



Green Synthesis of CeO_2 – MgFe_2O_4 /Sodium Alginate Nano-adsorbents for Dairy Wastewater Treatment Using Taguchi Optimization, IDOCRIW–WASPAS and RBF-ANN Modelling

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ABSTRACT

The study developed sodium-alginate-based green nanoadsorbents containing CeO_2 and MgFe_2O_4 for dairy wastewater treatment using Taguchi L27 design, ANOVA (Analysis of Variance), IDOCRIW–WASPAS (Integrated Determination of Objective Criteria Weights and Weighted Aggregated Sum Product Assessment), and RBF-ANN (Radial Basis Function–Artificial Neural Network) modelling. CeO_2 and MgFe_2O_4 were prepared from cerium nitrate hexahydrate and magnesium–ferric nitrate precursors, respectively, using *Cinnamomum tamala* leaf extract, and characterized by SEM–EDS. Wastewater dilution, pH, contact time and adsorbent dosage were evaluated. Best tested condition, consisting of 25% dilution, pH 7, 1.0 g L^{−1} dosage, and 90 min treatment produced 92.8% RBOD and 87.5% RCOD and achieved first rank in WASPAS. IDOCRIW assigned weights of 0.4253 and 0.5747 to %RBOD and %RCOD, respectively. Five-fold cross-validation provided R² values of 0.9605 and 0.9576 for the RBF-ANN predictions. These findings demonstrate the potential of the developed green nanoadsorbents for dairy wastewater treatment.

Keywords: Nanoadsorbent; Green synthesis; Waste water; Optimization; Radial Basis Function; Artificial Neural Network.

1. INTRODUCTION

The increasing discharge of dyes, pharmaceuticals, heavy metals, and other persistent contaminants into aquatic environments has intensified the need for efficient and sustainable wastewater-treatment technologies (Gaddala *et al.* 2025). Conventional treatment approaches are often limited by incomplete contaminant removal, high operational costs, secondary waste generation, and considerable energy demand (Amale *et al.* 2026). Sustainable urban wastewater management emphasizes water conservation, reclamation, reuse, nutrient recovery, rainwater harvesting, and energy recovery as closed-loop strategies for improving resource efficiency and environmental sustainability (Varma *et al.* 2024).

Among metal-oxide nanomaterials, cerium dioxide (CeO_2) has attracted significant attention because of its redox activity, oxygen-storage capability, chemical

stability, and potential for adsorption and photocatalytic applications. Ag-doped CeO_2 nanocomposites synthesized by co-precipitation exhibited a reduced band gap from 2.79 to 2.43 eV and achieved approximately 84% Methylene blue degradation within 70 minutes under solar irradiation, together with considerable antibacterial activity (Pachaiappan *et al.* 2026). A CeO_2 /CdS type-II heterojunction achieved 96.5% tetracycline degradation under simulated sunlight due to enhanced charge separation and interfacial electron migration (Luo *et al.* 2026).

The environmental functionality of CeO_2 has also been improved through carbon integration, metal doping, and defect engineering. A Cu-doped CeO_2 /carbon hybrid derived from Ce/Cu-BTC metal-organic-framework nanofibers exhibited adsorption capacities of 1460.4 mg g^{−1} for Congo red and 1906.9 mg g^{−1} for Methyl blue, while retaining more than 85% adsorption capacity after five regeneration cycles (Wang

et al. 2025). A visible-light-assisted $\text{CeO}_2/\text{Na}_2\text{SO}_3$ advanced oxidation system based on defect-engineered CeO_2 nanocubes showed a synergy factor of up to 88% for Methyl orange degradation, together with good pH tolerance and resistance to ion leaching (Han *et al.* 2024). $\text{Ti}/\text{nanoSnO}_2\text{-CeO}_2\text{-Bi}_2\text{O}_3$ electrodes developed for electrochemical wastewater treatment exhibited an oxygen-evolution potential of 2.06 V, an operational lifespan of 400 hours, and 60.03% hydrochlorothiazide removal under optimized conditions (Karimi *et al.* 2026). Green-synthesized MnFe_2O_4 nanoparticles effectively degraded Methylene blue under natural sunlight and reduced the toxicity of treated water, indicating their potential for wastewater remediation and agricultural water reuse (Mungle *et al.* 2026).

Biopolymer-based systems have also gained considerable attention because of their renewability, hydrophilicity, functional-group availability, and compatibility with inorganic nanoparticles. Sodium alginate–kaolin hydrogel composites used for continuous Congo red adsorption showed optimum operating conditions of 1.27 cm bed height, 20 mg L⁻¹ initial dye concentration, and 8.3 L h⁻¹ flow rate through Taguchi optimization (Roy *et al.* 2026). A sodium alginate hydrogel containing cellulose nanocrystals and polypyrrole was developed for solar-driven water purification and achieved evaporation rates of 1.47 and 2.81 kg m⁻² h⁻¹ under one- and two-solar irradiation with 91.3% evaporation efficiency under one irradiation (Hamid *et al.* 2025).

Green synthesis has emerged as a sustainable strategy for minimizing hazardous chemicals during nanoparticle preparation. Plant extracts containing polyphenols, flavonoids, sugars, proteins, and other phytochemicals can facilitate metal-ion complexation, nucleation, reduction, and stabilization. TiO_2 nanoparticles synthesized using *Cinnamomum tamala* leaf extract exhibited spherical anatase morphology, an average particle size of 38.34 nm, and a band gap of 3.32 eV, while achieving 86.50% Methylene blue degradation within 90 minutes under UV irradiation (Mukherjee *et al.* 2026). Magnetite nanoparticles synthesized using *Jatropha curcas* latex and *Cinnamomum tamala* leaf extract exhibited particle-size ranges of 20–42 nm and 26–35 nm, respectively, and demonstrated potential for dye adsorption, toxic-metal removal, antibacterial, antioxidant, and cytotoxic applications (Das *et al.* 2020).

