

Light-assisted synergistic effect of Zn-MOF@rGO nanocomposite for methylene blue degradation and toxicity analysis to water reclamation

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ABSTRACT

Integrating reduced graphene oxide (rGO) onto nanostructured Metal-organic frameworks (MOFs) offers a transformative strategy to amplify light harvesting in photocatalysis, suppressing charge carrier recombination and thus enhancing degradation processes. In this work, we develop a hybrid material (PUC-8@rGO) by incorporating rGO sheets onto Zn-MOF (PUC-8). The crystals of PUC-8 were prepared using the solvothermal method, and the nanocomposite material was synthesized using the wet-impregnation procedure. To measure the photocatalytic activity, prepared samples were utilized to degrade the methylene blue (MB) dye on exposure to visible light. Several factors affecting photocatalytic activity were examined, including pH, amount of dye, catalyst dosage and irradiation time to optimize photocatalysis. Remarkably, PUC-8@rGO exhibits an unprecedented 7 to 8-fold rate increase constant compared to PUC-8 and rGO, credited to its augmented BET surface area and a narrow band gap, which effectively prolongs electron-hole (e^-/h^+) recombination. Degradation pathway and intermediate product analysis were done using the LC-MS technique. The BOD (biological oxygen demand) and COD (chemical oxygen demand) levels in the water significantly reduced following treatment with PUC-8@rGO, falling within permissible limits for environmentally safe discharge. Furthermore, seed germination assays attest to low phytotoxicity, endorsing treated water for crop irrigation. Encouragingly, PUC-8@rGO displays potent cytotoxicity ($IC_{50} = 0.125$ mg/mL) against the human ovarian cancer cell line, SKOV3 as compared to HaCat (non-tumorous) cells ($IC_{50} = 0.25$ mg/mL), holding promising biomedical implications.

1. Introduction

The scarcity of safe drinking water is a critical global issue, intensified by pollutants like heavy metals, pesticides, antibiotics, and industrial dyes [1,2]. Dyes are extensively used in textiles, cosmetics, and pharmaceuticals, presenting unique challenges due to their persistence, toxicity, and bioaccumulation tendency [3,4]. Regulatory standards set limits for dye concentrations below 1 ppm, with acceptable biochemical oxygen demand (BOD) and chemical oxygen demand (COD) levels capped at 30 mg/L and 50 mg/L, respectively [5–7]. Textile production alone releases substantial dye effluents, estimated to reach approximately 100 tonnes annually [8]. Among these dyes, Methylene Blue (MB) is particularly harmful, as it blocks sunlight and oxygen in aquatic

environments [9], threatening ecosystem health due to its toxicity and resistance to biodegradation [10,11]. Traditional dye removal techniques, such as adsorption [12], coagulation [13], ultrafiltration [14], face limitations in dealing with MB's stability, highlighting the need for more advanced remediation approaches like photocatalysis. [15] Photocatalysis has emerged as a promising technology for pollutant degradation, utilizing light energy to activate semiconductor photocatalysts [16–19]. Metal oxide/sulfide nanoparticles and metal-coordinated polymer frameworks have potential, but optimization is still necessary to improve degradation efficiency [20–22]. Metal-organic frameworks (MOFs) have gained attention as photocatalysts due to their large surface area, customizable pores, and catalytically active sites, which aid in dye adsorption and breakdown [23–25]. However, MOFs face

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challenges such as high electron-hole recombination rates, limited charge transfer, poor recyclability, and limited light absorption, often requiring harmful UV light due to their large band gaps [26,27]. Addressing these issues calls for developing nanostructured materials or incorporating heterogeneous cocatalysts to enhance efficiency [28–30]. Nanostructured photocatalysts improve photon absorption, electron-hole generation, and reaction kinetics due to an increased surface area and more redox-active sites [31,32]. Reduced graphene oxide (rGO) has emerged as an effective cocatalyst known for its outstanding photoelectrical, thermal, and mechanical properties [33,34]. By providing robust support for MOFs, rGO enhances photocatalytic activity, improves recyclability, and provides superhydrophobic characteristics. In photocatalysis, rGO aids dye adsorption, facilitates active species movement, and captures excited electrons, thus reducing charge recombination [35–38]. Additionally, rGO improves interfacial charge transfer and prolongs electron-hole pair lifetimes by effectively separating photoinduced charges [28,39]. For example, Aadil *et al.* synthesized graphene-based composites like ZnO nanochips on graphene, achieving efficient degradation of Rhodamine-B and Methylene Blue under visible light [40–42]. Various graphene-MOF hybrids have been developed for photocatalytic applications, such as rGO/NH₂-MIL-125 (Ti) [43], ZIF-9@CA-Fe₃O₄/rGO/cellulose [44], and MOF-5@rGO, which leverage the electrostatic interactions between metal ions in MOFs and oxygen functional groups on rGO to reduce electron-hole recombination [33]. Furthermore, a heterogeneous PMS activator, Zn/Co-MOF@rGO-600, derived from a bimetallic MOF, was synthesized to degrade tetracycline (TC) [45]. In addition to MOFs, rGO-based composites like Cu-doped NiO/rGO have been developed, showing superior photocatalytic performance in Methylene Blue degradation compared to pristine NiO, underscoring rGO's importance in enhancing photocatalytic efficiency [46–48].

Although the literature extensively explores degradation pathways for MB, the reuse potential of treated water post-decomposition remains underexamined. Effective dye degradation offers environmental benefits if treated water can be repurposed for agriculture or other uses. For instance, Sonu *et al.* [49] developed a photocatalyst, TiO₂-TMAOH, for MB degradation, demonstrating the use of treated water in Vigna radiata seed germination to assess its suitability for irrigation. Such germination tests provide valuable insights into water quality after treatment, as organic contaminants in dye-laden wastewater can hinder plant growth and accumulate, impacting environmental health [50]. This study explores the synergistic potential of rGO-based nanocomposites, aiming to develop an efficient photocatalytic process for MB degradation and assess the feasibility of reusing treated water in environmental and agricultural applications.

This work develops a novel light-based degradation system (PUC-8@rGO) by incorporating reduced graphene oxide (rGO) sheets onto Zn-MOF (PUC-8) using wet-impregnation to break down methylene blue (MB). rGO was synthesized via a modified Hummers method, and the novel mixed ligand Zn-MOF (PUC-8) using 2,5-thiophene dicarboxylic acid and 1-(3-aminopropyl)imidazole linkers. The samples were characterized by SCXRD, FTIR, TGA, XPS, zeta potential, and BET, with surface morphology analyzed by HR-TEM and FE-SEM. PXRD analysis confirmed bulk phase purity. rGO incorporation turned partially hydrophilic PUC-8 into hydrophobic PUC-8@rGO, suitable for water treatment. PUC-8@rGO degraded 98.6 % of MB in 60 min under light irradiation, compared to 40 % by PUC-8 and rGO separately. This is due to rGO increasing the surface area and hydrophobicity, slowing photo-generated electron-hole pair recombination. Key photocatalysis parameters such as pH, catalyst amount, dye concentration, and exposure time were optimized. LC-MS examined degradation intermediates. The material showed significant anti-cancer activity against SKOV3 cells and was tested for seed germination to confirm treated water recyclability in agriculture.

2. Experimental section

2.1. Material and physical measurements

2,5-thiophene dicarboxylic acid (TDA), Zn(NO₃)₂·6H₂O and 1-(3-aminopropyl)imidazole were procured from Sigma Aldrich. FTIR spectra were determined using a Perkin Elmer FTIR 2000 spectrometer. The thermogravimetric analysis (TGA) data were implanted under the N₂ atmosphere using the SDT Q600 (V20.9 Build 20) instrument (Artisan Technology Group, Champaign, IL). PXRD experiments were conducted utilizing a PANalytical X'PertPRO X-ray diffractometer equipped with Cu K α radiation (λ = 1.54059 Å). The X-ray diffraction data (XRD) for the single crystal of PUC-8 (mounted on Hampton cryoloop) was collected using a Super-Nova (Mo) X-ray diffractometer comprising a micro-focus sealed X-ray tube with HyPix3000 detector and Mo-K α (λ = 0.71073 Å) as a source of x-rays. The Olex2 and ShelXL softwares were used for data-solving and refinement. The electronic spectra of the samples were recorded using a Hitachi 330 spectrophotometer. The surface characteristics were analyzed utilizing a Hitachi SU8010 field emission scanning electron microscope (FESEM). Additionally, the morphology and structure of the samples were investigated through Transmission Electron Microscopy (TEM) with high resolution (HR) using a Tecnai F-20 instrument. X-ray Photoelectron Spectroscopy (XPS) studies of PUC7 were conducted employing a PHI 5000 Versa Probe III instrument.

2.2. Synthesis of PUC-8

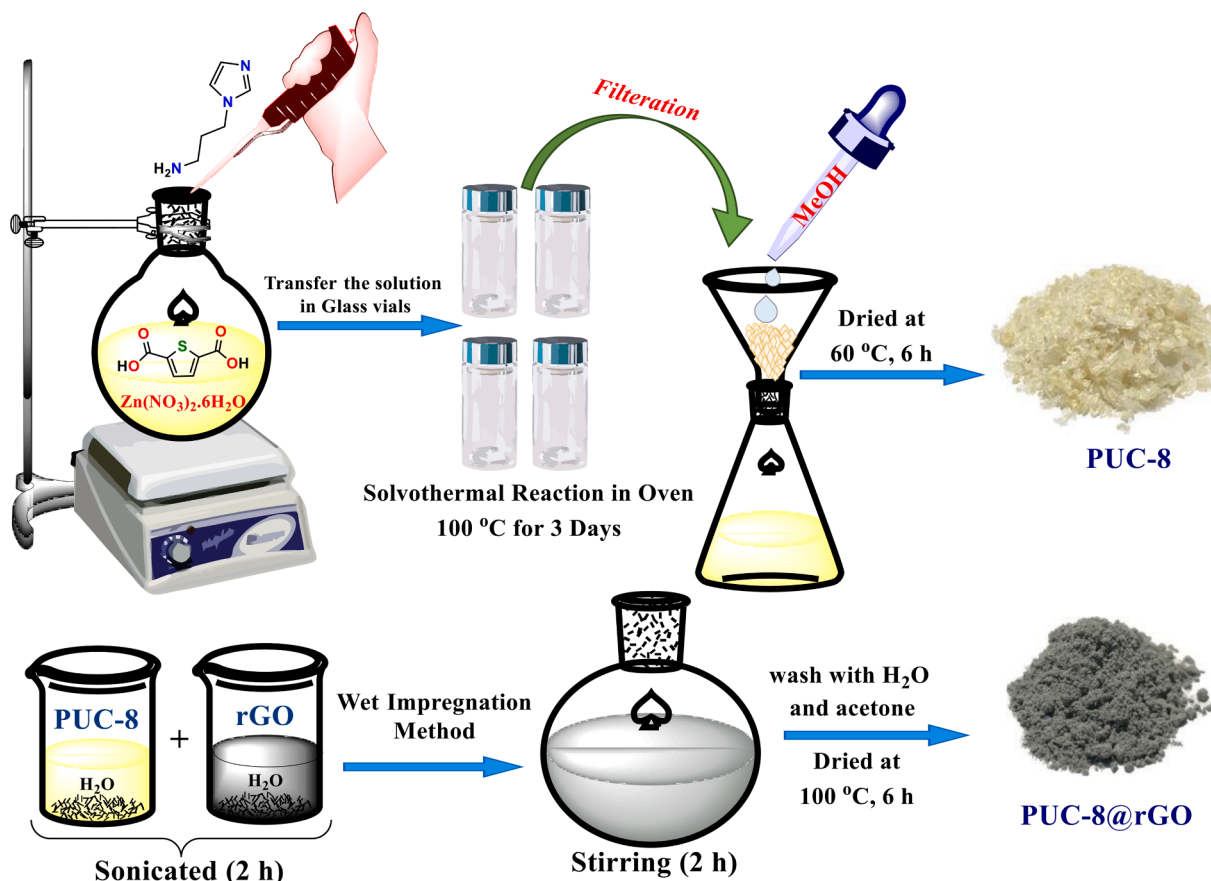
A simple and cost-effective solvothermal method was employed to successfully synthesize PUC-8 as depicted in [scheme 1](#). Firstly, 2,5-thiophene dicarboxylic acid (0.1 g, 0.58 mmol) and Zn(NO₃)₂·6H₂O (0.17 g, 0.58 mmol) were mixed in 20 mL of DMA:MeOH (4:1, v/v) solution. The solution was agitated for 10 min while adding 1-(3-aminopropyl)imidazole dropwise (69.2 μ L, 0.58 mmol). Subsequently, it was transferred into 5 mL glass vials and heated in an oven at 100 °C for 3 days, then gradually cooling to room temperature. The colourless block-shaped crystals of PUC-8 were then collected through filtration and rinsed multiple times with MeOH. [Yield = 81 %, based on TDA]. FTIR (cm⁻¹): 3455(w), 3256 (M), 3146 (M), 1612 (S), 1532 (S), 1352 (S), 1103 (M), 1033 (W), 814 (M), 764 (W), 525 (M).

2.3. Synthesis of PUC-8@rGO

The well-known Modified-hummers process was used for the synthesis of GO from graphite flakes. The reduction of GO in rGO was attained by using NaBH₄ as a reducing agent, as discussed in the [supplementary file](#). Further, PUC-8@rGO nanocomposites with various rGO contents were produced using a simple ultrasonic-assisted wet impregnation process as depicted in [scheme 1](#). In a typical procedure, 100 mg of fine-grinded PUC-8 in 30 mL water and a suitable amount of rGO (5, 10 and 15 wt%) in 10 mL water were sonicated separately for 2 h to obtain the well-dispersed solutions of both. The resulting suspension of PUC-8 was moved to a round bottom flask, and then the rGO solution of the relevant ratio was added gradually to the solution of PUC-8 with continuous stirring. After 2 h of stirring, grey coloured colloidal suspension of PUC-8@rGO was found. Further, it underwent filtration and washing with water, followed by acetone. Following this, the material was dried in an oven at 100 °C for a duration of 6 h.

