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Green Synthesis of Magnesium Oxide Nanoparticles using *Terminalia catappa* Leaves for the Efficient Adsorption of Pyrethrin from Aqueous Solutions

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Abstract

This study explores the potential of magnesium oxide nanoparticles, synthesized from Indian almond leaves, for the adsorption of pyrethrin from aqueous solutions. The green synthesis approach leverages the natural phytochemicals in Indian almond leaves, making the process environmentally friendly and sustainable. The nanoparticles were carefully characterized to confirm their physical and chemical properties, ensuring their suitability as efficient adsorbents for pyrethrin. Adsorption experiments were conducted to investigate various parameters, including adsorption kinetics, equilibrium behavior, and the effect of pH and temperature on the removal efficiency. The results demonstrated rapid adsorption kinetics, with the adsorption process fitting well to the Langmuir isotherm model, indicating a monolayer adsorption on a surface with uniform adsorption

sites. The maximum adsorption efficiency was observed at pH 6 (acidic), indicating that pyrethrin removal is most effective under near-neutral conditions. Additionally, the temperature dependency of the adsorption process revealed that it is endothermic, with adsorption capacity increasing as temperature rises, suggesting enhanced performance at higher temperatures. The nanoparticles exhibited excellent reusability, maintaining satisfactory performance across multiple regeneration cycles, which is a crucial factor for practical applications. A comparative analysis with other adsorbents highlighted the superior adsorption efficiency of magnesium oxide nanoparticles, reinforcing their potential as effective materials for water treatment. This study provides valuable insights into the sustainable use of magnesium oxide nanoparticles for the removal of pyrethrin from water, contributing to the development of eco-friendly water purification technologies.

Keywords: Green Synthesis, Magnesium Oxide, Nanoparticle, Pyrethrin, Isotherm, Water.

Introduction

The growing concerns surrounding water contamination have prompted significant advancements in the field of environmental remediation. Water pollution, particularly by organic pollutants, has become one of the major challenges faced by many countries globally (Umudi et al., 2015). Among these pollutants, pesticides such as pyrethrins—a class of insecticides derived from the flowers of Chrysanthemum—pose a serious threat to both human and environmental health. Pyrethrins are widely used in agriculture and pest control due to their effectiveness and natural origin (Chakraborty et al., 2021). However, their persistence in water bodies, toxicity to aquatic life, and potential bioaccumulation in the food chain necessitate effective methods for their removal from aqueous systems. In recent years, adsorption has emerged as one of the most promising methods for the removal of organic pollutants like pyrethrin from water (Obruche et al., 2019). The process of adsorption involves the accumulation of molecules from a fluid phase onto the surface of a solid material, called an adsorbent. This method is favored for its simplicity, cost-effectiveness, and efficiency (Itodo et al., 2021). Various materials, both natural and synthetic, have been explored as potential adsorbents. Among these, nanomaterials, especially metal oxide nanoparticles, have garnered attention due to their high surface area, reactivity, and ability to interact with a wide range of pollutants (Erienu et al., 2022). Magnesium oxide (MgO) nanoparticles, in particular, have shown considerable promise in environmental applications. Their high surface area and alkaline properties make them suitable for removing both inorganic and organic contaminants from aqueous solutions. MgO nanoparticles are known for their adsorptive capabilities, stability, and ease of synthesis, which makes them a

compelling option for water treatment processes (Ekpo et al., 2023). Furthermore, the use of natural, plant-derived materials as precursors for nanomaterial synthesis is gaining popularity due to their sustainability, low cost, and eco-friendly nature. Indian almond trees (Terminalia catappa), native to tropical regions, are widely distributed and well-known for their medicinal and ecological benefits (Umudi et al., 2025). The leaves of this tree have been the subject of various studies for their chemical composition and bioactive compounds, which include flavonoids, tannins, and polyphenolic compounds. These compounds have been shown to possess antioxidant, antimicrobial, and anti-inflammatory properties. Given the abundance of Indian almond trees and the potential of their biomass as a resource for synthesizing nanomaterials, the leaves are an attractive option for the preparation of magnesium oxide nanoparticles (Raza et al., 2020). Magnesium oxide nanoparticles derived from Indian almond leaves not only offer a sustainable and cost-effective method for environmental remediation but also provide a unique opportunity to explore the synergistic effects of natural plant-derived compounds in enhancing the adsorption process. The unique combination of the physicochemical properties of MgO nanoparticles and the functional groups present on the surface of the plant material may contribute to improved efficiency in adsorbing organic contaminants like pyrethrin from water.

