



Calotropis gigantea-mediated Green Synthesis of rGO–TiO₂ Nanocomposite for Efficient Decolorization of Textile Dye Effluent

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ABSTRACT

In the present study, a reduced graphene oxide–titanium dioxide (rGO–TiO₂) bio-nanocomposite (NC) was synthesized using the reducing potential of *Calotropis gigantea* leaf extract. The synthesized NC was subjected to multiple analytical techniques to assess its structural and morphological characteristics. XRD and FT-IR analyses confirmed that *Calotropis gigantea* leaf extract effectively reduced GO to rGO and facilitated the formation of the rGO–TiO₂ NC. SEM–EDX analysis revealed that the NC exhibited a layered sheet-like and microball-like morphology. The raw textile effluent used in this study was characterized. A comparative analysis was conducted to evaluate the color removal efficiency of the NC in textile wastewater effluent. The use of NC in combination with centrifugation resulted in the removal of 77% of the apparent color and 90% of the turbidity from the textile effluent. Treatment using NC coupled with gravitational sedimentation achieved 67% apparent color removal and 87% turbidity removal. Color removal efficiency improved by 29% when NC coupled with gravitational sedimentation was used, compared with the effluent treated in a commercial wastewater treatment plant. The present work demonstrates a novel, simple, and environmentally friendly method for producing rGO–based nanomaterials with potential applications in wastewater treatment.

Keywords: Green synthesis; *Calotropis gigantea*; rGO–TiO₂ nanocomposite; Textile effluent; Wastewater remediation.

1. INTRODUCTION

Textile wastewater is a significant environmental hazard in the Salem district of Tamil Nadu, India. The environmental impacts of textile dyes are well documented (Chockalingam *et al.* 2019; Myvizhi and Aruna Devi, 2020). The effluent from this region presents a unique challenge due to a high COD/BOD ratio of 2.68, indicating that only 37.1% of the organic load is biodegradable. Conventional wastewater treatment plants (WWTPs) are often ineffective at removing dissolved contaminants because of the high degree of recalcitrance in textile effluents. To address these limitations, nanomaterials such as titanium dioxide (TiO₂) and reduced graphene oxide (rGO) have emerged as highly effective solutions (Alias *et al.* 2025).

TiO₂ is widely studied for environmental remediation due to its chemical stability, non-toxicity, and strong photocatalytic activity (Nagaraj *et al.* 2025). Integrating TiO₂ with rGO was shown to create synergistic effects that can significantly enhance pollutant removal efficiency (Tismanar *et al.* 2022). El-Borady (2025) demonstrated that this combination

improved the adsorption and degradation of heavy metals and dyes under visible light.

Green synthesis utilizing plant extracts has gained prominence as an eco-friendly, cost-effective, and safe alternative to conventional nanoparticle synthesis. In this study, *Calotropis gigantea* leaf extract was selected as a novel bio-reductant for synthesizing rGO–TiO₂ NC. *C. gigantea* is a widely distributed plant known to produce secondary metabolites such as alkaloids, tannins, phenolics, and flavonoids (Sharma *et al.* 2024). These phytochemicals serve as excellent natural reducing and capping agents for the stable formation of nanoparticles (Mandal *et al.* 2022; Sivalingam, 2025). Utilizing this plant extract makes the biosynthesis process sustainable and economically beneficial.

Despite the proven efficacy of TiO₂ and rGO composites, there are notable gaps in the current literature regarding their application for real textile effluents. Existing research has primarily evaluated the NCs' capability to degrade and remove simulated dye solutions in a controlled lab environment. Also, while the individual use of *C. gigantea* has been documented for synthesizing simpler metal nanoparticles, such as silver

and zinc oxide, its application as a green reducing agent for complex rGO–TiO₂ bio-nanocomposites (NC) remains largely unexplored. By applying this novel NC to actual raw textile effluent, this research provides a practical, scalable, and greener strategy for industrial wastewater remediation.

The primary objective of this study is to synthesize a biogenic rGO–TiO₂ NC using the green reduction potential of the *C. gigantea* leaf extract. Secondly, the study aims to characterize the structural, optical, and morphological properties of the synthesized NC using UV–Vis spectroscopy, X-ray Diffraction (XRD) technique, Fourier Transform Infrared (FT-IR) spectroscopy, and Scanning Electron Microscopy–Energy Dispersive X-ray Spectroscopy (SEM–EDX). The study aims to evaluate the efficacy of the biogenic NC in treating raw textile effluent collected from the local dyeing industries. This includes optimizing experimental factors such as NC dosage, pH, and contact time. The final objective of this study is to perform a comparative analysis of color and turbidity removal efficiencies between the novel NC treatments (coupled with centrifugation or gravitational sedimentation) and the standard effluent output from a commercial WWTP.

