

Sustainable Nickel Catalysis for Water Remediation

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Abstract

Clean water is the need of the hour. Sustainable water remediation requires affordable, reusable and environmentally friendly catalytic system. In this direction, a nickel-incorporated polyaniline (PANI–Ni) catalyst was synthesized and tested for the reduction of selected organic pollutants in aqueous media. The catalyst showed effective degradation of model dyes such as methylene blue, rhodamine B, and p-nitrophenol under mild conditions. The chapter elaborates the characterization of the catalyst using Fourier-transform infrared spectroscopy (FTIR), Scanning Electron Microscopy-Energy Dispersive X-Ray (SEM-EDX), Powder X-ray diffraction (XRD) as well as optimization of catalyst loading and pH of the reaction medium. Moreover, it shades light on the recovery and recyclability of the PANI–Ni.

Keywords: Heterogeneous Catalysis; Organic Dye Degradation; Polyaniline-supported Nickel Catalyst; Wastewater Remediation

Introduction

Catalytic reduction has emerged as a promising strategy for transforming hazardous pollutants into less harmful products. In particular, heterogeneous catalysts are advantageous due to their ease of separation and recyclability. Nickel-based systems have gained attention owing to their affordability and catalytic activity. However, issues related to aggregation and stability often limit their performance.

To address these challenges, conducting polymers such as polyaniline provide an effective support matrix. Their unique electronic properties and structural versatility enable strong interactions with metal species, enhancing dispersion and catalytic efficiency. In this study, a PANI-supported nickel catalyst is developed and evaluated for wastewater remediation applications.

Industrial effluents containing synthetic dyes and nitroaromatic compounds are among the most persistent environmental pollutants (Ismail *et al.* 2019). These substances are widely used in textile, pharmaceutical, and chemical industries, and their discharge into water bodies poses serious ecological and health risks. A variety of techniques, such as reduction, oxidation, coagulation, adsorption, photochemical processes, and electrochemical methods, have been applied for the treatment of wastewater (Lanjwani *et al.*, 2024). Reductive degradation of organic dyes in presence of metal catalyst is one of the most sought-after techniques for water remediation (Arif, 2025).

Literature is abundant with palladium catalyzed reductive degradation of organic dyes (Bhat *et al.* 2020). Other metals such as Cobalt, platinum, gold, silver, nickel are also reported to be effective (Haleem *et al.* 2026).

Nickel being one of the cheapest and catalytically efficient metal, attracted attention from several groups all over the world for the development of cost effective heterogenous catalytic system for the reduction of nitrophenols (NP)/organic dyes as outlined in Table-1.

Table 1: Heterogeneous Nickel Catalysts for Reduction of Nitrophenol

Catalyst	Remark	Reference
PVDF-[C ₆ (mpy) ₂][NiCl ₄] ²⁻ Ionic liquid-based catalyst	NP: 90% Yield in 5 min, Recycled 4 times	Chinnappan & Kim, 2013
Ni-PAMAM-PVAm/SBA-15 Mesoporous silica-polyamidoamine-polyvinylamine supported Ni nanoparticles catalyst	NP: 98% Yield immediately Recycled 10 times	Kalbasi & Zamani 2014
L-lysine derived nickel nanoparticles	MB: 100% reduction in 160 s No recyclability reported	Khaskheli <i>et al.</i> , 2016
Tetrabutyl ammonium bromide stabilized Nickel nanoparticles	Methyl orange: Complete reduction Recyclable	Mondal <i>et al.</i> , 2018
Ni/CPM (carbon porous materials)	MB: Complete reduction in 13 min Recyclable 6 times	Veerakumar <i>et al.</i> , 2015
Polyaniline-NiO	MB: Complete reduction 23 min No recyclability reported	Jamil <i>et al.</i> , 2021
NiO-CMK-3 Nickel oxide nanoparticles dispersed in mesoporous carbon	MB: Complete reduction 3 min Recyclable 5 times	Younus <i>et al.</i> , 2024

To develop a sustainable catalytic approach for the removal of organic dyes, polyaniline (PANI) was chosen as supporting backbone for its chemical stability, low cost and easy to prepare and most importantly availability of metal chelation sites and nickel as the catalytically active metal. The following section presents the synthesis, characterization, and catalytic performance of polyaniline-anchored nickel (PANI–Ni) in the reduction of various organic dyes.