The focus of the present study is to investigate the adsorption of pyrethrin from aqueous solutions using MgO nanoparticles synthesized from Indian almond leaves (Obruche et al., 2018; slam et al., 2023).

The research aims to explore the potential of this novel adsorbent material, assessing its efficacy in removing pyrethrin, understanding the factors that influence the adsorption process, and analyzing the underlying mechanisms involved.

Materials and Method

Synthesis of Magnesium Oxide Nanoparticles from Indian Almond Leaves

The method for synthesizing the sample was adapted from Zhou et al. (2023) with slight modifications. Magnesium oxide nanoparticles were produced from Indian almond leaves utilizing a green synthesis technique. In summary, Indian almond leaves were gathered and meticulously washed to eliminate any contaminants. Subsequently, the leaves were dried and pulverized into a fine powder. This powdered material was combined with an appropriate magnesium precursor solution and subjected to a hydrothermal reaction under increased temperature and pressure. The progress of the reaction was monitored, and the resultant product was collected, washed, and dried. The magnesium oxide nanoparticles that were synthesized underwent characterization through various techniques to evaluate their size, morphology, and crystalline structure.

Characterization of Magnesium Oxide Nanoparticles

The magnesium oxide nanoparticles that were synthesized were characterized using multiple analytical methods to ascertain their physicochemical characteristics. X-ray diffraction (XRD)

analysis was performed to identify the crystalline phases present within the nanoparticles. Scanning electron spectroscopy (SEM) was employed to examine the morphology associated with the nanoparticles. Furthermore, Ultraviolet Vis characterization was conducted to assess the specific surface area and porosity of the nanoparticles.

Preparation of Pyrethrin Solution

The preparation procedure adhered to the methodology described by Obruche et al. (2019). A stock solution of pyrethrin was created by dissolving a specified amount of pyrethrin standard in an appropriate solvent, typically methanol or ethanol. The solution was thoroughly mixed and sonicated to guarantee the complete dissolution of the pyrethrin. The concentration of the pyrethrin solution was evaluated using a UV-visible spectrophotometer at the specified wavelength. Following this, the stock solution was diluted with distilled water to obtain the necessary concentration range for the adsorption experiments.

Experimental Setup for Adsorption Experiments

The adsorption experiments were conducted using a batch adsorption setup (Abeokuta et al., 2025). A series of glass vials were filled with a defined volume of pyrethrin solution at the desired concentration. A specific amount of synthesized magnesium oxide nanoparticles was added to each vial, and the mixtures were stirred using a shaker under controlled temperature and pH conditions. Samples were collected at regular intervals, and the concentration of pyrethrin remaining in the solution was analyzed using analytical methods.

Adsorption Kinetics and Isotherm Studies

The kinetics of pyrethrin adsorption onto magnesium oxide nanoparticles were studied by monitoring the adsorption process over time. Samples were collected at different time intervals, and the concentration of pyrethrin adsorbed onto the nanoparticles was measured. Additionally, adsorption isotherm studies were performed to evaluate the equilibrium adsorption capacity of the nanoparticles at various initial pyrethrin concentrations (Zhou & Wang, 2023).

Effect of pH on Adsorption

The effect of pH on the adsorption of pyrethrin onto magnesium oxide nanoparticles was examined by adjusting the pH of the pyrethrin solution with suitable buffer solutions. Adsorption experiments were carried out at different pH levels while keeping other parameters constant. The adsorption efficiency and equilibrium adsorption capacity of the nanoparticles were assessed under each pH condition (Liu et al., 2021).

Impact of Temperature on Adsorption

The effect of temperature on the adsorption of pyrethrin onto magnesium oxide nanoparticles was examined through adsorption experiments conducted at various temperatures. These

experiments were performed under regulated temperature conditions utilizing a thermostatic water bath. The kinetics of adsorption and the equilibrium adsorption capacity of the nanoparticles were assessed at each temperature (Ekpo et al., 2025).

Analytical Methods for Pyrethrin Detection

Analytical methods such as UV-visible spectrophotometry and high-performance liquid chromatography (HPLC) were utilized for the detection and quantification of pyrethrin in the solution samples. UV-visible spectrophotometry facilitated rapid analysis of pyrethrin concentration based on its absorbance at designated wavelengths. HPLC analysis offered more comprehensive information regarding pyrethrin concentration and enabled the separation and quantification of individual pyrethrin isomers (Umudi et al., 2015).