2. MATERIALS AND METHODS

2.1 Chemicals and Reagents

Analytical reagent (AR) grade graphite powder, titanium dioxide (TiO₂), potassium permanganate (KMnO₄), sulfuric acid (H₂SO₄, 98%), hydrochloric acid (HCl, 37%), and hydrogen peroxide solution (H₂O₂, 30%) were procured from HiMedia Laboratories Pvt. Ltd., India. Deionized water (DW) was used throughout the study. Filtration was performed using Whatman Grade 40 filter paper.

2.2 Sample Collection and Preparation of Leaf Extract

Calotropis gigantea leaves were collected from Tiruchengode, Tamil Nadu, India (11.3629° N, 77.8254° E). The leaves were sufficiently washed to remove dirt and other contaminants. They were shade-dried for 7 days at room temperature (35 °C) to completely remove moisture, and then powdered in a domestic blender. 10 g of the leaf powder was mixed with 100 mL DW in an Erlenmeyer flask and heated to 50 °C for 30 min. The solution was filtered using Whatman filter paper and centrifuged at 4000 rpm for 20 min. The supernatant was collected and stored at 4 °C for future use. Fig. 1 represents a schematic overview of the study.

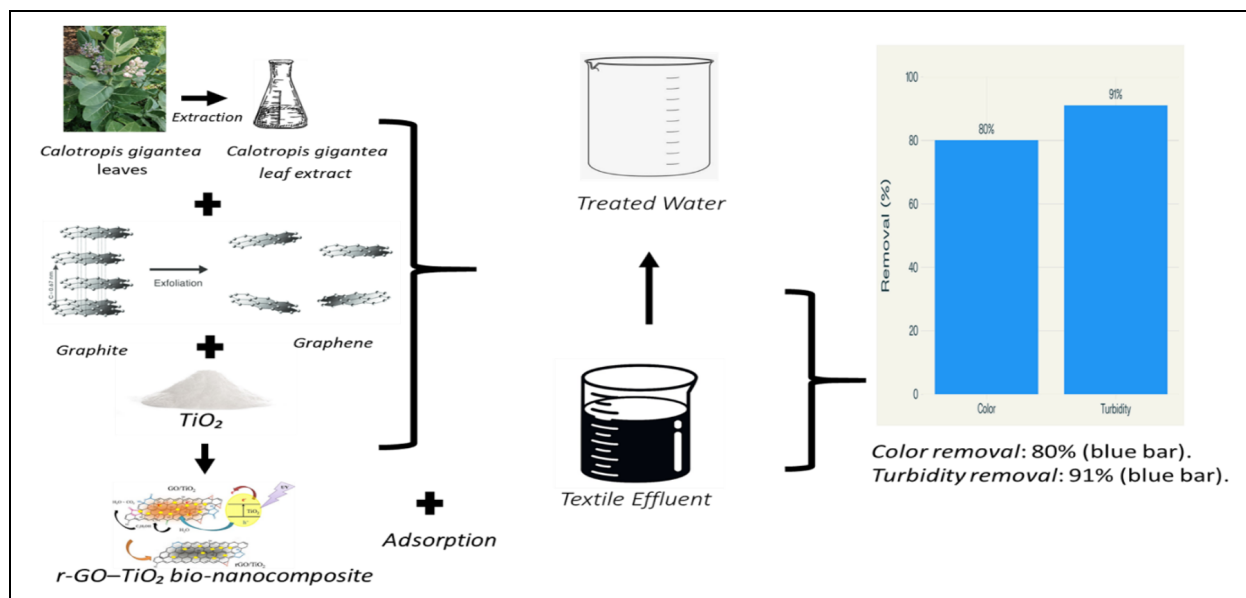


Fig. 1: Overall representation of textile effluent remediation using rGO–TiO₂ NC treatment

2.3 Synthesis of rGO–TiO₂ NC

The synthesis of the NC involves two steps. In the first step, graphite powder was oxidized to produce graphene oxide using a modified Hummers' method (Zaaba *et al.* 2017). 2 g each of sodium nitrate and graphite powder were dispersed in 50 mL of concentrated H₂SO₄. The mixture was combined with 5 g of potassium

permanganate and stirred continuously at 20 °C for 24 h using a magnetic stirrer. A 30% H₂O₂ solution was added until the mixture turned bright yellow. The resulting precipitate was washed several times with 5% aqueous HCl and distilled water, followed by centrifugation at 4000 rpm for 20 min. The GO pellet was then dried in a vacuum oven at 100 °C for 24 h. In the second step, 0.6 g of GO powder was dispersed in 100 mL of DW and

ultrasonicated for 30 min. Subsequently, 0.6 g of TiO₂ and 50 mL of *C. gigantea* leaf extract were added to the suspension. The resulting mixture was continuously stirred for 24 h at room temperature (25 ± 2 °C). The color of the suspension changed from brown to grey, indicating the reduction of GO to rGO and the successful formation of the rGO–TiO₂ NC. The resulting grey

precipitate was collected by centrifugation at 4000 rpm for 30 min. The obtained pellet was washed multiple times with DW and ethanol. Finally, the synthesized material was dried in a vacuum oven at 100 °C for 24 h to ensure complete dehydration. Fig. 2 represents the schematic procedure for the synthesis of rGO–TiO₂ NC using *C. gigantea* leaf extract.