Statistical optimization and multi-criteria decision-making approaches are increasingly incorporated into environmental treatment studies to improve process efficiency and treatment selection. Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR), Multi-Objective Optimization on the basis of Simple Ratio Analysis (MOOSRA), Weighted Aggregated Sum Product

Assessment (WASPAS), and Combined Compromise Solution (CoCoSo) methods were applied to evaluate acid-mine-drainage treatment technologies with sequential neutralization identified as the most suitable approach for reducing Fe, Cu, Zn, Ni, Mn, and Cd concentrations (Štirbanović *et al.* 2021). Environmental resilience was assessed using Integrated Determination of Objective Criteria Weights (IDOCRIW) and CoCoSo methods, identifying fossil-fuel subsidies, resource productivity, and water stress as key influential criteria (Ozdemir, 2024). Agricultural-waste-derived biocarbon materials have emerged as sustainable and low-cost adsorbents for removing toxic heavy metals from industrial wastewater. Surface functionalization can further enhance their adsorption efficiency and suitability for wastewater remediation (Rao *et al.* 2025). The integration of natural fibres, functional nanoparticles, and polymeric matrices provides an additional route for developing sustainable multifunctional materials. Natural fibre–nanoparticle hybrid composites can enhance mechanical performance, reduce material consumption, and provide additional environmental functionality, while data-driven optimization supports efficient formulation and process development (Sonya *et al.* 2025).

This study presents sodium-alginate-supported CeO_2 and MgFe_2O_4 green nanoadsorbents for the simultaneous treatment of BOD- and COD-containing dairy wastewater. The nanoparticles were synthesized using *Cinnamomum tamala* leaf extract and incorporated into a biodegradable sodium-alginate matrix. The work further introduces an integrated framework combining Taguchi experimental design, ANOVA, IDOCRIW–WASPAS multi-response optimization, and Radial Basis Function Artificial Neural Network (RBF-ANN) prediction. This combination provides a sustainable material design and systematic modelling strategy for optimizing dairy wastewater treatment without relying on conventional synthetic stabilizing agents.

2. MATERIALS AND METHODOLOGY

2.1 Materials and Wastewater Collection

Sodium alginate, cerium nitrate hexahydrate [$\text{Ce}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$], ferric nitrate nonahydrate [$\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$], and magnesium nitrate hexahydrate [$\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$] were used as the principal materials. Fresh *Cinnamomum tamala* leaves were used for the green synthesis of CeO_2 and MgFe_2O_4 nanoparticles. Sodium hydroxide or ammonium hydroxide was used for pH adjustment and precipitation, while calcium chloride was used as the ionic crosslinking agent for bead formation. All solutions were prepared using distilled water.

The wastewater was characterized for pH, BOD, and COD using standard analytical procedures. The pH

was measured by calibrated digital pH meter. The synthesized adsorbents were examined using Scanning electron microscopy coupled with Energy Dispersive X-ray Spectroscopy (SEM-EDS).

2.2 Preparation of *Cinnamomum tamala* Leaf Extract

Fresh *Cinnamomum tamala* leaves were washed thoroughly with distilled water, shade-dried, and pulverized. About 10 g of the dried leaf powder was heated in 100 mL of deionized water at 80 °C for 20 minutes under continuous stirring. The mixture was then kept at room temperature overnight and filtered using a filter paper. The aqueous extract was stored at 4 °C and used immediately for nanoparticle synthesis. Similarly, preparation of *C. tamala* plant extract by aqueous extraction of dried leaf powder at 60 °C for 30 minutes followed by filtration has been reported recently (Nagaraj *et al.* 2026).

2.3 Green Synthesis of CeO₂ NPs

Cerium nitrate hexahydrate was dissolved in 100 mL of deionized water to prepare 0.10 M precursor solution. This solution contained 4.34 g of Ce(NO₃)₃·6H₂O. About 100 mL of *Cinnamomum tamala* leaf extract was added slowly under continuous stirring. The pH was adjusted to 9.5 by 1 M sodium hydroxide solution. The mixture was maintained at 80 °C for 4 hours at constant stirring and then aged for 1 day at room temperature.

The precipitate was collected by filtration and washed with distilled water until wash liquid became nearly neutral. The product was dried at 60 °C overnight and calcined at 400 °C for 3 hours in a muffle furnace. The resulting CeO₂ powder was cooled, gently ground, and stored in an airtight container. Similarly, Mim *et al.* (2024) reported green-synthesis of cubic fluorite CeO₂ nanoparticles using *Oroxylum indicum* fruit extract as a reducing and stabilizing agent.

2.4 Green Synthesis of MgFe₂O₄ NPs

Magnesium nitrate hexahydrate and ferric nitrate nonahydrate were separately dissolved in distilled water to obtain 0.05 M and 0.10 M solutions. Accordingly, 1.28 g of Mg(NO₃)₂·6H₂O and 4.04 g of Fe(NO₃)₃·9H₂O were used for preparing 100 mL of each solution. The solutions were mixed to maintain the required Mg²⁺:Fe³⁺ molar ratio of 1:2.

