



Green Synthesized ZnO/rGO/*P. guajava* Nanocomposite for Photocatalytic Dye Degradation and Antifungal Studies

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Industrial discharge of dye-containing wastewater and microbial contamination pose environmental and health concerns, necessitating the development of stable and eco-friendly multifunctional materials. ZnO shows photocatalytic and antimicrobial activity, but its application is limited by rapid electron-hole recombination and reduced stability. To address these limitations, a ZnO/rGO/*Psidium guajava* nanocomposite was prepared using *P. guajava* leaf extract through a sol-gel method. *Psidium guajava* leaf extract was employed as a green reducing and stabilizing agent for ZnO/rGO nanocomposite synthesis, yielding a multifunctional material with photocatalytic and antifungal properties. Phytochemicals served as reducing and stabilizing agents during synthesis. The nanocomposite was characterized using XRD, FTIR, SEM, and UV-DRS, and photocatalytic activity was assessed for MG degradation under UV-A irradiation by varying pH, catalyst dosage, dye concentration, and reusability. The nanocomposite achieved ~100% MG degradation within 90 min at pH 7, 75 mg catalyst, and 2×10⁻⁴ M under UV-A irradiation. The nanocomposite showed a band gap of 2.9 eV, optimum catalyst dosage of 75 mg, and retained 85% degradation efficiency after five cycles. Scavenger studies indicated superoxide radicals as the primary reactive species. The nanocomposite exhibited limited antifungal activity consistent with reported ZnO/rGO composites, suggesting potential applicability for laboratory-scale wastewater treatment and antimicrobial studies.

Keywords: Reduced graphene oxide; Reactive oxygen species; Malachite green removal; Nanostructured photocatalyst; Environmental remediation; Charge separation.

1. INTRODUCTION

Industrial and urban development has increased the release of hazardous organic pollutants into aquatic systems, posing risks to ecosystem stability and human health. Dye-laden effluents from textile, paper, leather, and pharmaceutical industries are recalcitrant contaminants due to their complex aromatic structures and resistance to biodegradation (Kumar *et al.* 2025a; Kumar *et al.* 2025b). Synthetic dyes exhibit toxicity, including carcinogenic and mutagenic effects, impeding light penetration and disrupting aquatic ecosystems (Murhekar *et al.* 2021). Conventional treatment approaches, including adsorption, coagulation, and biological processes, show limited efficacy in complete mineralization and may generate secondary waste streams (Singh *et al.* 2025). Semiconductor-assisted photocatalysis has gained attention for decomposing toxic organic pollutants under light irradiation (Negash *et al.* 2023; Zhu *et al.* 2020), owing to its cost-effectiveness and solar energy utilization. Semiconductor photocatalysts generate electron-hole pairs that produce reactive oxygen species, facilitating degradation and mineralization of pollutants (Guo *et al.* 2023). ZnO has

attracted interest due to its photosensitivity, oxidative ability, non-toxicity, and cost-effectiveness for antimicrobial and photocatalytic applications, with a wide band gap of approximately 3.2 eV under UV light irradiation (Xia *et al.* 2022).

The practical applicability of ZnO is intrinsically constrained by the rapid recombination of photogenerated electron-hole pairs, along with its limited utilization of the visible light spectrum arising from its wide band gap (Bharathi *et al.* 2022). These inherent limitations markedly diminish its photocatalytic efficiency and hinder its performance under natural sunlight conditions (Salomão *et al.* 2021). In order to overcome these challenges, a range of modification strategies, including elemental doping, heterojunction engineering, and coupling with carbon-based materials, have been extensively investigated to enhance its photocatalytic performance (Wei *et al.* 2023). The advanced material modification strategies, including the incorporation of reduced graphene oxide (rGO), have emerged as a particularly effective route for enhancing photocatalytic performance. rGO, a two-dimensional carbonaceous material, is distinguished by its exceptional

electrical conductivity, large specific surface area, and superior electron mobility (Cai *et al.* 2021). When integrated with ZnO, rGO serves as an efficient electron acceptor and conductive network, facilitating rapid charge transport, promoting effective separation of photogenerated electron-hole pairs, and thereby suppressing their recombination (Li *et al.* 2021). Such improved charge carrier dynamics significantly prolong the lifetime of reactive species, ultimately leading to enhanced photocatalytic activity (Al-Dhabi *et al.* 2020). Furthermore, the incorporation of rGO introduces abundant adsorption sites for organic pollutants through π - π interactions, thereby further augmenting the overall degradation efficiency (Singh *et al.* 2022).

The development of green synthesis methodologies for nanomaterials has garnered considerable attention. *P. guajava* leaf extract was selected due to its abundance of polyphenols, flavonoids, and other bioactive compounds that can act as natural reducing and stabilizing agents during nanocomposite synthesis. These phytochemicals effectively function as both reducing and stabilizing agents, facilitating the synthesis of nanomaterials without reliance on hazardous chemical reagents (El-Maksoud *et al.* 2026). Such an eco-friendly strategy not only mitigates environmental impact but also enhances the biocompatibility and functional attributes of the resulting materials. *Psidium guajava* (guava) leaves have emerged as a promising bioresource, owing to their rich reservoir of bioactive phytochemicals, including quercetin, tannins, and polyphenols, which play a pivotal role in nanoparticle synthesis (Maheswari and Sugapriya, 2025). Naturally derived biomolecules assist in metal ion conversion while maintaining the stability of nanostructures with uniform size and shape. (Babae *et al.* 2021). Furthermore, guava leaf extract exhibits inherent antimicrobial and antifungal properties, which can impart additional biological functionality to the synthesized nanocomposites (Alsaif *et al.* 2025). Consequently, the integration of such plant-derived constituents into nanomaterials offers an advantage, combining environmentally benign synthesis with enhanced performance.