Methodology

Materials

Ni (OAc)₂·4H₂O, ammonium persulfate, MB, RhB, p-NP and all other chemicals were of commercial grades and used as such without further purification. Prior to its use, aniline was purified via distillation.

Preparation of Polyaniline Base (PANI)

Polyaniline was prepared via oxidative polymerization of aniline in acidic medium using ammonium persulfate as the oxidant (Roy *et al.* 2019). The resulting product was filtered, washed repeatedly to remove residual impurities, and dried to obtain the PANI salt which was further treated with sodium hydroxide to afford the PANI base.

Preparation of PANI- Ni

A suspension of PANI (1000 mg) in an aqueous solution (50 mL) of nickel acetate tetrahydrate (250 mg) was sonicated for 1 h. The resulting material was recovered by filtration, washed sequentially with water and acetone, and dried under vacuum at 40 °C for 8 h to yield PANI–Ni (1100 mg). The nickel loading, determined by ICP–AES, was 0.41 mmol g^{−1} (Roy *et al.* 2025).

Catalytic Reduction Procedure

Degradation of p-NP

In a representative experiment, PANI–Ni catalyst (5.0 mg) was introduced into an aqueous solution of p-nitrophenol (10 mL, 1 × 10^{−6} M) in a reaction flask. Subsequently, an aqueous solution of sodium borohydride (10 mL, 2 × 10^{−5} M) was added under continuous stirring. The reaction progress was monitored at ambient conditions using UV–visible spectroscopy. The pH of the reaction medium was maintained at 9.3. The concentration of p-nitrophenol was determined from the absorbance at λ_{max} = 400 nm.

Degradation of MB and RhB

In a typical experiment, a measured amount of PANI–Ni catalyst and an aqueous sodium borohydride solution (10 mL, 1.5×10^{-5} M) were sequentially added to an aqueous solution of methylene blue (MB) (10 mL, 1×10^{-6} M). The reaction mixture was monitored at room temperature using UV–visible spectroscopy. The concentration of MB was determined from its absorbance at $\lambda_{\text{max}} = 664$ nm.

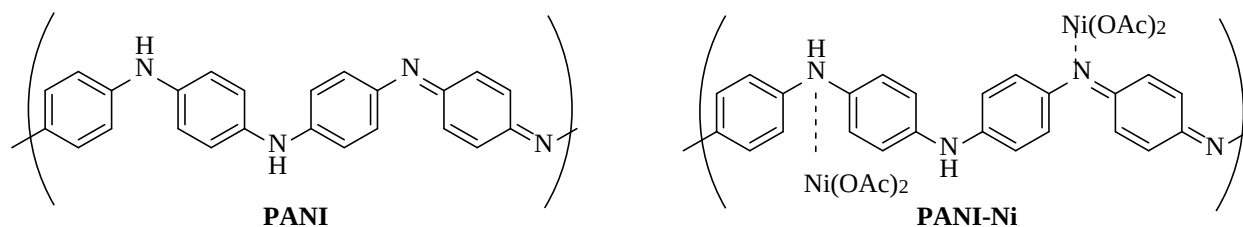
A similar procedure was followed for rhodamine B (RhB), with the reaction progress monitored at $\lambda_{\text{max}} = 554$ nm.

Results and Discussion

Characterization of PANI–Ni

Structural Characterization

The FTIR spectra of polyaniline (PANI) and polyaniline–nickel (PANI–Ni) (Figure 1) show no significant changes in the characteristic absorption bands after complexation with $\text{Ni}(\text{OAc})_2$. The key peaks corresponding to the quinoid ring (~ 1590 cm^{-1}), benzenoid ring (~ 1509 cm^{-1}), C–N stretching of secondary aromatic amine (~ 1295 cm^{-1}), N=Q=N and/or aromatic C–H in-plane deformation (~ 1170 and 1140 cm^{-1}), and C–H out-of-plane bending (~ 824 cm^{-1}) remain largely unchanged which is in agreement with similar study (Huerta *et al.* 2021). The probable structures of PANI and PANI–Ni are illustrated in Scheme 1.