Then, 100 mL of *Cinnamomum tamala* leaf extract was added gradually under continuous stirring. The pH was increased to 10 using 1 M sodium hydroxide solution. The suspension was heated at 80 °C for 3 hours and subsequently aged for 1 day at ambient temperature. The precipitate was filtered, washed several times with

deionized water, and dried at 80 °C for 12 hours. Likewise, co-precipitation of magnesium and iron salts followed by drying and calcination to form MgFe₂O₄ nanoparticles was reported by Meenakshi *et al.* (2026), where, dried precursor was calcined at 500 °C for 3 hours to promote formation of spinel MgFe₂O₄ phase. After cooling, the product was ground into fine powder and stored in an airtight container.

2.5 Preparation of Sodium-alginate Nanocomposite Beads

About 3 g of sodium alginate was dissolved in 300 mL of deionized water under continuous stirring at 80 °C for 2 hours. The CeO₂ powder was dispersed separately in the sodium alginate solution to produce the SA-CeO₂ suspension. The same procedure was followed with MgFe₂O₄ to obtain the SA-MgFe₂O₄ suspension. Each suspension was sonicated to improve nanoparticle dispersion.

The suspensions were added dropwise through a syringe into a 2% (w/v) calcium chloride solution. Ionic crosslinking between calcium ions and the carboxylate groups of sodium alginate produced stable spherical beads. The beads were cured for 12 hours, collected, washed using distilled water, and dried at 60 °C for 1 day. The adsorbents were designated as SA-CeO₂ and SA-MgFe₂O₄ nanocomposite beads.

2.6 Batch Treatment Experiments

Batch experiments were conducted to evaluate reduction of BOD and COD in dairy wastewater. The collected wastewater was diluted with distilled water according to the experimental design. For each treatment, 100 mL of diluted wastewater was transferred into a 250-mL conical flask. The pH was adjusted to the required level followed by the addition of the required quantity of nanocomposite adsorbent.

The flasks were placed in an orbital shaker and agitated at 200 rpm and 30 °C for the selected contact time. After treatment, the adsorbent beads were separated from the liquid phase by filtration. When required, the filtrate was passed through a membrane filter before BOD and COD analysis. Each experimental condition was performed in triplicate, and the average response was used for statistical analysis.

The BOD and COD reduction efficiencies were calculated using equation (1):

$$\%R = \frac{C_0 - C_f}{C_0} \times 100 \quad \dots (1)$$

2.7 Taguchi L27 Experimental Design

A Taguchi L27 OA was used to study effects of four operating factors on %RBOD and %RCOD. The investigated factors and levels are presented in Table 1.

Table 1. Input factors and levels

Factor	Parameter	Level 1	Level 2	Level 3
A	Wastewater dilution (%)	25	50	75
B	pH	4	7	10
C	Adsorbent dosage (g/L)	0.5	1.0	1.5
D	Contact time (minutes)	30	60	90

The same experimental design was applied to the SA-CeO₂ and SA-MgFe₂O₄ adsorbents when comparative analysis was performed. Since both responses were maximized, the larger-the-better signal-to-noise ratio was selected. Factor-level means and signal-to-noise ratios were used to identify the influential parameters and their optimum levels.

2.8 Analysis of Variance

ANOVA was performed to determine percentage contribution and statistical significance of wastewater dilution, adsorbent dosage, contact time and pH. The analysis included degrees of freedom, sum of squares, mean square, F-value, percentage contribution, and p-value. Factors with lower p-values and higher F-values were considered more influential in controlling the BOD and COD reduction efficiencies.

2.9 IDOCRIW-WASPAS Decision Analysis

The experimental results were further analyzed using the integrated IDOCRIW-WASPAS method (Mogaji *et al.* 2026). The 27 Taguchi trials were considered decision alternatives, while %RBOD and %RCOD were selected as benefit criteria. The IDOCRIW procedure was used to calculate objective criteria weights by integrating entropy and CILOS weighting principles.

The normalized decision matrix and the calculated weights were then introduced into the WASPAS method (Ocampo *et al.* 2024). Weighted sum and weighted product measures were calculated and the final WASPAS score was obtained using a coefficient of $\lambda=0.5$. The alternative with the highest WASPAS score was selected as the best experimentally tested treatment condition.

2.10 RBF-ANN Modelling

A Gaussian radial-basis-function artificial neural network was developed to predict %RBOD and %RCOD. Wastewater dilution, pH, adsorbent dosage and contact time were used as input variables, whereas %RBOD and %RCOD were used as output variables.

The RBF-ANN consisted of input layer, Gaussian radial-basis hidden neurons, and a linear output layer.

Five-fold cross-validation was used to evaluate generalization ability of network. The predictive performance was assessed by mean squared error (MSE), coefficient of determination (R^2), mean absolute error (MAE), root mean squared error (RMSE), and mean absolute percentage error (MAPE). Experimental and cross-validated predicted values were compared using parity plots and residual plots.

3. RESULTS AND DISCUSSION

3.1 Characteristics of Dairy Industry Wastewater

The collected dairy industry wastewater was characterized before treatment. The measured parameters included total suspended solids, total dissolved solids, electrical conductivity, pH, COD, BOD, sulphate, phosphate, ammoniacal nitrogen, nitrate nitrogen, and chloride. The observed values are presented in Table 2.