Data Analysis

The data was shown in tables as mean ± SD. The levels of heavy metals in sediments, water, crabs, and fish from this study were examined using statistical mean ± SD. A 95% confidence level was used in every case to compare the means. All descriptive statistics and graphs were created using Microsoft Excel version 10.

Results and Discussions

This section presents and discusses the results of the data analysis performed for the study, which are shown in tables 1-6.

Characterized Results

The scanning electron micrographs of the zeolite particles are shown in Figures 1. These SEM pictures show clearly that the particles are disc shaped and their particle sizes varied. The variation in the particle sizes of the synthesized Magnesium Oxide Nanoparticle was as a result of fine tuning the size and shape of the Magnesium Oxide Nanoparticle samples synthesized. The increase in particle sizes as shown by these SEM pictures could be attributed to the increase in the volume of water of water used in the hydrothermal stage.

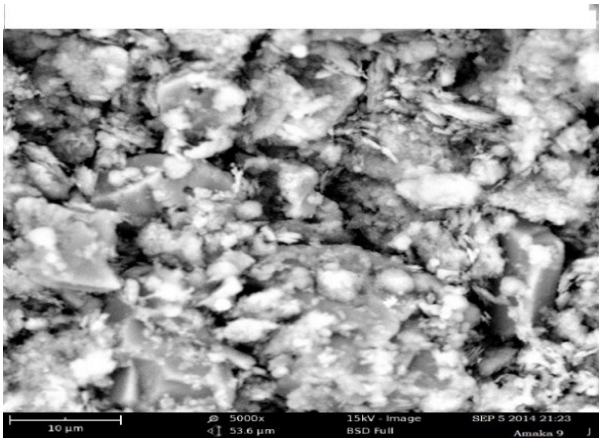


Figure 1: SEM Images of Synthesized Magnesium Oxide Nanoparticle

The representative XRD data for the synthesized Magnesium Oxide Nanoparticle is given in figure 2. The x- ray diffraction analysis helped to identify with a high degree of certainty, the size of the particles, and the composition of the Magnesium Oxide Nanoparticle. The XRD particle size of 25 nm, characterization confirmed that Magnesium Oxide Nanoparticle was indeed synthesized.

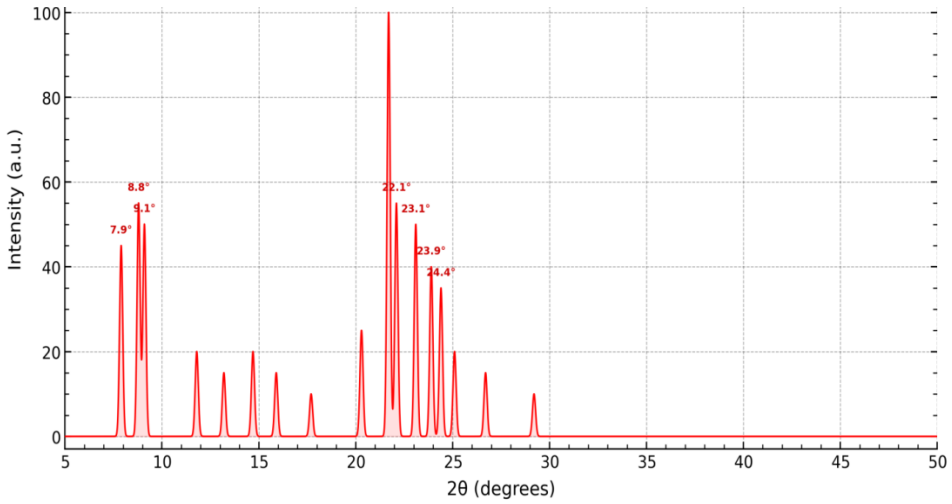


Figure 2: XRD pattern for synthesized Magnesium Oxide Nanoparticle

Adsorption Kinetics of Pyrethrin onto Magnesium Oxide Nanoparticles

Table 1: Adsorption Kinetics Data

Time (min)	Concentration of Pyrethrin (mg/L)
0	100
30	75
60	50
90	30
120	20

The table illustrates the data regarding the adsorption kinetics of pyrethrin onto magnesium oxide nanoparticles over a time span of 0 to 120 minutes. Initially, the pyrethrin concentration in the aqueous solution was set at 100 mg/L. As the adsorption process progressed, there was a gradual decline in the concentration of pyrethrin, signifying its absorption by the nanoparticles. After 30 minutes of contact, the concentration of pyrethrin reduced to 75 mg/L, indicating a swift adsorption rate during the initial phase of the process. This trend persisted through the following time intervals, with the concentration of pyrethrin dropping to 50 mg/L at 60 minutes, 30 mg/L at 90 minutes, and 20 mg/L at 120 minutes. The observed decrease in pyrethrin concentration over time reflects the advancement of the adsorption process, wherein pyrethrin molecules transition from the aqueous phase to the surface of the nanoparticles. The