The present study is directed toward the synthesis of a ZnO/rGO/*P. guajava* nanocomposite via a green sol-gel approach. The sol-gel technique offers superior control over particle size distribution, morphological characteristics, and compositional homogeneity, rendering it particularly suitable for the fabrication of advanced nanocomposite systems (Verma *et al.* 2022). The incorporation of rGO is envisaged to facilitate efficient electron transport and promote effective charge carrier separation. At the same time, the utilization of *P. guajava* leaf extract ensures an

environmentally benign and sustainable synthesis route. The prepared nanocomposite is expected to exhibit a reduced band gap along with enhanced photocatalytic activity under UV-A (365 nm) irradiation. The synthesized nanocomposite is further explored through its antifungal activity. The emergence of multifunctional nanocomposite materials capable of simultaneously eliminating organic pollutants and microbial contaminants has gained considerable importance for advanced and sustainable water treatment technologies (Padmavathy *et al.* 2026). The synergistic interaction between ZnO, rGO, and plant-derived phytochemicals enhances photocatalytic and biological activities, making multifunctional ZnO/rGO nanocomposites promising materials for addressing environmental pollution and microbial contamination. Combining green synthesis with nanocomposite design provides a promising approach for environmental remediation and antimicrobial applications; however, further studies involving real wastewater systems and practical operating conditions required. Despite extensive studies on ZnO/rGO photocatalysts, limited attention has been given to *P. guajava*-mediated green synthesis and its combined photocatalytic and antifungal applications. Therefore, the present study aims to develop a green-synthesized ZnO/rGO/*P. guajava* nanocomposite and evaluate its photocatalytic degradation and antifungal performance.

2. MATERIALS AND METHODS

2.1 Materials

Zinc sulphate heptahydrate ($\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$), Sodium hydroxide (NaOH), Ethanol ($\text{C}_2\text{H}_5\text{OH}$), Distilled water (DW), Graphite powder, potassium permanganate (KMnO_4), sulfuric acid (H_2SO_4), phosphoric acid (H_3PO_4), ascorbic acid, hydrogen peroxide (H_2O_2 , 30 wt.%), ethanol ($\text{C}_2\text{H}_5\text{OH}$), and distilled water (DW), *P. Guajava* leaves, Graphene oxide (GO), Zinc oxide (ZnO), Malachite Green (MG), Mueller Hinton Agar (MHA), Sabouraud Dextrose Agar (SDA), Sterile broth, 0.5 Mc Farland standard, Standard antimicrobial agents (control), *Candida albicans*, *Aspergillus niger*, *Escherichia coli*.

2.2 Synthesis of ZnO Nanoparticles

A precursor solution of $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$ was prepared using DW. NaOH solution was added dropwise under continuous stirring to form a homogeneous solution. The reaction mixture was maintained at 50–60 °C until a thick whitish gel was obtained. The formed gel was washed several times using DW and $\text{C}_2\text{H}_5\text{OH}$ to remove residual impurities. The washed product was

dried in an oven at 100–120 °C. The dried material was then ground and subjected to calcination at 400–600 °C for several hours to obtain ZnO nanoparticles.

2.3 Synthesis of rGO

GO was synthesized from graphite powder via chemical oxidation using KMnO_4 in a mixed acid medium of $\text{H}_2\text{SO}_4/\text{H}_3\text{PO}_4$ (9:1, v/v) at 50°C for 12 h. The resulting graphite oxide was dispersed in DW and stirred at 60°C for 12 h to obtain exfoliated GO, followed by filtration, centrifugation, and drying at 60°C for 24 hrs (Zhao *et al.* 2021). For reduction, GO (400 mg) was dispersed in 400 mL of distilled water (0.1 mg mL^{-1}), and ascorbic acid (4 g) was added. The mixture was stirred at 60°C for 30 min, and the product was collected by centrifugation at 4000 rpm for 40 min. Residual ascorbic acid was removed by treating with 30 wt.% H_2O_2 under stirring at 60°C for 30 min. The final product was centrifuged, washed with ethanol and distilled water three times, and dried at 120 °C for 24 h to obtain reduced graphene oxide (rGO).

2.4 Synthesis of *P. guajava*

Fresh leaves were collected and washed thoroughly with distilled water to remove impurities. The cleaned leaves were shade-dried at room temperature ($25 \pm 2^\circ\text{C}$) and then ground into a fine powder. For aqueous extraction, 5–10 g of the powdered sample was mixed with 100 mL of distilled water and heated at 60–80 °C for 20–30 minutes under continuous stirring, and kept under stirring for 24 hours at room temperature. The obtained powder was stored at 4 °C for further use.

2.5 Synthesis of ZnO/rGO/*P. guajava*

Graphene oxide was dispersed in distilled water and sonicated for 30–60 minutes to obtain a uniform suspension. Zinc oxide was then added to the GO suspension under continuous stirring to form a homogeneous solution. The *P. guajava* leaf powder was added slowly, and the mixture was maintained at 60–80 °C under stirring. During this process, the reduction of GO and the formation of ZnO nanoparticles occurred simultaneously. The reaction mixture was further stirred until precipitation was observed. The pH was adjusted using NaOH if required. The precipitate was collected by centrifugation, washed with distilled water and $\text{C}_2\text{H}_5\text{OH}$, and dried at 60–80 °C. Finally, the dried product was

calcined at 400–500 °C for 2–3 hours to obtain the 1, 3, 5 and 7 wt % ZnO/rGO/*P. guajava* composite. For the preparation of the composite, 1 g of ZnO was mixed with 10 mg of rGO and 10 mg of *P. guajava* extract under continuous stirring at 100 rpm for 3 h. The obtained product was dried and calcined at 400 °C. Different compositions (1, 3, 5, and 7 wt.%) were prepared by varying the rGO/*P. guajava* content while maintaining the ZnO amount constant.

2.6 Assessment of Antifungal Activity

The antimicrobial activity of the test compound ZnO/rGO/*P. guajava* was evaluated against *Candida albicans*, *Aspergillus niger* and *Escherichia coli* were used using standard antimicrobial assay procedures. The compound was dissolved in sterile water as a solvent to prepare a stock solution and subsequently diluted to obtain working concentrations of 10 µg/mL, 100 µg/mL, and 200 µg/mL. The bacterial strains were cultured on Mueller-Hinton Agar, while the fungal strain was maintained on Sabouraud Dextrose Agar, and all cultures were incubated under suitable conditions prior to the assay. A fresh inoculum of each microorganism was prepared in sterile broth and adjusted to match the 0.5 McFarland standard. The antimicrobial activity was assessed using the agar well diffusion method, where sterile agar plates were inoculated uniformly with the microbial suspension using a sterile swab. Wells were then aseptically punched into the agar, and different concentrations of ZnO/rGO/*P. guajava* were introduced into the respective wells. Plates were incubated at 37 °C for 24 hours for the fungal strain and at 28–30 °C for 48 hours. After incubation, the zones of inhibition surrounding the wells were measured in millimeters to determine the antimicrobial efficacy of the compound. All antimicrobial experiments were performed in triplicate ($n = 3$), the results were expressed as mean $\pm$ standard deviation, and the standard antifungal agent was used as the positive control.

The photocatalytic and antifungal behavior of the ZnO/rGO/*P. guajava* nanocomposite provides a basis for understanding its potential as a sustainable and multifunctional material. The observed performance may be due to the combined effect of ZnO, rGO, and plant-based components, although further studies are needed to confirm its behavior under different conditions as illustrated in Fig. 1.

