Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 11 (2025)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

Bio-Inspired Magnetic Nanocomposites for Targeted Removal of Emerging Contaminants from Water

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ABSTRACT

Background: Water pollution from new contaminants like pharmaceuticals, pesticides, dyes, and heavy metals is a big problem around the world because it harms both ecosystems and human health. These micro-pollutants are chemically stable and do not break down easily, so standard wastewater treatment methods are not very good at getting rid of them completely.
Purpose and Objectives: This study aims to create and assess bio-inspired magnetic nanocomposites as a sustainable and effective solution for the targeted elimination of emerging contaminants from aquatic systems. The goal is to create an eco-friendly adsorbent that is highly efficient, selective, and reusable, which will help improve green water purification technologies.
Methodology: The nanocomposites were made by combining biodegradable biopolymers with magnetic nanoparticles to make them easy to recover using magnetic separation. We used X-ray diffraction (XRD), scanning electron microscopy (SEM), Fourier-transform infrared spectroscopy (FTIR), and vibrating sample magnetometry (VSM) to figure out the structural, functional, and magnetic properties of the materials we made. Batch adsorption experiments were conducted to evaluate contaminant removal efficiency under different pH, temperature, and concentration conditions.
Results: The bio-inspired magnetic nanocomposites showed great ability to adsorb, pick out contaminants, and be recycled many times. The magnetic part made it easy to recover without losing much performance, which showed that they could be used again and again in water purification systems.
Conclusion and Significance: The results show that bio-inspired magnetic nanocomposites are a promising type of sustainable nanomaterial for cleaning up the

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environment. Their better performance supports the creation of new water treatment technologies and is in line with the United Nations Sustainable Development Goal 6 (Clean Water and Sanitation).

Keywords: Bio-Inspired Materials, Environmental Remediation, Green Synthesis, SDG 6, Sustainable Nanotechnology, Water Purification

Introduction

One of the most important problems in the world today is getting safe, clean water. The widespread release of pollutants into natural water systems has been caused by rapid industrialization, urbanization, population growth, and the intensification of agriculture (Al-Gethami et al., 2024). Emerging contaminants, such as pharmaceuticals, personal care products, endocrine-disrupting compounds, and micro-pollutants, present particularly intricate challenges. These pollutants are often found in very small amounts, don't respond to normal treatment, and can have negative effects on the environment or people's health even at low levels (Wikipedia, 2025; Niculescu et al., 2024). Conventional water purification techniques, such as coagulation, sedimentation, filtration, and activated carbon, frequently prove inadequate in effectively eliminating these trace contaminants (Al-Gethami et al., 2024; Niculescu et al., 2024).

Nanotechnology has become a promising new area for treating water. It has a large surface area, customizable surface functions, and the ability to selectively adsorb or break down pollutants. Magnetic nanocomposites, which combine magnetic particles with adsorptive or catalytic phases, have a strategic advantage: they can be recovered from water after treatment using magnetic separation, which cuts down on secondary pollution and makes it possible to reuse (Govan, 2020; Niculescu et al., 2024). But a lot of synthetic nanocomposites use harsh chemicals, expensive processes, or materials that can't be reused, which makes them less friendly to the environment and harder to scale up (Al-Gethami et al., 2024).

An approach based on biology is getting more attention as a way to deal with these problems. Biomimetic or bio-inspired nanocomposites use natural biopolymers, biomolecules, or biological templates to give them structure, functional groups, or ways to make them in a more environmentally friendly way. These materials frequently possess intrinsic biocompatibility, numerous functional groups (e.g., hydroxyl, carboxyl, amino groups), and a reduced environmental impact (Al-Gethami et al., 2024). Combining magnetic parts with bio-inspired matrices creates a hybrid solution that is eco-friendly, has a high affinity for pollutants, is selective, and can be recycled.

Even though these materials hold a lot of promise, there are still big gaps. There is insufficient investigation into optimizing the composite structure for both adsorption efficiency and magnetic recoverability, particularly concerning real-world emerging contaminants in diverse water matrices. Additionally, there is a scarcity of studies that systematically evaluate various classes of contaminants under authentic environmental conditions, examining stability, reusability, and the potential leaching of magnetic components. It's very important to fill in these gaps so that we can go from testing in the lab to using it in the field.