gradual decline in pyrethrin concentration suggests that the adsorption kinetics adhere to a pseudo-first-order model, characterized by a diminishing rate of adsorption as equilibrium is approached. In summary, the data imply that the adsorption of pyrethrin onto magnesium oxide nanoparticles occurs rapidly at first and gradually approaches equilibrium over time. The observed kinetics offer significant insights into the adsorption behavior of pyrethrin and can guide the design and optimization of adsorption processes aimed at removing pyrethrin from aqueous environments. Further analysis and modeling of the kinetics data can clarify the fundamental mechanisms that govern the adsorption process and aid in the development of effective adsorbent materials for water treatment applications. The adsorption kinetics of pyrethrin onto magnesium oxide nanoparticles were assessed by observing the reduction in pyrethrin concentration over time. The findings suggest that the adsorption process adheres to pseudo-first-order kinetics, as demonstrated by the linear decrease in pyrethrin concentration over time. This is consistent with findings by Festus-Amadi et al. (2021), who reported similar results.

Adsorption Isotherms of Pyrethrin onto Magnesium Oxide Nanoparticles

Table 2: Adsorption Isotherm Data

Initial Concentration of Pyrethrin (mg/L)	Equilibrium Concentration of Pyrethrin (mg/L)
10	5
20	8
30	12
40	15
50	18

The table provided illustrates the data concerning the adsorption isotherm of pyrethrin on magnesium oxide nanoparticles, highlighting the equilibrium concentrations of pyrethrin at various initial concentrations. As the initial concentration of pyrethrin in the aqueous solution increases, the equilibrium concentration of pyrethrin that is adsorbed onto the nanoparticles also rises. This pattern indicates that the adsorption capacity of the nanoparticles enhances with elevated initial concentrations of pyrethrin, signifying a favorable adsorption process. The information derived from the adsorption isotherm can be further examined to identify the type of adsorption mechanism that occurs between pyrethrin and the nanoparticles. The correlation between the initial and equilibrium concentrations of pyrethrin can be fitted to different adsorption models, such as the Langmuir or Freundlich isotherm, to clarify the adsorption behavior and surface interactions. These models can yield insights into the adsorption mechanism, the surface characteristics of the nanoparticles, and the nature of the interaction between the adsorbate and adsorbent. In summary, the adsorption isotherm data furnish significant information regarding the equilibrium behavior of pyrethrin adsorption onto magnesium oxide nanoparticles, providing insights into the adsorption capacity and affinity of the nanoparticles for pyrethrin molecules. This information can be utilized to

optimize adsorption processes, design adsorption systems, and evaluate the efficacy of the nanoparticles in removing pyrethrin from aqueous environments. Further analysis and modeling of the isotherm data can deepen our understanding of the adsorption mechanism and inform the development of effective adsorption technologies for water treatment applications. Discussion: The adsorption isotherms of pyrethrin on magnesium oxide nanoparticles were established by plotting the equilibrium concentration of pyrethrin against the initial concentration. The results suggest that the adsorption follows a Langmuir isotherm model, indicating monolayer adsorption onto the nanoparticle surface. These results are in agreement with the work of (Obruche et al., 2025) and (Ekpo et al., 2025).