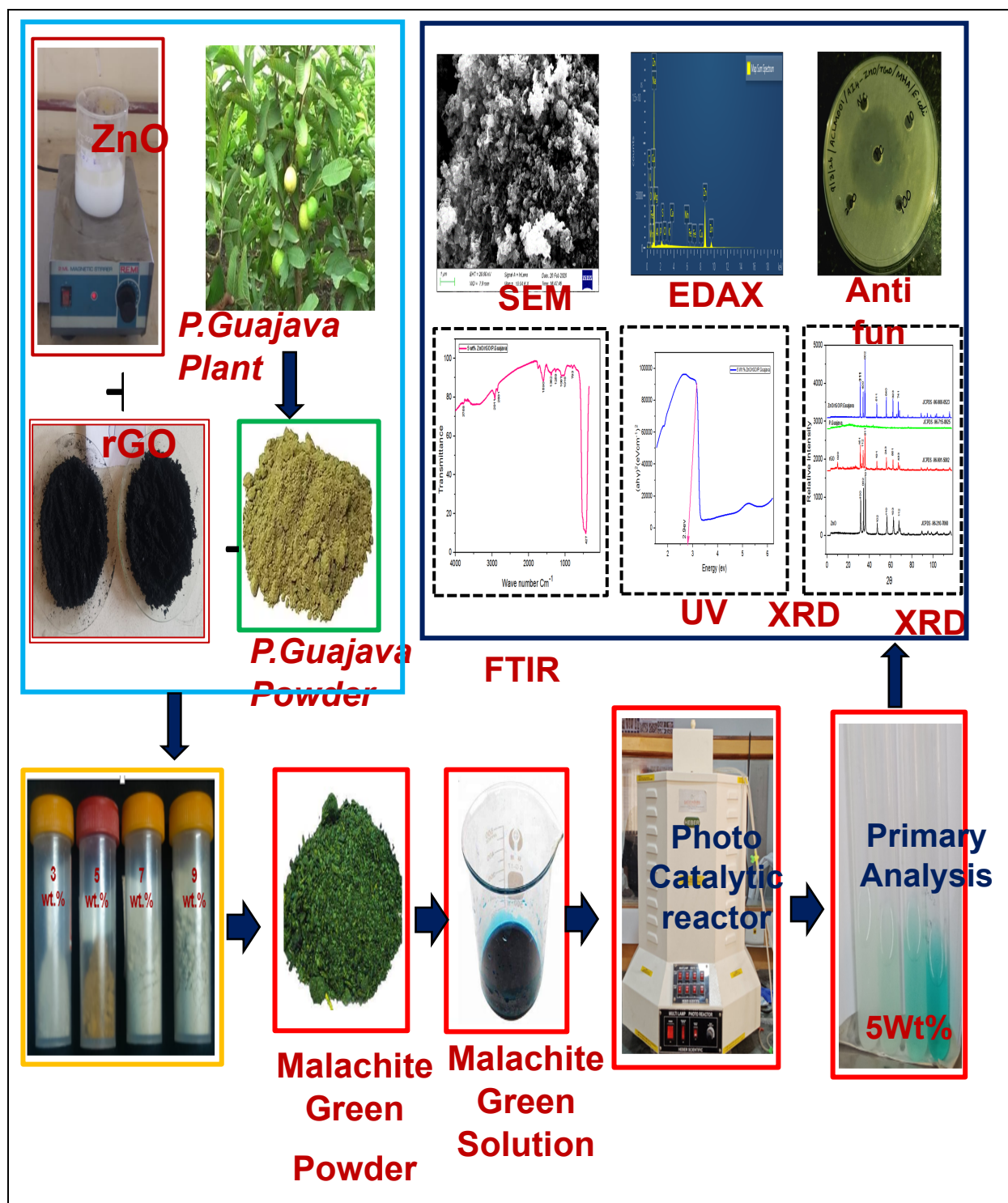


Fig. 1: Schematic illustration of the green synthesis and Photocatalytic degradation of the ZnO/rGO/*P. guajava* nanocomposite

3. CHARACTERIZATION

XRD analysis was performed using an ARL EQUINOX 3000 with Cu K α radiation over a 2θ range of 0–120°, based on Bragg's law, to examine the crystalline structure and phase composition of the samples. FTIR analysis was carried out using a JASCO FT/IR-6600 over

a wavenumber range of 7800–350 cm $^{-1}$ to identify functional groups and analyze the chemical composition of the samples. FESEM analysis was performed using a Carl Zeiss Sigma 300 to examine surface morphology, while EDS was employed for elemental composition analysis of the samples. UV–Vis–NIR analysis was performed using a JASCO V-670 over a wavelength

range of 190–2700 nm to evaluate the optical properties and absorption characteristics of the samples. Antimicrobial activity was evaluated by agar well diffusion using ZnO/rGO/*P. guajava* (10–200 µg/mL), and zones of inhibition were measured after incubation (24 h at 37 °C for bacteria; 28–30 °C for fungi) under aseptic conditions with appropriate controls.

4. RESULTS AND DISCUSSION

The photocatalytic degradation of MG dye using ZnO/rGO/*P. guajava* nanocomposites with varying weight percentages (1, 3, 5, and 7 wt.%) were evaluated under UV-A (365nm) irradiation. The degradation efficiency was monitored as a function of irradiation time (0–90 min), and the results are presented in Figure 2. The degradation efficiency increases progressively with irradiation time for all catalyst compositions. Kinetic analysis (pseudo-first-order model with R^2 values) and error analysis (mean $\pm$ SD, triplicate measurements) were incorporated into the photocatalytic degradation study. However, a significant variation in performance is observed depending on the wt.% of the nanocomposite. The 5 wt.% ZnO/rGO/*P. guajava* nanocomposite demonstrates the highest photocatalytic efficiency, achieving nearly complete degradation (~100%) within 90 minutes. This suggests that 5 wt.% represents the optimum catalyst loading for effective dye degradation. Therefore, the 5 wt.% ZnO/rGO/*P. guajava* nanocomposite was selected as the optimum composition for further characterization and application studies owing to its highest photocatalytic degradation efficiency among the investigated compositions (Wang *et al.* 2021).

