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Harnessing Green Chemistry For The Synthesis Of Nickel Oxide Nanoparticles In Effective Adsorption Of Microplastic From Water

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The persistent accumulation of microplastics in aquatic environments poses an emerging challenge for global water security. This study presents a novel, sustainable strategy for microplastic removal by employing nickel oxide (NiO) nanoparticles synthesized through a green chemistry route. Leveraging the phytochemical richness of plant extracts, the biosynthesis method avoids toxic reagents, reducing environmental burden while enhancing nanoparticle functionality. Comprehensive physicochemical characterization confirmed the crystalline nature, high surface area, and nano-scale morphology of the NiO particles. In adsorption experiments, the nanoparticles demonstrated remarkable affinity for microplastic contaminants, driven by surface charge interactions and hydrophobic attraction. Notably, the NiO adsorbent maintained performance across multiple reuse cycles, highlighting their practical applicability. This work pioneers the intersection of green nanomaterials and microplastic remediation, offering an eco-conscious and scalable pathway for advancing wastewater treatment technologies in the era of plastic pollution.

Key words: Green synthesis, Nickel oxide nanoparticles, Microplastics, Water treatment, Nanotechnology, Adsorption.

Highlights

- Nickel oxide nanoparticles synthesized using ginger extract via green chemistry
- UV–Vis confirms nanoparticle formation with absorption in the visible region
- TEM analysis reveals spherical NiO nanoparticles with uniform morphology
- NiO nanoparticles show high adsorption efficiency for microplastics in water
- Green-synthesized NiO offers a sustainable solution for water pollutant removal

1.Introduction

The increasing prevalence of microplastics in aquatic environments has emerged as a critical global environmental concern. These microscopic plastic particles, typically less than 5 mm in size, originate from a variety of sources including industrial effluents, household waste, and the degradation of larger plastic debris [1]. Due to their small size and persistence, microplastics are difficult to remove through conventional water treatment processes, posing risks to aquatic life and human health through bioaccumulation and potential toxicity [2]. In recent years, nanotechnology has offered promising avenues for advanced water purification techniques, particularly through the use of engineered nanomaterials with high surface area and functional reactivity [3]. Among these materials, Nickel Oxide (NiO) nanoparticles have garnered significant interest due to their unique structural, catalytic, and adsorptive properties [4]. However, traditional synthesis methods for NiO nanoparticles often rely on hazardous chemicals and energy-intensive processes, which contradict the principles of sustainability and environmental stewardship. To address this, green chemistry has emerged as a vital approach for the sustainable synthesis of nanomaterials. Green synthesis methods utilize benign solvents, renewable plant extracts, and eco-friendly reducing agents to minimize toxic byproducts and energy consumption [5]. Plant-mediated synthesis of metal oxide nanoparticles not only offers an environmentally benign alternative but also imparts additional functional groups to the nanoparticle surface, enhancing their adsorption performance [6]. This study aims to harness green chemistry techniques for the synthesis of NiO nanoparticles and evaluate their effectiveness in the adsorption and removal of microplastics from contaminated water systems [8]. The integration of green-synthesized nanomaterials in water treatment not only supports sustainable nanotechnology but also offers a novel pathway for addressing the persistent challenge of microplastic pollution. The contamination of aquatic environments by microplastics has become an urgent global concern due to their persistence, bioaccumulation, and potential toxic effects on both ecosystems and human health. Microplastics, defined as plastic particles smaller than 5 mm, are found in various sources, including wastewater, and their removal remains a significant challenge for conventional water treatment technologies [11]. Despite the adoption of several filtration and chemical methods, most traditional approaches fail to efficiently eliminate microplastics from water, owing to their small size, irregular shapes, and complex interactions with water components. As a result, new and innovative approaches are being explored to address this environmental issue effectively.

Nanotechnology, particularly the use of nanoparticles (NPs), has emerged as a promising solution for environmental remediation due to the unique physicochemical properties of nanoscale materials [12]. Among various types of nanoparticles, nickel oxide (NiO) nanoparticles (NPs) have attracted significant attention because of their high surface area, excellent chemical stability, and tunable properties that make them suitable for adsorptive removal of contaminants, including microplastics. NiO NPs have been investigated for their potential in various environmental applications, such as heavy metal removal, water treatment, and catalytic processes. However, conventional synthesis methods for NiO NPs often involve the use of toxic chemicals and high-energy processes, which are not aligned with the principles of sustainability and green chemistry.