2.4. Photocatalytic degradation experiments

The catalytic efficiency of PUC-8 and its composites with 5, 10 and 15 % (w/w) rGO was assessed by photocatalytic breakdown of MB. The electronic spectra of MB showed absorbance in the visible region (at 664 nm), This is accountable for the dye's blue coloration. Hence, the variation in absorbance at 664 nm was used to explain the findings of every



Scheme 1. Synthetic scheme of PUC-8 and PUC-8@rGO.

experiment. Firstly, some critical parameters such as time, catalyst dosage and pH were optimized to monitor the photocatalytic process. After optimization, 20 mg of PUC-8@rGO was dispersed in 20 mL (10 ppm) of MB and stirred for 40 min in the dark to attain the adsorption–desorption equilibrium. In the next step, the solution was transferred to a chamber containing a 100 W bulb as a visible light source to provide the reaction's photon energy.

Further, during the 60 min stirring process in light conditions, 3 mL aliquots of the solution were removed at a fixed interval of 10 min and centrifuged to remove any remaining particles of PUC-8@rGO. The remaining dye concentration in the supernatant was determined by UV–vis spectrophotometer. The percentage degradation efficacy of the catalyst was measured using Eq. (1) [51].

$$\text{DegradationEfficiency}(\%) = \frac{C_0 - C_t}{C_0} \times 100 \quad (1)$$

In the abovementioned equation, C_0 represents the initial dye concentration, and C_t represents the amount of dye remaining in the solution after irradiating for t min. C_t is calculated with the help of absorbance calibration curve of pure MB at different concentrations as shown in Fig. S1 and S2. To find out the degradation rate of MB over PUC-8@rGO, the experimental data was fitted in first-order kinetic equation as shown below [51].

$$\ln\left(\frac{C_0}{C_t}\right) = Kt \quad (2)$$

Where, t denotes the exposure time and K denotes the first-order rate constant value. C_0 denotes the initial dye concentration, while C_t indicates the dye concentration remaining in the solution after t minutes of irradiation. The degradation mechanism was explored by treating the

photocatalytic reaction suspension with different reagents known as radical scavengers with concentration of 1 mM, for instance benzoquinone (BQ), sodium iodide (NaI), isopropyl alcohol (IPA), and silver nitrate (SN) for scavenging $\cdot\text{O}_2^-$, $\cdot\text{OH}$, h^+ and e^- respectively. The reusability of PUC-8@rGO was checked by collecting the catalyst after completing the process via filtration, washing it with ethanol and deionized water, and further reusing it for the same photocatalytic process. It was repeated five times with the same procedure to prove the high regeneration capability of the catalyst.

The experimental section, including cytotoxicity analysis, seed germination experiments and BOD/COD calculations, is summarised in the [supplementary file](#).

3. Result and Discussion

3.1. Structural Description of PUC-8

The structural analysis of a mixed-ligand 2D metal–organic framework, PUC-8, was conducted using single-crystal X-ray diffraction (SCXRD). This MOF is based on 2,5-thiophene dicarboxylic acid (TDA) and 1-(3-aminopropyl)imidazole linkers and was produced through a solvothermal method. The crystallographic investigations confirmed that PUC-8 adopts a monoclinic crystal system with the $P2_1/c$ space group. In the PUC-8 structure, the fundamental unit consists of two central Zn^{2+} metal atoms coordinated by two imidazole units and three TDA molecules, as depicted in Fig. 1a and b. Each Zn^{2+} ion exhibits a distorted tetrahedral arrangement, coordinated by one nitrogen atom from an imidazole linker and three oxygen atoms from separate TDA linkers (Fig. 1c). These Zn^{2+} nodes are interlinked by TDA connectors, employing a $\mu^2-\eta^1\eta^1$ bridging mode. This arrangement forms a mononuclear secondary building block extending within the bc plane. Another

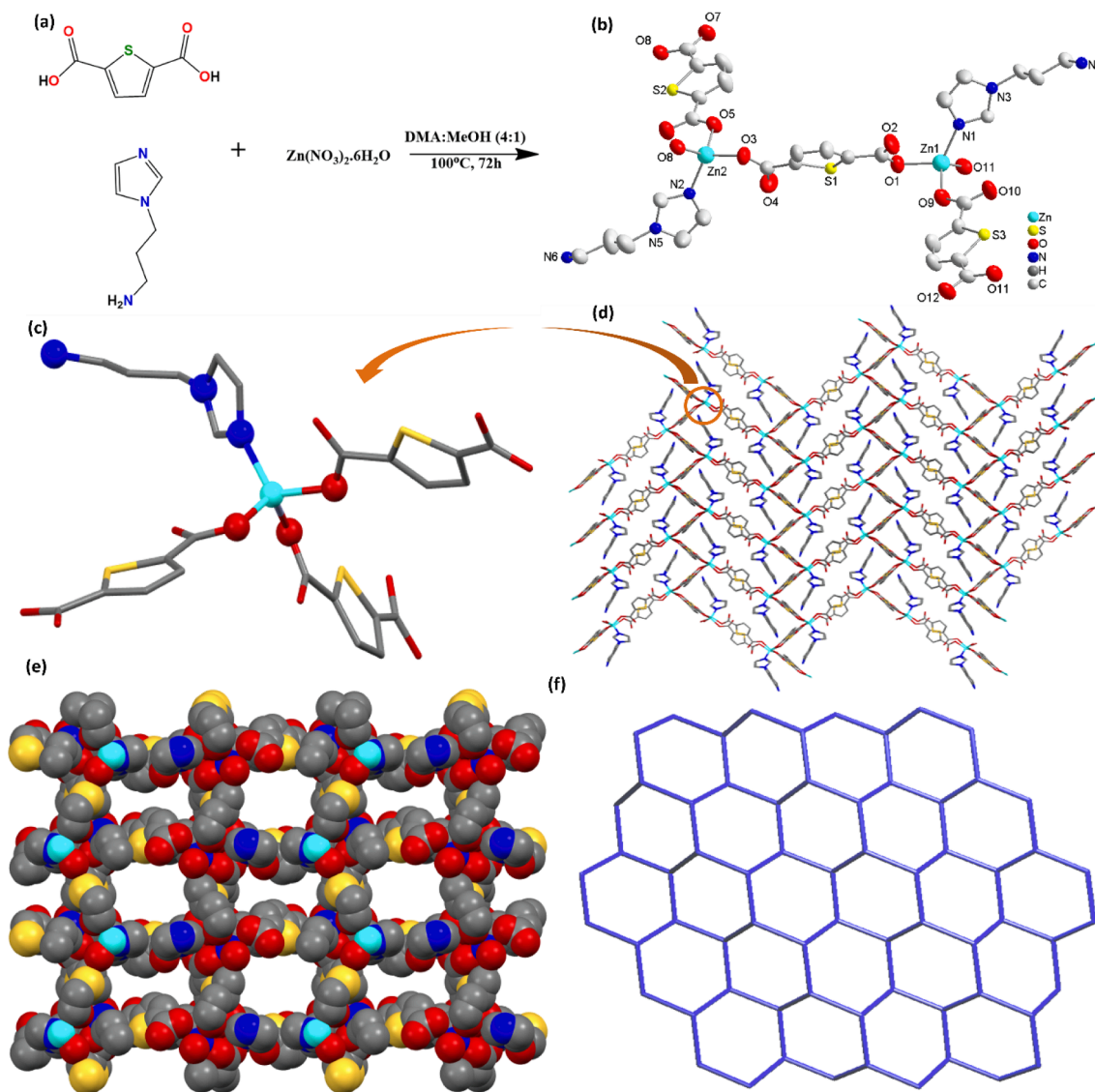


Fig. 1. Synthetic scheme of PUC-8 (a), Asymmetric unit of PUC-8 (b), distorted tetrahedral geometry of central metal ion, Zn^{2+} (c), 2D network plane of PUC-8 framework (d), Spacefill structure of PUC-8 representing two different types of cavities (e), Topology analysis of PUC-8 (f).

linker attached to the Zn^{2+} centre via terminal imidazole nitrogen atom, creating a 2D network plane, as presented in Fig. 1d. Notably, the 1° amine group of the imidazole ligand does not participate in zinc binding and remains unbound within the network.

The bonds between Zn-O and Zn-N exhibit bond lengths ranging from 1.942 to 1.985 Å and 1.988 to 1.992 Å, respectively. Analysis of the structure reveals two distinct cavity types. The first is a larger square-shaped cavity, while the second is a smaller dumbbell-shaped cavity (Fig. 1e). Using PLATON software, the estimated solvent-accessible void volume was calculated as 1571 Å³, equivalent to about 28.5 % of the total crystal volume. Using the ToposPro program, the network topology of PUC-8 showed a 3-connected net and was represented by the point symbol {6³} with a *hcb* topology. Additional crystallographic refinement parameters and specific bond angles/lengths for PUC-8 are provided in Table S1.

3.2. FT-IR, PXRD and TGA analysis of PUC-8 and PUC-8@rGO

The FT-IR analysis confirmed the coordination of elements in the synthesized materials with rGO. Characteristic bands of primary amine in the imidazole ligand were observed at 3430 and 3256 cm⁻¹ for

asymmetric and symmetric N-H bond stretches, respectively. No changes in these vibrations indicated no coordination of NH_2 with Zn-metal. PUC-8 exhibited a peak at 3146 cm⁻¹ for C-H stretching vibrations, and the absence of peaks around 1700 cm⁻¹ suggested carboxylate deprotonation. Peaks at 1612 and 1352 cm⁻¹ corresponded to asymmetric and symmetric carbonyl group stretching vibrations (C=O), with a strong peak at 1532 cm⁻¹ for C=N stretching in the imidazole ring. Peaks at 1033 and 1103 cm⁻¹ represented $\nu_{\text{C-N}}$ stretching and imidazole bending, respectively, while a sharp peak at 814 cm⁻¹ confirmed C-S bond stretching in the thiophene ring [52]. Peaks between 500 and 800 cm⁻¹ indicated successful coordination of Zn metal with N-atom of imidazole linker (Zn-N, 764 cm⁻¹) and O-atom of carboxylate containing ligand (Zn-O, 525 cm⁻¹) [53]. FT-IR spectra of rGO showed peaks at 1628 and 3547 cm⁻¹ for aromatic C=C and OH stretching vibrations, respectively [54,55]. The presence of characteristic peaks of PUC-8 and rGO ($\nu_{\text{C=C}}$) in PUC-8@rGO at their respective positions confirmed the successful incorporation of rGO in MOF crystals [56]. Interaction between the NH_2 group and different functional groups on rGO was suggested by merging the NH stretching peaks of PUC-8 into a broad peak, along with the presence of rGO's OH stretching vibration between 3500–3600 cm⁻¹ in the composite.

The experimental PXRD pattern of the synthesized material is completely matched with the simulated one (taken from SCXRD data), proving the purity of PUC-8 in the bulk phase (Fig. 2b). Moreover, the typical peaks at $2\theta = 6.9^\circ, 9.7^\circ, 11.4^\circ, 15.0^\circ, 16.9^\circ, 19.5^\circ$ and 22.9° are closely related to the (020), (002), (031), (200), (042), (004) and (062) reflections of PUC-8 respectively, verifying the successful synthesis of PUC-8 (Fig. S3). The characteristic peak of rGO is also present in nanocomposite PUC-8@rGO, confirming the effective coupling of rGO with PUC-8. Using diffraction data, valuable physical parameters such as the percentage of crystallinity and grain size were determined using the Scherrer equation [57].

$$D = \frac{K\lambda}{\beta \cos \theta} \quad (3)$$

K stands for Scherrer constant, D is the crystallite size, λ stands for the wavelength of incident X-ray, β indicates the FWHM value of the respective peak, and θ denotes the diffraction angle. FWHM is the width of a peak measured between points on the curve where the function reaches half of its maximum value.

$$\%Crystallinity = \frac{\text{Area under crystalline peaks}}{\text{Total area}} \times 100 \quad (4)$$

The full width at half maximum (FWHM), denoted as β , for both PUC-8 and PUC-8@rGO nanomaterials, was determined by analyzing their most intense and single peaks [57,58]. Utilizing the peak position and

associated broadening, the crystallite size was computed using the Scherrer equation [59,60]. The average crystallite size of PUC-8 and PUC-8@rGO was measured as 43.8 nm and 21.5 nm, respectively. The results revealed % crystallinity values of 76 % for PUC-8 and 71 % for PUC-8@rGO. A summary of all significant crystallographic features is presented in Table 1.