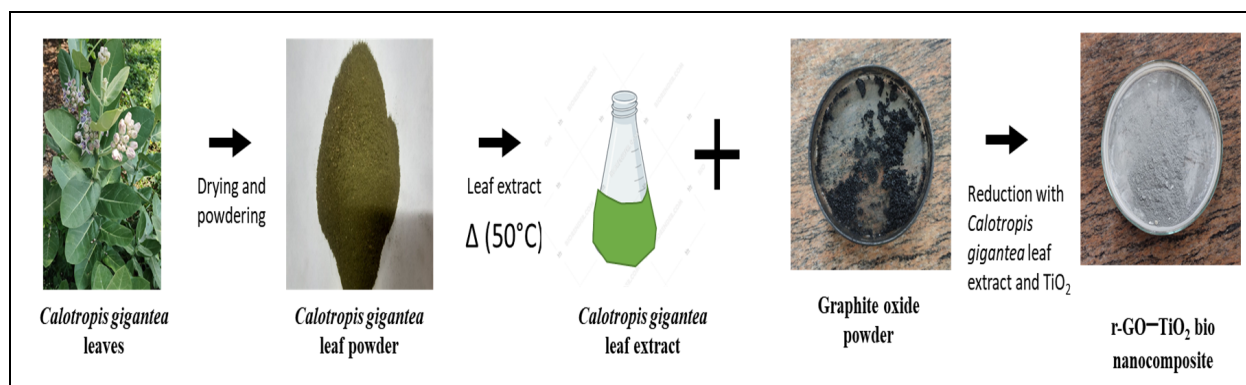


Fig. 2: rGO–TiO₂ NC preparation from *Calotropis gigantea* leaf extract

2.4 NC Characterization

The synthesized NC was subjected to an array of analytical characterization methods. The UV-Vis spectrum was recorded over the wavelength range of 200 to 800 nm using a Hitachi U-2900 double-beam spectrophotometer equipped with a 1 cm path-length quartz cuvette. Functional groups were analyzed by FT-IR spectroscopy using KBr pellets over the range of 4000–400 cm⁻¹. The crystal structure of rGO–TiO₂ NC was assessed using XRD with a Bruker D8 Advance X-ray diffractometer, using Cu K α₁ radiation (1.54060 Å, 40 kV, and 35 mA). Morphology and composition were analyzed using SEM (JEOL JSM-6390LA) coupled with EDX (Oxford X-MaxN) with an accelerating voltage of 0.5–30 kV and a resolution of 136 eV.

2.5 Preliminary Characterization of Textile Wastewater

Raw effluent (inlet) and the treated effluent from WWTP (outlet) were collected from a textile industry in Salem, Tamil Nadu, India. The samples were stored in the laboratory overnight at 4 ± 2 °C and analyzed the following day using procedures described in *Standard Methods for the Examination of Water and Wastewater* (APHA, AWWA, WEF, 2017). All experiments using the effluents were conducted within 14 days to prevent degradation of pollutants during storage. Parameters measured included temperature, pH, apparent color, turbidity, conductivity, total dissolved solids (TDS), COD, BOD, chloride, sulfate, and metals (Ca, Na, Cu, Mn, and Zn).

2.6 Optimal rGO–TiO₂ Dosage for Textile Wastewater Remediation

The optimal NC dosage was determined by testing multiple NC-to-effluent ratios and observing reductions in color and turbidity. Standard Methods of APHA 2120-B and 2130-B (APHA, AWWA, and WEF, 2017) were used to determine the apparent color and turbidity of each sample, respectively. Triplicate textile effluent samples were treated with NC at various dosages under continuous stirring at 300 rpm and room temperature (28 ± 3 °C) for 1 h. It was followed by centrifugation at 4000 rpm for 10 min. Removal efficiency (*R*) was calculated (in %) using the formula:

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

where *C_o* and *C_f* are the initial and final values of apparent color (Hazen) or turbidity (NTU), respectively.

2.7 Influence of Initial pH on Textile Wastewater Treatment using rGO–TiO₂

To understand the influence of initial pH on the textile effluent remediation process, six separate aliquots of textile effluents at pH values ranging from 2 to 8 were prepared by adjusting the pH with HCl/NaOH solution. 30 mL of effluent at each pH value was mixed with 0.5 g/L NC, and stirred at 300 rpm for 1 h at room temperature (28 ± 3 °C). Centrifugation was performed at 4000 rpm for 10 min before measuring apparent color and turbidity with a photometer (Merck, NOVA 60) and a bench turbidimeter (Water Analyzer 371), respectively.