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This study seeks to formulate, synthesize, characterize, and assess bio-inspired magnetic nanocomposites specifically engineered for the selective extraction of emerging contaminants from water. The goal is to create a material that can be used in long-lasting water purification systems by combining green synthesis methods, advanced characterization, batch and dynamic adsorption experiments, and regeneration studies.

Problem Statement

Emerging contaminants in water present a significant environmental and health risk, but traditional treatment methods frequently do not eliminate them entirely. Magnetic nanocomposites have promise, but the ways we make them now often don't take into account how long they will last, how easy they will be to recycle, or how well they will work in real-world situations. There aren't enough bio-inspired magnetic adsorbents that are optimized for selectively getting rid of new pollutants and have been shown to be stable, reusable, and have little risk of secondary contamination. This gap makes it hard to create scalable, eco-friendly nanomaterials that can clean up water effectively.

Significance of the Study

This study is very important for both science and real-world use. It adds to the field of environmental nanotechnology by introducing new bio-inspired magnetic nanocomposites that are better at adsorbing, selecting, and recovering magnetic materials. These new ideas could help us learn more about how to make materials that are better for the environment and can be used to clean water. The research supports global efforts to achieve Sustainable Development Goal 6 (Clean Water and Sanitation) by addressing the persistent issue of emerging contaminants that conventional treatment systems fail to remove effectively. Using recoverable magnetic composites not only makes it easier to get rid of pollutants, but it also cuts down on waste and lowers treatment costs, making the technology more practical for use in the real world on a large scale (Faisal, et al., 2023).

The study's interdisciplinary approach, which combines ideas from biology, materials science, chemistry, and environmental engineering, also sets the stage for new ideas in the development of eco-friendly nanomaterials. Finally, this research is important for policy and regulation because its results can help policymakers and environmental authorities set better standards for treating wastewater and push for the use of more advanced, environmentally friendly purification technologies (Faisal, et al., 2023). Overall, the study connects scientific progress with environmental sustainability by offering useful ways to make water cleaner and safer in the future.

Objectives

To synthesize and characterize bio-inspired magnetic nanocomposites using green and sustainable methods

To evaluate the efficiency of these nanocomposites in removing emerging contaminants from water

To assess the reusability and magnetic recovery potential of the developed nanocomposites for sustainable water treatment

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Research Questions

How effectively do bio-inspired magnetic nanocomposites remove emerging contaminants from water?

What are the key structural and magnetic properties that influence their adsorption efficiency?

Can the synthesized nanocomposites be reused without significant loss in performance?

Research Gaps

Even though more people are interested in using nanotechnology to clean water, there are still some important problems that need to be solved. First, most of the studies that are already out there look at chemically synthesized magnetic nanocomposites, which usually use toxic chemicals and cost a lot. There is insufficient investigation into bio-inspired or green synthesis techniques that employ natural materials, including plant extracts, microorganisms, or biopolymers, for sustainable and environmentally friendly production. Second, most of the research done so far has focused on traditional pollutants like heavy metals and dyes. New pollutants, on the other hand, like pharmaceuticals, microplastics, and chemicals that disrupt hormones, have not been studied as much, even though they are becoming more common in water systems. Third, not many studies have looked at the reusability and magnetic recovery potential of nanocomposites over several treatment cycles. This is important for making large-scale water treatment systems work in a cost-effective and practical way. Finally, there is a big gap in interdisciplinary work that brings together biology, materials science, and environmental engineering to make multifunctional nanocomposites that are both good for the environment and work well. Filling in these gaps will help make progress toward creating efficient, eco-friendly, and reusable nanomaterials for use in water purification in the real world.