Scheme 1: (A) Proposed Structure of Polyaniline (PANI) and (B) Polyaniline-Supported Nickel (PANI–Ni)

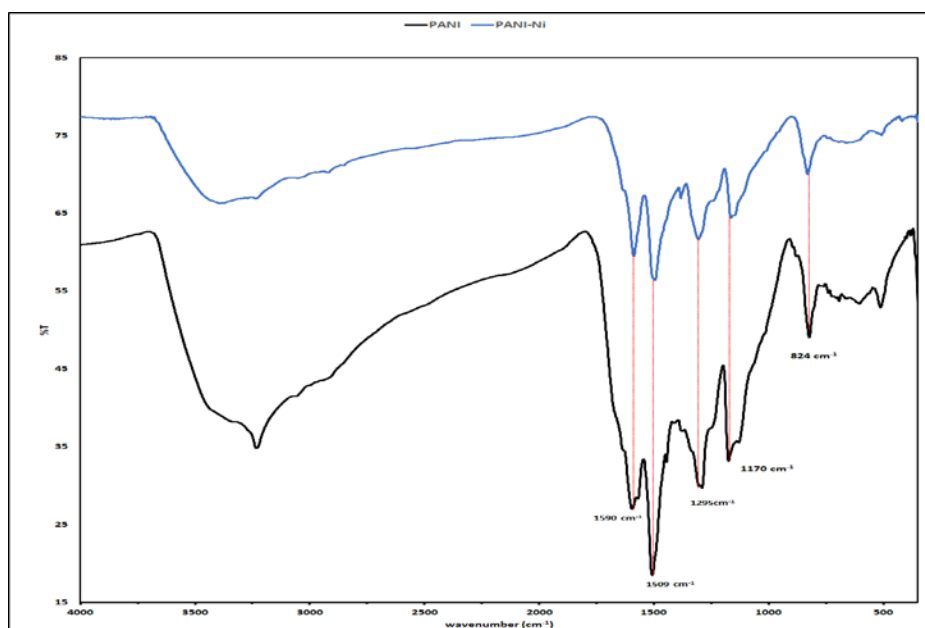


Figure 1: FTIR Spectra of Polyaniline (PANI) and Nickel-Modified Polyaniline (PANI–Ni)

Morphological and Elemental Analysis

The morphology of PANI–Ni, as examined by SEM–EDX (Figure 2), shows a rough and porous aggregated structure, with a nickel content of approximately 3.4%.