Table 2. Physicochemical characteristics of dairy industry wastewater

Parameter	Range
TDS (mg/L)	2400.25–2626.77
TSS (mg/L)	1538.96–1778.28
pH	5.18–5.33
EC	2.37–2.72
BOD	917–1076
COD	9931.28–11538.33
Phosphate	32.93–40.62
Sulphate	201–235
Nitrate nitrogen	356.50–379.90
Ammoniacal nitrogen	115–142
Chloride	860.18–867.95

The relatively high BOD and COD values indicate a considerable organic load in the wastewater. Therefore, reduction of both parameters was selected to evaluate the treatment performance of the sodium-alginate-based nanocomposite adsorbent.

3.2 Characterization of Sodium-alginate-based Nanocomposite Adsorbents

Fig. 1 shows the SEM-EDS analysis performed to examine the surface morphology and elemental composition of the synthesized SA-CeO₂ and SA-MgFe₂O₄ nanocomposite beads. The SEM micrograph of SA-CeO₂ (Fig. 1a) reveals an irregular and heterogeneous surface morphology with relatively compact regions, pronounced surface roughness, and wrinkled or fibrous features. Localized clusters and small

surface cavities are also visible, indicating non-uniform deposition or aggregation of the CeO_2 phase within the sodium-alginate matrix. The corresponding EDS spectrum (Fig. 1b) shows signals assigned to C, O, Na, and Ce. The strong Ce peaks confirm the successful incorporation of the cerium-containing oxide phase into the alginate matrix.

The SA- MgFe_2O_4 beads (Fig. 1c) similarly exhibit an irregular, coarse, and compact morphology with elongated particles and rough surface regions. Some localized agglomerated domains and surface voids are evident, which may arise from the distribution and clustering of MgFe_2O_4 particles during bead formation and drying. The EDS spectrum (Fig. 1d) confirms the presence of C, O, Na, Mg, and Fe, with prominent Fe and O signals and a detectable Mg peak, supporting the

incorporation of the MgFe_2O_4 phase into the sodium-alginate matrix.

Importantly, the EDS spectra show a Na signal rather than a clearly identifiable Ca signal. The SEM-EDS results demonstrate the formation of rough and heterogeneous SA-based composite structures and confirm the presence of Ce in SA- CeO_2 and Mg/Fe in SA- MgFe_2O_4 , respectively. Another recent study has also used SEM analysis to examine gelatin-sodium alginate-modified CeO_2 nanoparticles synthesized for Basic Yellow 28 and Basic Blue 41 dye degradation. The micrographs revealed predominantly near-spherical nanostructures, confirming successful nanoparticle formation and surface modification (Mahalakshmi *et al.* 2026).

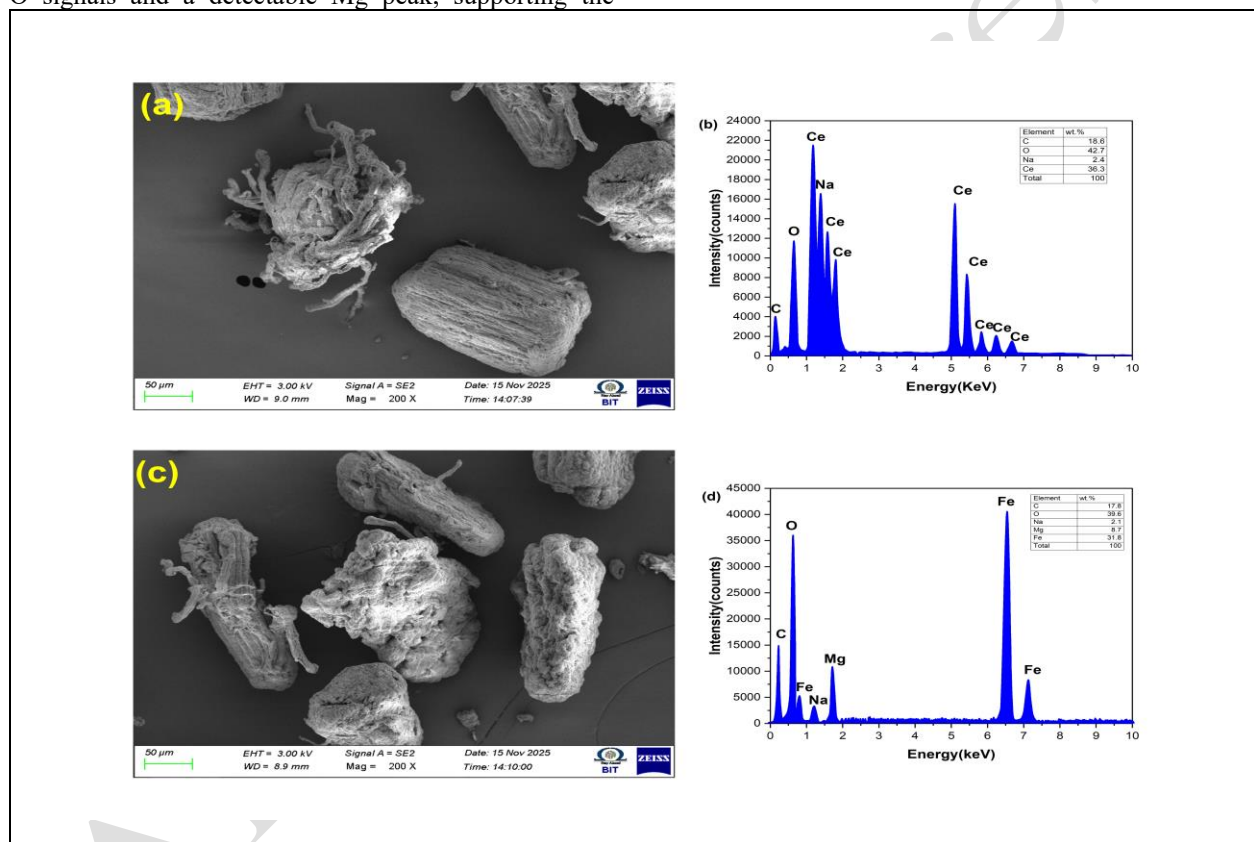


Fig. 1: SEM and EDS spectra of (a, b) SA- CeO_2 and (c, d) SA- MgFe_2O_4 nanocomposite beads