The thermal stability of PUC-8 before and after adding rGO into the framework was investigated via the TGA (Thermogravimetric analysis) approach, carried out under the N_2 atmosphere. PUC-8 showed high thermal stability because a slight % weight loss of 20 % was observed till $275^\circ C$ due to the removal of solvent molecules in the framework cavity. Further, on increasing the temperature to $390^\circ C$ a mass loss of 47 % was observed owing to partial collapse of the framework. Finally, the weight loss above $390^\circ C$ indicated the complete decomposition of PUC-8 into ZnO. As illustrated in Fig. S4a, the thermal stability of PUC-8 was enhanced by incorporating rGO sheets, making it a material of great interest for water remediation over its components. Moreover, the Raman spectra of PUC-8@rGO and rGO are shown in Fig. S4b, where two firm peaks are observed. Vibrational modes connected to graphene defects and edge structures are related to the D band at 1343.6 cm^{-1} for rGO and 1341 cm^{-1} for PUC-8@rGO. In the graphene lattice, the stretching vibrations of sp^2 hybridized carbon atoms are represented by the G band, which is situated at 1584 cm^{-1} for rGO and 1584.4 cm^{-1} for PUC-8@rGO [61]. The D and G bands' intensity ratio (I_D/I_G) significantly increased from 1.004 to 1.017. This increase indicates two crucial things: first, graphene's sp^2 hybridized carbon network becomes more

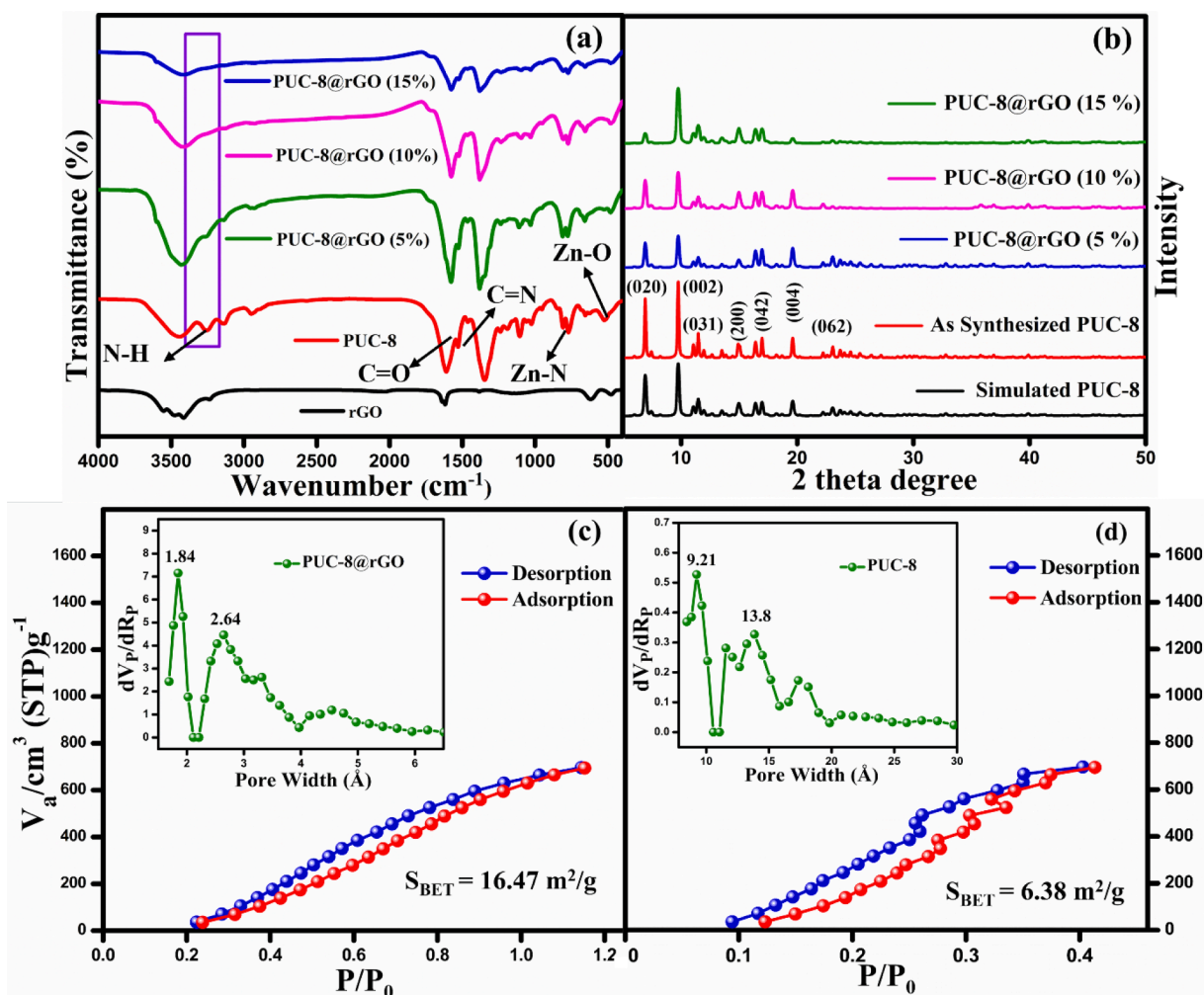


Fig. 2. (a) FTIR and (b) PXRD spectra of PUC-8 and its composites with 5, 10 and 15% (w/w) of rGO composition, N_2 sorption isotherms of PUC-8@rGO (c) and PUC-8 (d), inset: pore size distribution of PUC-8 and PUC-8@rGO based on adsorption isotherm measurements.

Table 1
Crystallographic features for PUC-8 and PUC-8@rGO.

Reflection number	PUC-8				PUC-8@rGO			
	2 θ	Miller Indices	FWHM (β)	Crystallite size (nm)	2 θ	Miller Indices	FWHM (β)	Crystallite size (nm)
1	6.91	(020)	0.158	50.1889	6.91	(020)	0.32	24.7807
2	9.75	(002)	0.159	49.7833	9.75	(002)	0.36	21.9876
3	14.97	(200)	0.261	30.1785	14.97	(200)	0.42	18.7538
4	19.60	(004)	0.173	45.2506	19.60	(004)	0.38	20.6009
	Average size = 43.8503 nm				Average size = 21.53075 nm			

disordered when PUC-8 is incorporated into rGO nanosheets [62]. The second effect of this disorder is the formation of defects, which can operate as photocatalytic reaction sites. These results imply that there are more active sites in the PUC-8@rGO composites, which probably helps them perform better in photocatalytic degradation [63].

The pore diameter or surface area of PUC-8 and PUC-8@rGO were measured using BET analysis, and adsorption features were estimated via nitrogen adsorption–desorption isotherm. The plotted isotherm of both the materials favoured type IV curve with H_3 hysteresis loop (Fig. 2c and d). A remarkable rise in the surface area of PUC-8 ($6.38 \text{ m}^2/\text{g}$) was noticed on the incorporation of rGO ($16.47 \text{ m}^2/\text{g}$), exhibiting the nanostructural properties of the composite. In contrast, the average pore diameter of PUC-8 was decreased after composite formation owing to the insertion of rGO. The pore diameter value lies between 2–50 nm, suggesting the microporous nature of synthesized materials (inset image of Fig. 2c and d).

The potential to enhance the surface-active region because of the increased surface area of PUC-8@rGO led to more charge transport, proving the high degradation rate of PUC-8@rGO compared to PUC-8 alone. Moreover, the zeta potential measurements of PUC-8 and PUC-8@rGO were recorded in triplicate to determine the mean zeta potential value. As depicted in Fig. S5, the potential value of PUC-8 becomes more negative on the addition of rGO, indicating the more negative surface charge of PUC-8@rGO (-9.2 mV) as compared to PUC-8 (-1.7 mV) due to presence of anionic graphene surface. Hence, PUC-8@rGO

showed enhanced degradation activity toward cationic MB dye due to its more anionic nature.

3.3. FE-SEM and HR-TEM analysis of rGO, PUC-8 and PUC-8@rGO

FE-SEM and HR-TEM techniques analyzed the microscopic morphologies and structural features of PUC-8 and nanocomposite. Fig. 3 displays FE-SEM and HR-TEM images of rGO, PUC-8, and PUC-8@rGO. At 500 nm magnification, Fig. 3a and b show 2D nanosheet-like rGO and bulk crystals of PUC-8, respectively. PUC-8 was grown in situ on 2D rGO sheets, forming a sandwich-like structure (Fig. 3c).

HR-TEM revealed smooth, stacked rGO nanosheets with an interplanar spacing of 0.06 nm (Fig. 3d). PUC-8 crystals dispersed randomly on rGO sheets in PUC-8@rGO (Fig. 3e). SAED patterns indicated the crystalline structure of rGO and the composite. HR-TEM also depicted random dispersion of block-shaped PUC-8 nanoparticles on rGO (Fig. S6a). Grinding and sonication produced PUC-8@rGO nanoparticles with an average size of 11.9 nm (Fig. S6b). EDS mapping of PUC-8 and PUC-8@rGO elements is shown in Fig. S7.

3.4. XPS analysis

XPS was carried out to get valuable information related to the surface chemical composition, bonding and oxidation mode of elements in the material. Fig. 4a depicts the comprehensive scan survey XPS spectra (0

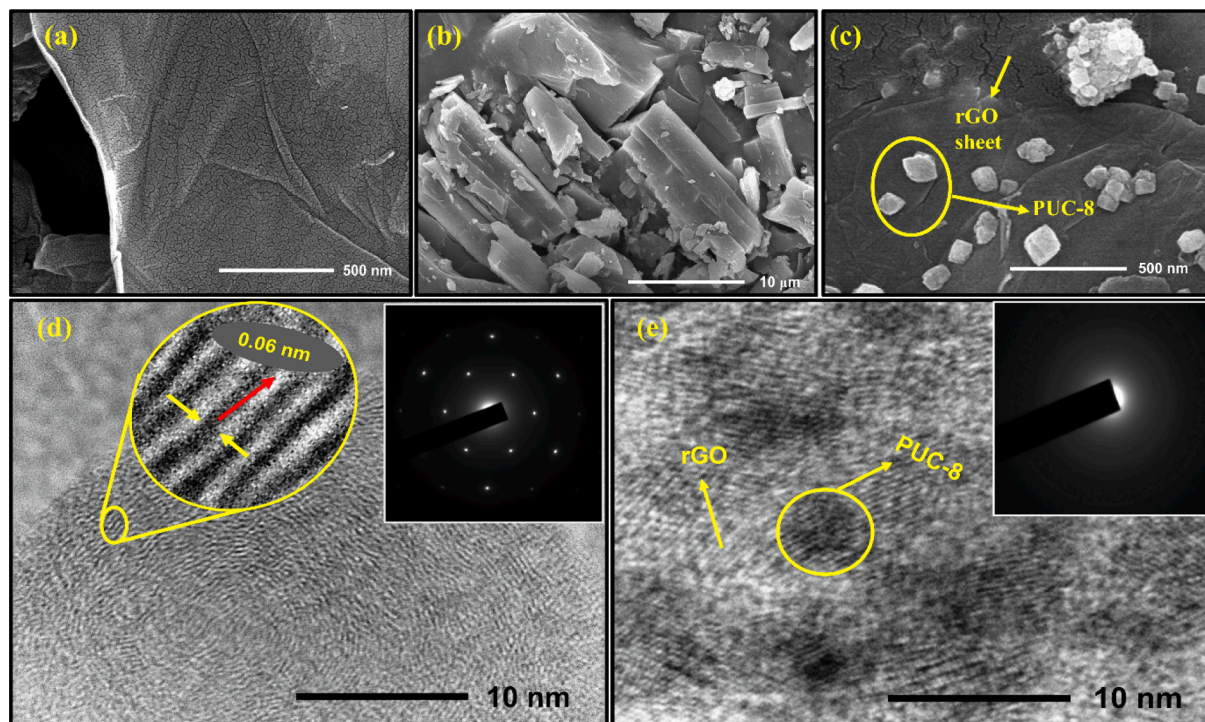


Fig. 3. FESEM images of rGO (a) PUC-8 (b) and PUC-8@rGO (c), HRTEM images of rGO (d) and PUC-8@rGO (e), inset: (selected area electron diffraction) SAED pattern of rGO and PUC-8@rGO to check the crystallinity of synthesized materials.

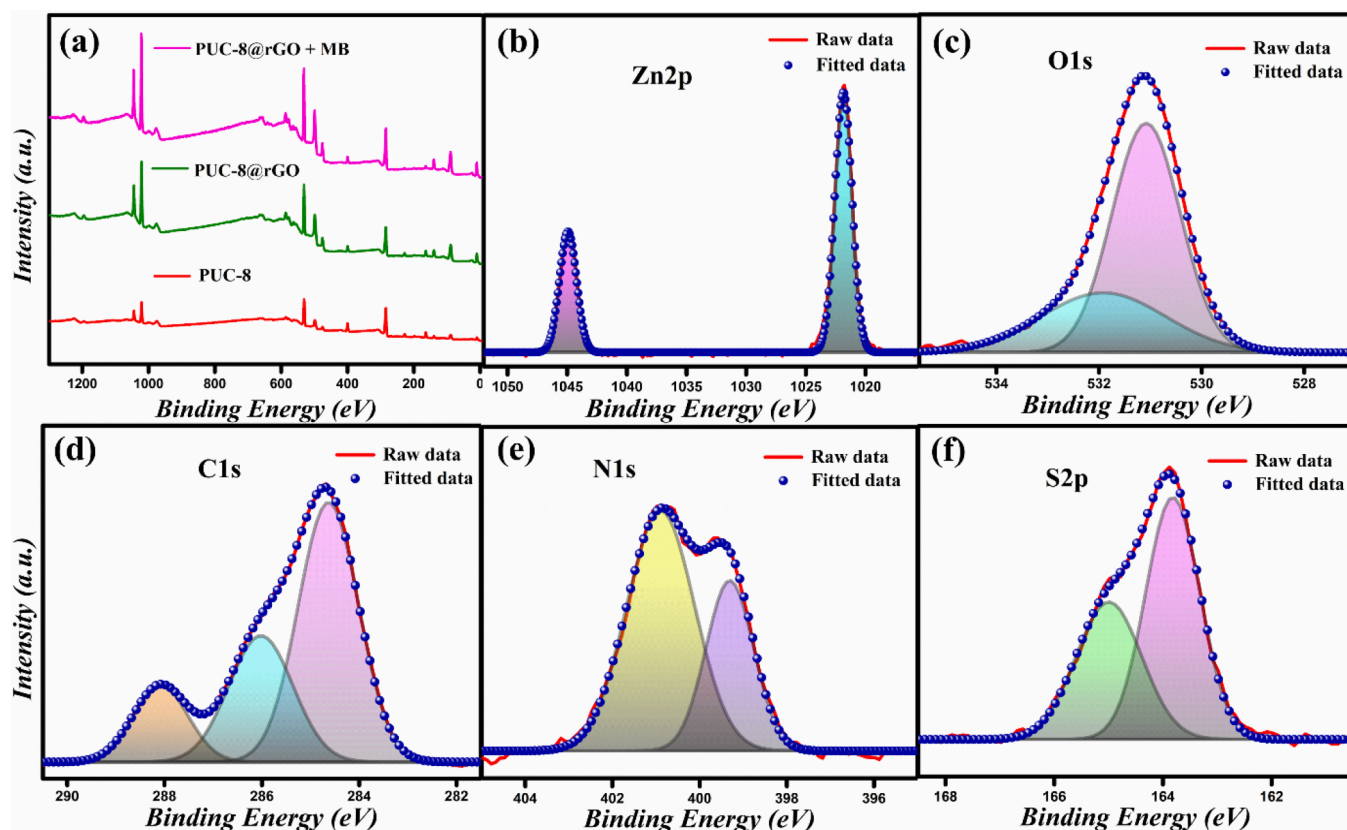


Fig. 4. High-resolution XPS survey spectrum of PUC-8, PUC-8@rGO and PUC-8@rGO after degradation of MB (a), XPS spectra of different elements present in PUC-8@rGO, Zn 2p (b), O 1s (c), C 1s (d), N 1s (e) and S 2p (f).

to 1300 eV) of PUC-8, PUC-8@rGO and PUC-8@rGO after the degradation of MB. The binding energies corresponding to all the elements (Zn, C, N, O, S) present in PUC-8 are at their respective positions, as reported in the literature, confirming the successful synthesis of PUC-8. Wherein the XPS spectra of Zn 2p show two individual peaks at 1021.9 eV and 1044.9 eV, typically attributed to Zn 2p_{3/2} and Zn 2p_{1/2} representing the presence of Zn(II) in the PUC-8 network with bonding of Zn atom towards N-atom of imidazole unit and O-atom of carboxylate linker (Fig. 4b) [64]. C 1s spectra of PUC-8 having two deconvoluted peaks at 284.6 eV and 288 eV exhibited unsaturated bonding of C = C and C = N, respectively, and the peak at 286 eV attributed to saturated bonds of C (C-N/C-C/C-O) (Fig. 4d) [65]. As depicted in Fig. 4e, the presence of imidazolyl N (C-N) and bonding between Zn-N is proved by two deconvoluted peaks at 399.3 eV and 400.9 eV in the N 1s spectra of PUC-8. The XPS spectra of O 1s and S 2p showed two independent peaks for each from 531–532 eV and 163 to 165 eV, which are ascribed to Zn-O/C = O bonding and thiophene S, respectively (Fig. 4c and 4f). A similar pattern of all the peaks corresponding to their respective elements is present in PUC-8@rGO, with a slight change in intensities due to the interaction between rGO sheets and the PUC-8 framework, suggesting the successful synthesis of the composite. All the elements of PUC-8@rGO remain intact at their respective positions of binding energies even after degradation of MB, indicating high stability of composite material, as shown in Fig. S8–S12.