$$(A_o - A_t) / A_o \times 100 \quad \dots (1)$$

Where, A_o = Initial absorbance of dye before irradiation

A_t = absorbance of dye after irradiation

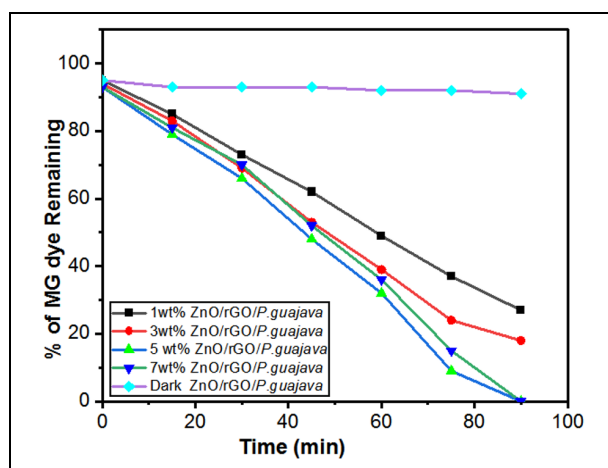


Fig. 2: Photodegradation of MG with ZnO/rGO/*P.guajava* catalysts under UV-A Light. [MG] = 4×10^{-4} M, airflow rate = 8.1 ml s^{-1} , pH = 7.0, $I_{UV} = 1.381 \times 10^{-6} \text{ einstein L}^{-1} \text{ s}^{-1}$

4.1 XRD

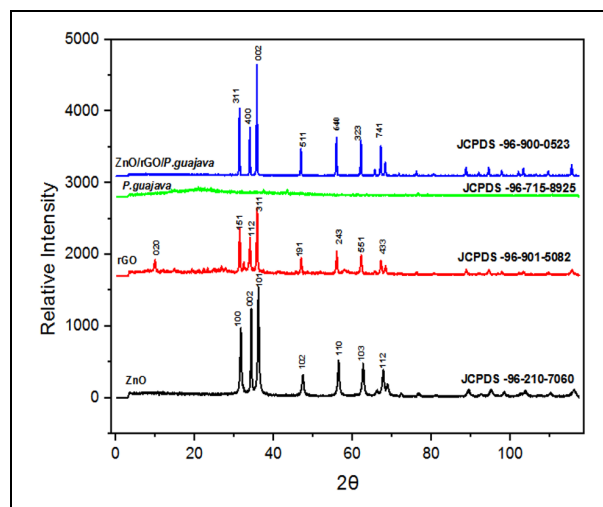


Fig. 3: XRD pattern of ZnO, rGO, *P. guajava*, ZnO/rGO/*P. guajava*

The XRD pattern obtained from Fig. 3 shows both sharp diffraction peaks and a broad low-angle feature, suggesting the presence of crystalline as well as less-ordered components is amorphous. The reflections in the 2θ range of 31° – 68° can be associated with ZnO, while a broad peak around $2\theta = 9.85^\circ$ may be attributed to rGO. A diffused background is also observed, which could be related to the amorphous nature of the *P. guajava* extract. The ZnO peaks appear to correspond to the (100), (002), (101), (102), (110), (103), and (112) planes, indicating a hexagonal wurtzite-type structure. The crystallite size and dislocation density were recalculated using corrected FWHM values to ensure accuracy. Peak broadening and slight intensity variations further support the successful incorporation of rGO and *P. guajava* extract within the ZnO matrix, indicating composite formation. The absence of additional distinct peaks may suggest that no significant secondary crystalline phases are present. The calculated d-spacing values are close to reported values, and the average crystallite size is estimated to be in the range of 26–30 nm, indicating a nanocrystalline nature. The relatively sharp peaks and limited broadening may point to good crystallinity with low lattice distortion. The (101) reflection appears relatively more intense, which could indicate a preferred orientation. The broad feature around $2\theta = 9.85^\circ$ may correspond to the (001) plane of rGO. The higher d-spacing (8.96 Å) compared to graphite could be due to residual functional groups and partial reduction. The peak broadness suggests low crystallinity and a disordered layered structure, with possible contributions from microstrain and structural defects. The *P. guajava* extract does not show distinct diffraction peaks but contributes as a broad amorphous background, consistent with its organic nature. These components may play a role during synthesis and could influence particle growth and dispersion. The coexistence of ZnO-

related peaks, a broad rGO feature, and an amorphous background suggests that ZnO, rGO, and *P. guajava* may be present within the composite system and is discussed in Table 1. The collective information confirms the successful incorporation of ZnO, rGO, and *P. guajava*-derived constituents into the synthesized nanocomposite. The ZnO/rGO/*P. guajava* composite is confirmed by peak broadening and reduced intensity, indicating successful incorporation of rGO and plant extract with ZnO, without impurity phases

4.2 UV-DRS

The UV-DRS spectra reveal that pure ZnO shows a well-defined absorption edge around 400–420 nm, corresponding to a band gap of 3.0–3.2 eV, which is characteristic of its intrinsic electronic transition. In contrast, rGO exhibits a broader absorption profile extending into the visible region, with a comparatively lower band gap of 2.5 eV, arising from its π - π^* electronic

transitions and delocalized electron structure. For the ZnO/rGO/*P. guajava* composite, the absorption edge is observed to shift slightly toward the higher wavelength region relative to pure ZnO. The band gap, estimated from the Tauc plot using

$$(\alpha h\nu)^2 = A(h\nu - E_g) \quad \dots (2)$$

is found to be 2.9 eV. The obtained band gap of 2.9 eV shows a slight reduction compared to pure ZnO, indicating improved visible light absorption due to rGO incorporation and interaction with *P. guajava* derived components. The intermediate band gap of the composite, between ZnO and rGO, indicates modified optical behavior. This change is attributed to ZnO-rGO interaction and the influence of *P. guajava* phytochemicals, which may introduce additional electronic states and enhance light absorption, as shown in Fig. 4.