3.3 Taguchi L27 Experimental Results

The Taguchi L27 design was used to study effects of wastewater dilution, adsorbent dosage, pH and contact time on %RBOD and %RCOD. The factor levels were 25–75% dilution, pH of 4–10, dosage of 0.5–1.5 g L^{-1} and contact time of 30–90 minutes (Table 3).

Table 3. Taguchi L27 experimental matrix and measured BOD and COD reduction efficiencies

Run	Dilution (%)	pH	Dosage (g/L)	Time (min)	%RBOD	%RCOD
1	25	4	0.5	30	68.4	61.7
2	25	4	1.0	60	78.9	72.6
3	25	4	1.5	90	87.6	81.8
4	25	7	0.5	60	82.1	76.4
5	25	7	1.0	90	92.8	87.5
6	25	7	1.5	30	86.3	80.7
7	25	10	0.5	90	77.2	70.8

8	25	10	1.0	30	72.6	66.1
9	25	10	1.5	60	83.7	77.9
10	50	4	0.5	60	62.8	55.4
11	50	4	1.0	90	73.9	67.2
12	50	4	1.5	30	67.1	60.6
13	50	7	0.5	90	77.8	71.5
14	50	7	1.0	30	73.4	67.1
15	50	7	1.5	60	86.5	80.9
16	50	10	0.5	30	55.9	48.7
17	50	10	1.0	60	68.7	62.0
18	50	10	1.5	90	78.6	72.3
19	75	4	0.5	90	57.3	49.8
20	75	4	1.0	30	51.8	44.2
21	75	4	1.5	60	65.6	58.4
22	75	7	0.5	30	56.7	49.5
23	75	7	1.0	60	71.4	64.8
24	75	7	1.5	90	84.2	78.3
25	75	10	0.5	60	51.2	43.6
26	75	10	1.0	90	63.8	56.7
27	75	10	1.5	30	57.9	50.9

The %RBOD values varied from 51.2 to 92.8%, whereas %RCOD ranged from 43.6 to 87.5%. The highest simultaneous reduction was obtained in Run 5 at 25% dilution, pH 7, a dosage of 1.0 g L⁻¹, and 90 minutes. Under this condition, %RBOD and %RCOD reached 92.8 and 87.5%, respectively.

The lower wastewater dilution produced higher removal efficiencies because the organic load was lower and the available adsorption sites were sufficient for pollutant capture. Increasing the dosage improved treatment performance by increasing number of available active sites. Similarly, increase in contact time enhanced pollutant transfer from liquid phase to adsorbent surface. Maximum response at pH 7 indicates a favorable balance between alginate functional groups, oxide surface charge, and wastewater stability. Abdelkareem *et al.* (2026) used the Taguchi L16 design to optimize Methylene blue adsorption using cigarette ash–sodium alginate beads by varying pH, temperature, dye concentration, adsorbent dosage, and contact time. The optimum conditions achieved 97.21% removal, with pH contributing 47.0% as the most influential factor.

3.4 Taguchi Response Analysis

The mean-response results for %RBOD are shown in Table 4.

Table 4. Mean-response analysis for RBOD

Factor	Level 1	Level 2	Level 3	Delta	Rank
Dilution (%)	81.07	71.63	62.21	18.86	1

pH	68.16	79.02	67.73	11.29	4
Dosage (g/L)	65.49	71.92	77.50	12.01	2
Time (min)	65.57	72.32	77.02	11.46	3

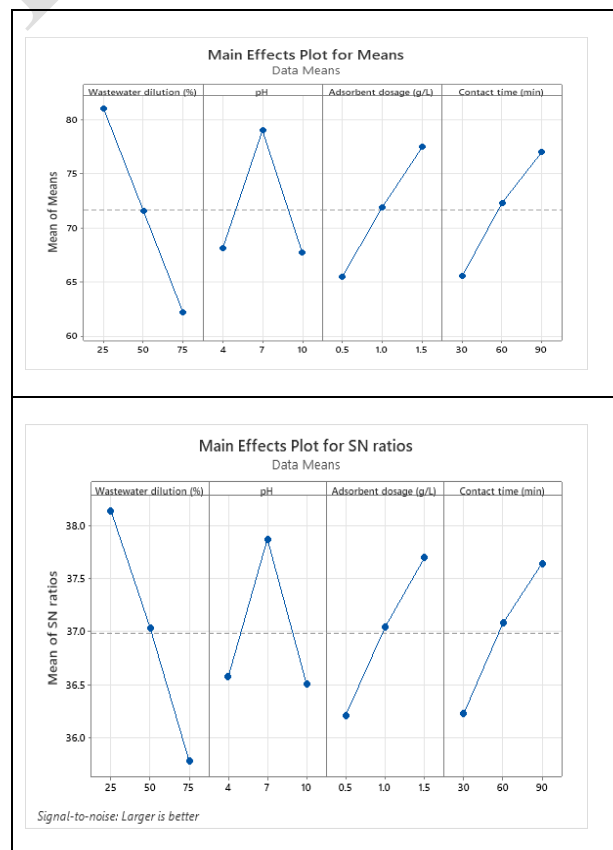
For %RBOD, the dilution factor produced the largest response variation followed by dosage, contact time, and pH. The highest factor levels were dilution level 1, pH level 2, dosage level 3, and contact-time level 3, corresponding to A1–B2–C3–D3.