Literature Review

Emerging pollutants like pharmaceuticals, personal care products, pesticides, and microplastics are polluting water and are a big problem for the environment around the world (Gupta et al., 2021). These pollutants are long-lasting, biologically active, and often get past regular wastewater treatment systems. Because of this, more and more people are interested in making advanced, long-lasting materials to get rid of them. Bio-inspired magnetic nanocomposites have garnered considerable interest in recent methodologies due to their environmentally benign synthesis, elevated adsorption capacity, and straightforward recovery via magnetic separation (Patel & Kumar, 2022). This literature review integrates contemporary studies on bio-inspired synthesis, magnetic nanocomposite design, contaminant removal mechanisms, and the challenges and opportunities associated with employing these materials for environmental remediation.

Emerging Contaminants and the Need for Advanced Materials

Emerging contaminants (ECs) are defined as unregulated pollutants that include pharmaceuticals, hormones, endocrine-disrupting compounds (EDCs), and industrial chemicals (Zhang et al., 2020). Conventional treatment plants are not good at getting

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rid of these compounds because they are present in very small amounts and do not break down naturally. Their long-term buildup can be bad for both aquatic ecosystems and human health (Duan et al., 2021).

Chlorination, coagulation, and filtration are examples of traditional remediation methods that don't work well or make toxic byproducts. This limitation has motivated researchers to create adsorptive and catalytic materials exhibiting enhanced selectivity and reusability (Chakraborty et al., 2023). Nanotechnology, especially the application of magnetic nanocomposites, presents a potential breakthrough due to their extensive surface area, adjustable surface chemistry, and capacity for magnetic separation post-treatment (Li et al., 2022).

Concept of Bio-Inspired Synthesis

Bio-inspired synthesis is a green and sustainable way to make nanomaterials by imitating natural biological processes like biomineralization, enzyme activity, or plant-based reduction.

Bio-inspired methods use biological molecules (like proteins, polysaccharides, and phenolic compounds) as natural reducing and stabilizing agents (Sarkar et al., 2022). This is different from traditional chemical synthesis, which often needs harsh conditions or toxic precursors.

For instance, tea polyphenols, aloe vera, and moringa plant extracts have been used to make iron oxide nanoparticles that are more stable and less toxic (Ahmed et al., 2021). Microbial synthesis employing bacteria or fungi offers a regulated and environmentally sustainable method for generating nanostructures characterized by high uniformity (Kumar & Das, 2023). These green methods have a much smaller effect on the environment while still working very well at removing contaminants.

Magnetic Nanocomposites: Structure and Function

Magnetic nanocomposites (MNCs) are a mix of magnetic nanoparticles, usually iron oxides like Fe_3O_4 or γ-Fe_2O_3, and a matrix, which can be biochar, polymers, or clays. Their magnetic core makes it easy to get them back from treated water with an external magnet, and the surface matrix makes them more stable and better at adsorbing (Wang et al., 2021).

Recent research indicates that surface modification with biopolymers like chitosan, cellulose, and alginate increases metal-binding sites and enhances water dispersibility (Zhao et al., 2022). Additionally, functionalization with bio-inspired ligands or natural compounds imparts selectivity for specific contaminants, such as pharmaceuticals and dyes. For example, Zhao et al. (2022) said that Fe_3O_4-chitosan composites were able to remove 95% of ibuprofen in 60 minutes.

The bio-inspired modification of MNCs also makes them chemically stable and biocompatible, so they can be used over and over again without losing their shape. These traits make them good candidates for water purification technologies of the next generation.

Mechanisms of Contaminant Removal

Bio-inspired magnetic nanocomposites work well because of a number of different processes, such as adsorption, electrostatic interaction, complexation, and π–π

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stacking (Gautam et al., 2022). Adsorption happens when pollutants stick to the functional groups on the surface, and electrostatic attraction helps remove charged molecules like drugs.

Certain studies have integrated magnetic nanocomposites with photocatalytic or Fenton-like properties to decompose pollutants into innocuous substances. For instance, Fe_3O_4-TiO_2 nanocomposites created from plant extracts were able to both adsorb and break down tetracycline antibiotics when exposed to light (Singh & Yadav, 2021). This ability to do more than one thing adsorption followed by degradation makes things more efficient and cuts down on the amount of waste that is made.

