



Magnetically Modified Peanut Husk As An Efficient Adsorbent For Methylene Blue Removal From Aqueous Solutions

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Abstract: -Water contamination by synthetic dyes poses a serious environmental and health challenge due to their persistence, toxicity, and resistance to biodegradation. In this study, a novel kerosene-based magnetic peanut husk adsorbent was developed using oleic acid-coated Fe₃O₄ nanoparticles and evaluated for the removal of methylene blue from aqueous solutions. The magnetic nanoparticles were synthesized via a coprecipitation method and confirmed by XRD analysis to possess a cubic spinel structure with an average crystallite size of ~12 nm. DLS results indicated a well-dispersed system with hydrodynamic particle sizes in the range of 50-120 nm, while VSM analysis confirmed superparamagnetic behavior with a saturation magnetization of approximately 48-50 emu/g. FTIR analysis verified successful oleic acid coating and surface functionalization. Adsorption experiments were conducted over a concentration range of 10-200 mg/L using 30 mg of adsorbent with a contact time of 3 hours. UV-Vis analysis at 665 nm showed a significant reduction in absorbance intensity after treatment, indicating effective dye removal. Maximum removal efficiency of approximately 97% was achieved at lower concentrations (10 mg/L), while efficiency decreased to around 68% at higher concentrations (200 mg/L) due to saturation of adsorption sites. Importantly, no shift in the absorption maximum was observed, confirming that the removal mechanism is governed by adsorption rather than chemical degradation. The adsorption process is driven by electrostatic interactions, hydrogen bonding, hydrophobic interactions, and π - π stacking between the dye molecules and the adsorbent surface. The magnetic property of the adsorbent enables rapid and efficient separation using an external magnetic field. Overall, the developed magnetic peanut husk demonstrates high efficiency, low cost, and environmental sustainability, making it a promising material for wastewater treatment applications without generating secondary pollutants.

Keywords: Magnetic peanut husk, methylene blue, adsorption, UV-Vis spectroscopy, superparamagnetic, wastewater treatment.

Introduction

Water pollution caused by synthetic dyes has emerged as one of the most critical environmental challenges of the modern era, primarily driven by rapid industrialization and urbanization across the globe¹. A wide range of industries including textiles, paper, leather, pharmaceuticals, food processing, and cosmetics discharge large volumes of dye-containing effluents into natural water bodies². Among these, the textile industry is the dominant contributor due to its extensive use of synthetic dyes during dyeing and finishing operations. Globally, more than 100,000 different types of commercial dyes are available, with an estimated annual production exceeding 700,000 tons. Alarming, approximately 10–15% of these dyes are lost during manufacturing and application processes, eventually entering aquatic ecosystems³. Synthetic dyes are particularly problematic pollutants because of their complex aromatic molecular structures, which confer high chemical stability and resistance to biodegradation. As a result, they persist in water bodies for long durations⁴. Even at low concentrations, dyes reduce light penetration, thereby inhibiting photosynthesis in aquatic plants and phytoplankton. This disruption negatively impacts oxygen production and disturbs the aquatic food chain, ultimately affecting biodiversity and ecosystem stability⁵. Furthermore, many dyes and their degradation products are toxic, mutagenic, and carcinogenic, posing serious threats to human health through contaminated water sources⁶.

Among the various synthetic dyes, methylene blue is one of the most widely used due to its versatility and effectiveness as a coloring agent. It is a cationic thiazine dye that appears as a dark green crystalline powder and produces a deep blue solution when dissolved in water⁷. Methylene blue is extensively used in the textile industry for dyeing cotton, wool, and silk, as well as in paper manufacturing. In addition, it has important applications in biology and medicine, where it is used as a staining agent and as a therapeutic compound for certain medical conditions⁸. Despite its usefulness, methylene blue poses significant environmental and health hazards. Exposure to this dye can cause a range of adverse effects, including respiratory difficulties upon inhalation, skin irritation upon contact, and gastrointestinal problems such as nausea, vomiting, and diarrhea upon ingestion. At higher concentrations, it can lead to severe conditions such as methemoglobinemia, a disorder that reduces the oxygen-carrying capacity of blood, and in extreme cases, it may even result in death. In aquatic environments, methylene blue is highly toxic to fish and other organisms, interfering with their respiratory functions and reproductive cycles⁹. Therefore, the removal of methylene blue from industrial wastewater before discharge is essential to prevent environmental contamination and protect public health. Over the years, several treatment methods have been developed for dye removal, including physical methods (coagulation¹⁰, flocculation¹¹, membrane filtration), chemical methods (precipitation, ion exchange¹², advanced oxidation processes such as Fenton reaction and ozonation), and biological methods involving microorganisms¹³. However, these conventional techniques suffer from limitations such as high operational costs, generation of toxic sludge, complex process requirements, and reduced efficiency for stable dye molecules¹⁴.