In response to the growing demand for environmentally friendly methods, the green synthesis of nanoparticles has gained considerable attention. Green synthesis utilizes natural resources such as plant extracts, microorganisms, and bio-based materials to replace hazardous chemicals in the production of nanoparticles [15]. This method is not only environmentally benign but also offers cost-effective, scalable, and reproducible approaches for synthesizing nanoparticles. The green synthesis of NiO NPs using plant extracts has proven to be a promising route, offering an eco-friendly alternative to traditional chemical synthesis while maintaining the functional properties of the nanoparticles. This research provides a valuable contribution to the field of environmental nanotechnology, offering insights into the potential of green-synthesized NiO NPs as an effective and sustainable solution for microplastic removal from wastewater.

2. Experimental

2.1. Preparation of plant extract

Fresh ginger rhizomes were purchased from a local market and thoroughly washed with distilled water to remove any dirt, dust, or contaminants. The rhizomes were then peeled to remove the outer skin, ensuring that only the inner fresh tissue was used for extraction. Then grinded the fresh ginger and filter the extract. The resulting clear filtrate was collected as the ginger extract and stored in a clean glass container at 4°C for further use in the synthesis of NiO NPs.

2.2. GreenSynthesis of Nickel Oxide Nanoparticles

The ginger extract was gradually added dropwise to the 0.01M nickel chloride solution under continuous stirring at room temperature and NaOH used for the pH maintain. The addition rate and stirring speed were controlled to ensure the uniform mixing of the extract with the nickel salt solution. During this process, the reduction of nickel ions was observed as a colour change to green then filter the solution and dried overnight in hot air oven.

2.3. Adsorption Experiment of Microplastics in Pond Water

The adsorption experiments were conducted using natural pond water contaminated with microplastics. The pond water was collected from Ananthankulam, North Konam. The initial physicochemical parameters such as pH, turbidity, conductivity, and were recorded. n a typical batch experiment, 100 mL of microplastic-contaminated pond water was transferred to a conical flask, and 50 mg of synthesized NiO nanoparticles was added. The mixture was agitated on a magnetic stirrer at 200-300 rpm for at room temperature (28 ± 2 °C). The experiment repeats with contact time (10,30,60,90,120) mins, adsorbent Dosage (10,20,30,40,50) mg and pH (3-12). Then filter the solution and concentration of the various contaminants can be examined by UV/Atomic Adsorption Spectroscopy. The residual microplastics were quantified using dynamic light scattering (DLS) or optical microscopy or and Fourier-transform infrared spectroscopy (FTIR) to identify and compare changes in particle number and composition.

3. Characterization of NiO NPs

3.1. UV–Visible Spectroscopy(UV–Vis): Vis spectroscopy was employed to study the optical absorption properties of the material. The absorption spectra help determines the band gap energy using Tauc plots. This analysis provides insights into the electronic transitions and optical behaviour

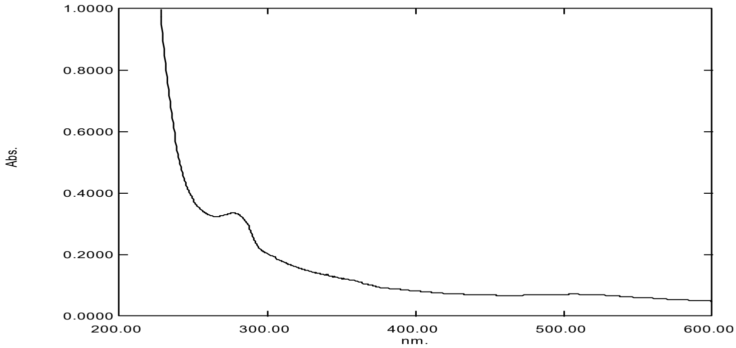
3.2. Transmission Electron Microscopy (TEM): TEM was carried out to examine the morphology, particle size, and structural details at the nanoscale. High-resolution images revealed the shape and dispersion of particles.