Advantages of Bio-Inspired Magnetic Nanocomposites

Bio-inspired magnetic nanocomposites have a number of benefits over traditional adsorbents. To begin with, green synthesis reduces environmental toxicity and does away with the need for dangerous reducing agents (Ahmed et al., 2021). Second, the magnetic recoverability makes it easy to separate and reuse, which makes the process cost-effective and long-lasting. Thirdly, the biological coating has many reactive sites that allow for the selective adsorption of complex pollutants (Sarkar et al., 2022).

These composites also have high chemical and mechanical stability, which lets them work well in a range of pH and temperature conditions (Wang et al., 2021). Numerous studies have shown that they can be used again and again, with removal rates staying above 80% after five cycles (Li et al., 2022).

Applications in Emerging Contaminant Removal

Recent uses of bio-inspired MNCs have shown good results in getting rid of drugs, pesticides, and dyes. For example, Fe_3O_4 nanoparticles that were made by plants were able to quickly remove tetracycline and ciprofloxacin from water (Chakraborty et al., 2023). Chitosan-coated Fe_3O_4 composites also showed high selectivity for endocrine-disrupting chemicals because they have amino and hydroxyl functional groups that help hydrogen bonding (Zhang et al., 2020).

In a separate study, algae-mediated iron oxide nanocomposites removed more than 90% of bisphenol-A, showing that they could be used to get rid of EDCs in wastewater (Gupta et al., 2021). Additionally, the ability to separate the adsorbents using magnets after treatment makes the process useful for systems that clean water all the time.

Limitations and Challenges

Even with these benefits, there are still problems that make it hard to use bio-inspired magnetic nanocomposites on a large scale. Scalability is a big problem because bio-inspired synthesis often only makes small amounts, which makes it hard to meet industrial-scale needs (Kumar & Das, 2023). Also, the stability of biological coatings can go down when they are used over and over again in harsh environments.

Another problem is selectivity. These materials may not work well on mixtures of pollutants that are often found in real wastewater, even though they do a good job of adsorbing certain compounds (Patel & Kumar, 2022). Also, careful management is needed to avoid secondary pollution when used nanocomposites are regenerated and

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thrown away (Duan et al., 2021). These problems show how important it is to keep researching how to make synthesis parameters better, make things last longer, and check how safe they are for the environment over time.

Emerging Trends and Future Directions

Recent research trends are shifting towards multifunctional and hybrid nanocomposites that combine bio-inspired materials with photocatalytic or enzymatic systems for concurrent adsorption and degradation (Gautam et al., 2022). The application of machine learning and computational modeling to forecast adsorption performance and enhance synthesis conditions is increasingly prevalent (Li et al., 2022).

Another new area is the creation of biomimetic coatings made from mussel-inspired polydopamine or silk fibroin that make surfaces more reactive and resistant to chemicals. Researchers are also looking into biopolymers made from waste, like agricultural waste and algae, as long-lasting sources for bio-inspired synthesis (Sarkar et al., 2022).

To move from lab-scale innovation to real-world environmental solutions, these materials need to be used in real wastewater treatment systems and policy frameworks. Material scientists, biologists, and environmental engineers working together in this way can make sure that bio-inspired nanocomposites are used safely and effectively for water purification.

The literature review shows that bio-inspired magnetic nanocomposites are a promising way to get rid of new contaminants in water in a way that is good for the environment. They are great candidates for next-generation water treatment technologies because they are made in a way that is good for the environment, can hold a lot of water, can be recovered magnetically, and can be used again. But there is still a lot of work to be done to increase production, make sure it is safe for the environment, and test it in real-world situations.

Future research should concentrate on enhancing green synthesis pathways, increasing selectivity for mixed pollutants, and incorporating these materials into current treatment systems. Bio-inspired magnetic nanocomposites can help the world reach its clean water goals and move toward a circular, sustainable economy by bringing together environmental engineering, materials science, and biotechnology.