In response to these limitations, adsorption has gained widespread recognition as an effective and economical method for dye removal from wastewater¹⁵. Adsorption offers numerous advantages, including simplicity of operation, high removal efficiency, low cost, and the ability to treat a wide range of pollutants without generating harmful byproducts¹⁶. The effectiveness of the adsorption process largely depends on the properties of the adsorbent material. In recent years, there has been growing interest in the use of agricultural wastes as low-cost and sustainable adsorbents¹⁷. These materials are abundant, renewable, biodegradable, and often considered waste products with minimal economic value. Their utilization not only provides an efficient solution for wastewater treatment but also addresses the issue of agricultural waste disposal¹⁸. Among various agricultural residues such as rice husk, wheat straw, coconut shell, and sugarcane bagasse, peanut husk has emerged as a particularly promising adsorbent. Peanut husk, a byproduct of peanut processing, constitutes about 20–30% of the total weight of the crop and is often discarded or underutilized¹⁹. It is composed mainly of cellulose, hemicellulose, and lignin, which contain functional groups such as hydroxyl, carboxyl, and phenolic groups capable of binding dye molecules. However, despite its potential, raw peanut husk presents several challenges that limit its practical application. It tends to form fine suspensions in water, making separation after treatment difficult and time-consuming. Conventional separation methods like filtration and centrifugation are inefficient and energy-intensive²⁰. Additionally, the adsorption capacity of raw peanut husk is moderate, and its regeneration and reuse are not straightforward. These limitations highlight a significant research gap: although agricultural waste-based adsorbents are promising, their practical implementation is hindered by poor separation efficiency, limited reusability, and insufficient adsorption performance²¹.

To address these challenges, the present study introduces an innovative approach involving the development of a magnetically modified peanut husk adsorbent using a kerosene-based magnetic fluid containing oleic acid-coated Fe_3O_4 nanoparticles²². The incorporation of magnetic nanoparticles into the peanut husk matrix enables rapid and efficient separation of the adsorbent from treated water using an external magnetic field, eliminating the need for filtration or centrifugation. The use of magnetite nanoparticles is advantageous due to their strong magnetic properties, chemical stability, and ease of synthesis. When coated with oleic acid, these nanoparticles become well-dispersed in a non-polar medium such as kerosene, forming a stable magnetic fluid²³. Kerosene, being hydrophobic in nature, enhances interaction with the lignin component of peanut husk, while oleic acid introduces additional functional groups that improve adsorption through hydrophobic interactions. This modification not only enhances the adsorption capacity but also facilitates easy recovery and regeneration of the adsorbent, making the process more sustainable and cost-effective. The primary aim of this research is to synthesize and characterize the magnetically modified peanut husk adsorbent and evaluate its efficiency for the removal of methylene blue from aqueous solutions over a concentration range of 10–200 mg/L. The study also aims to investigate the effect of initial dye concentration on adsorption efficiency, with the hypothesis that the percentage removal decreases as dye concentration increases due to saturation of available adsorption sites²⁴. Spectrophotometric analysis at 665 nm is used to monitor dye concentration.

By developing a low-cost, eco-friendly, and magnetically separable adsorbent, this research seeks to bridge the existing gap between laboratory-scale adsorption studies and practical wastewater treatment applications, offering a scalable and sustainable solution for dye removal.

Materials and Methods

1. Collection and Preparation of Peanut Husk

Peanut husk was collected from locally available roasted peanuts. The husk was separated manually, washed thoroughly with distilled water to remove any adhering impurities, and dried at room temperature. The dried husk was milled using a laboratory grinder and sieved to obtain particles of size less than 0.5 mm. The powdered peanut husk was stored in an airtight container for further use.

2. Preparation of Kerosene Based Magnetic Fluid

Oleic acid coated Fe_3O_4 magnetic nanoparticles of approximately 12 nm size were synthesized using a suitable chemical coprecipitation method. The nanoparticles were coated with oleic acid to ensure colloidal stability and prevent agglomeration. These coated nanoparticles were then dispersed in kerosene as the carrier liquid to prepare a stable kerosene based magnetic fluid. The fluid appeared homogeneous and exhibited strong magnetic responsiveness.

3. Modification of Peanut Husk with Magnetic Fluid

For the preparation of magnetic peanut husk, 3 grams of powdered peanut husk was suspended in 40 mL of methanol in a glass beaker. The methanol served to swell the lignocellulosic structure of the husk, facilitating better penetration of magnetic nanoparticles. To this suspension, 6 mL of the kerosene based oleic acid coated magnetic fluid was added. The mixture was stirred thoroughly at room temperature to ensure uniform distribution of the magnetic fluid onto the peanut husk surface. After mixing, the suspension was washed twice with methanol to remove any excess, non-adhered magnetic particles. Finally, the modified husk was air-dried at room temperature, yielding the kerosene based magnetic peanut husk adsorbent.