Table 5. Mean-response analysis for %RCOD

Factor	Level 1	Level 2	Level 3	Delta	Rank
Dilution (%)	75.06	65.08	55.13	19.92	1
pH	61.30	72.97	61.00	11.97	3
Dosage (g/L)	58.60	65.36	71.31	12.71	2
Time (min)	58.83	65.78	70.66	11.82	4

The %RCOD response followed the same general pattern (Table 5). Dilution was the most influential parameter, followed by dosage, pH, and contact time based on the mean response. The combined Taguchi factor-level optimum was A1–B2–C3–D3: 25% dilution, pH 7, 1.5 g L⁻¹ dosage, and 90 minutes.

For the signal-to-noise response, factor ranking for %RBOD were dilution > dosage > contact time > pH (Fig. 2 a,b). For %RCOD, the corresponding ranking was dilution > dosage > contact time > pH (Fig. 2 c,d).



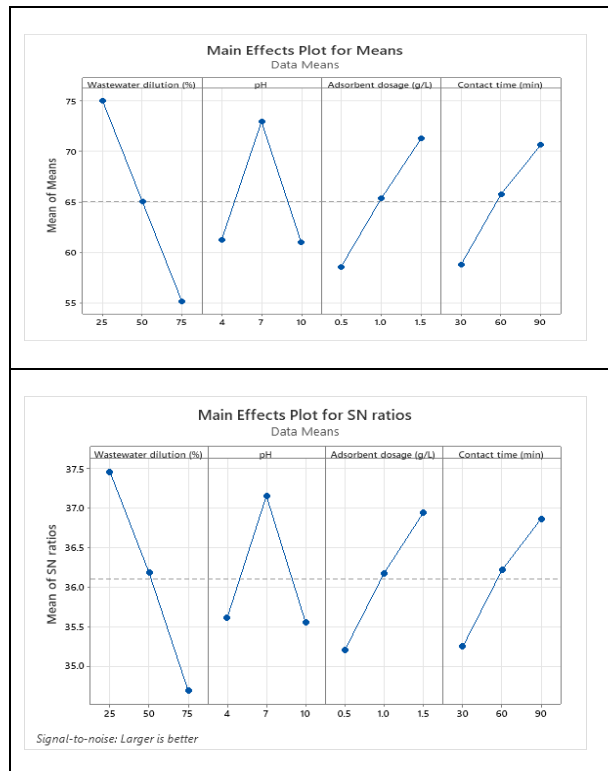


Fig. 2: Main-effect plots of mean responses and S/N for (a, b) %RBOD and (c, d) %RCOD

3.5 ANOVA Analysis

ANOVA was conducted using the main-effect model to quantify the contribution of each operating factor (Table 6).

Table 6. ANOVA results for %RBOD and %RCOD

Response	Factor	F-value	p-value	Contribution (%)
%RBOD	Dilution	374.26	<0.001	44.16
%RBOD	pH	172.43	<0.001	20.35
%RBOD	Dosage	152.12	<0.001	17.95
%RBOD	Contact time	139.63	<0.001	16.48
%RBOD	Error	—	—	1.06
%RCOD	Dilution	392.95	<0.001	44.33
%RCOD	pH	184.42	<0.001	20.81
%RCOD	Dosage	160.18	<0.001	18.07
%RCOD	Contact time	139.79	<0.001	15.77
%RCOD	Error	—	—	1.02

Wastewater dilution was the dominant factor for both responses, contributing 44.16% to the variation in %RBOD and 44.33% to the variation in %RCOD. This strong influence is associated with the change in organic loading caused by dilution. The contributions of pH, dosage, and contact time was also substantial, confirming that treatment efficiency depends on the combined chemical and mass-transfer conditions.

For %RBOD, the additive model produced $R^2 = 0.9894$, adjusted $R^2 = 0.9847$, and predicted $R^2 = 0.9761$. The low residual contribution demonstrates good agreement between the measured responses and the Taguchi main-effect model. The %RCOD model explained approximately 98.98% of the response variation. Similarly, Dalanta *et al.* (2021) used ANOVA to statistically validate the D-optimal mixture model developed for optimizing the AC/TiO₂/CeO₂ composite used in petroleum refinery wastewater treatment. The analysis confirmed adequate model reliability for predicting TDS, COD, phenol, NH₃-N, pH, and electrical conductivity responses.

3.6 IDOCRIW–WASPAS Analysis

The IDOCRIW method assigned a weight of 0.42526 to %RBOD and 0.57474 to %RCOD (Table 7). The greater weight of %RCOD indicates that COD reduction had a stronger influence on the integrated decision matrix.

Table 7. IDOCRIW-derived objective weights

Criterion	IDOCRIW Weight
%RBOD	0.42526
%RCOD	0.57474
Total	1.00000

Table 8. Leading alternatives ranked using the WASPAS method

Rank	Run	Dilution (%)	pH	Dosage (g/L)	Time (min)	%RBOD	%RCOD	WASPAS Score
1	5	25	7	1.0	90	92.8	87.5	1.00000
2	3	25	4	1.5	90	87.6	81.8	0.93873
3	15	50	7	1.5	60	86.5	80.9	0.92777
4	6	25	7	1.5	30	86.3	80.7	0.92554
5	24	75	7	1.5	90	84.2	78.3	0.90015

Run 5 obtained the highest WASPAS score of 1.00000 and was ranked first. This result confirms that condition of 25% dilution, pH 7, 1.0 g L⁻¹ dosage, and 90 minutes provided the best simultaneous measured reduction of BOD and COD (Table 8).