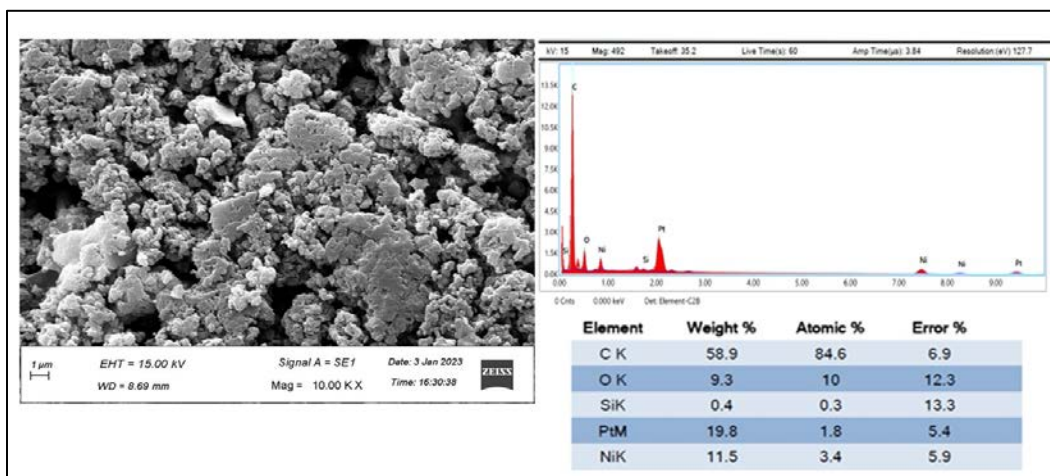


Figure 2: SEM Micrograph and Corresponding EDX Analysis of PANI–Ni

XRD pattern of PANI–Ni

X-ray diffraction (XRD) patterns of PANI and PANI–Ni were recorded over a 2θ range of $5\text{--}50^\circ$ with a step size of 0.02° , using $\text{Cu K}\alpha_1$ radiation ($\lambda = 1.54 \text{ \AA}$). PANI exhibited broad diffraction peaks at approximately $2\theta = 20^\circ$ and 26.3° , indicative of its predominantly amorphous nature (Figure 3). A similar diffraction profile was observed for PANI–Ni, suggesting that incorporation of nickel does not significantly alter the polymer backbone. NiO showed distinct peaks in XRD around $2\theta \sim 37.5^\circ$ (111), 43.3° (200), 62.9° (220), and 75.4° (311) (Hamzah *et al* 2025) whereas Ni (0) particles exhibited characteristic peaks around 44.5° (111), 51.8° (200), and 76.4° (220) (Zhu *et al* 2025). As no distinct peaks corresponding to metallic Ni or NiO were detected in PANI–Ni, this indicates the absence of reduction or hydrolysis of $\text{Ni}(\text{OAc})_2$.

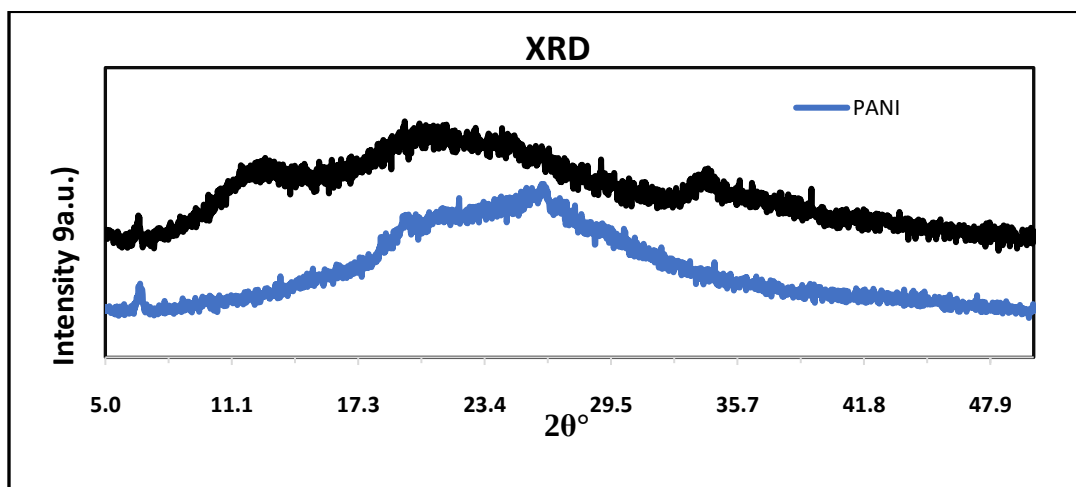


Figure 3: Powder XRD Pattern of the PANI and PANI–Ni Catalyst

Catalytic degradation of p-NP

The catalytic reduction of p-nitrophenol (p-NP) using PANI–Ni (5 mg) in the presence of sodium borohydride was monitored by UV–visible spectroscopy at $\lambda = 400 \text{ nm}$ (Figure 4A). Complete conversion was achieved

within 12 min, accompanied by the emergence of a characteristic absorption band of p-aminophenol at $\lambda = 290$ nm.

Increasing the loading of PANI-Ni catalyst showed much faster reduction of the p-NP as shown in Figure-4B. The observation is in line with expectation as the increased amount of catalysts provided a higher active site for the reduction (Roy *et al.* 2019). Recently $\text{Ni}_3\text{S}_2@\text{NF}$ (Nickel Foam treated with sulfide) reported similar trend in reduction of p-NP in presence of NaBH_4 (Cao *et al.* 2026). Moreover, the catalyst afforded 93.35% of p-NP within 25 min.