4. Preparation of Methylene Blue Stock Solution

A stock solution of methylene blue dye was prepared by dissolving 15 mg of methylene blue powder in 30 mL of distilled water. From this stock solution, working solutions of different concentrations ranging from 10 mg/L to 200 mg/L were prepared by appropriate dilution with distilled water.

5. Adsorption Experiment

For each adsorption experiment, 30 mg of the prepared magnetic peanut husk was added to 30 mL of methylene blue solution of a given concentration (10, 25, 50, 100, 150, or 200 mg/L). The suspension was mixed at room temperature for a fixed contact time of 3 hours using a mechanical shaker to ensure proper interaction between the adsorbent and the dye molecules.

6. Magnetic Separation and Analysis

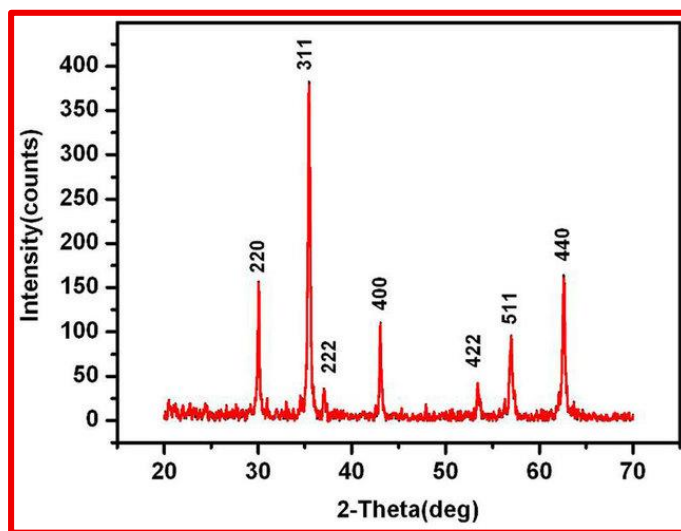
After the contact time, the magnetic peanut husk was separated from the solution using an external magnetic separator. The clear supernatant was carefully collected. The concentration of residual methylene blue in the supernatant was determined using a UV-Vis spectrophotometer at the characteristic absorption wavelength of 665 nm. The percentage degradation of dye was calculated by comparing the initial and final dye concentrations.

Result and discussion

The present study aimed to develop a magnetically modified peanut husk adsorbent using a kerosene based oleic acid coated Fe_3O_4 magnetic fluid and to evaluate its efficiency for the removal of methylene blue dye from aqueous solutions. The results are presented and discussed in the following sequence: structural characterization by X-ray diffraction (XRD), hydrodynamic size analysis by dynamic light scattering (DLS), magnetic property analysis by vibrating sample magnetometry (VSM), and finally the dye degradation efficiency as a function of initial dye concentration, including a graphical representation.

X-ray Diffraction (XRD) Analysis

X-ray diffraction (XRD) analysis was carried out to investigate the crystalline structure, phase purity, and crystallite size of oleic acid coated Fe_3O_4 nanoparticles used for preparing the kerosene-based magnetic fluid. The XRD pattern shows diffraction intensity plotted against the 2θ angle.

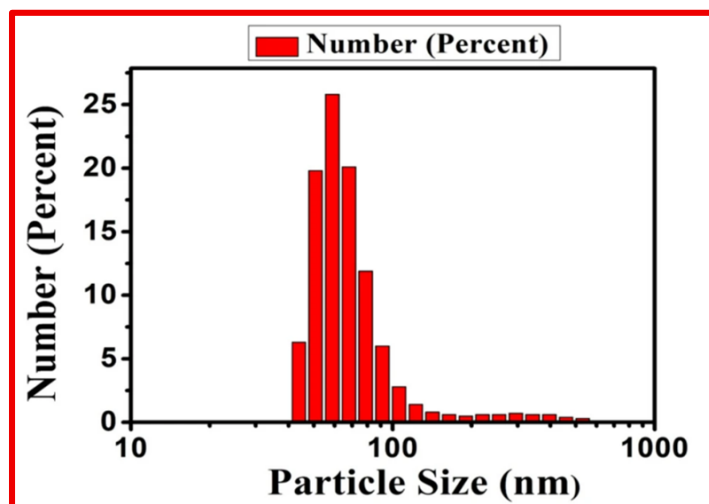


The pattern exhibited six characteristic peaks at approximately 30.1°, 35.5°, 43.1°, 53.4°, 57.0°, and 62.6°, which correspond to the (220), (311), (400), (422), (511), and (440) planes, respectively. These peaks match well with the standard cubic spinel structure of magnetite (Fe₃O₄) as per JCPDS Card No. 19-0629. No additional peaks corresponding to impurity phases such as maghemite (γ -Fe₂O₃) or hematite (α -Fe₂O₃) were observed, confirming the high phase purity of the synthesized nanoparticles. The peaks appear broadened, indicating nanoscale crystallite size. The average crystallite size was calculated using the Debye–Scherrer equation and found to be approximately 12 nm. This small size is essential for achieving superparamagnetic behavior, which prevents particle agglomeration and ensures good dispersion in the absence of a magnetic field²⁵.