3.5. Selectivity experiments

To check the selectivity of PUC-8@rGO towards the degradation of organic dyes, we have selected four cationic and anionic dyes (Rhodamine B, Methyl orange, Reactive black-5 and Methylene blue) for analysis. 10 ppm of these dyes was treated separately with PUC-8 (1 mg in 1 mL) for 60 min. A negligible change in absorbance was noticed in

RB, whereas a slight decrease could be seen in the case of MO and RB5 (Fig. S14). The maximum degradation was observed in MB. This could be explained based on the cationic charge on MB and its size, which is fit for the pore size of the composite. Hence, MB was nominated for further experiments to learn about the degradation behaviour of synthesized material.

Further, the photocatalytic efficiency of PUC-8@rGO was evaluated by comparing its performance in degrading MB dye at different compositions of reduced graphene oxide (rGO). The study tested three different compositions of PUC-8@rGO: 5 %, 10 %, and 15 % (w/w) of rGO. The photocatalytic efficiency was determined by comparing the percentage degradation of MB dye (at a concentration of 10 ppm) using equal amounts of each composite for 1 h. According to the results obtained, the composite with a 10 % composition of rGO exhibited the highest performance in decomposing MB dye compared to the other two compositions, as shown in Fig. S15. Hence, PUC-8@rGO (10 %) was selected as the most active photocatalyst.

3.6. Effect of operational parameters on dye degradation

To optimize the sensitivity of PUC-8@rGO to MB, critical parameters such as catalyst dosage, pH, and initial dye concentration were investigated. Increasing PUC-8@rGO dosage from 0.2 to 1 g/L (in 10 ppm MB solution) resulted in a consistent rise in degradation rate due to more active sites on the catalyst's surface. However, a slight decline was observed beyond 1 g/L, attributed to increased turbidity hindering light penetration and reducing photoactive radical production [29]. Secondly, the influence of varying initial MB concentrations (10, 20, 30, 40, and 50 mg) on PUC-8@rGO's degradation efficacy was assessed. Fig. S13 illustrates a decrease in degradation rate with rising initial MB concentration. Higher dye concentrations hindered photon energy penetration onto the catalyst, reducing active radical generation and

slowing down the degradation process.

The impact of pH on dye degradation relies on electrostatic interactions between the catalyst and organic compounds, governed by their surface charge properties. Generally, cationic dye degradation, like MB, is more favourable in alkaline conditions. pH ranging from 3 to 12 was explored to assess MB photodegradation. Adjustments were made using 0.1 M HCl and NaOH solutions. A sharp increase in degradation occurred from pH 3 to 8, followed by a slight decrease at pH 12. At low pH, electrostatic repulsion between cationic dye molecules and the anionic surface of PUC-8@rGO inhibited degradation. Conversely, increased surface hydroxylation at high pH promoted OH^- oxidation to $\cdot\text{OH}$ radicals, enhancing MB breakdown. Optimal degradation was achieved at pH 8 due to maximal electrostatic adsorption and hydroxylation effects. PUC-8@rGO exhibited consistent degradation across a broad pH range, indicating its versatile pH adaptability (Fig. 6a).

3.7. Kinetics of photocatalytic degradation

Fig. 5a, b, and c illustrate the time-dependent photocatalytic degradation of MB using PUC-8, rGO, and PUC-8@rGO, respectively. PUC-8@rGO exhibited the most significant decrease in absorbance at 664 nm after 60 min of light exposure, achieving a degradation rate of 98.6 % (Fig. 5f). Comparatively, PUC-8 and rGO individually showed around 40 % degradation. The catalytic behaviour of pure precursors and their composites with and without light was studied to assess adsorption efficiency in darkness and degradation ability in light (Figs. 5e and S16). To assess the photolysis of MB, a 10 ppm aqueous solution of MB was exposed to light for 60 min under continuous stirring. During this period, 3 mL aliquots were collected at 10 min intervals, and the remaining dye concentration in the supernatant was analyzed using a UV-vis spectrophotometer. The results, presented in Fig. S17a, show negligible degradation of MB over the 60 min exposure, confirming that the observed MB degradation is attributable solely to the photocatalytic action of PUC-8@rGO.

To elucidate the rate-controlling phenomena of MB degradation over PUC-8@rGO and its components, time study results underwent pseudo-first-order and pseudo-second-order kinetic analyses. The pseudo-second-order kinetic plot (Fig. S17b) was ruled out due to its relatively low correlation coefficient ($R^2 = 0.667$). Conversely, the pseudo-first-order kinetic curve exhibited a better linear relationship with a high correlation coefficient ($R^2 = 0.975$), confirming the model's applicability (Fig. 6c). Similar kinetic behavior was observed with pure PUC-8 and rGO. The rate constant values, derived from the curve slope, revealed a rate constant for PUC-8@rGO (0.07 min^{-1}) approximately 7 times greater than pure PUC-8 (0.01 min^{-1}) and nearly 8 times greater than bare rGO (0.009 min^{-1}). These results support the role of rGO in enhancing photoexcited electron-hole pair separation and lattice conductivity, leading to the composite photocatalyst's superior degradation performance.

3.8. Mechanism of photocatalysis and elucidation of active species

Based on heterojunction photocatalysis (Fig. 7), the degradation mechanism involves creating a heterojunction by depositing rGO sheets around PUC-8@MOF to enhance photoinduced charge separation through strong chemical bonding between semiconductors with similar band potentials. Band gap analysis of PUC-8 and its composite with rGO using UV-vis diffuse reflectance spectra revealed a smaller band gap (2.95 eV) for PUC-8@rGO compared to pure PUC-8 (4.02 eV) (Fig. S18). A narrowed band gap reduces the energy required for electron-hole transitions between valence and conduction phases. Upon light illumination, electrons (e^-) transfer from the valence band (VB) to the conduction band (CB) of PUC-8@rGO, forming holes (h^+) in the VB and e^- s in the CB. Recombination of electron-hole pairs is minimized by rGO, enabling photoexcited e^- s from the CB of PUC-8 to move quickly to rGO sheets due to enhanced conjugation and conductivity. Holes in the VB react with water molecules to generate $\cdot\text{OH}$ via oxidation. At the same time, excited e^- s in the CB and rGO sheets are trapped by O_2 molecules to

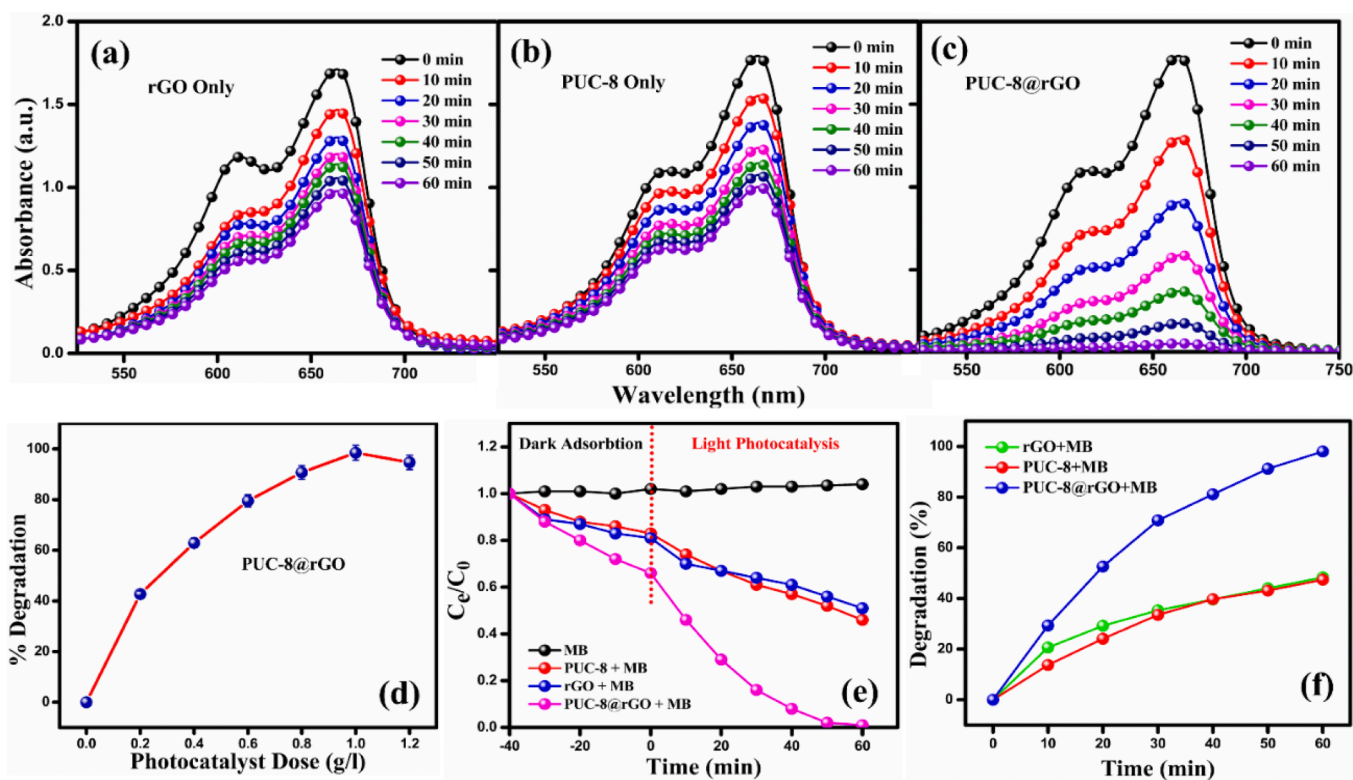


Fig. 5. UV-vis degradation spectra of MB for a time period of 60 min in the presence of rGO (a), PUC-8 (b) and PUC-8@rGO (c), dosage study of PUC-8@rGO (d), degradation of MB under dark and light conditions with various synthesized materials (e), comparison of degradation efficiency of rGO, PUC-8 and PUC-8@rGO (f).

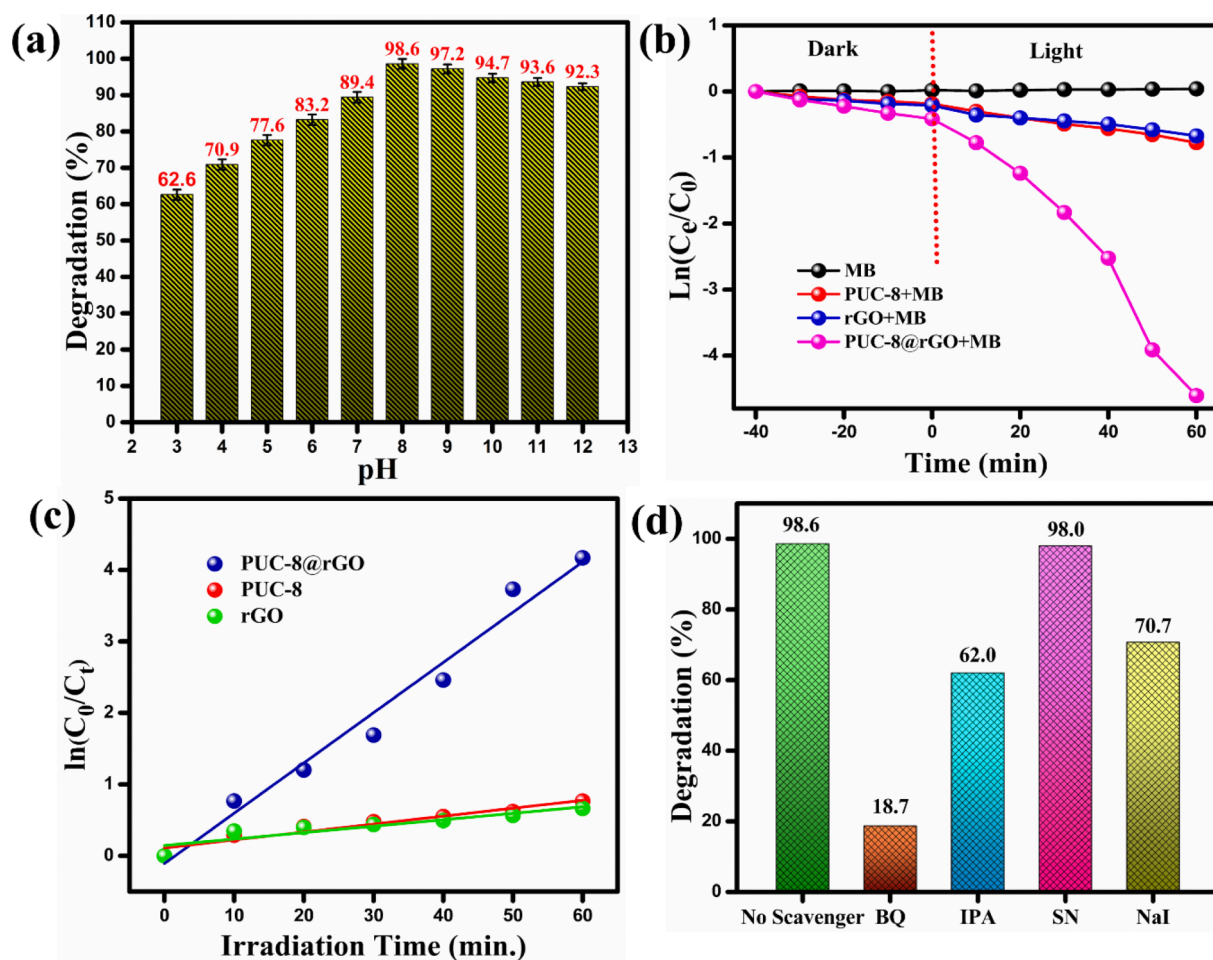


Fig. 6. The pH effect on degradation efficiency of PUC-8@rGO towards MB (a), pseudo-first-order kinetic graph of MB decomposition with different synthesized materials (b), linear plots of pseudo-first-order kinetic models applied for MB degradation using different photocatalysts (c), the effect of radical scavenger (BQ, IPA, SN and NAI) on degradation efficiency to elucidate the active species (d).