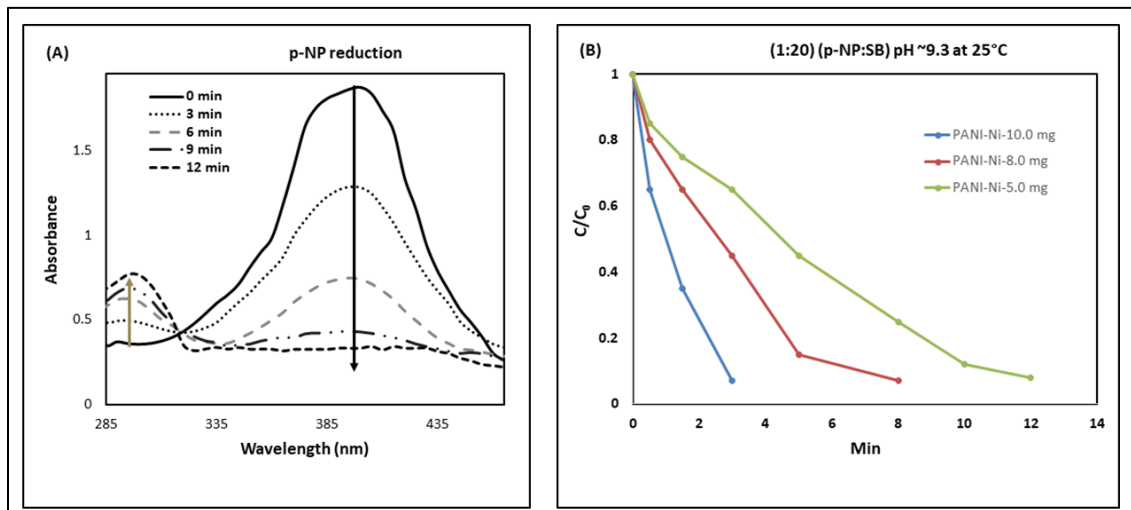


Figure 4: (A) Catalytic Reduction of p-nitrophenol (p-NP) in the Presence of PANI-Ni (5 mg); (B) Dependence of p-NP Degradation on PANI-Ni Catalyst Loading

Catalytic reduction of Methylene Blue (MB)

The reduction of methylene blue (MB) was investigated in the presence of sodium borohydride (1.5×10^{-5} M) using different loadings of PANI-Ni catalyst. A decrease in catalyst amount from 10.0 mg to 3.0 mg led to a corresponding increase in the time required for complete reduction, from 5 min to 25 min (Figure 5).

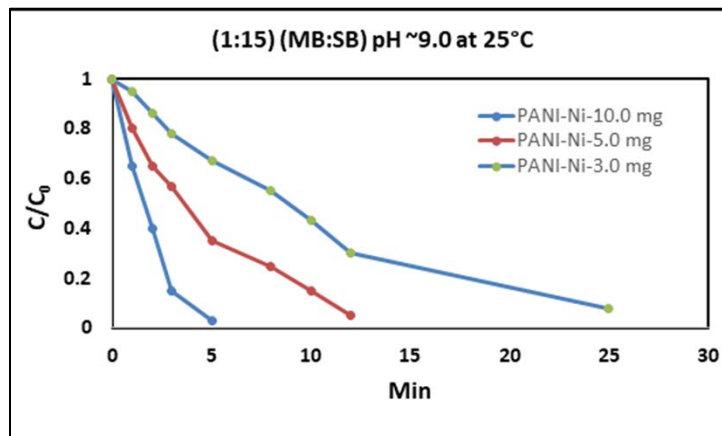


Figure 5: Dependence of Methylene Blue (MB) Degradation on PANI-Ni Catalyst Loading

A pH-dependent study (pH 8.5–11.0) was conducted using 10.0 mg of PANI-Ni catalyst. The reaction proceeded rapidly at pH 8.5, reaching near-complete conversion within 4 min, while at pH 11 only partial reduction was observed even after 50 min (Figure 6).

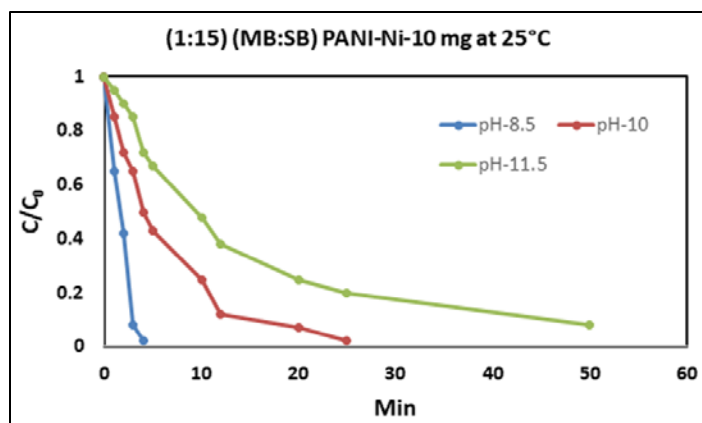


Figure 6: Influence of pH on the Reduction of Methylene Blue (MB) in the Presence of PANI–Ni and Sodium Borohydride

Table-2 shows a comparison of PANI-Ni with recently reported Ni catalyzed reduction of MB.