2.8 Kinetics of Contaminant Removal from Textile Wastewater

To study the kinetics of contaminant removal from textile effluent, 0.5 g/L NC was added to 30 mL of textile effluent in an Erlenmeyer flask. The suspension was stirred continuously at room temperature ($28 \pm 3^\circ\text{C}$), and samples were collected at various time intervals ranging from 5 to 120 min. The samples were then centrifuged at 4000 rpm for 10 min, followed by the determination of R for apparent color and turbidity. Treated water was compared with WWTP effluent to assess efficiencies using apparent color, turbidity, and COD.

2.9 Separating NC via Decantation

To reduce the cost of the proposed treatment, the settling time after the treatment process was investigated. In a 125 mL Erlenmeyer flask, 90 mL of effluent and 3 mL of NC (containing 0.5 g/L of NC) were mixed at room temperature under continuous stirring for 1 h. Once the adsorption was complete, the mixture was decanted into a 100 mL graduated test tube for a settling test. The centrifugation step was eliminated to reduce operating costs. The test tube volume was monitored from 5 min to 180 min until the decanted volume remained constant.

2.10 Statistical Analysis

All measurements were performed in triplicate and are reported as mean $\pm$ standard deviation in the tables. Student's t -test was performed to compare the color and turbidity removal efficiencies between the WWTP and NC treatments using IBM SPSS Statistics (Version 20). The calculated t -values were used to determine the statistical significance of differences between the treatments.

3. RESULTS AND DISCUSSION

3.1 NC Preparation and Characterization

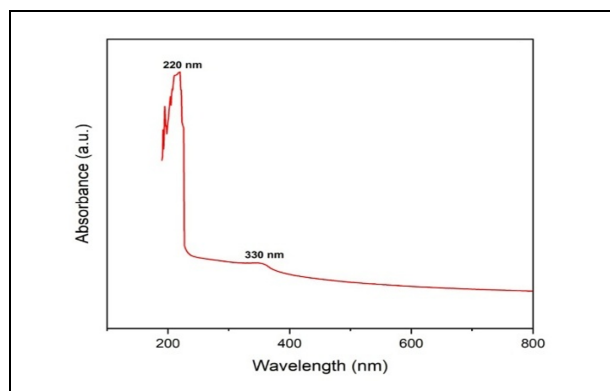


Fig. 3: UV-Vis spectrum of rGO-TiO₂ NC

The formation of a black pellet and the transition of the suspension color from brown to grey suggested the successful formation of GO and rGO-TiO₂ NC, respectively. These findings were subsequently confirmed by UV-Vis, FT-IR, and XRD characterization, as shown in Figs. 3–5.

From Fig. 3, it is evident that the *C. gigantea* leaf extract-synthesized rGO-TiO₂ NC exhibited UV absorption peaks at 220 nm and 330 nm. The peak at 220 nm is attributed to the $\pi \rightarrow \pi^*$ transition of aromatic C–C bonds. The hybridization with rGO enhances the light-harvesting capacity of the composite, introducing a band gap and a slight red shift compared to pure TiO₂. Similar observations were noted for green-synthesized rGO nanoparticles prepared using *Nigella sativa* seed extract by Mirza *et al.* (2022). They reported that the maximum prominent absorbance peaks were observed at 217 nm and 327 nm.

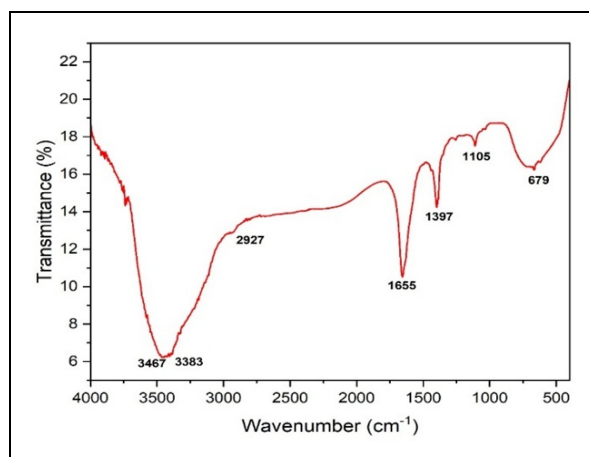


Fig. 4: FT-IR spectrum of rGO-TiO₂ NC

In the FT-IR profile (Fig. 4), NC exhibited a characteristic absorption peak at 1655.16 cm^{-1} , which may be attributed to the stretching vibration of the carbonyl (C=O) group. A wide, prominent peak observed between 3000 and 3500 cm^{-1} corresponds to the hydroxyl (O–H) stretching vibration. The peaks at 1397 cm^{-1} and 1105 cm^{-1} are associated with C=C vibrations and C–O stretching vibrations, respectively. A broad band below 1000 cm^{-1} corresponds to the Ti–O–Ti linkage in TiO₂. The FT-IR spectrum exhibited trends similar to those reported by Aziz *et al.* (2021) for an rGO-TiO₂ nanocomposite synthesized via pulsed laser ablation for dye adsorption applications. In their study, characteristic absorption bands were observed at 1637 cm^{-1} and 3333 cm^{-1} . The additional absorption bands observed in the present study may be attributed to phytochemical constituents derived from the leaf extract used during green synthesis. The FT-IR results further confirmed the reduction of GO and the successful incorporation of TiO₂ onto the rGO sheets.