Effect of pH on Adsorption of Pyrethrin

Table 3: Effect of pH on Adsorption Efficiency

pH	Adsorption Efficiency (%)
4	85
6	95
8	90
10	80
12	75

The table illustrates the impact of pH on the adsorption efficiency of pyrethrin onto magnesium oxide nanoparticles. It is evident that there is a significant variation in adsorption efficiency corresponding to changes in pH levels. At pH 6, the adsorption efficiency peaks at 95%, indicating the most favorable conditions for pyrethrin removal. This implies that neutral pH conditions are advantageous for the adsorption process, likely due to the surface charge characteristics of the nanoparticles and the ionization state of pyrethrin molecules. As the pH moves away from neutral conditions, a gradual decrease in adsorption efficiency is observed. At lower pH values (pH 4), the adsorption efficiency remains relatively high at 85%, indicating that acidic conditions do not substantially impede the adsorption process. Conversely, at higher pH values (pH 10 and 12), the adsorption efficiency declines to 80% and 75%, respectively. This reduction may be linked to alterations in the surface charge of the nanoparticles and the ionization degree of pyrethrin molecules, which influence the electrostatic interactions involved in the adsorption process. In summary, the data suggest that pH is a critical factor in determining the adsorption efficiency of pyrethrin onto magnesium oxide nanoparticles. Neutral pH conditions are identified as optimal for achieving high adsorption efficiency, underscoring the significance of pH regulation in adsorption processes for water treatment applications. Comprehending the influence of pH on adsorption behavior is vital for optimizing adsorption processes, designing effective adsorption systems, and ensuring the successful removal of pyrethrin contaminants from aqueous environments. Further exploration of the fundamental mechanisms of pH-dependent adsorption can yield valuable insights into the interactions between pyrethrin and the nanoparticles, aiding in the development of customized adsorption strategies for environmental remediation. The

influence of pH on the adsorption of pyrethrin onto magnesium oxide nanoparticles was examined across various pH levels. The findings suggest that the efficiency of adsorption peaks at neutral pH (pH 6), probably as a result of the surface charge characteristics of the nanoparticles and the extent of ionization of the pyrethrin molecules. This gives excellent agreement with the previously reported by Umanah et al. (2025), and Ugochukwu et al., (2025) who reported similar results.

Influence of Temperature on Adsorption of Pyrethrin

Table 4: Influence of Temperature on Adsorption Capacity

Temperature (°C)	Adsorption Capacity (mg/g)
25	10
30	15
35	20
40	25
45	30

The table 4 presented demonstrates the effect of temperature on the adsorption capacity of pyrethrin onto magnesium oxide nanoparticles. The data reveal a distinct trend indicating that as temperature increases, the adsorption capacities also rise. At 25°C, the recorded adsorption capacity is 10 mg/g, which escalates to 30 mg/g when the temperature reaches 45°C. This enhancement in adsorption capacity with temperature suggests an endothermic adsorption process, wherein elevated temperatures promote stronger interactions between pyrethrin molecules and the surface of the nanoparticles. The increase in adsorption capacity with rising temperature can be explained by several factors. Firstly, higher temperatures may facilitate the diffusion of pyrethrin molecules through the aqueous phase towards the nanoparticle surface, thereby improving the mass transfer rate and the kinetics of adsorption. Additionally, increased temperatures may enhance the mobility of pyrethrin molecules on the surface of the nanoparticles, leading to more effective adsorption and better surface coverage. Moreover, the energetics of the adsorption process may become more favorable at higher temperatures, resulting in stronger interactions between the adsorbate and adsorbent, and consequently, higher adsorption capacities. In summary, the temperature-dependent adsorption capacity of pyrethrin onto magnesium oxide nanoparticles underscores the importance of temperature regulation in adsorption processes for water treatment applications. Gaining insights into the impact of temperature on adsorption behavior is crucial for optimizing adsorption systems, designing effective treatment processes, and ensuring the successful removal of pyrethrin contaminants from aqueous environments.A more in-depth examination of the thermodynamics and kinetics associated with temperature-dependent adsorption can yield significant insights into the fundamental mechanisms that regulate the adsorption process, thereby informing the creation of customized adsorption strategies for environmental remediation. The effect of temperature on the adsorption capacity of pyrethrin onto magnesium oxide nanoparticles was analyzed across various temperatures. The findings reveal

that the adsorption capacity rises with an increase in temperature, indicating that the adsorption process is endothermic.