Table 2: Reduction of MB using different Ni catalysts

Catalyst	MB Reduction	Reference
PANI-Ni	10 mg catalyst afforded complete reduction within 5 min	Current Study
Cellulose Acetate Composite Membrane Fabricated with Nickel Nanoparticles (CA/Ni)	20 mg of CA/Ni afforded 88% reduction in 28 min	Bawazeer 2025
NiO nanoparticles-loaded mesoporous carbon (NiO/CMK-3)	100 mg of NiO/CMK-3 afforded complete reduction within 3 min	Younus <i>et al.</i> 2024
gellan gum-co-polymethacrylic acid hydrogel supported Ni-Cu bimetallic composite (GG-co-PMAA)@Ni-Cu	(GG-co-PMAA)@Ni-Cu afforded Complete reduction within 4 min	Afsheen <i>et al.</i> 2026

Catalytic reduction of Rhodamine B (RhB)

The reduction of rhodamine B (RhB), a xanthene dye, was carried out using sodium borohydride (10 mL, 2×10^{-5} M) and PANI–Ni (10.0 mg), achieving complete conversion within 15 min (Figure 7). A systematic increase in catalyst loading from 5.0 mg to 15.0 mg led to a noticeable enhancement in the reaction rate (Figure 8).

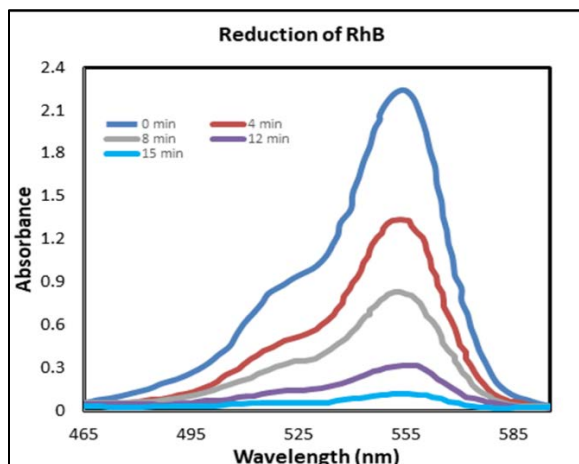


Figure 7: Catalytic Reduction of Rhodamine B (RhB) using PANI–Ni (10 mg) with Sodium Borohydride at pH 8.7

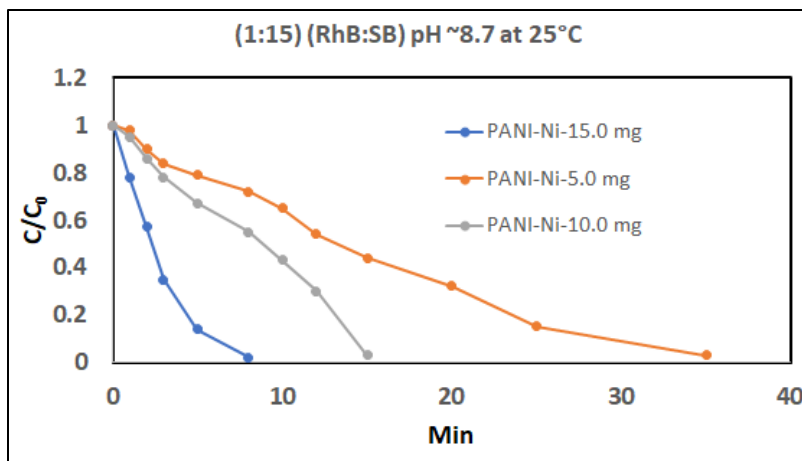


Figure 8: Influence of PANI-Ni Catalyst Loading on the Degradation of Rhodamine B (RhB)

Recently a $\text{NiFe}_2\text{O}_4@\text{C}/\text{PPy}$ Catalyst reported for the degradation of RhB in presence of SB affording ~80% reduction of RhB under optimal condition within 100 min (Thomas *et al.* 2025).