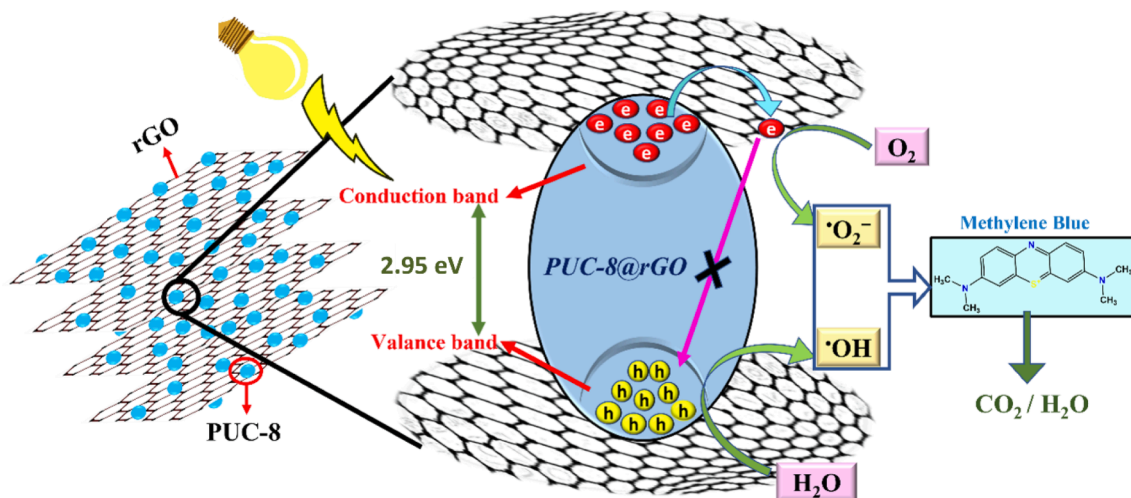
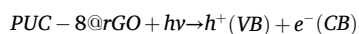


Fig. 7. Proposed mechanism for visible light assisted degradation of MB using PUC-8@rGO photocatalyst.

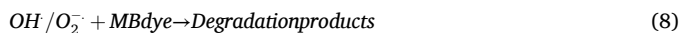
produce superoxide anion radicals ($\bullet\text{O}_2^-$). These free radicals initiate degradation reactions, converting organic contaminants (MB) into less harmful products like H₂O and CO₂.

Both components of PUC-8@rGO play vital roles: PUC-8 prevents rGO layer stacking, enhancing the surface area for dye molecule

adsorption, while rGO acts as an electron acceptor, maximizing free radical production. This proposed mechanism aligns with the findings of the photocatalytic degradation study [66].



(5)



In situ radical trapping tests were performed to elucidate the specific roles of different active species involved in the photocatalysis mechanism. Various radical scavengers were introduced into the MB solution to identify the primary species responsible for breaking down organic pollutants. The degradation rate was initially observed to be 98.6 % before adding any reducing agent, indicating robust photocatalytic activity. The addition of radical scavengers such as BQ, IPA, SN, and NaI led to varying degrees of degradation inhibition: BQ significantly reduced the degradation rate to 18.7 %, suggesting that superoxide anion radicals ($O_2^{\cdot-}$) are the predominant species responsible for the degradation process (Fig. 6d). In contrast, IPA and NaI showed moderate inhibitory effects (62 % and 70.7 % degradation rates, respectively), indicating that hydroxyl radicals ($OH^{\cdot}$) and holes (h^+) play secondary roles in the degradation mechanism. The negligible effect of SN further confirmed the minimal involvement of electrons (e^-) in the photocatalytic degradation process. This comprehensive analysis underscores the complex interplay of active species in PUC-8@rGO photocatalysis, highlighting the pivotal role of superoxide anion radicals in initiating and sustaining the efficient degradation of methylene blue and other organic pollutants.

3.9. LC-MS studies for product analysis

LC-MS was utilized to identify intermediate products and degradation pathways of MB. Fig. S19 and S20 display the ESI mass spectra of MB before and after degradation. Initially, a prominent peak at $m/z = 284$ was observed in the LC-MS spectra of MB, which nearly disappeared after 1 h of degradation, indicating complete dissociation of dye molecules and formation of new products. The likely degradation pathway, depicted in Fig. 8, involves the generation of $O_2^{\cdot-}$ by the reaction of excited electrons with O_2 molecules, which can react with H^+ to form H_2O_2 . With the presence of H_2O_2 and $OH^{\cdot}$, the central aromatic ring of MB may undergo opening, attributed to sulfur oxidation to sulfoxide and NH_2 group development [67,68]. The N-demethylation of the peripheral rings might be because of the aerial oxidation process [69]. The initial degradation intermediates with probable functional groups were recognized by LC-MS results having m/z at 279, 277, 275 and 251. Further oxidation of the obtained products leads to the construction of their possible byproducts, and a complete degradation of MB in CO_2 and H_2O molecules is expected at the end of the process.

3.10. Eco-Toxicological analysis: Seed germination

Fig. S21 displays seed germination images over a time period of 5 days. Organic pollutants like dye hindered seed growth by adhering to cell walls and membranes. However, rGO, PUC-8, and PUC-8@rGO exhibited effective germination rates due to the presence of zinc, aiding redox reactions within plants, as suggested by scientific research

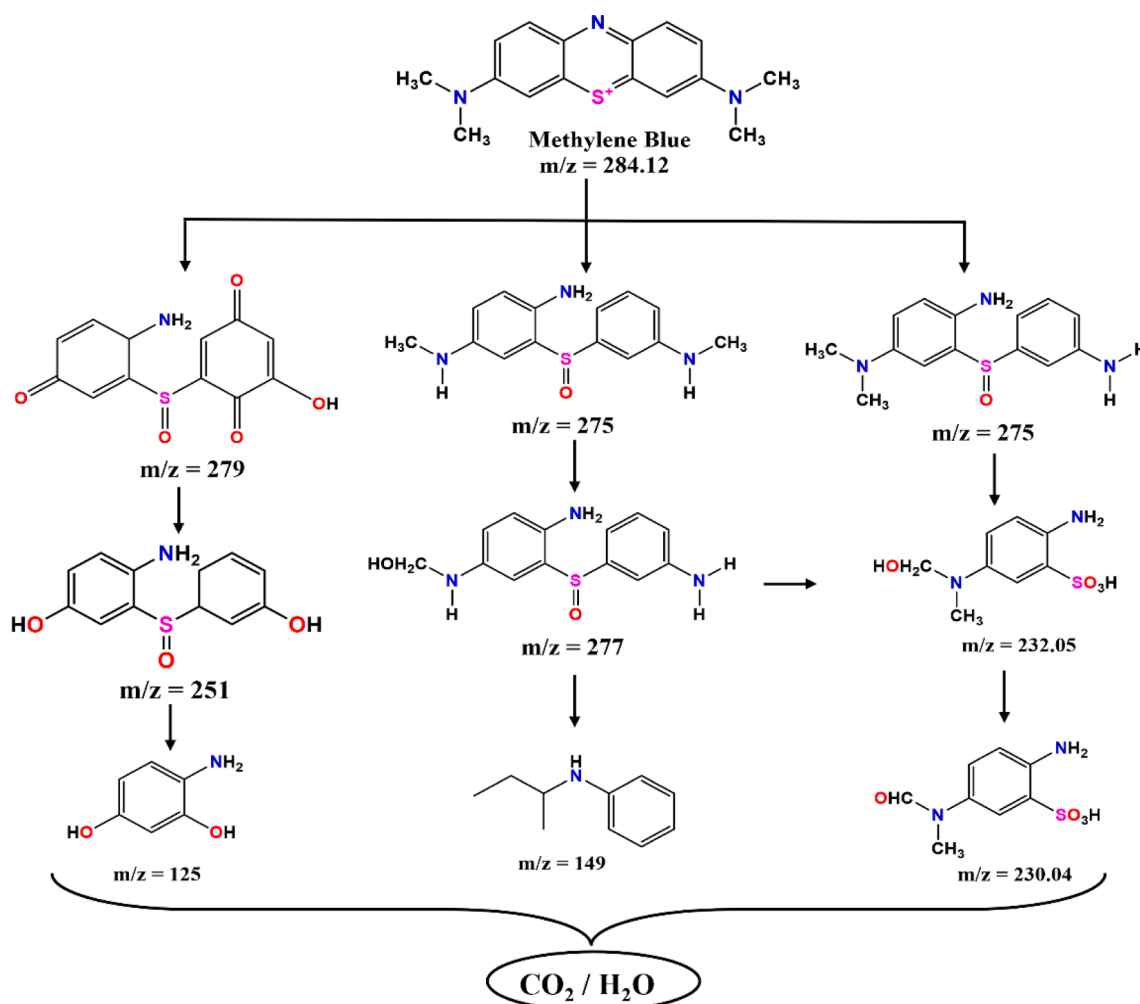


Fig. 8. Degradation pathway of MB (based on LCMS results) in the presence of PUC-8@rGO under visible light irradiation.

[70]. However, at a higher concentration of PUC-8@rGO, the germination rate index was increased and much higher than the control. Fig. 9b assesses sample phytotoxicity by measuring their impact on root length during seed germination. Higher values indicate accelerated germination rates. PUC-8@rGO exhibited reduced phytotoxicity compared to PUC-8, suggesting partial elimination of phenols and other phytotoxic compounds [50].

Distinctive properties of prepared samples significantly influenced seed anti-proliferative activity, particularly in Vigor Index values. PUC-8@rGO exhibited a higher seeding vigor index than the control group, attributed to zinc catalyzing seed growth (Fig. 9c). Seed germination ability was assessed by root and shoot length (Fig. 9d), which were higher than the control. However, at higher concentrations (100 ppm), root length decreased. At 12.5 and 25 ppm of PUC-8@rGO, root and shoot lengths increased compared to control and treated water.

Moreover, Physico-chemical properties of dyed wastewater were compared before and after treatment, detailed in Table S2. Treatment with PUC-8@rGO decreased BOD from 46.13 mg/L to 32 mg/L and COD from 292 mg/L to 112 mg/L, meeting safe discharge limits. Additionally, treated water exhibited reduced TDS compared to dyed water.

3.11. Cytotoxicity

The MTT test was used to measure the *in vitro* cytotoxicity of PUC-8, rGO, and PUC-8@rGO at four different doses (0.125 mg/mL, 0.25 mg/mL, 0.5 mg/mL, and 1 mg/mL) towards HaCat and SKOV3 after a 24 h exposure (Fig. 10). The results showed that PUC-8 exhibited no

cytotoxic activity in HaCat or SKOV3. The cytotoxicity of rGO was dose-dependent, and more cytotoxicity was seen in the case of SKOV3.

PUC-8@rGO was more cytotoxic than rGO at any given concentration. This can be seen by comparing the half maximal inhibitory concentration (IC_{50}) value for PUC-8@rGO ($IC_{50} = 0.25$ mg/mL) and rGO ($IC_{50} = 1$ mg/mL) in HaCat cells. At lower concentrations (0.125 mg/mL), PUC-8@rGO was non-toxic to HaCat cells compared to SKOV3; However, it shows toxicity at higher concentrations. Further, the results were confirmed using morphological analysis. Cells treated with PUC-8@rGO changed the morphological features and became more spherical and detached from the surface than control cells. The highest proportion of cells exhibiting characteristics of cell death observed under the optical microscope occurred at a concentration of 1 mg/mL of PUC-8@rGO (Fig. 11e and 12e). The images of HaCat cells (Fig. S22 and S23) and SKOV3 cells (Fig. S24 and S25) indicate cell death under a microscope subjected to different concentrations of PUC-8 and rGO separately.

3.12. Regeneration and stability of PUC-8@rGO

PUC-8@rGO was investigated through five cycles of MB photocatalytic degradation to ensure chemical stability. After each cycle, it was thoroughly rinsed with deionized water and ethanol, filtered, and reactivated at 80 °C. Results showed a slight decrease in degradation efficiency from 98.6 % to 88.1 % (Fig. 13a). Moreover, the XRD patterns (Fig. 13b) revealed no significant framework decomposition before or after MB degradation, maintaining structural integrity and crystallinity.