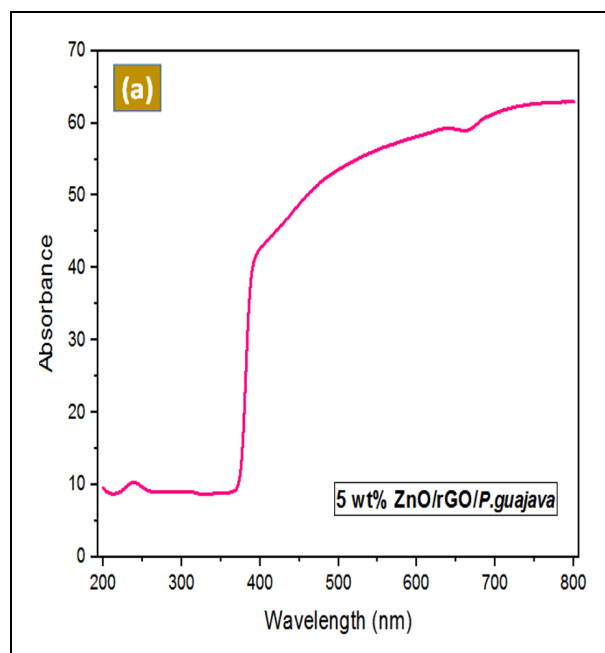
Table 1. XRD parameters of ZnO, rGO, and ZnO/rGO/*P. guajava* composite

Material	Crystal Structure	FWHM	$\beta = \text{FWHM} \times \pi / 180$	Crystallite Size (nm) $D = K\lambda / \beta \cos\theta$	d-Spacing	DI
ZnO	Hexagonal Wurtzite	5.906	0.1030344	23.18	3.61	0.0041
rGO	Orthorhombic	0.354	0.1030344	26.94	3.61	0.2497
<i>P. guajava</i>	Amorphous	3.74	62.624222	7.1	24.96	0.469
ZnO/rGO/ <i>P. guajava</i>	Orthorhombic	0.354	0.1030344	26.94	3.615	0.24

4.3 FTIR

The FTIR spectrum of the ZnO/rGO/*P. guajava* composite (Fig. 5) shows characteristic Zn–O stretching at 400–600 cm^{-1} , confirming ZnO nanoparticles. rGO-related peaks include C=O ($\sim 1700 \text{ cm}^{-1}$), C=C ($1550\text{--}1600 \text{ cm}^{-1}$), and C–O ($1000\text{--}1300 \text{ cm}^{-1}$), indicating residual oxygen-containing functional groups. Compared to the individual components, noticeable peak shifts and intensity variations in Zn–O, C=C, and O–H bands indicate strong interfacial interactions between ZnO, rGO, and *P. guajava*-derived phytochemicals. The broad band at $3200\text{--}3500 \text{ cm}^{-1}$ is assigned to O–H stretching from hydroxyl groups, adsorbed moisture, and *P. guajava* phytochemicals, while peaks near 2900 cm^{-1} correspond to C–H stretching of plant-derived compounds. Compared to pure ZnO and rGO, peak shifts and intensity changes indicate interactions among ZnO, rGO, and phytochemical constituents. These characteristic Zn–O, C=C, C–O, and O–H vibrational bands, together with the observed peak shifts, provide evidence for the interaction between ZnO, rGO, and *P. guajava*-derived phytochemicals, confirming successful composite formation. The observed interactions between ZnO, rGO, and *P. guajava*-derived functional groups are

consistent with recent reports, indicating improved composite stability and functional properties (Paul *et al.* 2025).



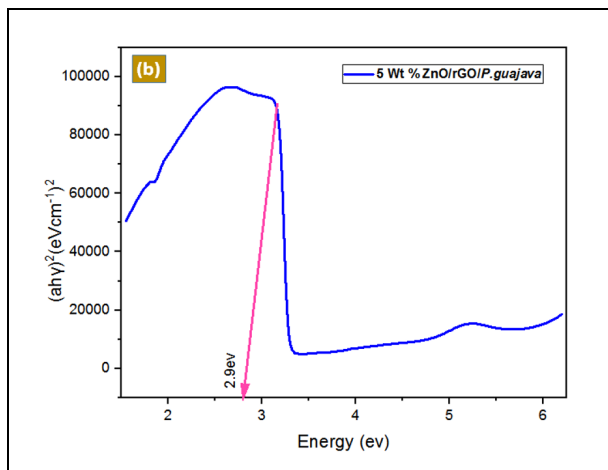


Fig. 4: (a) UV–DRS spectrum and corresponding and (b) Tauc plot showing band gap of 5wt.% ZnO/rGO/*P. guajava*

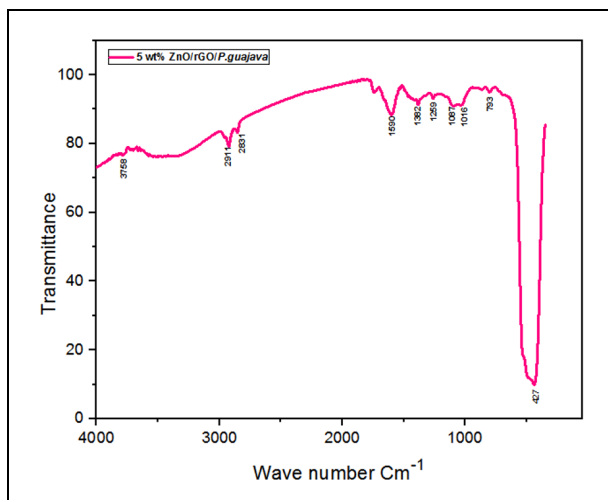


Fig. 5: FTIR Pattern of 5wt.% of ZnO/rGO/*P. guajava*

4.4 Morphological Studies SEM with EDX Mapping

The SEM images (Fig. 6a-b) of the 5 wt.% ZnO/rGO/*P. guajava* composite shows a rough, irregular morphology with ZnO nanoparticles uniformly distributed on rGO sheets. Low magnification (1 μm) reveals agglomerated clusters, while high magnification (200 nm) confirms ZnO attachment on wrinkled rGO layers. The porous and rough surface suggests enhanced

active surface area for photocatalytic activity. The SEM–EDX analysis (Fig. 6c-d) has been revised by including particle size distribution, elemental mapping, and quantitative analysis, confirming uniform ZnO distribution on rGO and validating composite formation. No significant particle separation is observed, indicating good dispersion of ZnO on rGO. *P. guajava* extract likely acted as a reducing and stabilizing agent, controlling particle growth and reducing agglomeration. EDX confirms Zn, O, and C elements corresponding to ZnO, rGO, and plant-derived residues, with a minor Na peak attributed to precursor impurities. The combined SEM and EDX results reveal the attachment of ZnO nanoparticles on rGO sheets and the presence of Zn, O, and C elements, thereby confirming the successful formation of the ZnO/rGO/*P. guajava* nanocomposite. The effective distribution of ZnO nanoparticles over rGO sheets may facilitate enhanced interfacial interaction and improved photocatalytic behavior, which is consistent with previous ZnO/rGO-based studies.