4. Results and Discussion

4.1. UV- Visible Spectroscopy of Nickel oxide nanoparticles

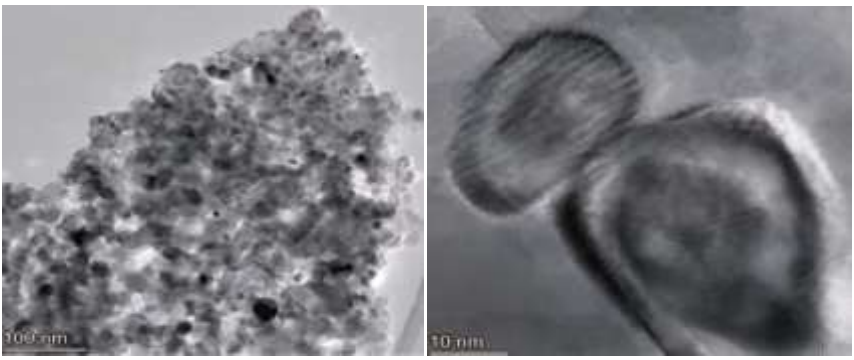
The optical properties of the synthesized NiO nanoparticles were investigated using UV–Visible spectroscopy in the wavelength range of 200–600 nm. As shown in Figure 1, the absorption spectrum exhibits a prominent peak around 300 nm, which is characteristic of NiO nanoparticles and is attributed to electronic transitions from the valence band to the conduction band. This absorption behaviour confirms the formation of NiO nanoparticles and suggests the presence of quantum confinement effects due to the nanoscale dimensions of the particles. The band gap energy (Eg) was estimated using the Tauc plot method, assuming a direct allowed transition. The extrapolation of the linear portion of the plot of (αhν)2(\alpha h\nu) ^2(αhν)2 versus hνh\nuhν yielded a band gap in the range of 3.4–3.8 eV, which is consistent with previously reported values for nanoscale NiO. The slight variation in band gap energy compared to bulk NiO (typically ~3.6 eV) is attributed to quantum confinement eff**ects** due to reduced particle size. These results confirm the successful formation of NiO nanoparticles and provide insights into their potential for optoelectronic and adsorption applications.

Fig.1. UV-Visible Spectra of synthesized Nickel Oxide nanoparticles



4.2. TEM Analysis

Fig.2. TEM image of synthesized Nickel Oxide nanoparticles



High-resolution transmission electron microscopy (HRTEM) was employed to examine the morphology and crystallinity of the synthesized nickel oxide (NiO) nanoparticles. As shown in Fig. 2, the nanoparticles appear as dark, nearly spherical particleswith an average diameter ranging from 5- 15nm. The particles are well-dispersed relatively uniform distribution and minimal agglomeration. The image was captured at a magnification scale of 100nmand 10 nm allowing for clear visualization of individual particles. The HRTEM image reveals distinct lattice fringes, indicative of high crystallinity. The measured interplanar spacing is approximately 0.241 nm, which corresponds to the (111) crystallographic plane of face-centered cubic (FCC) NiO, in agreement with JCPDS No. 47-1049. The clarity of the fringes suggests that the nanoparticles are predominantly single crystalline. Fig. X. HRTEM image of NiO nanoparticles showing lattice fringes with an inter planar spacing of 0.241 nm, corresponding to the (111) plane of FCC NiO. Scale bar: nanoparticles were successfully synthesized using an eco-friendly green synthesis approach employing ginger (Zingiber officinale) extract as a bio reducing agent.

5.Microplastic adsorption Efficiency

The removal efficiency of microplastics (MPs) from pond water using green-synthesized NiO NPs was evaluated under varying conditions: contact time, nanoparticle dosage, pH, and microplastic concentration. The removal of microplastics (MPs) by green-synthesized nickel oxide (NiO) nanoparticles involves multiple adsorption mechanisms that enhance efficiency. These mechanisms are influenced by the physicochemical properties of both the microplastics and the nanoparticles, as well as the functional groups introduced by the ginger extract during synthesis. Microplastics in water often acquire negative surface charges due to the adsorption of dissolved organic matter and functional groups. NiO nanoparticles, particularly in slightly acidic to neutral pH, can exhibit positive surface charges. This electrostatic attraction between oppositely charged surfaces facilitates the binding of microplastics to the nanoparticle surface. The nanoporous structure and high surface area of NiO NPs provide abundant active sites for adsorption. Microplastics may become adsorbed or embedded in agglomerates of NiO nanoparticles due to physical entrapment or bridging flocculation.

