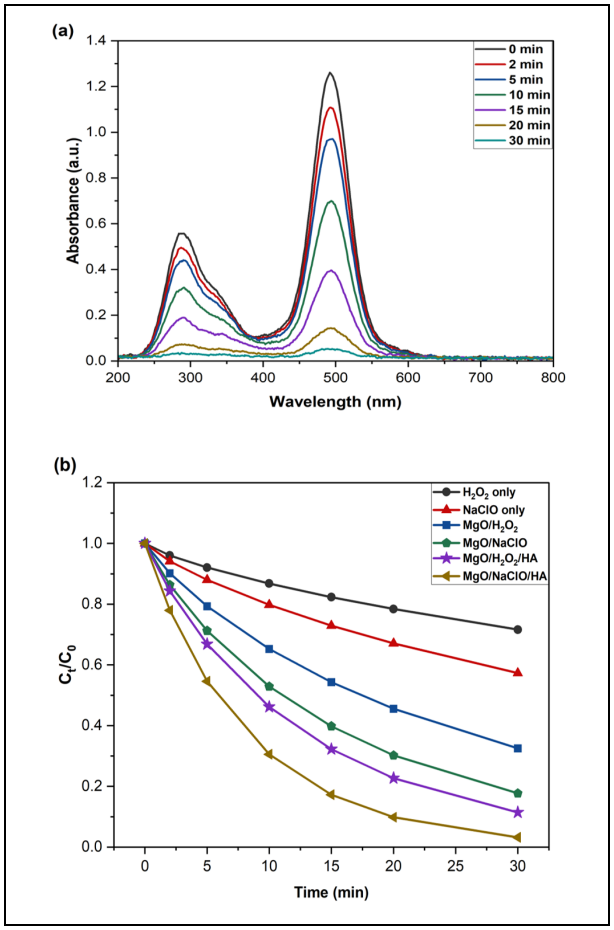


Fig. 12: (a) Time-dependent UV–visible absorption spectra and (b) normalized concentration ratio (Ct/C0) of Reactive Orange 16 using MgO nanoparticles prepared with *Cardiospermum halicacabum* leaf extract

The catalytic behavior of green-synthesized magnesium oxide nanoparticles was investigated using Reactive Orange 16 as the model contaminant. Two treatment systems, MgO/H_2O_2/hydroxylamine and MgO/NaClO/hydroxylamine, were evaluated and compared with corresponding controls lacking either MgO nanoparticles or hydroxylamine. Fig. 12 shows the progressive reduction in the characteristic absorption band of Reactive Orange 16 at approximately 493 nm. Its decreasing intensity with reaction time indicated dye removal, while the nearly diminished band after 30 min demonstrated substantial decolorization.

The addition of hydroxylamine changed the removal efficiency from 67% to 89% in the MgO/H_2O_2 system and from 82% to 97% in the MgO/NaClO treatment. Control experiments containing only H_2O_2 or NaClO produced 28% and 42% removal, respectively. The improved response observed after introducing MgO nanoparticles confirmed their contribution to oxidant activation and dye–catalyst interactions. The MgO/NaClO/hydroxylamine combination exhibited the highest apparent degradation rate of 0.117 min^{-1}, compared with 0.074 min^{-1} for MgO/H_2O_2/hydroxylamine. Similarly, iron oxide nanoparticles for methylene blue removal – Myristica fragrans-derived iron oxide nanoparticles achieved 85.59% MB removal within 180 min, with strong antioxidant activity (IC_{50} = 40.88 µg mL^{-1}) and antibacterial performance (Salim *et al.* 2025). This difference may result from variations in reactive-species generation and oxidant stability. These systems should be described as MgO-assisted catalytic oxidation processes rather than Fenton-like reactions because MgO does not provide the iron redox cycle required for Fenton chemistry.

Table 8. Apparent rate constants for reactive orange 16 removal by different MgO-assisted oxidation systems

Process	MgO–H_2O_2	MgO–NaClO	MgO–H_2O_2/HA	MgO–NaClO /HA
k(min^{-1})	0.037	0.057	0.074	0.117

The rate constants previously reported for iron-based systems cannot be transferred to MgO because magnesium oxide does not undergo an Fe^{3+}/Fe^{2+} redox cycle. Therefore, the four k_{app} values must be calculated from the experimental Reactive Orange 16 data using:

$$\ln\left(\frac{C_0}{C_t}\right) = k_{app}t \qquad \dots (10)$$

The MgO-assisted systems operate through surface adsorption, oxidant activation, and reactive-species formation rather than conventional Fenton chemistry. Hydration and surface-peroxide development may be represented as (Mukherjee *et al.* 2025):

$$MgO + H_2O \rightleftharpoons Mg(OH)_2 \qquad \dots (11)$$

$$\equiv Mg - OH + H_2O_2 \rightleftharpoons Mg - OOH + H_2O \dots (12)$$

For the hypochlorite treatment, the relative abundance of OCl^- and HOCl depends strongly on solution pH (Sharmiladevi *et al.* 2024):

$$OCl^- + H^+ \rightleftharpoons HOCl \quad \ldots (13)$$

Interactions between hydrogen peroxide and hypochlorite can also generate singlet oxygen. The resulting reactive oxygen species attack the azo chromophore and aromatic groups of Reactive Orange 16, producing smaller transformation products:

ROS + RO16 → degradation intermediates

Hydroxylamine may alter oxidant activation and reactive-species production; however, its enhancing effect must be confirmed from the measured rate constants. The system with the largest k_{app} and removal percentage should therefore be identified as the most effective MgO-assisted catalytic oxidation treatment. It should not be described as a Fenton-like process because no iron catalyst is present.

4. CONCLUSIONS

Magnesium oxide nanoparticles were successfully synthesized through an environmentally responsible method using *Cardiospermum halicacabum* leaf extract. Taguchi L27 optimization and ANOVA demonstrated that extract concentration was the main factor governing nanoparticle yield, accounting for 54.02% of the observed variation. The optimized condition of 0.10 M $Mg(NO_3)_2 \cdot 6H_2O$, 100 g L^{-1} leaf extract, 65 °C, and 75 min yielded 0.13913 ± 0.00035 g of MgO nanoparticles, closely agreeing with the predicted value of 0.13926 g. Among the predictive approaches, SVR showed superior accuracy with a cross-validated R^2 of 0.9999 and minimal residual error.

Spectroscopic and structural analyses verified the successful formation of crystalline cubic MgO, while the biological assays demonstrated concentration-dependent antibacterial effects. The nanoparticles also effectively promoted Reactive Orange 16 removal through oxidant-assisted catalytic oxidation. Hydroxylamine substantially enhanced the reaction, and the MgO/NaClO/hydroxylamine system delivered the best performance, with an apparent rate constant of 0.117 min^{-1} and 96.8% removal within 30 min. Overall, the study establishes green-synthesized MgO nanoparticles as promising multifunctional materials for microbial control and treatment of dye-bearing wastewater. These results confirm that *Cardiospermum halicacabum*-mediated MgO nanoparticles are effective, low-cost multifunctional agents combining antibacterial action with rapid (30 min), high-efficiency (96.8%) dye degradation. Future investigations should examine catalyst recyclability, degradation-product toxicity, mineralization efficiency, reaction mechanisms, and performance in actual textile effluents.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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