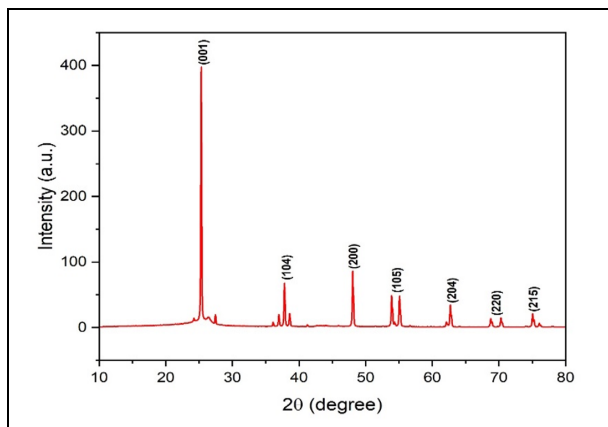


Fig. 5: XRD pattern of rGO–TiO₂ NC

The XRD profile confirmed the crystalline nature of the synthesized NC. The distinct diffraction peaks at $2\theta = 25.3^\circ$ ($\sim 24.5^\circ$) correspond to the rGO plane. Absence of sharp peaks at 10° verified successful

reduction of GO. The higher intensity peaks correspond to TiO₂. The crystalline nature and average crystallite size of the attached TiO₂ were quantitatively determined using the Scherrer equation. Based on the most intense diffraction peak at $2\theta = 25.3^\circ$, the average crystallite size was calculated to be 23.26 nm. Abd Ali *et al.* (2022) prepared rGO–TiO₂ NC by the chemical reduction method and characterized r-GO, TiO₂, and NC by the XRD technique. The XRD profile of the present study shows exact similarity to the reported profile. Hence, the results confirm the successful attachment of TiO₂ to the oxygen-containing functional groups on the rGO sheet.

Fig. 6 shows SEM images at various magnifications of the synthesized NC. A flaky, multi-layered rGO sheet was visible on which TiO₂ particles were uniformly distributed across the surface and along the edges. This attachment indicates a strong interfacial contact essential for carrying out photocatalysis of textile wastewater.