4.5 Antifungal Activity

The antifungal activity of the 5 wt.% ZnO/rGO/*P. guajava* nanocomposite was evaluated by agar well diffusion against different fungal strains. The observed inhibition zones indicate interaction with fungal organisms and concentration-dependent behavior. ZnO nanoparticles exhibit antifungal activity due to surface reactivity and ROS generation, affecting fungal cell membranes (Sharma *et al.* 2023). Similarly, graphene-based materials such as graphene oxide and reduced graphene oxide show antifungal properties due to their high surface area and interactions with microbial cells. (Izzi *et al.* 2023). The antifungal response can be associated with the combined contribution of ZnO, rGO, and plant-derived constituents, supporting the multifunctional nature of the synthesized nanocomposite. Figure 7 shows ZnO nanoparticles dispersed on rGO sheets with *P. guajava* phytochemical residues. These phytochemicals likely aid surface stabilization and remain associated with the composite. The antifungal response is attributed to the combined effect of ZnO, rGO, and plant-derived constituents. Clear inhibition zones confirm antifungal activity, and individual material contributions are given in Table 2. The ZnO/rGO/*P. guajava* composite exhibits measurable antifungal activity.

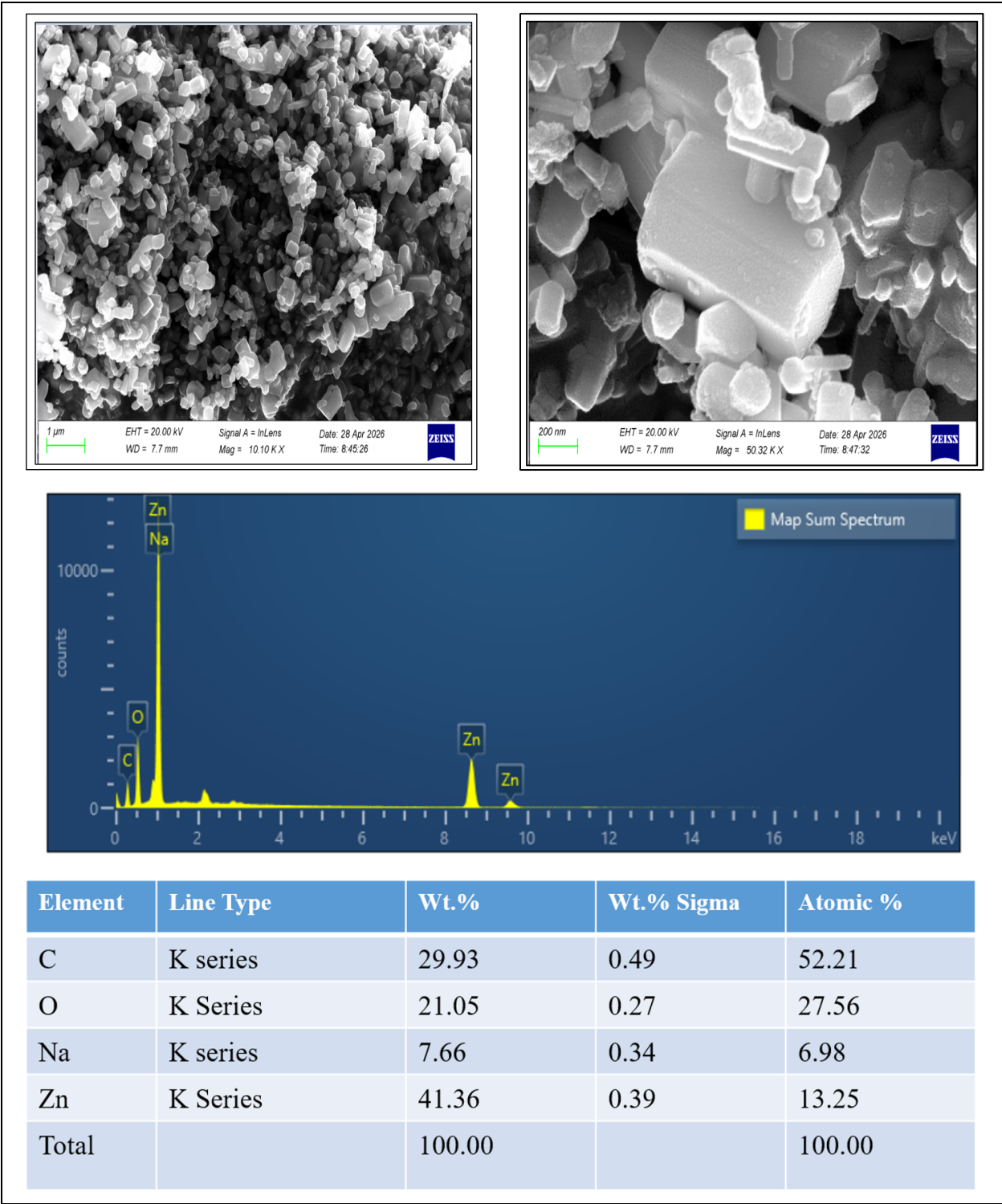


Fig. 6: (a, b) SEM images, (c) EDX spectrum, and (d) Elemental composition of 5 wt.% ZnO/rGO/*P. guajava*



Fig. 7: Agar well diffusion assay confirming concentration-dependent Antifungal activity of 75 wt.% ZnO/rGO/*P. guajava*

Table 2. Zone of inhibition values of 5 wt.% ZnO/rGO/*P. guajava* nanocomposite against tested fungal strains at varying concentrations

Organism	NC/PC (mm)	10µg/mL (mm)	100 µg/mL (mm)	200 µg/mL (mm)
<i>Candida albicans</i>	3.4	—	1.5	2
<i>Aspergillus niger</i>	—	—	—	—
<i>Escherichia coli</i>	4	—	2	2

4.6 Influence of Process Parameters on Photodegradation of MG by ZnO/rGO/*P. guajava* Catalyst With UV-A Light

4.6.1 Influence of pH

The photocatalytic degradation of malachite green using the ZnO/rGO/*P. guajava* nanocomposite was studied over a pH range of 4–8 under UV-A irradiation (Fig. 8). The degradation efficiency was strongly dependent on pH due to variations in catalyst surface charge and dye–catalyst interactions. Maximum degradation was observed at pH 7, achieving nearly complete removal within 90 min, attributed to favorable adsorption and enhanced generation of reactive oxygen species ($\bullet\text{OH}$ and $\text{O}_2\bullet^-$). The presence of rGO facilitated efficient charge separation and reduced electron–hole recombination, improving photocatalytic performance. Lower efficiency at pH 4–5 was due to competition of H^+ ions for active sites and suppressed radical formation, while at pH 6 and 8 moderate activity was observed. At higher pH, excess OH^- ions may induce electrostatic repulsion, reducing dye–catalyst interaction. Thus, pH 7 was identified as the optimum condition for MG degradation using the ZnO/rGO/*P. guajava* nanocomposite, demonstrating its efficient photocatalytic performance under neutral conditions supported by previous literature reports (Padmavathy *et*

al. 2026), and the rate constant values are discussed in Table 3.