Recyclability Studies

For any sustainable catalytic system, recyclability is one of the most important criteria. Herein the PANI-Ni catalyst was treated with MB and recovered after filtration and reused in the next cycle (Figure-9). PANI-Ni showed excellent reduction of MB till 6th cycle. Slight activity loss was observed during the course of this study. To understand the loss in activity, Ni content of the fresh and recovered PANI-Ni was compared. PANI-Ni fresh showed 0.41 mmol g^{-1} Ni vs 0.35 mmol g^{-1} Ni after the 6th cycle. PANI-Ni recovered was further analyzed by XPS and it showed presence of Ni (0) and Ni(II) (Figure-10). A TEM analysis of the recovered PANI-Ni revealed presence of nickel nanoparticles of > 25 nm (Figure-11). The activity loss is a combined effect of nickel leaching, reduction followed by agglomeration of nickel particles.

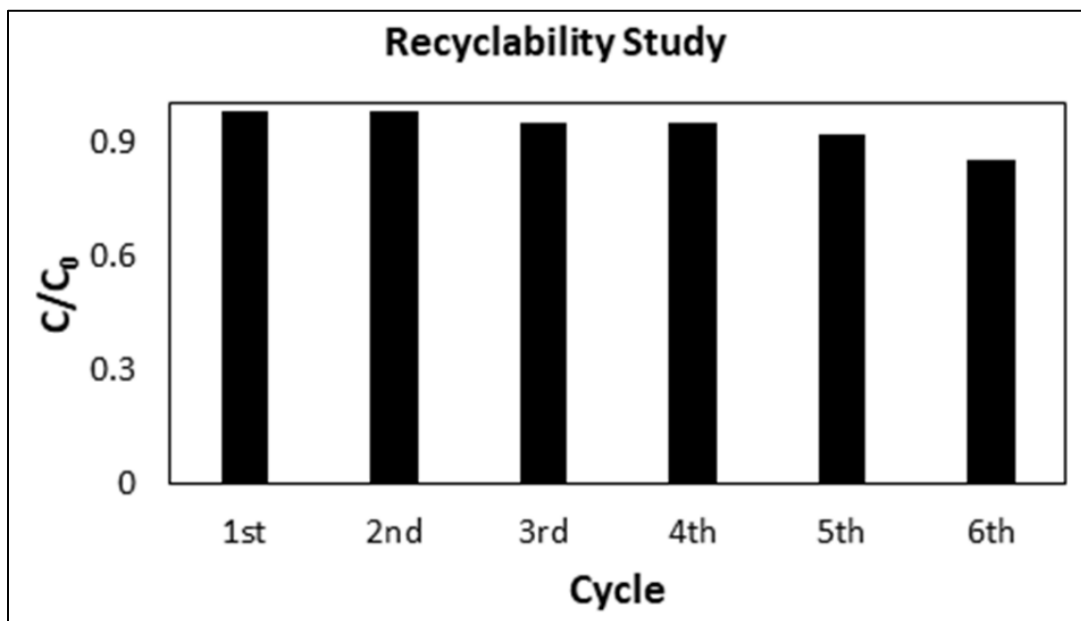


Figure 9: Recyclability Study of PANI-Ni for the Reduction of Methylene Blue (MB) in the Presence of Sodium Borohydride