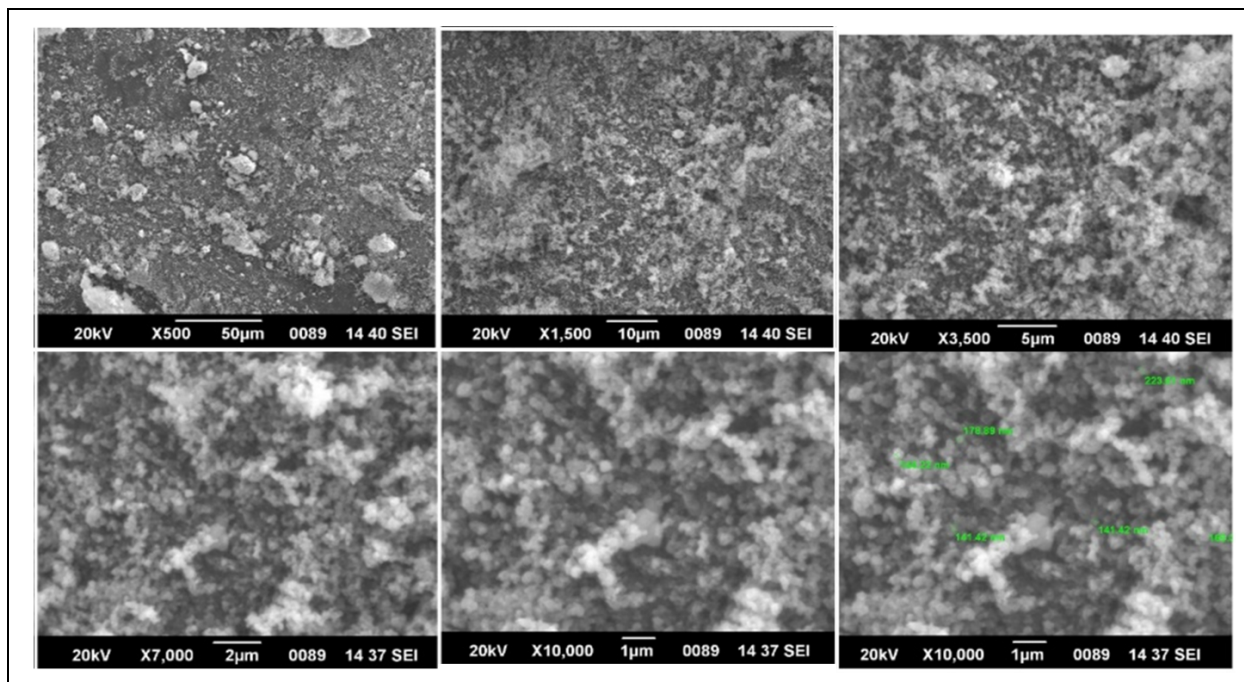


Fig. 6: SEM micrographs of rGO–TiO₂ NC at different magnifications

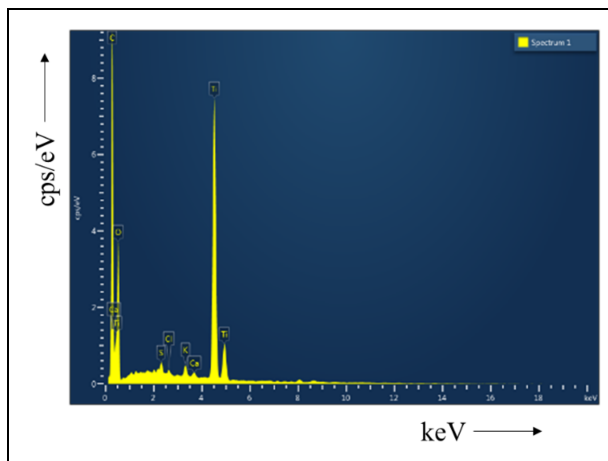


Fig. 7: EDX spectrum of rGO–TiO₂ NC

The EDX spectrum (Fig. 7) confirmed the high purity of the synthesized NC with carbon, oxygen, and titanium. The image indicates that these elements were incorporated during synthesis. The absence of extraneous peaks confirms that the biogenic synthesis method using *C. gigantea* leaf extract does not introduce significant impurities. The observations visually corroborate with the structural features of rGO–TiO₂ NC synthesized by conventional physical and chemical methods (Ahmadkhaniha *et al.* 2017; Aruchamy *et al.* 2025).

3.2 Preliminary Characterization of Textile Wastewater

Table 1. Characteristics of textile dye effluent

S. No.	Parameter	Mean ± SD
1	Temperature (°C)	31.5 ± 0.4
2	pH	6 ± 0.1
3	Apparent color (Hazen)	490 ± 10.2
4	Turbidity (NTU)	250 ± 8
5	Conductivity (mS/cm)	4.8 ± 0.1
6	TDS (g/L)	2.7 ± 0.1
7	COD (mg O ₂ /L)	750 ± 14
8	BOD (mg O ₂ /L)	280 ± 6
9	Calcium (mg/L)	102 ± 2
10	Potassium (mg/L)	100 ± 3
11	Sodium (mg/L)	99 ± 1.5
12	Chlorides (mg/L)	74.1 ± 0.4
13	Sulfates (mg/L)	23.1 ± 0.2
14	Copper (mg/L)	7.12 ± 0.2
15	Manganese (mg/L)	1.5 ± 0.09
16	Zinc (mg/L)	0.1 ± 0.03

Table 1 presents the baseline parameters, including temperature, pH, and other physicochemical attributes of textile wastewater. The wastewater temperature was found within the permissible limit set by

Brazilian environmental law (CONAMA 430). The collected wastewater was found to be opaque, vividly dark blue, and turbid, with turbidity visible to the naked eye. Sulfates and chlorides were found to be 23.1 and 74.1 mg/L, respectively. The major metal measurements were presented in Table 1 to establish baseline characteristics for the study.

The high COD/BOD ratio of 2.68 indicates that only 37% of the organic load is biodegradable. The presence of organic matter in the wastewater may be attributed to the use of various textile-processing chemicals, including enzymes, dyes (reactive, direct, and sulfur-rich), silicones, and softeners. This highlights the significant degree of resistance of this effluent. For such cases, physical and chemical treatment methods, such as pH-adjusted decantation, decantation–flocculation (the current WWTP process), and adsorption, may be more suitable. The presence of ions such as Na⁺, Ca²⁺, and K⁺ in the effluent may be attributed to the use of soaps, bleaching agents, and alkaline additives (e.g., NaOH) during textile dyeing, bleaching, and finishing operations.

3.3 Optimal rGO–TiO₂ Dosage for Textile Wastewater Remediation

Fig. 8 shows the effect of initial NC concentration on the removal rates of apparent color and turbidity in the medium. The removal efficiency improved as the NC dosage increased up to a threshold, beyond which it plateaued due to saturation of active surface sites. An optimal dosage was determined to avoid excess use, which could alter the economics of the remediation process.