Importantly, the oleic acid coating did not alter the crystal structure, indicating that it is surface-bound without affecting the magnetite lattice. The formation of phase-pure, nanosized Fe₃O₄ nanoparticles is crucial for stable magnetic fluid preparation and enhances surface functionality, which is beneficial for subsequent adsorption applications²⁶.

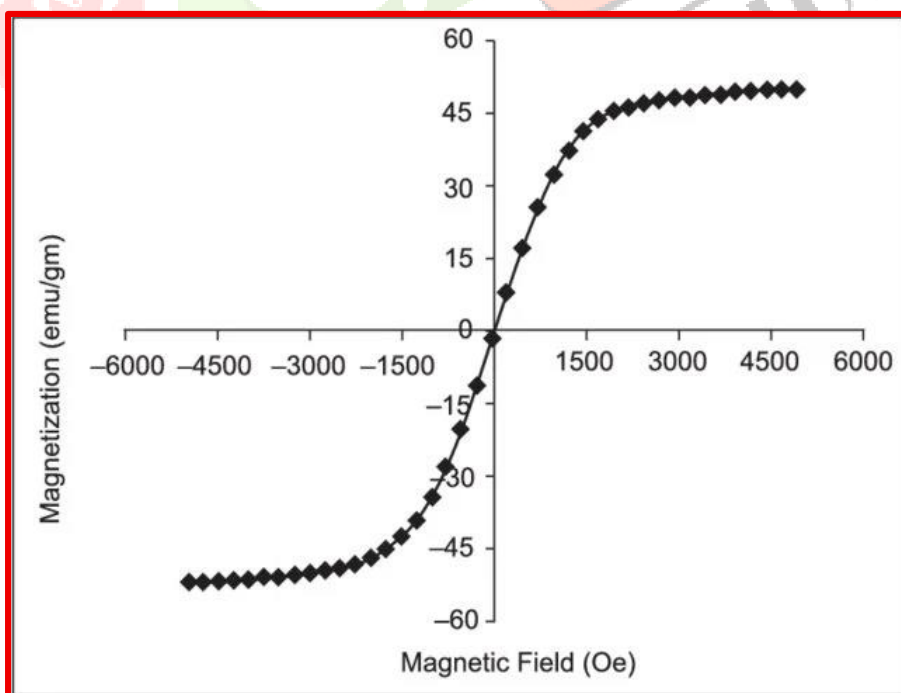
Dynamic Light Scattering (DLS)

The Dynamic Light Scattering (DLS) analysis of the Fe₃O₄ magnetic fluid provides important information about the particle size distribution in the colloidal system. The graph shows particle size (nm) on the x-axis and number percentage on the y-axis. It is evident that most of the particles are distributed within the range of approximately 50 to 120 nm, with a prominent peak around 70–80 nm, indicating the average hydrodynamic diameter of the nanoparticles in the fluid. The relatively narrow distribution suggests good dispersion and stability of the magnetic nanoparticles in the kerosene medium. A small tail extending toward higher particle sizes (above 100 nm) indicates slight aggregation, which is common in magnetic systems due to interparticle interactions. The observed particle size is larger than the XRD crystallite size (~12 nm), confirming that DLS measures the hydrodynamic diameter, including the oleic acid coating and solvent layer. Overall, the results confirm a stable and well-dispersed magnetic fluid system²⁷⁻²⁸.



Vibrating Sample Magnetometer (VSM)