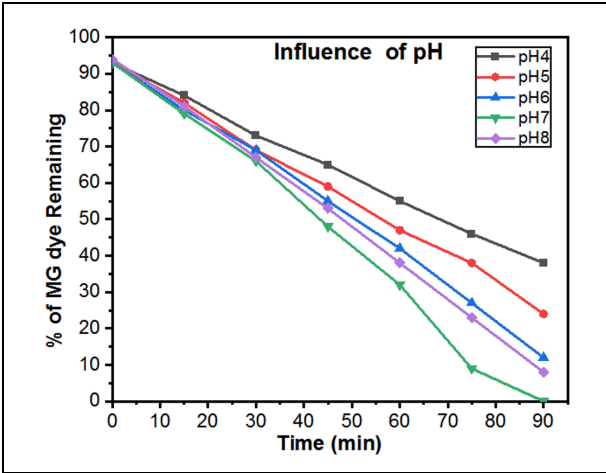


Fig. 8: Influence of pH on UV- Degradation [MG] = 4×10^{-4} M, 5 wt.% ZnO/ rGO/*P.guajava* = 2 g L^{-1} , airflow rate = 8.1 mL s^{-1} , irradiation time = 60 min, $I_{\text{UV-A}} = 1.381 \times 10^{-6} \text{ einstein L}^{-1} \text{ s}^{-1}$

Table 3. Rate constant values for MG dye degradation at different pH conditions using ZnO/rGO/*P. guajava* nanocomposites under UV-A irradiation

S. No.	pH	Rate Constant $k \text{ (min}^{-1}\text{)}$
1	4	0.014
2	5	0.021
3	6	0.031
4	7	0.047
5	8	0.028

4.6.2 Influence of Dye Concentration

The photocatalytic degradation efficiency of MG using ZnO/rGO/*P. guajava* nanocomposites (Fig. 9) was strongly dependent on initial dye concentration. The highest degradation was observed at $2 \times 10^{-5} \text{ M}$ due to sufficient active sites and improved light penetration, which enhanced reactive oxygen species generation. With increasing concentration (3×10^{-5} to $5 \times 10^{-5} \text{ M}$), the

efficiency decreased due to reduced light penetration (screening effect), competition for active sites, and surface saturation. The accumulation of intermediate species may further suppress radical activity, resulting in lower degradation performance. Therefore, $2 \times 10^{-5} \text{ M}$ was identified as the optimum dye concentration for efficient MG degradation, consistent with reported photocatalytic studies (Padmavathy *et al.* 2026) and the rate constant value of all concentrations is discussed in Table 4.

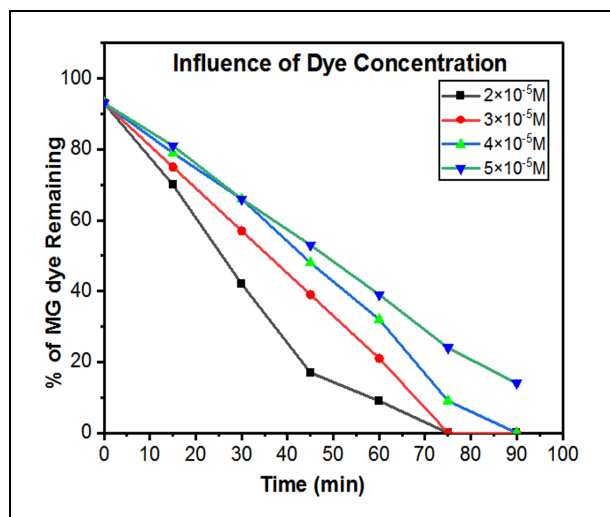


Fig. 9: Influence of dye concentration UV-A (degradation). 5 wt.% ZnO/rGO/P. *guajava* = 3 g L⁻¹, airflow rate = 8.1 mL s⁻¹, pH = 7.0, irradiation time = 60 min

Table 4. Rate constant values for MG dye degradation of ZnO/rGO/P. *guajava* nanocomposites at different dye concentrations under UV-A light

S. No.	Initial Concentration	Rate Constant k (min ⁻¹)
1	2×10^{-5}	0.041
2	3×10^{-5}	0.033
3	4×10^{-5}	0.025
4	5×10^{-5}	0.018

4.6.3 Influence of Catalyst Dosage

The photocatalytic efficiency of the ZnO/rGO/P. *guajava* nanocomposite is governed by a critical balance between active site availability and light penetration. Figure.10. reveals that a 75 mg catalyst dosage is the optimum threshold, as it maximizes the generation of reactive oxygen species while maintaining favorable solution transparency, as reported in similar ZnO-based systems (Padmavathy *et al.* 2026). In contrast, lower dosages (25–50 mg) suffer from a surface area deficit, leaving dye molecules untreated due to a lack of available active sites. Conversely, exceeding the optimum at 100 mg triggers a shielding effect where high turbidity causes light scattering, preventing UV-A radiation from reaching the catalyst surface. Table.5. shows the rate constant values for MG dye degradation

of ZnO/rGO/P. *guajava* nanocomposites at different catalyst dosages. The obtained results indicate that 75 mg is the optimum catalyst dosage for effective MG degradation under the investigated conditions, which is comparable with previously reported ZnO-based photocatalytic systems (Padmavathy *et al.* 2026)

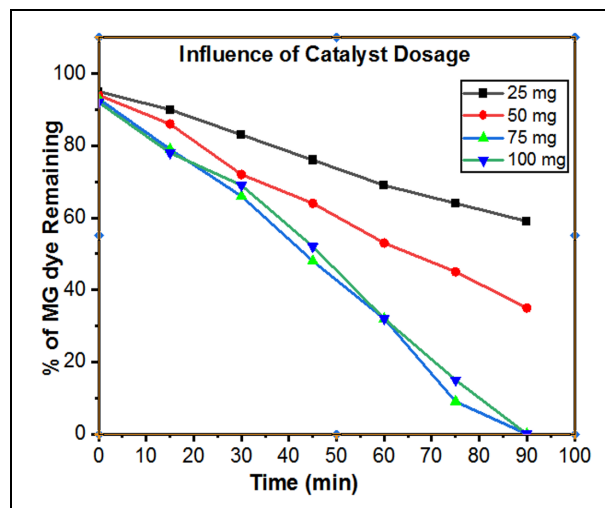


Fig. 10: Influence of Catalyst Loading on UV-A (degradation). [MG]= $4 \times 10^{-4} \text{ M}$ 5 wt.%ZnO/rGO/P. *guajava* = 2 g L⁻¹, airflow rate = 8.1 mL s⁻¹, irradiation time = 60 min, $I_{UV-A} = 1.381 \times 10^{-6} \text{ einstein L}^{-1} \text{ s}^{-1}$