The Taguchi factor-level optimum and the best measured WASPAS run differ only in dosage. Therefore, Run 5 is reported as the best tested experimental condition. The Taguchi combination containing 1.5 g L⁻¹ should be verified through an additional confirmation experiment before being reported as the final Taguchi optimum. In a prior study, the optimized WASPAS method was used to rank wastewater reuse allocation alternatives in a water/wastewater supply system using economic, socio-cultural, environmental, and technological criteria. The environmental reuse option achieved the highest score of 0.176, followed by

landscape irrigation, industrial reuse, artificial aquifer recharge, recreational use, and agricultural irrigation (Azbari *et al.* 2022).

3.7 RBF-ANN Prediction

A Gaussian RBF-ANN model was developed using wastewater dilution, adsorbent dosage, pH, and contact time input variables. The target outputs were %RBOD and %RCOD. Five-fold cross-validation was used to assess predictive capability of the network (Table 9; Fig. 3).

Table 9. Five-fold cross-validated performance of Gaussian RBF-ANN model

Response	R ²	MSE	RMSE	MAE	MAPE (%)
%RBOD	0.96045	5.3059	2.3035	1.8236	2.7131
%RCOD	0.95759	6.3276	2.5155	1.9660	3.3108

The RBF-ANN model achieved R² values of 0.96045 for %RBOD and 0.95759 for %RCOD. The

corresponding RMSE values were 2.3035 and 2.5155%, indicating relatively small prediction deviations. The MAPE values of 2.7131 and 3.3108% further demonstrate the satisfactory predictive accuracy of the model.

The cross-validated predictions followed the experimental trends across the L27 runs. The residual values were distributed around zero without a pronounced systematic pattern, indicating that the RBF-ANN captured the nonlinear relationship between the operating parameters and wastewater-treatment responses (Fig. 4). In a recent study, *Cinnamomum tamala* essential oil extraction using RSM and ANN, achieved high prediction accuracies of R² = 0.984 and 0.993, respectively. Artificial neural network showed superior predictive performance, identifying 800 W microwave power, a 1:1 liquid-to-plant ratio, and 85 minutes extraction time as optimal conditions (Mohanty *et al.* 2026).