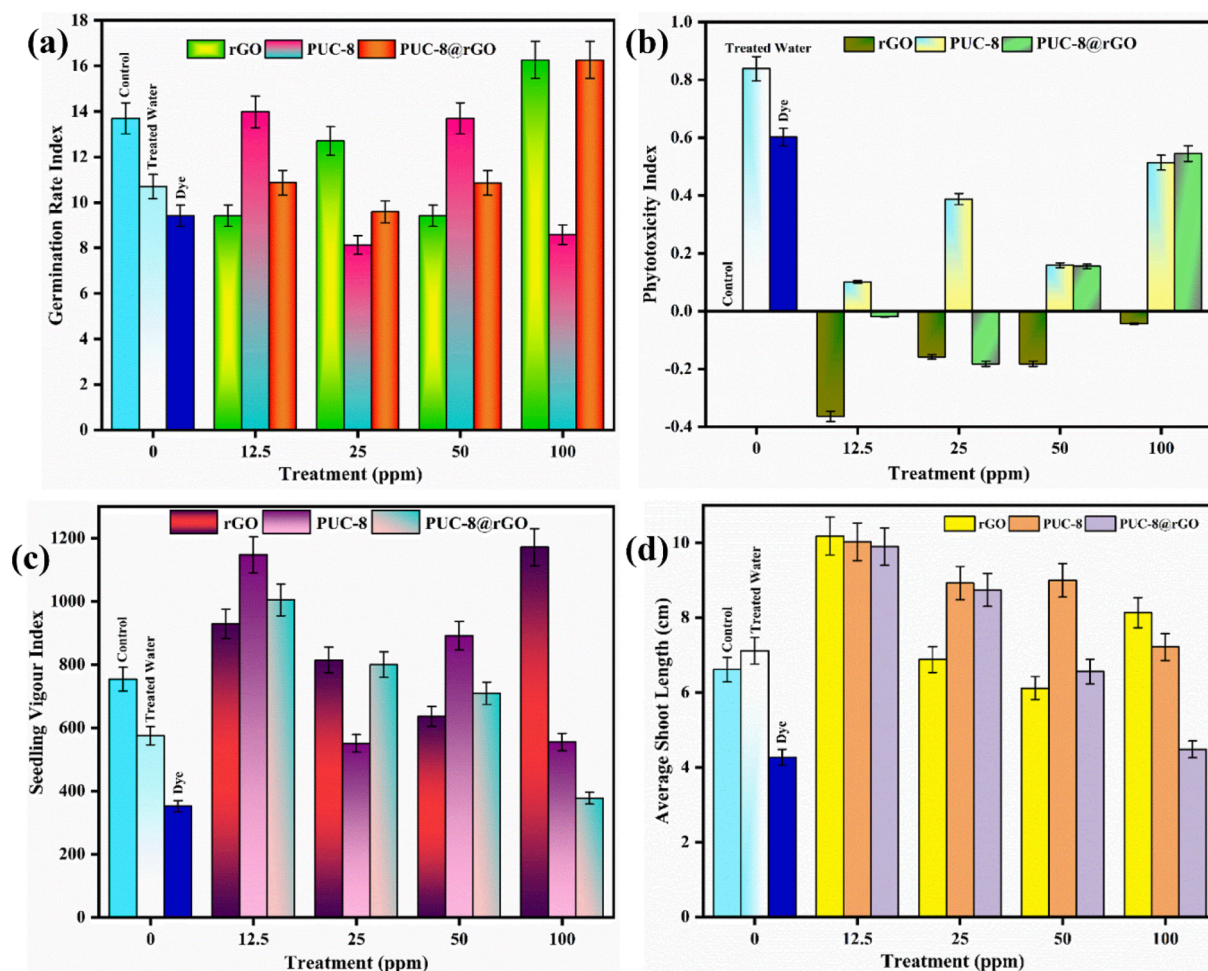


Fig. 9. Germination rate index (a), Phytotoxicity index (b), Seedling vigour index (c) and average shoot length (d) of seed germination at different concentrations (varied from 12.5 to 100 ppm) of rGO, PUC-8 and PUC-8@rGO.

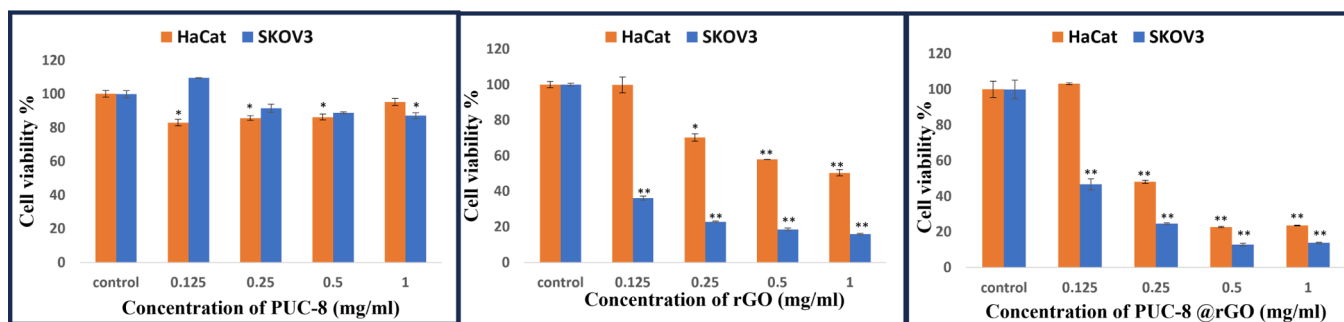


Fig. 10. Bar diagram showing cell viability of different concentrations of PUC-8, rGO and PUC-8@rGO (mg/mL) after 24 h of treatment in HaCat and SKOV3 with respect to control. Data is presented as mean $\pm$ SD. Statistical significance is shown by * $p < 0.05$ and ** $p < 0.01$ vs control.

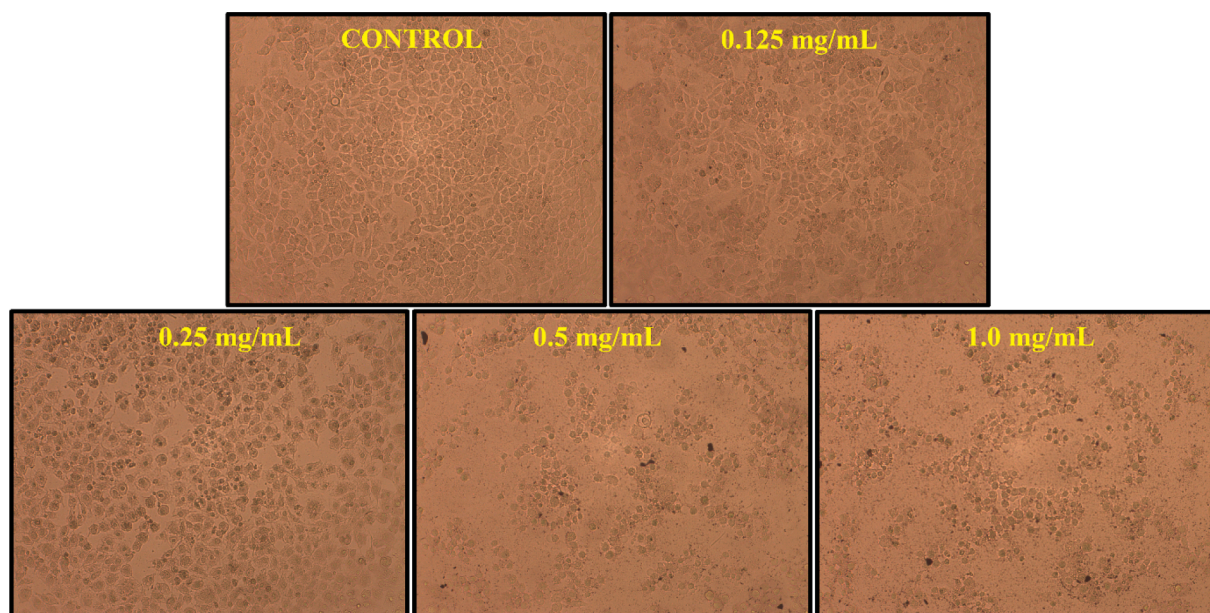


Fig. 11. Representative pictures of HaCat cells treated with different concentrations of PUC-8@rGO: Control, 0.125 mg/mL, 0.25 mg/mL, 0.5 mg/mL and 1 mg/mL (Original magnification X100).

This underscores the recyclability of our adsorbent, which is crucial for economic viability in practical applications.

3.13. Statistical analysis

The novel photocatalytic system, PUC-8@rGO, outperforms PUC-8 and rGO individually in methylene blue (MB) degradation. PUC-8 has an average crystallite size of 43.8 nm with 76 % crystallinity, while PUC-8@rGO has a smaller size of 21.5 nm with 71 % crystallinity. Whereas, the particle size for PUC-8@rGO determined by HRTEM technique was 11.9 nm. BET results showed that the incorporation of rGO led to a significant increase in the surface area of PUC-8, from 6.38 m²/g to 16.47 m²/g. The PUC-8@rGO achieves a remarkable degradation efficiency of 98.6 % in 60 min, with a high rate constant value of 0.07 min⁻¹, surpassing PUC-8 and bare rGO by approximately 7 and 8 times, respectively. Correlation analysis identifies key parameters influencing photocatalytic activity, and PUC-8@rGO performs consistently across a wide pH range (3–12). LC-MS analysis elucidates degradation intermediates, supporting process efficacy. The material also exhibits significant anti-cancer activity against SKOV3 cells (IC₅₀ = 0.125 mg/mL), indicating potential biomedical applications. PUC-8@rGO demonstrates superior photocatalytic degradation activity for MB dye, as shown in Table S3. This table compares various reported photocatalysts used for the degradation of MB, highlighting that PUC-8@rGO exhibits

the best performance.

4. Conclusion

This study successfully synthesized PUC-8 and PUC-8@rGO composites using solvothermal and wet impregnation methods, achieving a highly efficient photocatalytic material for Methylene Blue (MB) degradation under visible light. PUC-8@rGO demonstrated a remarkable 7 to 8-fold increase in photocatalytic rate (98.6 % removal of MB dye), attributed to its enhanced BET surface area and reduced band gap, which effectively mitigated charge recombination. Key parameters influencing photocatalysis, such as pH, dye concentration, catalyst dose, and irradiation time, were optimized to maximize degradation efficiency. Furthermore, the production of active species ($\cdot\text{O}_2^- > \cdot\text{OH} > \text{h}^+$) upon irradiation acted as potent oxidants, facilitating the efficient degradation of dye molecules. Analysis of degradation pathways and intermediates confirmed the material's effectiveness in reducing BOD and COD levels to environmentally safe standards. The low phytotoxicity, validated through seed germination assays, further suggests that treated water is suitable for agricultural irrigation. Additionally, PUC-8@rGO exhibited significant cytotoxicity against human ovarian cancer cells, indicating its promising biomedical potential. Overall, PUC-8@rGO holds substantial promise for both environmental and biomedical applications, showcasing a versatile and effective approach to

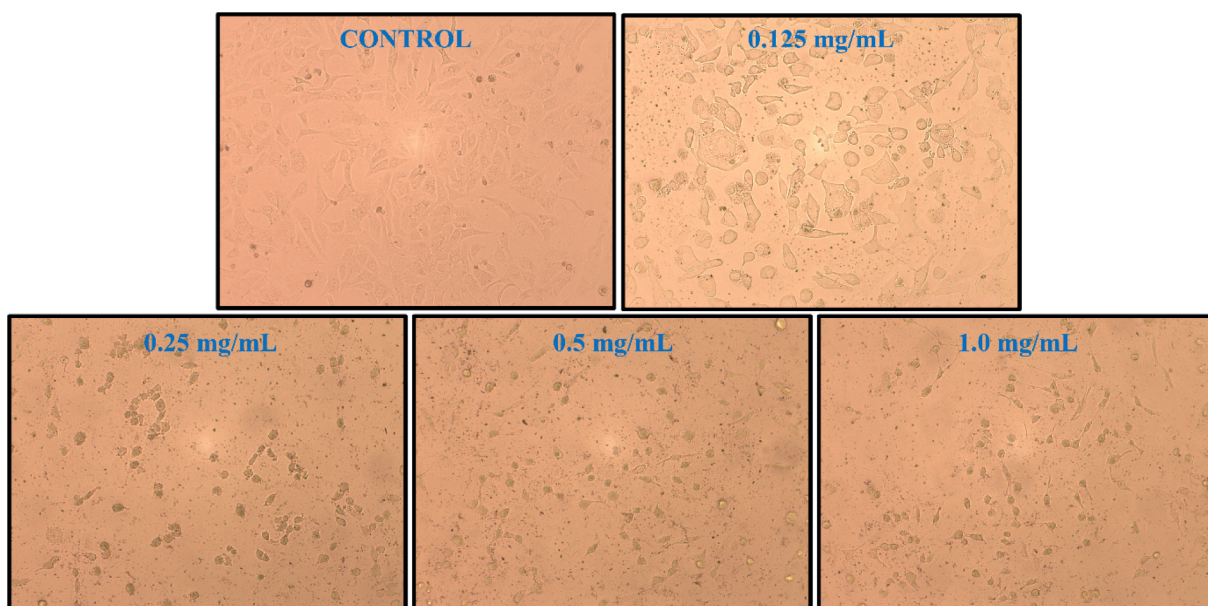


Fig. 12. Representative pictures of SKOV3 cells treated with various concentrations of PUC-8@rGO: Control, 0.125 mg/mL, 0.25 mg/mL, 0.5 mg/mL and 1 mg/mL (Original magnification X100).

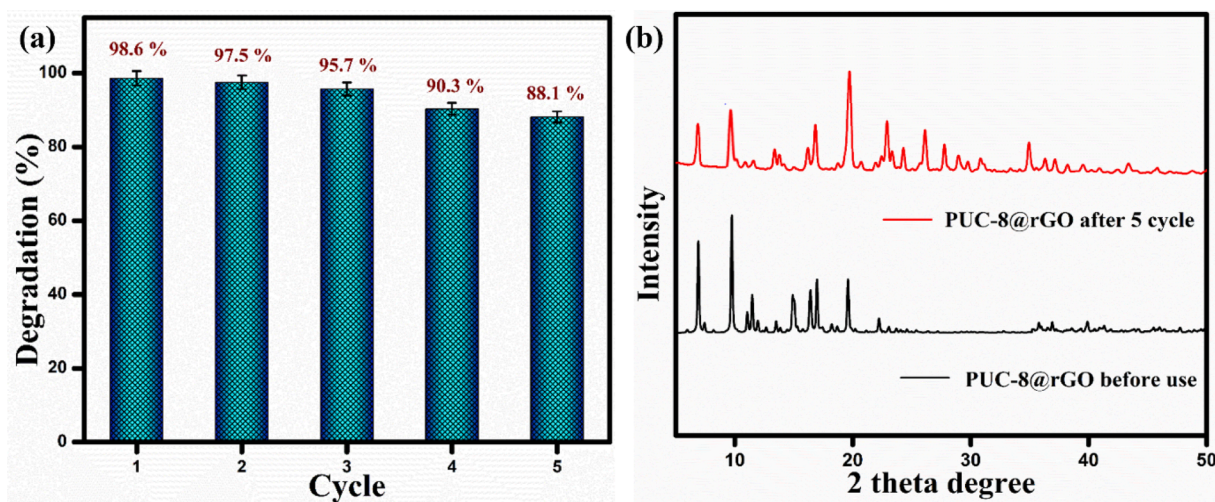


Fig. 13. Recyclability study of PUC-8@rGO up to 5 cycles (a), PXRD spectra of PUC-8@rGO before and after use in degradation process (b).

wastewater treatment and beyond.