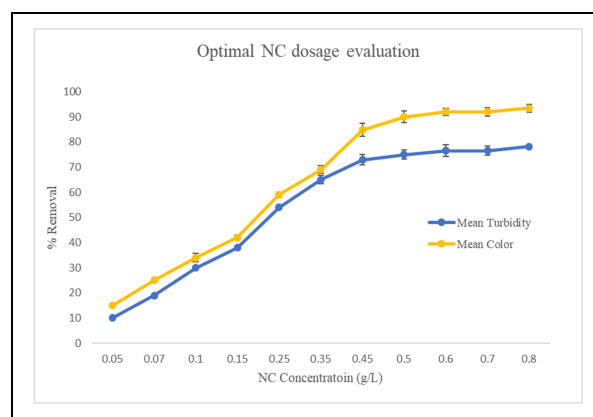


Fig. 8: Effect of rGO–TiO₂ NC concentration on the removal of color and turbidity from textile wastewater

From the graph, 1 mL of 0.5 g/L NC in 30 mL of textile effluent was determined to be the optimal dose for maximizing the removal of apparent color and turbidity. Beyond 0.5 g/L, the graph registered a plateau. The final NC concentration in the effluent was calculated to be 16.13 mg/L. The achieved discoloration efficiency

was reported as 77%. Sofia *et al.* (2025) demonstrated that the rGO/TiO₂/g-C₃N₄ nanocomposite synthesized using *Plectranthus amboinicus* leaf extract exhibited ~99% removal of methylene blue from water. Since textile effluent is a mixture of various dyes, heavy metals, and salts, direct comparison with individual dye-based studies cannot be made.

3.4 Influence of Initial pH on Textile Wastewater Treatment Using rGO–TiO₂

The effect of initial pH on removal efficiencies of color and turbidity is illustrated in Fig. 9. There was a slight change in removal efficiency among the various initial pH suspensions tested. This indicates that it is not necessary to adjust the initial pH to a specific level before proceeding with the remediation methodology.

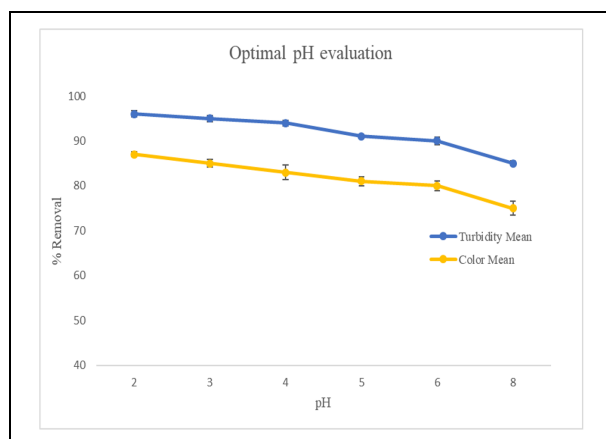


Fig. 9: Effect of initial pH on the removal of color and turbidity from textile wastewater using rGO–TiO₂ NC

The novel NC was found to be versatile in removing color and turbidity, achieving levels beyond 70%. From an economic point of view, it eliminates the need for additional pH adjustment steps before the NC treatment. However, previous research, such as Kocijan *et al.* (2022), reported 68.4% as the maximum

degradation efficiency at pH 6.0 for organic dyes in water using NC synthesized by the sol-gel method.

3.5 Effect of Contact Time on the Removal Efficiencies

Fig. 10 shows that the removal process is time-dependent and that there was a steady increase in the removal efficiencies of apparent color and turbidity over time.

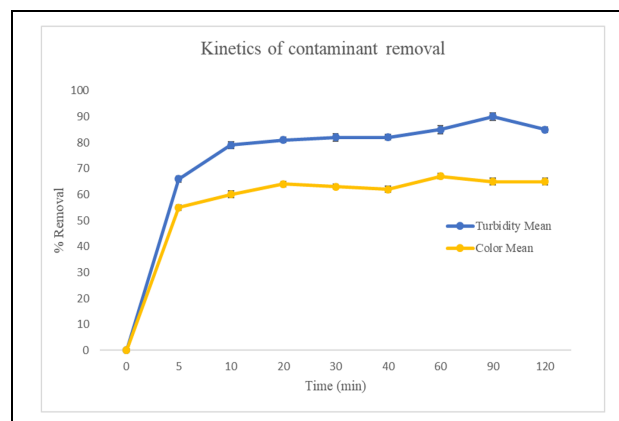


Fig. 10: Effect of contact time on the removal of color and turbidity from textile wastewater using rGO–TiO₂ NC

The removal efficiency increased exponentially in the first 5 min, followed by a gradual increase up to 60 min, beyond which a steady-state plateau was observed. The system achieved equilibrium after 1 h, yielding an apparent color removal of 77% and turbidity removal of 90%. Hence, 1 h of contact time was found to be optimal for the remediation of textile effluent.

3.6 Performance Comparison and Mechanism

Table 2 presents the measured values of apparent color, turbidity, and COD, along with their efficiency comparisons of rGO–TiO₂ NC (centrifugation) and WWTP.