Removal Efficiency (E %) = $C_0 - C_e / C_0 * 100$ ------------ (1)

Where (E %) is the ratio of difference in concentration before and after adsorption.

Table 1. Removal Efficiency (%) of Microplastics under Different Conditions using Green-Synthesized NiO Nanoparticles

Contact time (min)	Removal efficiency (%)	Dosage (mg)	Removal efficiency (%)	pH	Removal efficiency (%)
10	61.2	10	58.4	4	64.5
30	75.4	20	72.6	6	78.8
60	82.3	30	84.2	7	89.1
90	89.7	40	91.3	8	91.3
120	90.1	50	91.7	10	85.4

The removal of microplastics increased significantly with time, achieving a plateau at 120 minutes with 89.7% efficiency. Beyond this, minimal improvement was observed, indicating that equilibrium was reached. The adsorption performance increased with higher dosages of NiO NPs. Maximum efficiency (~91.7%) was observed at 50 mg/L. The slight improvement beyond 40 mg/L indicates that most adsorption sites become saturated, and excess particles may agglomerate, reducing effectiveness. Adsorption was strongly influenced by pH. Optimal removal occurred at pH 8 (91.3%), suggesting favourable electrostatic interactions between negatively charged microplastic surfaces and positively charged NiO NP sites. At lower pH, competition with H^+ ions hindered adsorption.