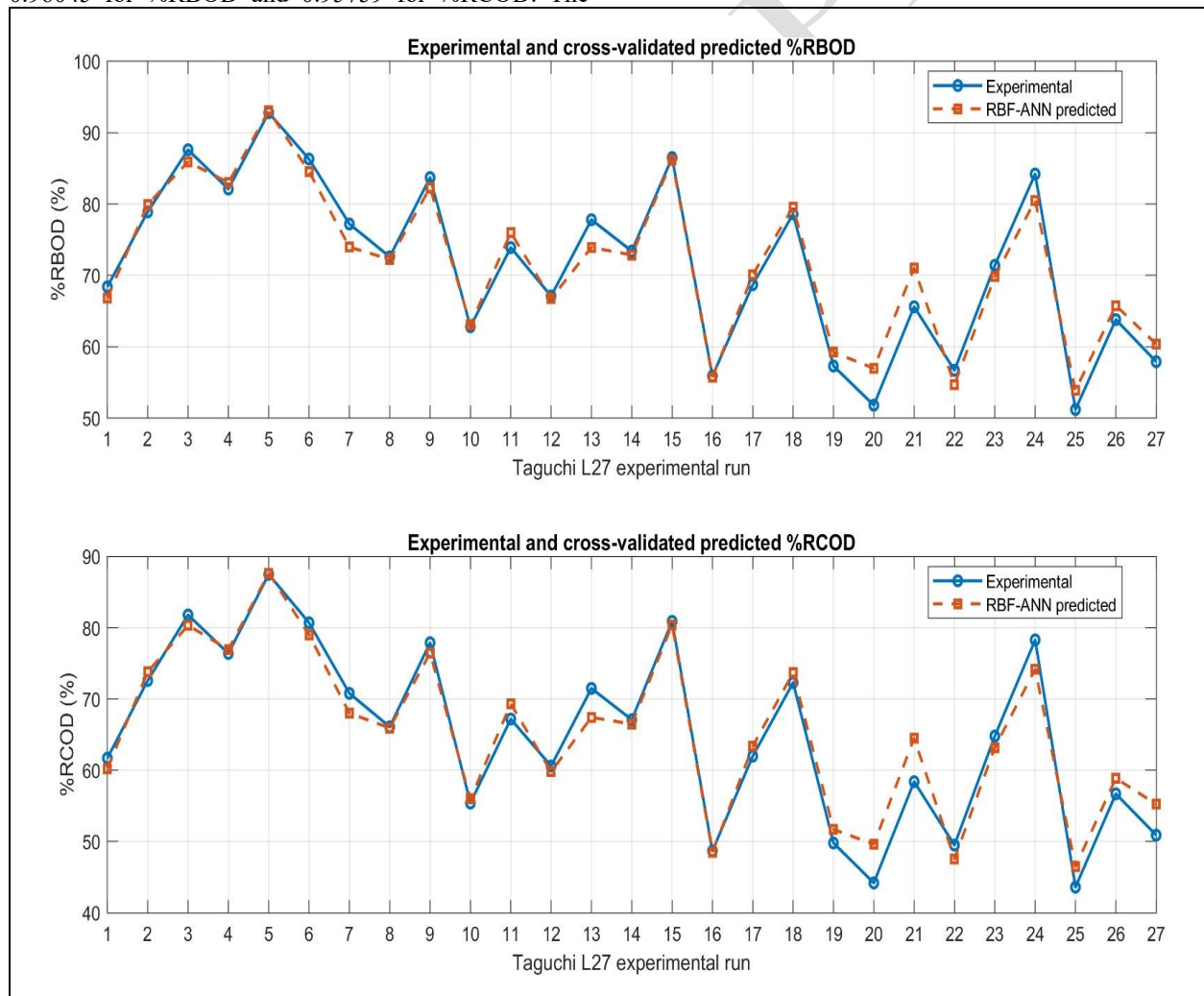


Fig. 3: Experimental versus five-fold cross-validated RBF-ANN predictions for (a) %RBOD and (b) %RCOD

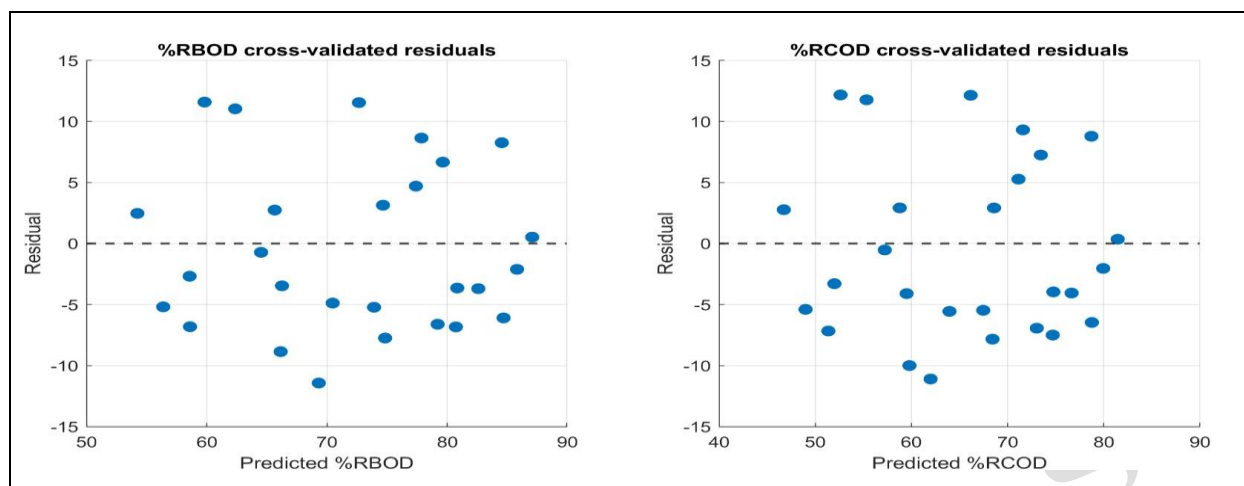


Fig. 4: Residual plots for the five-fold cross-validated RBF-ANN predictions of (a) %RBOD and (b) %RCOD

3.8 Overall Treatment Condition

Based on the integrated WASPAS ranking, the best experimentally demonstrated treatment condition was 25% wastewater dilution, pH 7, 1.0 g L⁻¹ adsorbent dosage, and 90 minutes contact time. This condition achieved 92.8% RBOD and 87.5% RCOD and was assigned first rank with a WASPAS score of 1.00000. The results demonstrate that the sodium-alginate-based nanocomposite adsorbent can effectively reduce the organic load of dairy industry wastewater under optimized operating conditions.

4. CONCLUSION

CeO₂ and MgFe₂O₄ nanoparticles were green-synthesized using *Cinnamomum tamala* leaf extract and incorporated into sodium-alginate-based nanocomposite adsorbents for the treatment of dairy industry wastewater. The developed materials were evaluated for BOD and COD reduction using Taguchi L27 experimental design, IDOCRIW–WASPAS analysis, and Gaussian radial-basis-function artificial neural network modelling.

The Taguchi analysis identified wastewater dilution as the most influential factor, contributing 44.16% to %RBOD and 44.33% to %RCOD variation. The factor-level optimum for both responses was 25% wastewater dilution, pH 7, adsorbent dosage of 1.5 g/L, and contact time of 90 minutes. The highest experimentally observed performance was obtained in Run 5, using 25% dilution, pH 7, 1.0 g/L adsorbent dosage, and 90 minutes contact time, with 92.8% RBOD and 87.5% RCOD reduction.

The IDOCRIW method assigned weights of 0.4253 to %RBOD and 0.5747 to %RCOD. Based on the WASPAS evaluation, Run 5 achieved the first rank with a score of 1.00000, confirming its overall suitability for

simultaneous BOD and COD reduction. The five-fold cross-validated RBF-ANN model provided satisfactory prediction accuracy, with R² values of 0.96045 for %RBOD and 0.95759 for %RCOD. The corresponding RMSE values were 2.3035 and 2.5155, respectively.

Overall, the green-synthesized CeO₂ and MgFe₂O₄-based sodium-alginate adsorbents demonstrated considerable potential for dairy wastewater treatment. The combined use of Taguchi optimization, multi-criteria decision-making, and RBF-ANN modelling provided a reliable framework for identifying effective operating conditions and predicting treatment performance.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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