Table 2. Comparison of the treatment efficiencies of rGO–TiO₂ NC (centrifugation) and WWTP

Parameters	Textile Effluent	WWTP Effluent	rGO–TiO ₂ Effluent	Efficiency of rGO–TiO ₂ Treatment (%)	Efficiency of WWTP (%)	% Improvement in rGO–TiO ₂ Treatment
Color (Hazen)	445 ± 8.9	275.0 ± 8.2	102 ± 3.6	77.08	38.20	38.88
Turbidity (NTU)	210 ± 5.6	28 ± 1.4	21.5 ± 1.4	89.76	86.67	3.10
COD (mgL ⁻¹)	710.8 ± 8.1	372.7 ± 6.6	280 ± 5.6	60.61	47.57	13.04

Steady-state conditions for discoloration and turbidity removal were achieved at 1 h, beyond which no appreciable change was observed. The underlying mechanism could be the formation of reactive oxygen species during the process. The rGO sheets might act as electron scavengers to support an advanced electron-transfer pathway (Das and Adak, 2024). The comparison

of effluent treated with rGO–TiO₂ (centrifugation) with WWTP effluent shows a 38.88% improvement in color removal ($t(4) = 33.50$, $p < 0.001$), a 3.1% improvement in turbidity removal ($t(4) = 6.85$, $p = 0.002$), and a 13.04% improvement in COD reduction ($t(4) = 18.55$, $p < 0.001$). Industries commonly employ the coagulation–flocculation–decantation method using aluminum sulfate

at pH 9–10 for the removal of suspended solids. However, these processes are largely ineffective in eliminating dissolved contaminants such as heavy metals and dyes. Hence, additional adsorption-based treatment may be required to achieve complete remediation of industrial WWTP effluents. Several researchers have investigated adsorption as a tertiary treatment for textile effluents to reduce COD.

3.7 Separation via Gravitational Decantation

Even without centrifugation, the decanted volume stabilized at 10 mL after 30 min. Table 3 presents the apparent color and turbidity data following treatment and a 2 h settling period.

The outcomes showed that while centrifugation significantly enhanced the overall efficiency, NC treatment followed by gravitational decantation remains highly effective. The decantation method resulted in 28.54% improvement in apparent color removal ($t(4) =$

45.68, $p < 0.001$). A 1% improvement in turbidity removal was found to be statistically similar ($t(4) = 1.70$, $p = 0.164$ (ns)). This parity in turbidity removal suggests that the NC can match the performance of existing industrial plants using only natural sedimentation and can significantly reduce energy requirements. Many studies are being conducted on water samples spiked with textile dyes to determine the remediation potential of novel nanoparticles. However, this research demonstrated that rGO–TiO₂ has potential for treating complex industrial wastewater effluents. The rGO–TiO₂ NC exhibits desirable properties such as enhanced water dispersibility, broad pH applicability, and a tendency toward sedimentation. These characteristics make the nanocomposite a promising candidate for wastewater treatment applications. For efficient recovery of the NC, additional techniques such as adsorption or low-to-medium-speed centrifugation could be employed to accelerate the process compared to gravitational sedimentation.

Table 3. Comparison of the treatment efficiencies of rGO–TiO₂ NC (decantation) and WWTP

Parameters	Textile Effluent	WWTP Effluent	rGO–TiO ₂ Effluent After Settling	Efficiency of rGO–TiO ₂ Treatment (%)	Efficiency of WWTP (%)	% Improvement in rGO–TiO ₂ Treatment
Color (Hazen)	445 ± 8.9	275.0 ± 1.5	148 ± 4.5	66.74	38.20	28.54
Turbidity (NTU)	210 ± 5.6	28 ± 1.8	25.9 ± 1.2	87.67	86.67	1.00

4. CONCLUSION

In this study, a sustainable green synthesis approach employing *Calotropis gigantea* leaf extract was successfully developed for the synthesis of an rGO–TiO₂ bio-nanocomposite. Analytical characterization confirmed the effective attachment of TiO₂ micro-balls onto the rGO matrix. The remediation performance of the synthesized rGO–TiO₂ NC compares favorably with existing industrial technologies. While traditional coagulation–flocculation methods primarily target suspended solids, they remain ineffective for dissolved recalcitrant dyes. The remediation of real-world textile effluent demonstrated that this bio-nanocomposite significantly outperforms existing industrial coagulation–flocculation standards, achieving a 90% reduction in turbidity, 77% color removal, and a 61% reduction in COD within one hour. While these results suggest an enhanced effect in which rGO may improve photocatalytic efficiency, the precise charge-transfer kinetics mechanism requires further elucidation through advanced electrochemical studies. Despite the high performance observed, the study is limited by the need for additional evaluation of the nanocomposite's reusability and long-term stability in complex effluents. Therefore, future research could focus on the operational

economics and scalability of this approach to ensure its viability as a cost-effective and environmentally friendly tertiary treatment strategy for large-scale industrial wastewater management.

DATA AVAILABILITY STATEMENT

Data available on request.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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