CRediT authorship contribution statement

Kushal Arya: Writing – review & editing, Writing – original draft, Software, Formal analysis, Data curation. **Ajay Kumar:** . **Aashima Sharma:** Writing – review & editing. **Kanika Thakur:** Writing – review & editing. **Ravinder Kumar:** Writing – review & editing, Supervision. **Surinder Kumar Mehta:** Writing – review & editing, Validation. **Surinder Singh:** Writing – review & editing. **Vinod Kumar:** Writing – review & editing, Validation. **Ramesh Kataria:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.inoche.2024.113768>.

Data availability

Data will be made available on request.

References

- [1] U. Patel, B. Parmar, A. Dadhania, E. Suresh, Zn(II)/Cd(II)-Based Metal-Organic Frameworks as Bifunctional Materials for Dye Scavenging and Catalysis of Fructose/Glucose to 5-Hydroxymethylfurfural, *Inorg. Chem.* 60 (2021) 9181–9191, <https://doi.org/10.1021/acs.inorgchem.1c01208>.
- [2] Y. Ma, D. You, Y. Fang, J. Luo, Q. Pan, Y. Liu, F. Wang, W. Yang, Confined growth of MOF in chitosan matrix for removal of trace Pb(II) from reclaimed water, *Sep. Purif. Technol.* 294 (2022) 121223, <https://doi.org/10.1016/j.seppur.2022.121223>.
- [3] I.M. El-Sewify, A. Radwan, A. Shahat, M.F. El-Shahat, M.M.H. Khalil, Superior adsorption and removal of aquaculture and bio-staining dye from industrial wastewater using microporous nanocubic Zn-MOFs, *Microporous Mesoporous Mater.* 329 (2022) 111506, <https://doi.org/10.1016/j.micromeso.2021.111506>.
- [4] S.H. Teo, C.H. Ng, A. Islam, G. Abdulkareem-Alsultan, C.G. Joseph, J. Janaun, Y. H. Taufiq-Yap, S. Khandaker, G.J. Islam, H. Znad, M.R. Awual, Sustainable toxic dyes removal with advanced materials for clean water production: A comprehensive review, *J. Clean. Prod.* 332 (2022) 130039, <https://doi.org/10.1016/j.jclepro.2021.130039>.
- [5] N. Hu, C. Chen, J. Tan, W. Wang, C. Wang, H. Fan, J. Wang, P. Müller-Buschbaum, Q. Zhong, Enhanced Adsorption of Methylene Blue Triggered by the Phase Transition of Thermoresponsive Polymers in Hybrid Interpenetrating Polymer Network Hydrogels, *ACS Appl. Polym. Mater.* 2 (2020) 3674–3684, <https://doi.org/10.1021/acsapm.0c00661>.
- [6] D. Masekela, N.C. Hintsho-Mbita, B. Ntsendwana, N. Mabuba, Thin Films (FTO/BaTiO₃/AgNPs) for Enhanced Piezo-Photocatalytic Degradation of Methylene Blue and Ciprofloxacin in Wastewater, *ACS Omega* 7 (2022) 24329–24343, <https://doi.org/10.1021/acsomega.2c01699>.
- [7] H.M. Solayman, M.A. Hossen, A. Abd Aziz, N.Y. Yahya, K.H. Leong, L.C. Sim, M. U. Monir, K.D. Zoh, Performance evaluation of dye wastewater treatment technologies: A review, *J. Environ. Chem. Eng.* 11 (2023) 109610, <https://doi.org/10.1016/j.jece.2023.109610>.
- [8] V. Katheresan, J. Kansedo, S.Y. Lau, Efficiency of various recent wastewater dye removal methods: A review, *J. Environ. Chem. Eng.* 6 (2018) 4676–4697, <https://doi.org/10.1016/j.jece.2018.06.060>.
- [9] I. Khan, K. Saeed, I. Zekker, B. Zhang, A.H. Hendi, A. Ahmad, S. Ahmad, N. Zada, H. Ahmad, L.A. Shah, T. Shah, I. Khan, Review on Methylene Blue: Its Properties, Uses, Toxicity and Photodegradation, *Water (Switzerland)*. 14 (2022), <https://doi.org/10.3390/w14020242>.
- [10] V.H. Nguyen, T. Lee, T.D. Nguyen, Solvothermal Synthesis of Bismuth-Based Halide Perovskite Nanostructures for Photocatalytic Degradation of Organic Pollutants under LED Light Irradiation, *ACS Appl. Nano Mater.* 6 (2023) 3435–3445, <https://doi.org/10.1021/acsanm.2c05218>.
- [11] R.Q. Jia, Y.J. Chen, L.Y. Zuo, Y.J. Jin, B. Li, L.Y. Wang, Enhancing the Photocatalytic Degradation Efficiency of Dyes of Copper-Based Metal-Organic Frameworks through a Dimension-Induced Structural Strategy, *Inorg. Chem.* 62 (2023) 442–453, <https://doi.org/10.1021/acs.inorgchem.2c03538>.
- [12] S. Soni, P.K. Bajpai, J. Mittal, C. Arora, Utilisation of cobalt doped Iron based MOF for enhanced removal and recovery of methylene blue dye from waste water, *J. Mol. Liq.* 314 (2020) 113642, <https://doi.org/10.1016/j.molliq.2020.113642>.
- [13] S. Ihaddaden, D. Aberkane, A. Boukerroui, D. Robert, Removal of methylene blue (basic dye) by coagulation-flocculation with biomaterials (bentonite and *Opuntia ficus indica*), *J. Water Process Eng.* 49 (2022) 102952, <https://doi.org/10.1016/j.jwpe.2022.102952>.
- [14] E. Oyarce, B. Butter, P. Santander, J. Sánchez, Polyelectrolytes applied to remove methylene blue and methyl orange dyes from water via polymer-enhanced ultrafiltration, *J. Environ. Chem. Eng.* 9 (2021), <https://doi.org/10.1016/j.jece.2021.106297>.
- [15] N. Singh, S. Jana, G.P. Singh, R.K. Dey, Graphene-supported TiO₂: study of promotion of charge carrier in photocatalytic water splitting and methylene blue dye degradation, *Adv. Compos. Hybrid Mater.* 3 (2020) 127–140, <https://doi.org/10.1007/s42114-020-00140-w>.
- [16] I. Ahmad, M. Muneer, A.S. Khder, S.A. Ahmed, Novel Type-II Heterojunction Binary Composite (CdS/AgI) with Outstanding Visible Light-Driven Photocatalytic Performances toward Methyl Orange and Tetracycline Hydrochloride, *ACS Omega* 8 (2023) 22708–22720, <https://doi.org/10.1021/acsomega.3c01517>.
- [17] Z. Kalaycıoğlu, B. Özügür Uysal, Ö. Pekcan, F.B. Erim, Efficient Photocatalytic Degradation of Methylene Blue Dye from Aqueous Solution with Cerium Oxide Nanoparticles and Graphene Oxide-Doped Polyacrylamide, *ACS Omega* 8 (2023) 13004–13015, <https://doi.org/10.1021/acsomega.3c00198>.
- [18] D.G. Ayu, S. Gea, N. Andriyani, D.J. Telaumbanua, A.F.R. Piliang, M. Harahap, Z. Yen, R. Goei, A.I.Y. Tok, Photocatalytic Degradation of Methylene Blue Using N-Doped ZnO/Carbon Dot (N-ZnO/CD) Nanocomposites Derived from Organic Soybean, *ACS Omega* 8 (2023) 14965–14984, <https://doi.org/10.1021/acsomega.2c07546>.
- [19] M. Jamil, M.N. Akhtar, M. Imran, A. Javaid, H.K. Zafar, M. Sohail, M.A. AlDamen, M. Fitta, M.A. Khanfar, R.A. Al-Qawasmeh, Photocatalytic degradation of methylene blue dye and electrocatalytic water oxidation over copper(II) complex with mixed ligands, *J. Photochem. Photobiol. A Chem.* 446 (2024) 115095, <https://doi.org/10.1016/j.jphotochem.2023.115095>.
- [20] F. Mubarak, H. Rafique, J. Najeeb, S. Akram, H. Munir, S. Naeem, N. Kausar, N. Ashraf, Synthesis of amino acids-functionalized iron oxide nanoparticles for response surface methodology-based statistical optimization of photocatalytic degradation of methylene blue, *Int. J. Environ. Sci. Technol.* 21 (2023) 2489–2504, <https://doi.org/10.1007/s13762-023-05137-8>.
- [21] M.M. Gomaa, M.S. Abdel-wahed, Synthesis of Sb 2 S 3 nanosphere layer by chemical bath deposition for the photocatalytic degradation of methylene blue dye, *13 (2023) 22054–22060*. doi: 10.1039/d3ra02062b.
- [22] R. Kumar, R. Kumar, R. Kataria, S.C. Sahoo, P.K. Nanda, Solid-State Thermolysis of 1D and 3D Cd-Coordination Polymers of L-methionine Derived Ligand to CdS Nanospheres: Facile Synthesis, Characterization and Dye degradation Studies, *J. Mol. Struct.* 1243 (2021) 130817, <https://doi.org/10.1016/j.molstruc.2021.130817>.
- [23] K. Arya, A. Kumar, S. Mehra, A. Divya, S.K. Kumar, R.K. Mehta, Exploration and removal of multiple metal ions using mixed-linker-architected Zn-MOF in aqueous media, *Sep. Purif. Technol.* 307 (2023) 122551, <https://doi.org/10.1016/j.seppur.2022.122551>.
- [24] A. Kirandeep, A. Kumar, S.C. Sharma, E. Sahoo, V. Zangrando, R. Saini, S. Kataria, Kumar Mehta, Metal organic framework as “turn-on” fluorescent sensor for Zr(IV) ions and selective adsorbent for organic dyes, *Microchem. J.* 171 (2021) 106824, <https://doi.org/10.1016/j.microc.2021.106824>.
- [25] A. Kumar, V. Mutreja, V. Anand, S.K. Mehta, E. Zangrando, R. Kataria, Solvent templated luminescent metal-organic frameworks for specific detection of vitamin C in aqueous media, *J. Mol. Struct.* 1284 (2023) 135365, <https://doi.org/10.1016/j.jmolstruc.2023.135365>.
- [26] C.B. Ong, L.Y. Ng, A.W. Mohammad, A review of ZnO nanoparticles as solar photocatalysts: Synthesis, mechanisms and applications, *Renew. Sustain. Energy Rev.* 81 (2018) 536–551, <https://doi.org/10.1016/j.rser.2017.08.020>.
- [27] P. Zhou, J. Cheng, Y. Yan, S. Xu, C. Zhou, Ultrafast preparation of hydrophobic ZIF-67/copper mesh via electrodeposition and hydrophobization for oil/water separation and dyes adsorption, *Sep. Purif. Technol.* 272 (2021) 118871, <https://doi.org/10.1016/j.seppur.2021.118871>.
- [28] S. Rani, S. Kapoor, B. Sharma, S. Kumar, R. Malhotra, N. Dilbaghi, Fabrication of Zn-MOF@rGO based sensitive nanosensor for the real time monitoring of hydrazine, *J. Alloys Compd.* 816 (2020) 152509, <https://doi.org/10.1016/j.jallcom.2019.152509>.
- [29] M. Malekkiani, F. Ravari, A. Heshmati Jannat Magham, M. Dadmehr, H. Groiss, H. A. Hosseini, R. Sharif, Fabrication of Graphene-Based TiO₂@CeO₂ and CeO₂@TiO₂ Core-Shell Heterostructures for Enhanced Photocatalytic Activity and Cytotoxicity, *ACS Omega*. 7 (2022) 30601–30621. doi: 10.1021/acsomega.2c04338.
- [30] C. Yang, X. You, J. Cheng, H. Zheng, Y. Chen, A novel visible-light-driven In-based MOF/graphene oxide composite photocatalyst with enhanced photocatalytic activity toward the degradation of amoxicillin, *Appl. Catal. B Environ.* 200 (2017) 673–680, <https://doi.org/10.1016/j.apcatb.2016.07.057>.
- [31] K.D.R.N. Kalubowila, M.S. Gunewardene, J.L.K. Jayasingha, D. Dissanayake, C. Jayathilaka, J.M.D. Jayasundara, Y. Gao, J.K.D.S. Jayanetti, Reduction-Induced Synthesis of Reduced Graphene Oxide-Wrapped Cu₂O/Cu Nanoparticles for Photodegradation of Methylene Blue, *ACS Appl. Nano Mater.* 4 (2021) 2673–2681, <https://doi.org/10.1021/acsanm.0c03320>.
- [32] T. Kousar, K.M. Katubi, S. Zulfiqar, Z.A. Alrowaili, M.Z. Ansari, M.S. Al-Buriah, M. Aadil, W. Hassan, F. Mahmood, M. Hussain, Synthesis of nanostructured gadolinium doped mixed ferrite: A novel catalyst for the mineralization of textile dyes, *Ceram. Int.* 49 (2023) 19641–19651, <https://doi.org/10.1016/j.ceramint.2023.02.234>.
- [33] Q.V. Thi, M.S. Tamboli, Q. Thanh Hoai Ta, G.B. Kolekar, D. Sohn, A nanostructured MOF/reduced graphene oxide hybrid for enhanced photocatalytic efficiency under solar light, *Mater. Sci. Eng. B Solid-State Mater. Adv. Technol.* 261 (2020) 114678. doi: 10.1016/j.mseb.2020.114678.
- [34] S. Kumar, A.K. Ojha, B. Ahmed, A. Kumar, J. Das, A. Materny, Tunable (violet to green) emission by high-yield graphene quantum dots and exploiting its unique properties towards sun-light-driven photocatalysis and supercapacitor electrode materials, *Mater. Today Commun.* 11 (2017) 76–86, <https://doi.org/10.1016/j.mtcomm.2017.02.009>.
- [35] A. Negash, S. Mohammed, H.D. Weldekirstos, A.D. Ambaye, M. Gashu, Enhanced photocatalytic degradation of methylene blue dye using eco-friendly synthesized rGO@ZnO nanocomposites, *Sci. Rep.* 13 (2023) 1–12, <https://doi.org/10.1038/s41598-023-48826-7>.
- [36] K. Vanasundari, P. Ponnarasi, G. Mahalakshmi, A eco-friendly, green synthesis of Ag loaded WO₃/rGO nanocomposites for effective UV light photocatalytic degradation of 4-nitrophenol and antimicrobial activity, *Diam. Relat. Mater.* 142 (2024) 110859, <https://doi.org/10.1016/j.diamond.2024.110859>.
- [37] Y. ling Yang, Z. Huang, Y. ying Liu, D. Guo, Q. Zhang, J. ming Hong, Mechanism exploration of highly conductive Ni-metal organic frameworks/reduced graphene oxide heterostructure for electrocatalytic degradation of paracetamol: Functions of metal sites, organic ligands, and rGO basement, *J. Colloid Interface Sci.* 629 (2023) 667–682. doi: 10.1016/j.jcis.2022.09.112.
- [38] M.A. Al-Tahan, B. Miao, S. Xu, M. Hou, M.R. Shatat, M. Asad, Y. Luo, A.E. Shreshr, J. Zhang, Ni-doped Fe-MOF@rGO nanohybrid as a functional separator for ultra-long cyclability in lithium-sulfur cells, *Colloids Surfaces A Physicochem. Eng. Asp.* 682 (2024) 132899, <https://doi.org/10.1016/j.colsurfa.2023.132899>.
- [39] S. Sundriyal, M. Sharma, A. Kaur, S. Mishra, A. Deep, Improved electrochemical performance of rGO/TiO₂ nanosheet composite based electrode for supercapacitor applications, *J. Mater. Sci. Mater. Electron.* 29 (2018) 12754–12764, <https://doi.org/10.1007/s10854-018-9393-5>.
- [40] G. Nazik, M. Aadil, S. Zulfiqar, W. Hassan, A. Rahman, S.M. Ibrahim, K. Naseem, T. A. Sheikh, M.N. Akhtar, Synthesis of doped metal sulfide nanoparticles and their graphene reinforced nanohybrid for Pb(II) detection, *Zeitschrift Fur Phys, Chemie.* 237 (2023) 1257–1285, <https://doi.org/10.1515/zpch-2023-0252>.
- [41] T. Kousar, M. Aadil, S. Zulfiqar, S.M. Ibrahim, S. Mubeen, W. Hassan, K. Shafiq, F. Mahmood, Facile synthesis of graphene anchored rare earth doped mixed metal