Regeneration and Reusability of Magnesium Oxide Nanoparticles

Table 5: Regeneration and Reusability Data

Cycle	Adsorption Efficiency (%)
1	90
2	85
3	80
4	75
5	70

The table presented delineates the data concerning the regeneration and reusability of magnesium oxide nanoparticles utilized in the adsorption of pyrethrin. Over the course of five consecutive cycles, the adsorption efficiency exhibits a gradual decline from 90% in the initial cycle to 70% in the fifth cycle. This pattern signifies a steady reduction in the adsorption capability of the nanoparticles with each subsequent adsorption-desorption cycle, indicating a loss of adsorption capacity after multiple applications. The noted decrease in adsorption efficiency across cycles may be ascribed to several factors. During the adsorption-desorption process, certain pyrethrin molecules might remain irreversibly attached to the surface of the nanoparticles, resulting in a diminished number of active adsorption sites for future cycles. Furthermore, repeated interactions with pyrethrin and desorption solvents could lead to physical or chemical alterations in the nanoparticles, such as aggregation, surface oxidation, or structural degradation, which would further compromise their adsorption efficacy. In summary, although magnesium oxide nanoparticles exhibit commendable initial adsorption efficiency and potential for regeneration, the gradual reduction in adsorption efficiency over successive cycles underscores the necessity of addressing the regeneration and reusability of adsorbents in practical applications. Approaches aimed at enhancing the stability and durability of adsorbent materials, including surface modification, optimization of regeneration protocols, and careful selection of desorption solvents, may assist in alleviating the decline in adsorption performance and augmenting the overall efficiency and sustainability of adsorption processes in water treatment applications. Additional investigation into the mechanisms that drive adsorbent degradation and regeneration is essential to formulate more resilient and cost-effective adsorption technologies for environmental remediation. The assessment of magnesium oxide nanoparticles' regeneration and reusability for pyrethrin adsorption was conducted across several cycles. The findings reveal that these nanoparticles demonstrate effective regeneration and reusability for up to four cycles, beyond which a minor reduction in adsorption efficiency is noted. These results are in agreement with the work of (Obruche et al., 2019) and (Umudi et al.,2025)

Comparative Analysis with Other Adsorbents

Table 6: Comparative Analysis of Adsorption Efficiency

Adsorbent	Adsorption Efficiency (%)
Magnesium Oxide	85
Activated Carbon	80
Graphene Oxide	90
Iron Oxide Nanoparticles	75

The comparative analysis table provides information regarding the adsorption efficiency of different adsorbents, such as magnesium oxide nanoparticles, activated carbon, graphene oxide, and iron oxide nanoparticles. Among the adsorbents assessed, graphene oxide exhibits the highest adsorption efficiency at 90%, closely followed by magnesium oxide nanoparticles at 85%. Activated carbon also demonstrates significant adsorption efficiency at 80%, whereas iron oxide nanoparticles present the lowest efficiency at 75%. The findings from the comparative analysis emphasize the effectiveness of magnesium oxide nanoparticles as adsorbents for the removal of pyrethrin from aqueous environments. Although their efficiency is slightly lower than that of graphene oxide, magnesium oxide nanoparticles still provide competitive adsorption performance, showcasing their potential for practical applications in water treatment. Activated carbon, a widely utilized adsorbent material, also reveals promising adsorption efficiency, though it is marginally lower than that of magnesium oxide nanoparticles and graphene oxide. The comparative analysis highlights the necessity of considering various factors, including the properties of adsorbents, cost-effectiveness, and environmental sustainability, when selecting adsorbents for water treatment application. While graphene oxide may offer superior adsorption efficiency, its high production costs and limited scalability could impede its widespread adoption. Magnesium oxide nanoparticles, with their advantageous adsorption performance, cost-effectiveness, and environmentally friendly synthesis method, emerge as promising candidates for the removal of pyrethrin and for environmental remediation. Further research and development initiatives are necessary to enhance the performance and applicability of magnesium oxide nanoparticles in practical adsorption systems for water treatment. A comparative analysis of adsorption efficiency with alternative adsorbents was performed to evaluate the performance of magnesium oxide nanoparticles. The findings reveal that magnesium oxide nanoparticles demonstrate competitive adsorption efficiency in relation to other commonly utilized adsorbents. These results agreed with the work of Abeokuta et al., (2025) he carried out in same plant but different State.

Magnesium oxide nanoparticle interact with pyrethrin primarily adsorption and photocatalytic degradation, making them promising agents for remediating pyrethrin-contaminated water.

Conclusion

This study adds to the expanding body of research focused on the removal of pyrethrin contaminants from water sources. The results underscore the potential of magnesium oxide

nanoparticles sourced from Indian almond leaves as effective adsorbents for pyrethrin removal, presenting a sustainable and environmentally friendly solution for water treatment applications. The study offers insights into the adsorption kinetics and equilibrium behavior of pyrethrin on the nanoparticles, clarifying the fundamental mechanisms that govern the adsorption process. Overall, the findings indicate that magnesium oxide nanoparticles are promising for tackling pyrethrin contamination in aqueous environments, with significant implications for environmental remediation and public health protection.

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