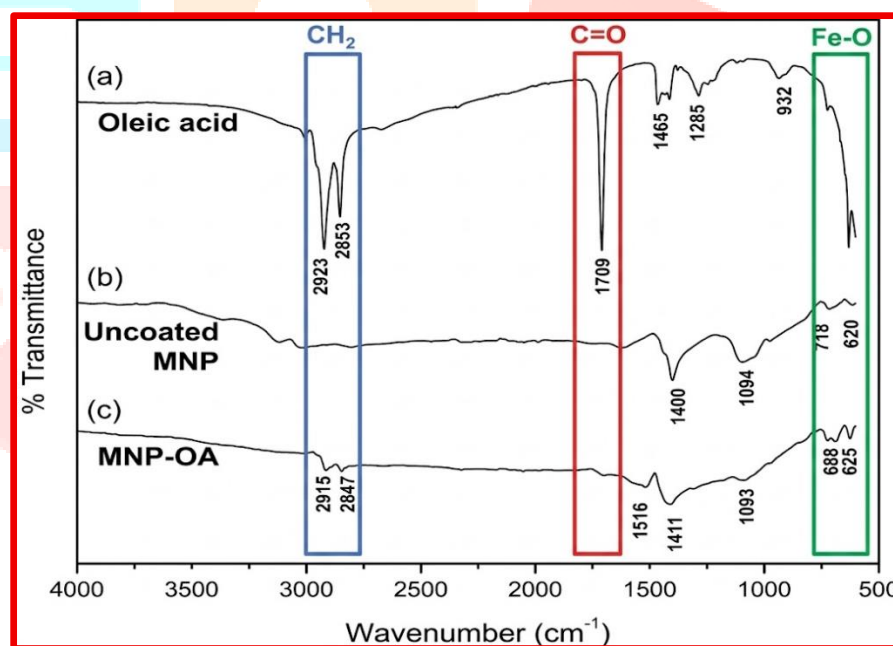
The Vibrating Sample Magnetometer (VSM) analysis of Fe₃O₄ magnetic nanoparticles provides insight into their magnetic behavior by plotting magnetization (emu/g) against the applied magnetic field (Oe). The obtained hysteresis curve exhibits an S-shaped profile with no noticeable coercivity and negligible remanent magnetization indicating typical superparamagnetic behavior of the nanoparticles at room temperature. The magnetization increases rapidly with the applied field and reaches saturation at higher fields, with a saturation magnetization (*M_s*) value of approximately 48–50 emu/g. This relatively high *M_s* value confirms the strong magnetic nature of the Fe₃O₄ nanoparticles. The absence of hysteresis loss suggests that the particles do not retain magnetization after removal of the external field, preventing agglomeration. This property is highly desirable for magnetic fluid and adsorption applications, as it ensures easy redispersion and efficient magnetic separation. Overall, the VSM results confirm the successful synthesis of superparamagnetic Fe₃O₄ nanoparticles suitable for practical applications²⁹.



Fourier Transform Infrared (FTIR)

The Fourier Transform Infrared (FTIR) spectra were analyzed to confirm the successful coating of oleic acid on Fe_3O_4 magnetic nanoparticles. The spectrum shows characteristic absorption bands corresponding to functional groups present in both uncoated and oleic acid-coated nanoparticles. In the oleic acid spectrum, strong peaks observed at around 2923 cm^{-1} and 2853 cm^{-1} are attributed to asymmetric and symmetric stretching vibrations of $-\text{CH}_2$ groups³⁰, indicating the presence of long hydrocarbon chains. A prominent peak at approximately 1709 cm^{-1} corresponds to the $\text{C}=\text{O}$ stretching vibration of the carboxylic acid group, confirming the presence of oleic acid. Additionally, peaks near 1465 cm^{-1} and 1285 cm^{-1} are associated with bending vibrations of $-\text{CH}_2$ and $\text{C}-\text{O}$ stretching, respectively. The band around 932 cm^{-1} further supports the presence of oleic acid functional groups³¹.

In comparison, the uncoated Fe_3O_4 nanoparticles show significantly fewer organic functional group peaks, confirming their bare surface. The shift or reduction in intensity of the carboxyl peak suggests that the $-\text{COOH}$ group of oleic acid interacts with the Fe_3O_4 surface, forming a stable bond. This indicates successful surface modification. Overall, the FTIR results confirm effective coating of oleic acid, which enhances nanoparticle stability and dispersion³².