Fig. 5 Effect of contact time on the adsorption capacity

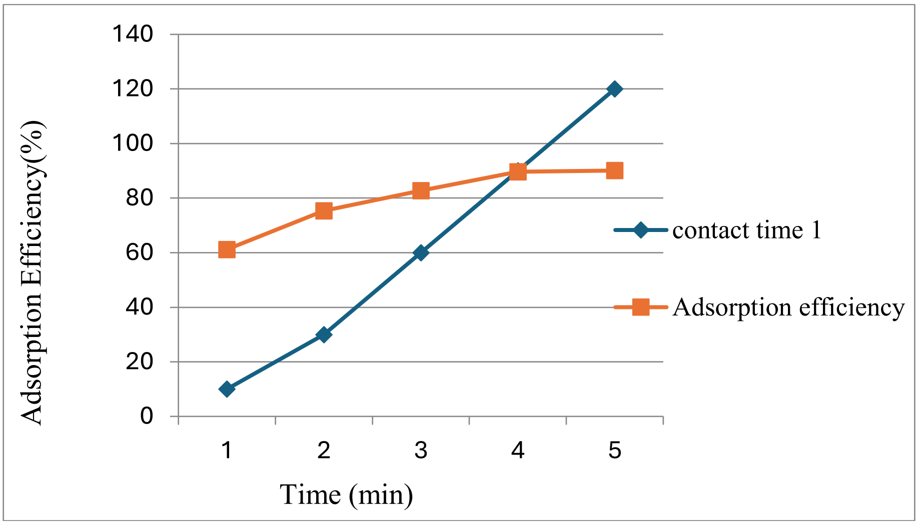


Fig. 6 Effect of Dosage on the adsorption capacity

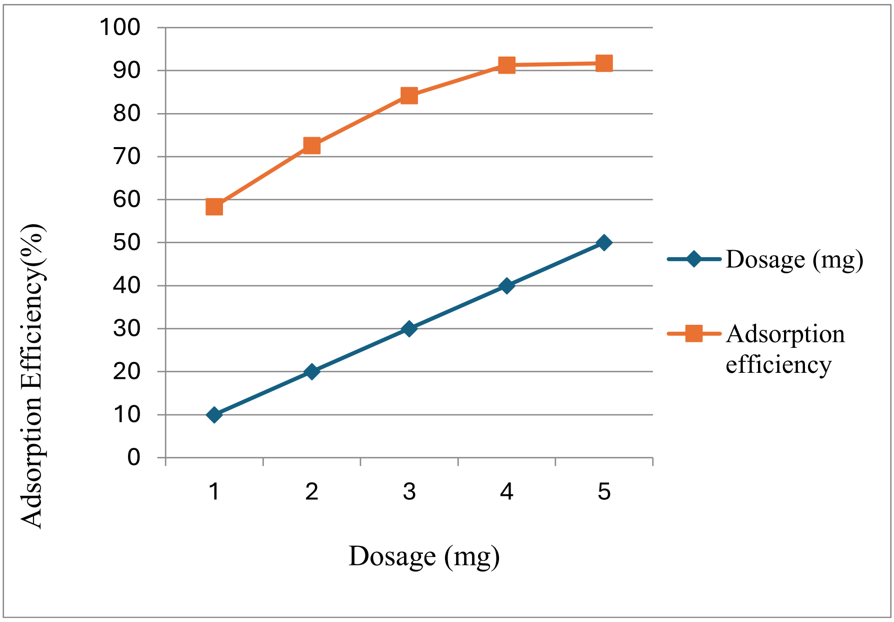
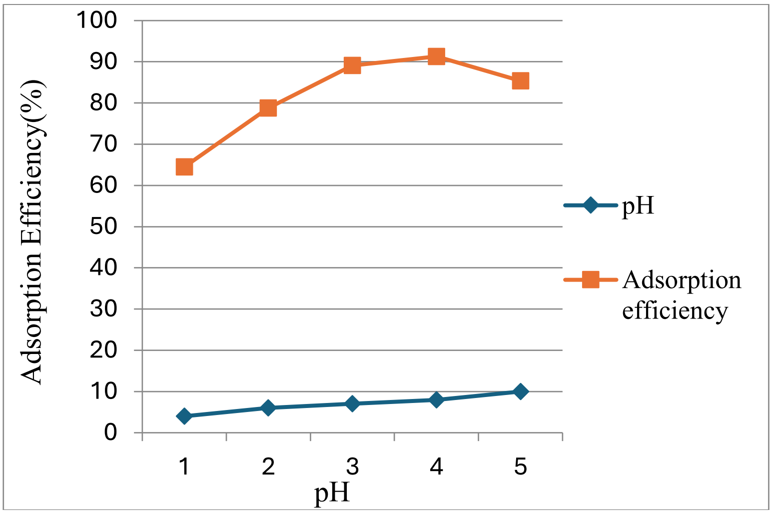


Fig.7 Effect of pH on the adsorption capacity



Conclusion

Nickel oxide (NiO) nanoparticles were successfully synthesized via a green chemistry approach using Zingiber officinale (ginger) extract, serving as an eco-friendly reducing and stabilizing agent. The synthesized NiO nanoparticles exhibited favourable physicochemical properties including high surface area, active functional groups making them highly effective for the adsorption of microplastics from pond water. The structural, morphological, optical, and vibrational properties were comprehensively characterized using TEM and UV–Vis techniques.TEM imaging further validated the nanostructure, revealing quasi-spherical, well-dispersed particles ranging between 5–15 nm in diameter. The UV–Visible absorption spectrum showed a characteristic absorption peak around 300 nm, and the calculated optical band gap energy (~3.8 eV) suggested a quantum confinement effect. Adsorption experiments revealed that the removal efficiency reached a maximum of **~91.7%** under optimized conditions (pH 8, 120 minutes contact time, 40 mg/L NiO dosage). The adsorption mechanism was attributed to electrostatic interactions, hydrogen bonding, surface complexation, and hydrophobic interactions between the microplastic particles and bio functionalized NiO surfaces. This green synthesis method offers a sustainable and low-cost alternative to conventional nanomaterials, reducing the reliance on hazardous chemicals and aligning with environmental safety standards. The findings demonstrate the strong potential of plant-mediated NiO nanoparticles in tackling microplastic contamination in aquatic environments and contribute to the advancement of green nanotechnology for wastewater treatment.

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.

Data availability statement

All relevant data are included in the paper or its supplementary information.

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