- ferrite nanorods: A potential candidate for azo dye mineralization, *J. Rare Earths*. 42 (2024) 907–916, <https://doi.org/10.1016/j.jre.2023.07.002>.
- [42] K. Chaudhary, M. Aadil, S. Zulfiqar, S. Ullah, S. Haider, P.O. Agboola, M.F. Warsi, I. Shakir, Graphene oxide and reduced graphene oxide supported ZnO nanochips for removal of basic dyes from the industrial effluents, *Fullerenes Nanotub. Carbon Nanostructures*. 29 (2021) 915–928, <https://doi.org/10.1080/1536383X.2021.1917553>.
- [43] L. Huang, B. Liu, Synthesis of a novel and stable reduced graphene oxide/MOF hybrid nanocomposite and photocatalytic performance for the degradation of dyes, *RSC Adv.* 6 (2016) 17873–17879, <https://doi.org/10.1039/c5ra25689e>.
- [44] S.F. Zhang, H. Li, C. Hou, L.N. Liu, Y. Wang, M.K. Zhao, C. Liang, Recyclable ZIF-9@CA-Fe3O4/RGO/cellulose composite membrane as efficient catalysts for activating peroxymonosulfate to degrade methylene blue, *Cellul.* 27 (2020) 3287–3300, <https://doi.org/10.1007/s10570-020-02998-x>.
- [45] M. Qi, P. Lin, Q. Shi, H. Bai, H. Zhang, W. Zhu, A metal-organic framework (MOF) and graphene oxide (GO) based peroxymonosulfate (PMS) activator applied in pollutant removal, *Process Saf. Environ. Prot.* 171 (2023) 847–858, <https://doi.org/10.1016/j.psep.2023.01.069>.
- [46] B. Bashir, M.U. Khalid, M. Aadil, S. Zulfiqar, M.F. Warsi, P.O. Agboola, I. Shakir, Cu₂Ni_{1-x}O nanostructures and their nanocomposites with reduced graphene oxide: Synthesis, characterization, and photocatalytic applications, *Ceram. Int.* 47 (2021) 3603–3613, <https://doi.org/10.1016/j.ceramint.2020.09.209>.
- [47] M. Aadil, A. Rahman, S. Zulfiqar, I.A. Alsafari, M. Shahid, I. Shakir, P.O. Agboola, S. Haider, M.F. Warsi, Facile synthesis of binary metal substituted copper oxide as a solar light driven photocatalyst and antibacterial substitute, *Adv. Powder Technol.* 32 (2021) 940–950, <https://doi.org/10.1016/j.apt.2021.01.040>.
- [48] M.F. Warsi, B. Bashir, S. Zulfiqar, M. Aadil, M.U. Khalid, P.O. Agboola, I. Shakir, M. A. Yousef, M. Shahid, Mn_{1-x}Cu_xO₂/reduced graphene oxide nanocomposites: Synthesis, characterization, and evaluation of visible light mediated catalytic studies, *Ceram. Int.* 47 (2021) 5044–5053, <https://doi.org/10.1016/j.ceramint.2020.10.082>.
- [49] K. Sonu, S.H. Puttaiah, V.S. Raghavan, S.S. Gorthi, Photocatalytic degradation of MB by TiO₂: studies on recycle and reuse of photocatalyst and treated water for seed germination, *Environ. Sci. Pollut. Res.* 28 (2021) 48742–48753, <https://doi.org/10.1007/s11356-021-13863-0>.
- [50] M.J.M. Rusan, A.A. Albalasmeh, S. Zuraiqi, M. Bashabsheh, Evaluation of phytotoxicity effect of olive mill wastewater treated by different technologies on seed germination of barley (*Hordeum vulgare* L.), *Environ. Sci. Pollut. Res.* 22 (2015) 9127–9135, <https://doi.org/10.1007/s11356-014-4004-3>.
- [51] M. Siddiq, A.G. Taki, M. Aadil, S. Mubarik, E.W. Cochran, S. Zulfiqar, A.A. Mohammed, S. Ijaz, Microwave-assisted synthesis of tentacles like Ag-doped copper oxide nano-ceramics: Structural, optical, and anti-campylobacter studies, *Ceram. Int.* 49 (2023) 36590–36599, <https://doi.org/10.1016/j.ceramint.2023.08.342>.
- [52] M. Kofranek, T. Kovár, H. Lischka, A. Karpfen, Ab initio studies on heterocyclic conjugated polymers: structure and vibrational spectra of thiophene, oligothiophenes and polythiophene, *J. Mol. Struct. Theochem.* 259 (1992) 181–198, [https://doi.org/10.1016/0166-1280\(92\)87013-P](https://doi.org/10.1016/0166-1280(92)87013-P).
- [53] Z. Gao, X. Zhang, P. Xu, J. Sun, Dual hydrogen-bond donor group-containing Zn-MOF for the highly effective coupling of CO₂ and epoxides under mild and solvent-free conditions, *Inorg. Chem. Front.* 7 (2020) 1995–2005, <https://doi.org/10.1039/d0qi00068j>.
- [54] M. Akhtar, S.N. Abdou, T. Abdullah, M.H.H. Mahmoud, Z. Sabir, Z.A.K. Khattak, S. Zafar, S. Zulfiqar, Wet chemical synthesis of C@Nd2O3/rGO nanocomposite: A visible light trigger photocatalyst for efficient water remediation, *Opt. Mater. (Amst.)* 135 (2023) 113255, <https://doi.org/10.1016/j.optmat.2022.113255>.
- [55] M. Sabir, M. Ramzan, M. Imran, S.R. Ejaz, A. Anwar, S. Ahmad, M. Aamir, M. Aadil, Synthesis of La_{1-x}Gd_xFe_{1-y}Co_yO₃/r-GO nanocomposite with integrated features for the treatment of hazardous industrial effluents, *Ceram. Int.* 48 (2022) 9134–9145, <https://doi.org/10.1016/j.ceramint.2021.12.098>.
- [56] M. Aadil, S. Zulfiqar, H. Sabeeh, M.F. Warsi, M. Shahid, I.A. Alsafari, I. Shakir, Enhanced electrochemical energy storage properties of carbon coated Co3O4 nanoparticles-reduced graphene oxide ternary nano-hybrids, *Ceram. Int.* 46 (2020) 17836–17845, <https://doi.org/10.1016/j.ceramint.2020.04.090>.
- [57] M. Aadil, A.G. Taki, S. Zulfiqar, A. Rahman, M. Shahid, M.F. Warsi, Z. Ahmad, A. A. Althman, S. Mohammad, Gadolinium doped zinc ferrite nanoarchitecture reinforced with a carbonaceous matrix: a novel hybrid material for next-generation flexible capacitors, *RSC Adv.* 13 (2023) 28063–28075, <https://doi.org/10.1039/d3ra05290g>.
- [58] W. Wazir, Z. Ahmad, S. Zulfiqar, E.W. Cochran, S. Mubarik, T. Kousar, H. H. Smaili, J.J. Shim, H.A. Alsalmah, M. Aadil, Synergistic effects of noble metal doping and nanoengineering on boosting the azo dye mineralization activity of nickel oxide, *Ceram. Int.* 49 (2023) 38026–38035, <https://doi.org/10.1016/j.ceramint.2023.09.133>.
- [59] M.U. Khalid, K.M. Katubi, S. Zulfiqar, Z.A. Alrowaili, M. Aadil, M.S. Al-Buriah, M. Shahid, M.F. Warsi, Boosting the electrochemical activities of MnO₂ for next-generation supercapacitor application: Adaptation of multiple approaches, *Fuel* 343 (2023) 127946, <https://doi.org/10.1016/j.fuel.2023.127946>.
- [60] T. Li, M. Aadil, S. Zulfiqar, A. Anwar, S.M. Yakout, N.M. Panduro-Tenazoa, S. Mubeen, Synthesis of doped and porous CuO with boosted light-harvesting features for the photocatalytic mineralization of azo dyes, *Ceram. Int.* 49 (2023) 27827–27836, <https://doi.org/10.1016/j.ceramint.2023.05.272>.
- [61] X. Li, J. Guan, H. Jiang, X. Song, P. Huo, H. Wang, rGO modified R-CeO₂/g-C₃N₄ multi-interface contact S-scheme photocatalyst for efficient CO₂ photoreduction, *Appl. Surf. Sci.* 563 (2021) 150042, <https://doi.org/10.1016/j.apsusc.2021.150042>.
- [62] M. Song, J. Li, M. Xu, Z. Xu, X. Song, X. Liu, J. Zhang, Y. Yang, X. Xie, W. Zhou, P. Huo, Facile synthesis of MOF-808/RGO-based 3D macroscopic aerogel for enhanced photoreduction CO₂, *J. Colloid Interface Sci.* 668 (2024) 471–483, <https://doi.org/10.1016/j.jcis.2024.04.195>.
- [63] Y. Kuang, J. Shang, T. Zhu, Photoactivated Graphene Oxide to Enhance Photocatalytic Reduction of CO₂, *ACS Appl. Mater. Interfaces*. 12 (2020) 3580–3591, <https://doi.org/10.1021/acsami.9b18899>.
- [64] M. Zeraati, M. Moghaddam-Manesh, S. Khodamoradi, S. Hosseinzadegan, A. Golpayegani, N.P.S. Chauhan, G. Sargazi, Ultrasonic assisted reverse micelle synthesis of a novel Zn-metal organic framework as an efficient candidate for antimicrobial activities, *J. Mol. Struct.* 1247 (2021) 131315, <https://doi.org/10.1016/j.molstruc.2021.131315>.
- [65] S. Koppula, P. Jagasia, M.K. Panchangam, S.B. Manabolu Surya, Synthesis of bimetallic Metal-Organic Frameworks composite for the removal of Copper(II), Chromium(VI), and Uranium(VI) from the aqueous solution using fixed-bed column adsorption, *J. Solid State Chem.* 312 (2022) 123168, <https://doi.org/10.1016/j.jssc.2022.123168>.
- [66] M.M. Kaid, O. Elbanna, S.A. El-Hakam, H.M. El-Kaderi, A.A. Ibrahim, Effective photocatalytic degradation of organic dyes using ZNC/rGO nanocomposite photocatalyst derived from ZIF-8/rGO thermolysis for water treatment, *J. Photochem. Photobiol. A Chem.* 430 (2022) 114001, <https://doi.org/10.1016/j.jphotochem.2022.114001>.
- [67] B. Yang, P. Zhou, X. Cheng, H. Li, X. Huo, Y. Zhang, Simultaneous removal of methylene blue and total dissolved copper in zero-valent iron/H₂O₂ Fenton system: Kinetics, mechanism and degradation pathway, *J. Colloid Interface Sci.* 555 (2019) 383–393, <https://doi.org/10.1016/j.jcis.2019.07.071>.
- [68] A. Houas, H. Lachheb, M. Ksibi, E. Elaloui, C. Guillard, J.M. Herrmann, Photocatalytic degradation pathway of methylene blue in water, *Appl. Catal. B Environ.* 31 (2001) 145–157, [https://doi.org/10.1016/S0926-3373\(00\)00276-9](https://doi.org/10.1016/S0926-3373(00)00276-9).
- [69] L. Wu, Q. Xie, Y. Lv, Z. Zhang, Z. Wu, X. Liang, M. Lu, Y. Nie, Degradation of methylene blue by dielectric barrier discharge plasma coupled with activated carbon supported on polyurethane foam, *RSC Adv.* 9 (2019) 25967–25975, <https://doi.org/10.1039/c9ra05238k>.
- [70] F.F.D. Almeida, A.P. Araújo, B.J.R. Alves, Seeds with high molybdenum concentration improved growth and nitrogen acquisition of rhizobium-inoculated and nitrogen-fertilized common bean plants, *Rev. Bras. Ciência Do Solo*. 37 (2013) 367–378, <https://doi.org/10.1590/s0100-06832013000200008>.



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