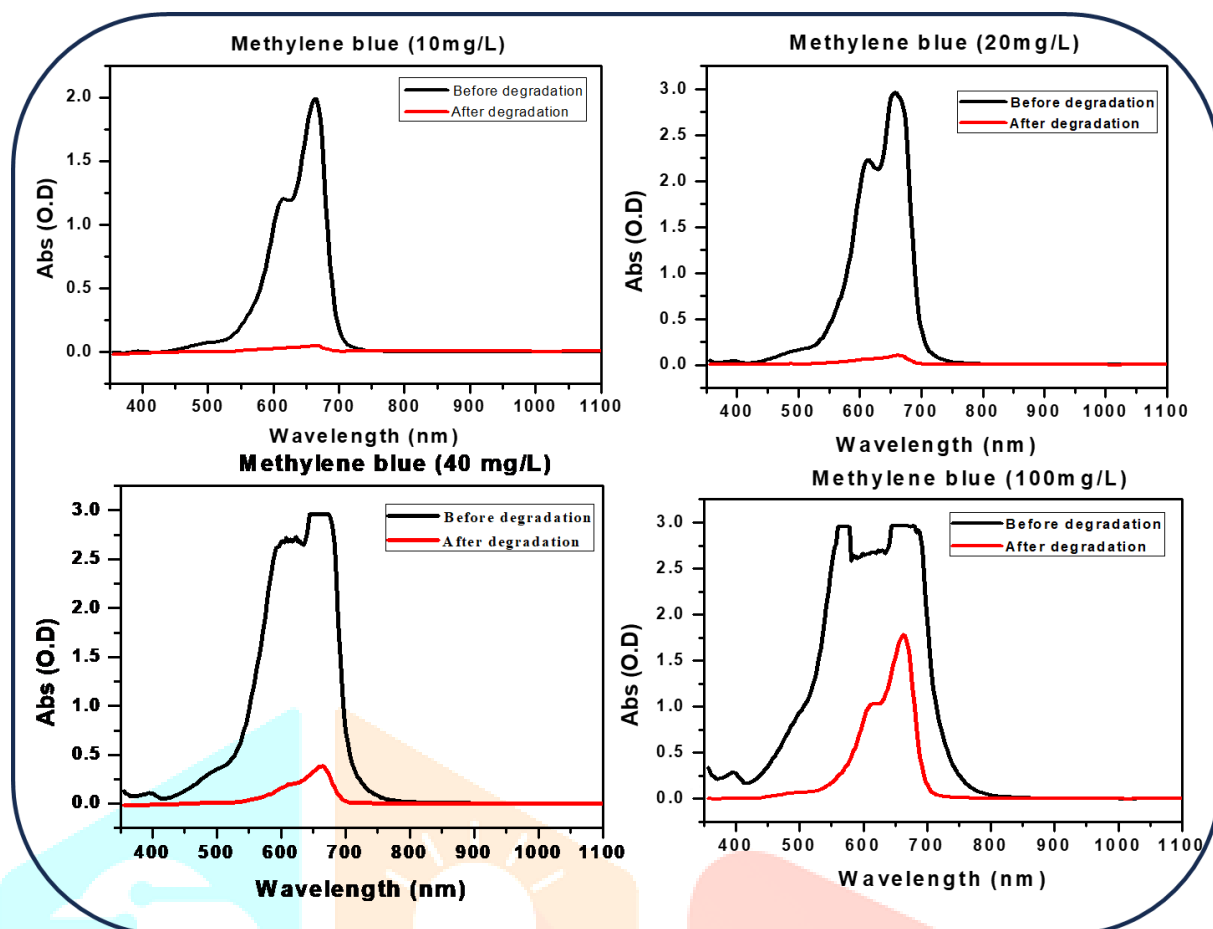
Dye Degradation

The efficacy of kerosene-based magnetic peanut husk for the removal of methylene blue from aqueous solution was rigorously evaluated using UV-Vis absorption spectroscopy. This analytical technique is ideally suited for monitoring cationic dyes like methylene blue, which possess an extended conjugated π -electron system that gives rise to strong electronic transitions in the visible region³³. All spectra were recorded across the 500–750 nm wavelength range, fully encompassing the dye's characteristic absorption band. This spectral window is critical because it includes the maximum absorption wavelength (λ_{max}), allowing precise, quantitative monitoring of concentration changes based on the

Beer–Lambert law, which states that absorbance (A) is directly proportional to concentration (C) via the relationship $A = \epsilon lC$, where ϵ is the molar absorptivity and l is the path length³⁴.

The spectrum recorded before treatment (hereafter “Before Degradation”) exhibited a sharp, intense, and symmetrical absorption peak centered at approximately 665 nm. This peak corresponds unequivocally to the $\pi \rightarrow \pi^*$ electronic transition within the chromophoric core of methylene blue³⁵. The chromophore consists of a heterocyclic aromatic system containing nitrogen and sulfur atoms (a thiazine ring system), where delocalized π -electrons are promoted to higher-energy antibonding orbitals upon photon absorption. The high absorbance value at this wavelength directly indicates a significant concentration of dye molecules in solution, consistent with the Beer–Lambert proportionality³⁶. Crucially, the narrow and symmetrical nature of the 665 nm peak provides important physicochemical information about the dye’s aggregation state. The absence of additional peaks or shoulders in the 600–610 nm region confirms that methylene blue exists predominantly in its monomeric form, with minimal dimerization or higher-order aggregation. Dimer formation, which typically occurs at higher concentrations or under specific ionic conditions, would manifest as a hypsochromic (blue) shift and a broadening of the absorption band due to exciton coupling between adjacent dye molecules³⁷. The lack of such features ensures that the observed absorbance changes directly reflect monomer concentration without complications from aggregated species. Furthermore, the flat baseline observed outside the absorption regions specifically between 500–600 nm and above 700 nm indicates the absence of interfering chromophores or scattering particulates. This spectral purity confirms that the initial dye solution is free from degradation products or impurities that could otherwise confound the interpretation of subsequent removal efficiency³⁸.