Table 5. Rate constant values for MG dye degradation of ZnO/rGO/P. *guajava* nanocomposites at different catalyst dosages under UV-A light

S. No.	Catalyst Dosage (mg)	Rate Constant k (min ⁻¹)
1	25	0.011
2	50	0.024
3	75	0.046
4	100	0.039

4.6.4 Influence on Catalyst Reusability

The reusability of the ZnO/rGO/P. *guajava* nanocomposite was evaluated over five consecutive cycles for MG dye degradation, as represented in Fig. 11. The catalyst exhibited excellent stability, with the degradation efficiency decreasing only slightly from 100% in the first cycle to 85% in the fifth cycle. The good reusability is mainly attributed to the presence of rGO, which helps maintain the stability of ZnO and improves charge transfer during the photocatalytic process. The small reduction in efficiency may be due to minor catalyst loss during washing and recovery, as well as the accumulation of degradation residues on the catalyst surface after repeated use. These results indicate that the prepared nanocomposite exhibits good stability and reusability under laboratory conditions and may be considered for further evaluation in wastewater treatment studies.

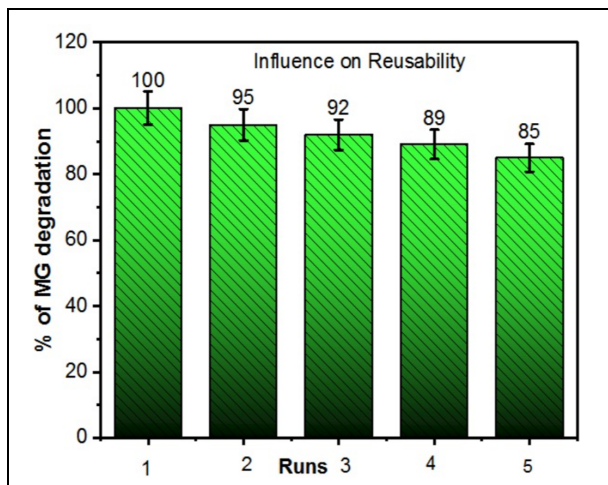


Fig. 11: Influence on reusability – UV-A [MG] = 4×10^{-4} M, 1 wt.% ZnO/rGO/*P.guajava* = 3 g L⁻¹, airflow rate = 8.1 mL s⁻¹, pH = 7.0, irradiation time = 60 min, $I_{UV} = 1.381 \times 10^{-6}$ einstein L⁻¹ s⁻¹

4.6.5 Scavenger Study

The scavenger experiment was conducted to identify the primary reactive oxygen species (ROS) responsible for photocatalytic degradation. When IPA (isopropanol), a hydroxyl radical ($\bullet$ OH) scavenger, was added, the degradation efficiency dropped most significantly from 100% to just 22%, indicating that $\bullet$ OH radicals are the dominant active species. The addition of KI (hole scavenger) reduced activity to 39%, suggesting holes (h^+) also play a considerable secondary role. BQ (benzoquinone) reduced degradation to 56%, confirming a moderate contribution of superoxide radicals ($\bullet$ O₂⁻), while AgNO₃ suppressed activity to 34%, reflecting a supporting role of electrons (e^-). These results collectively confirm that hydroxyl radicals ($\bullet$ OH) are the most influential species driving the photocatalytic degradation process, followed by h^+ , e^- , and $\bullet$ O₂⁻, suggesting a predominantly valence band hole-mediated oxidation mechanism is shown in the Figure 12.

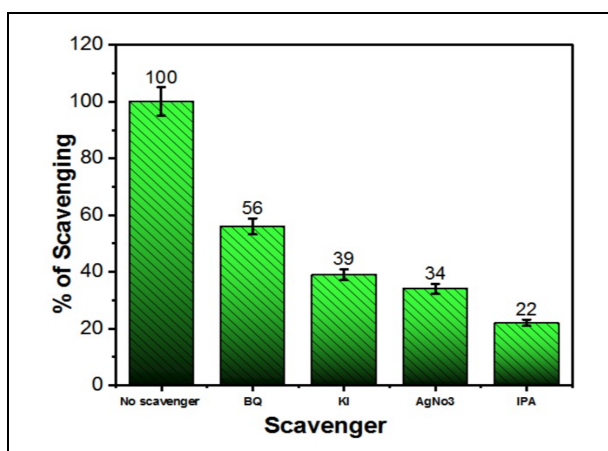


Fig. 12: Scavenger study for the photocatalytic degradation mechanism

5. CONCLUSIONS

The green synthesized ZnO/rGO/*P. guajava* nanocomposite was successfully prepared and demonstrated photocatalytic and antifungal performance. The prepared nanocomposite achieved 85% degradation of Malachite Green dye at pH 7, catalyst dosage of 75 mg, and initial dye concentration of 2×10^{-5} M within 90 min under UV-A irradiation. This study lies in the green synthesis strategy combined with the multifunctional role of *P. guajava* phytochemicals, which act as both reducing and stabilizing agents while simultaneously enhancing photocatalytic and antifungal performance through improved charge transfer dynamics. The nanocomposite retained about 85% degradation efficiency after five cycles, demonstrating good laboratory-scale stability and reusability, while further studies are required to evaluate its practical applicability. In addition, the synthesized material showed limited antifungal activity against the tested strains, with further optimization required before practical antimicrobial application. The present study is limited to laboratory conditions using model dye solutions and standard fungal strains; therefore, performance under real wastewater matrices and biocompatibility with biological systems remain to be established. The study is limited by its reliance on UV-dependent photocatalytic activity, which restricts practical solar utilization efficiency. The absence of real wastewater testing limits validation under complex environmental conditions, necessitating further studies for practical applicability. Future studies should focus on extending photocatalytic activity to visible-light irradiation through doping or heterojunction engineering, evaluating long-term catalyst stability under repeated use and varying environmental conditions, and assessing scale-up feasibility for practical wastewater treatment applications.

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AVAILABILITY OF DATA AND MATERIAL

The data that support the findings of this study are available from the corresponding author upon reasonable request.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the author used ChatGPT in order to improve the English text. After using this tool, the author reviewed and edited the content

as needed and takes full responsibility for the content of the publication.

DATA AVAILABILITY

Data will be made available on request.

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This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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