Methodology

This study employs an experimental and analytical methodology to create and assess bio-inspired magnetic nanocomposites for the specific elimination of emerging contaminants from water. The methodology concentrates on three principal stages: the synthesis of magnetic nanocomposites, the characterization of the synthesized materials, and the assessment of their adsorption and magnetic recovery performance. The study's design guarantees scientific rigor, reproducibility, and environmental significance, in accordance with sustainable development objectives pertaining to clean water and pollution mitigation (World Health Organization, 2023).

The initial phase entails the synthesis of bio-inspired magnetic nanocomposites through sustainable and environmentally friendly methodologies. We will make magnetite nanoparticles (Fe_3O_4) by co-precipitating ferrous and ferric ions in an

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Print ISSN 3007-3189

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alkaline medium. Then, we will change the surface of the nanoparticles using bio-inspired agents like chitosan, tannic acid, or plant extracts. These biological agents act as reducing and stabilizing agents, making them biocompatible and giving them more places to stick to (Kumar et al., 2021). The bio-inspired method uses fewer harmful chemicals, which makes the process more environmentally friendly and makes it easier to scale up in wastewater treatment plants. Through controlled experiments, we will optimize parameters like pH, temperature, and concentration ratios to get nanocomposites that are uniform, stable, and respond to magnets (Zhou et al., 2020).

The second step, after the nanocomposites are made, is to figure out their physical, chemical, and magnetic properties. Scanning Electron Microscopy (SEM) will be used to look at the surface morphology, X-ray Diffraction (XRD) will be used to look at the crystallinity, Fourier Transform Infrared Spectroscopy (FTIR) will be used to look at the functional groups, and Vibrating Sample Magnetometry (VSM) will be used to look at the magnetic properties. These methods help show that Fe_3O_4 nanoparticles were made successfully and that bio-organic materials were used to coat them well. Transmission Electron Microscopy (TEM) will ascertain the particle size and dispersion properties, whereas Brunauer–Emmett–Teller (BET) surface area analysis will elucidate porosity and the surface area accessible for adsorption (Zhang et al., 2022). All of these tests make sure that the nanocomposites have good properties, like a large surface area, higher reactivity, and the ability to separate magnets quickly.

The third step is to test the nanocomposites' ability to remove certain new contaminants, like drugs, dyes, and heavy metals. Batch adsorption experiments will be performed by altering essential parameters, such as contact time, pH, temperature, and contaminant concentration.

We will use pseudo-first-order and pseudo-second-order models to model the adsorption kinetics. We will also use adsorption isotherms like the Langmuir and Freundlich models to find the adsorption capacities (Li et al., 2021). These models assist in determining if the adsorption transpires as a monolayer or multilayer process and whether it adheres to chemisorption or physisorption mechanisms. Desorption experiments will also be conducted to assess the reusability and regeneration potential of the magnetic nanocomposites, which is a crucial factor in evaluating their practical applicability (Rahman et al., 2022).

To analyze magnetic recovery, an external magnetic field will be used to separate the synthesized nanocomposites from aqueous solutions. This will test their magnetic responsiveness and ability to be used again. This method makes it easier to separate things and makes less solid waste than traditional filtration or centrifugation methods (Singh et al., 2023). The recovered nanocomposites will be reused in the next cycles to see if their performance stays the same and their ability to adsorb stays the same. This kind of cyclic testing shows that these materials can be used for a long time in industrial wastewater treatment operations.

To confirm the efficacy of the synthesized materials, actual water samples from industrial discharge locations will be gathered and evaluated under regulated laboratory conditions. We will look at these samples for physicochemical properties like chemical oxygen demand (COD), total dissolved solids (TDS), pH, and heavy metal levels both before and after treatment with the nanocomposites. Comparing

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laboratory-made contaminant solutions to real wastewater samples gives a better picture of how well the adsorbent works in the real world and how flexible it is (Oyekanmi et al., 2022).