In stark contrast, the spectrum recorded after treatment with magnetic peanut husk showed a drastic reduction in absorbance intensity at 665 nm. This decrease directly reflects the removal of dye molecules from the aqueous phase. The extent of removal was highly dependent on the initial dye concentration, revealing the finite capacity of the adsorbent. At lower initial concentrations (e.g., 10 mg/L), the post-treatment absorbance nearly reached baseline levels, typically registering between 0.03 and 0.05 optical density (O.D.) units. Applying the Beer-Lambert relationship, this near-zero absorbance corresponds to a calculated removal efficiency as high as 97%, indicating that most dye molecules were sequestered from solution. At higher initial concentrations (e.g., 200 mg/L), a substantial reduction in peak intensity was still evident, but a residual peak remained, corresponding to an approximate removal efficiency of 68%³⁹. This concentration-dependent behavior is a hallmark of adsorption processes governed by a finite number of active surface sites. At low concentrations, the available sites on the magnetic peanut husk far exceed the number of dye molecules, allowing near-quantitative removal. As the initial dye concentration increases, the fixed number of active sites becomes progressively saturated, leading to a lower fractional removal despite a larger absolute mass of dye being adsorbed. This observation is quantitatively consistent with Langmuir or Freundlich isotherm behavior, where adsorbent capacity limits removal at high equilibrium concentrations⁴⁰.



A critically important observation from the spectral data is that the position of λ_{max} remained unchanged at 665 nm both before and after treatment. No hypsochromic (blue) shift or bathochromic (red) shift was observed in the residual absorption peak. This spectral invariance is profoundly significant from a mechanistic perspective. If the dye molecules had undergone chemical degradation or transformation, the conjugated π -electron system would have been disrupted, leading to the formation of new molecular species with fundamentally different electronic configurations. Such chemical changes would inevitably produce new absorption peaks or cause a shift in λ_{max} . For example, oxidative degradation pathways—such as those involving hydroxyl radicals ($\bullet\text{OH}$)—typically cleave aromatic rings or break conjugated double bonds, generating smaller organic fragments (e.g., organic acids, aldehydes) that absorb only in the ultraviolet region (200–400 nm) and are entirely invisible in the visible spectrum. Partial degradation might result in peak broadening or the appearance of intermediate absorption bands due to the coexistence of parent dye molecules and partially oxidized products⁴¹. The complete absence of such spectral changes—no new peaks, no peak shifts, no broadening beyond experimental noise—provides compelling evidence that no chemical bond breakage within the chromophoric system has occurred. Consequently, the dominant mechanism responsible for dye removal is adsorption rather than chemical degradation. The dye molecules remain chemically intact; they are simply transferred from the aqueous phase to the solid adsorbent surface. This distinction is crucial for process design: adsorption concentrates the pollutant without transforming it, whereas degradation destroys the pollutant. Here, the unchanged λ_{max} definitively rules out degradation pathways⁴².

The magnetic peanut husk functions as an exceptionally efficient adsorbent due to its unique combination of surface chemistry and structural properties. The removal process is governed by several synergistic physicochemical interactions. Electrostatic attraction plays a primary role: methylene blue in aqueous solution carries a positive charge (a cationic dye), while the surface of peanut husk naturally contains negatively charged functional groups, including deprotonated carboxylates ($-\text{COO}^-$) from pectin and hemicellulose, and hydroxyl groups ($-\text{O}^-$) from lignin and cellulose at appropriate pH values. These opposite charges create a strong Coulombic attraction that draws the dye molecules rapidly to the surface. In addition to electrostatic forces, hydrogen bonding contributes significantly. The cellulose component of peanut husk is rich in hydroxyl ($-\text{OH}$) groups, which can act as hydrogen bond donors to the electronegative heteroatoms (nitrogen and sulfur) present in the thiazine ring system of methylene blue. Each hydrogen bond, while individually weak, collectively adds substantial binding energy⁴³.

Hydrophobic interactions are also significant, particularly due to the kerosene-based magnetic coating. Kerosene contains aliphatic hydrocarbons, and the magnetic nanoparticles are typically stabilized with oleic acid—a long-chain unsaturated fatty acid. These hydrophobic moieties create nonpolar regions on the adsorbent surface that have a high affinity for the aromatic, planar structure of methylene blue. The dye's central aromatic ring system and its dimethylamino substituents are largely nonpolar, favoring partitioning onto hydrophobic surface domains rather than remaining in the polar aqueous medium. Furthermore, π - π stacking interactions between the aromatic rings of lignin (a polyphenolic biopolymer abundant in peanut husk) and the conjugated π -system of methylene blue provide additional stabilization. In π - π stacking, the electron clouds of two aromatic systems overlap face-to-face or edge-to-face, creating attractive dispersion forces. This interaction is particularly strong because methylene blue's extended conjugation makes it an excellent π -electron donor and acceptor. The combination of electrostatic attraction, hydrogen bonding, hydrophobic effects, and π - π stacking creates a high-affinity, multivalent binding interface that explains the impressive removal efficiencies observed⁴⁴.