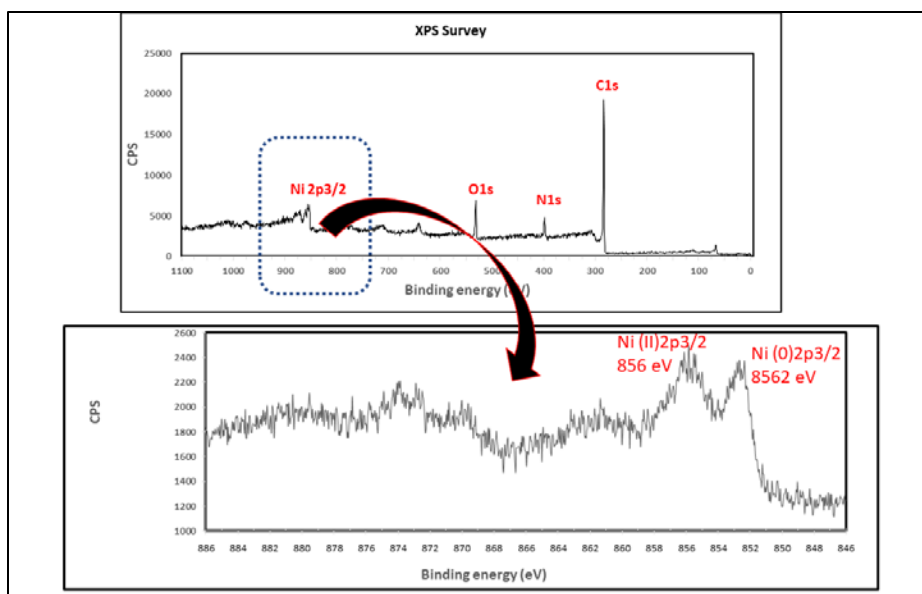


Figure 10: XPS Study of the Recovered PANI-Ni Catalyst

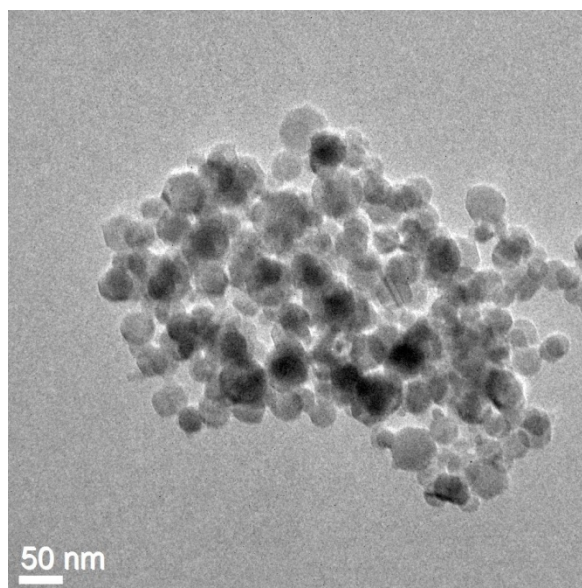


Figure 11: TEM Characterization of the Recovered PANI-Ni Catalyst

Table 3 presents a comparative study of recyclability of the PANI-Ni and recently reported Ni catalyst in degradation of dyes.

Table 3: Recyclability of Ni Catalysts in Dye Degradation

Catalyst	Dye	Remark	Reference
PANI-Ni	MB	Activity dropped after 6 cycle and agglomeration of Ni particle observed	Current Study
NiO/CMK-3	MB	Recycled for 5 times. Very low level of Ni leaching and structural integrity of the catalyst established	Younus <i>et al.</i> 2024
GG-co-PMAA@Ni-Cu	MB	Recycled for 5 consecutive cycles with 87% catalytic activity	Afsheen <i>et al.</i> 2026
Ni ₃ S ₂ @NF	p-NP	Retained 90% activity after 15 cycles	Cao <i>et al.</i> 2026

Conclusion

In this work, a polyaniline-supported nickel catalyst (PANI–Ni) was prepared and applied for the reduction of organic pollutants such as p-nitrophenol, methylene blue, and rhodamine B. The catalyst showed good activity under mild conditions, enabling rapid conversion of these substrates.

The material could be readily recovered after the reaction and reused over several cycles with only a small decrease in activity. Characterization of the recovered catalyst by XPS, TEM, and metal analysis indicates that the loss in performance is likely due to a combination of nickel leaching, changes in the oxidation state of the active sites, and aggregation of nickel species within the polymer framework.

These observations help to better understand the stability of polymer-supported nickel systems and the factors that influence their long-term performance. The results suggest that PANI–Ni can serve as a useful catalyst for wastewater treatment, and that further improvements in catalyst design could enhance its durability and practical applicability.

Acknowledgement

The author is thankful to the Department of Chemistry, Ramsaday College, India for the facilities.

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