The incorporation of magnetic properties into the peanut husk adsorbent addresses a common challenge in adsorption technology: the difficulty of separating fine adsorbent particles from treated water. Upon application of an external magnetic field (e.g., from a permanent magnet), the dye-loaded magnetic peanut husk particles are rapidly and efficiently drawn to the magnet, allowing the adsorbent to be easily removed from the solution. The resulting supernatant is visually clear, and its UV-Vis spectrum confirms the effectiveness of the process by showing minimal residual absorbance at 665 nm. This magnetic separability eliminates the need for centrifugation or filtration, making the process scalable and operationally simple. The flat baseline and absence of scattering in the post-separation spectrum further indicate that no adsorbent fines remain in suspension, confirming complete magnetic recovery.

Applying the Beer-Lambert law quantitatively, the degradation (more accurately, removal) efficiency was calculated using the formula: Efficiency (%) = $[(A_0 - A_t)/A_0] \times 100$, where A_0 is the initial absorbance at 665 nm and A_t is the absorbance after treatment. The observed efficiencies ranged from 68% at high initial concentrations (200 mg/L) to as high as 97% at low concentrations (10 mg/L). This

concentration dependence, as previously discussed, reflects the finite adsorption capacity of the magnetic peanut husk. From an environmental remediation perspective, achieving 97% removal of a synthetic cationic dye from water is highly significant. Methylene blue, like many synthetic dyes, is resistant to biodegradation, toxic to aquatic organisms, and harmful to aquatic ecosystems because it attenuates light penetration, reducing photosynthetic activity of submerged macrophytes and phytoplankton. The near-complete removal of color and chromophores demonstrates the effectiveness of this treatment method for wastewater remediation⁴². The fact that the dye remains intact (adsorbed rather than degraded) means that the spent adsorbent must be disposed of or regenerated appropriately; however, the ease of magnetic separation greatly facilitates this subsequent step. Overall, the UV-Vis analysis presented here provides clear, quantitative, and mechanistically informative evidence that kerosene-based magnetic peanut husk is an exceptionally effective adsorbent for methylene blue removal, operating through a combination of electrostatic attraction, hydrogen bonding, hydrophobic interactions, and π - π stacking, with unchanged λ_{max} confirming adsorption rather than chemical degradation as the dominant pathway³⁹.

Conclusion

This study successfully developed a novel, low-cost, and environmentally sustainable adsorbent by magnetically modifying peanut husk using a kerosene-based magnetic fluid containing oleic acid-coated Fe_3O_4 nanoparticles. Comprehensive characterization confirmed the suitability of the material: XRD revealed phase-pure Fe_3O_4 with a cubic spinel structure and average crystallite size of ~ 12 nm; DLS showed a well-dispersed system with hydrodynamic particle sizes of 50–120 nm; VSM confirmed superparamagnetic behavior with saturation magnetization of ~ 48 –50 emu/g; and FTIR verified successful oleic acid coating. Adsorption experiments conducted over a concentration range of 10–200 mg/L using 30 mg of adsorbent with 3 hours contact time demonstrated that the magnetic peanut husk achieves a maximum removal efficiency of approximately 97% at lower concentrations (10 mg/L), decreasing to around 68% at higher concentrations (200 mg/L) due to saturation of finite adsorption sites. Critically, UV-Vis spectroscopy at 665 nm showed that the position of λ_{max} remained unchanged before and after treatment, with no hypsochromic or bathochromic shifts, providing definitive evidence that the dominant removal mechanism is adsorption rather than chemical degradation. The dye molecules remain chemically intact and are simply transferred from the aqueous phase to the solid adsorbent surface.

The exceptional adsorption efficiency is attributed to multiple synergistic physicochemical interactions: electrostatic attraction between positively charged methylene blue and negatively charged surface functional groups (carboxylates and hydroxyls), hydrogen bonding between cellulose hydroxyl groups and heteroatoms (N and S) of the dye, hydrophobic interactions facilitated by kerosene and oleic acid, and π - π stacking between lignin aromatic rings and the conjugated system of methylene blue. The superparamagnetic property enables rapid and efficient separation of the dye-loaded adsorbent using an external magnetic field, eliminating the need for centrifugation or filtration, and making the process

scalable and operationally simple. From an environmental perspective, achieving 97% removal of methylene blue—a synthetic cationic dye that is resistant to biodegradation, toxic to aquatic organisms, and harmful to aquatic ecosystems—is highly significant. The use of agricultural waste (peanut husk) as the base material provides additional benefits of low cost, renewability, and waste utilization. Overall, the kerosene-based magnetic peanut husk demonstrates high efficiency, magnetic separability, and environmental sustainability, making it a promising material for wastewater treatment applications without generating secondary pollutants.

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