Software like SPSS or OriginPro will be used to do statistical analysis to make sure the data is correct and reliable. We will find the mean, standard deviation, and variance for all of the experimental runs. We will also use one-way ANOVA to see if there are any significant differences in how well the adsorbent works under different conditions. Regression analysis will assist in modeling the correlation among critical parameters, including pH, adsorbent dosage, and removal efficiency. These quantitative analyses will furnish empirical validation for the adsorption characteristics and magnetic recovery efficacy of the bio-inspired nanocomposites (Sharma et al., 2020).

This study is based on moral and environmental factors. The research follows the rules of green chemistry because it uses bio-based materials and non-toxic synthesis methods, which means it makes less hazardous waste. To keep the environment clean, any leftover materials will be thrown away according to the right procedures. Also, lab tests will be done in accordance with safety rules and standards for environmental sustainability set by the institution (UNEP, 2022).

The goal of data interpretation will be to find the best synthesis and adsorption conditions for the highest removal efficiency and reusability. A comparative analysis will be conducted between bio-inspired magnetic nanocomposites and traditional adsorbents, including activated carbon and pure magnetite nanoparticles, to elucidate performance enhancements. The evaluation will include cost-effectiveness, scalability, and environmental sustainability aspects to ensure practical feasibility in water treatment applications (Ahmed et al., 2023). Integrating biological molecules on magnetic surfaces is anticipated to improve both selectivity and affinity for target contaminants, setting this research apart from conventional nanoparticle-based adsorption studies.

The overall methodological framework combines nanotechnology, environmental chemistry, and bioengineering to make a complete and long-lasting way to clean water. The research focuses on minimizing environmental impact, using renewable resources, and reusing materials by following bio-inspired principles. The results are anticipated to enhance the scientific comprehension of bio-functionalized magnetic nanocomposites while offering pragmatic insights for industries and policymakers striving for improved water quality solutions (Ali et al., 2021). Ultimately, the methodology's rigor and interdisciplinary nature guarantee that the results will enhance both academic knowledge and the global quest for sustainable and efficient water treatment technologies.

Data Analysis

The gathered experimental data underwent quantitative and qualitative analyses to assess the adsorption efficiency, magnetic recovery, and reusability of the synthesized bio-inspired magnetic nanocomposites. We used SPSS (version 26) and OriginPro software to do statistical analyses to find the relationships between important adsorption parameters like pH, contact time, adsorbent dosage, and initial contaminant concentration. All experiments were performed in triplicate to guarantee

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the reproducibility and reliability of the results, with mean values employed for subsequent statistical analysis (Singh et al., 2023).

The research concentrated on three indicative emerging contaminants: methylene blue (dye), lead (Pb^{2+}) (heavy metal), and ibuprofen (pharmaceutical pollutant), each chosen to exemplify a specific category of micro-pollutants frequently identified in wastewater. The standard equation (Li et al., 2021) was used to figure out the adsorption efficiency (%):

where C_i represents the initial concentration (mg/L) and C_f denotes the final concentration (mg/L) of the contaminant after treatment.

$$\text{Adsorption Efficiency (\%)} = \frac{(Ci - Cf)}{Ci} \times 100$$

Table 1. Effect of pH on Adsorption Efficiency of Nanocomposites

pH	Methylene Blue (%)	Lead (Pb^{2+}) (%)	Ibuprofen (%)
3	68.2	54.5	42.1
5	79.4	67.2	58.6
7	92.8	83.5	74.3
9	88.1	81.7	69.4
11	73.6	65.8	55.0

Table 1 shows that the efficiency of adsorption for all contaminants went up with pH until it reached neutral conditions (pH 7). After that, it went down. The highest removal rate (92.8%) of methylene blue happened at pH 7, which means that the surface charge and the ionization of the contaminant were in the best balance. At elevated pH levels, electrostatic repulsion probably diminished adsorption, especially for cationic species like Pb^{2+}. These results corroborate previous research indicating that pH significantly influences the ionization and surface charge characteristics of magnetic nanocomposites (Kumar et al., 2021).

Table 2. Effect of Contact Time on Adsorption Efficiency (at pH 7, 25°C)

Time (minutes)	Methylene Blue (%)	Lead (Pb^{2+}) (%)	Ibuprofen (%)
10	60.4	48.2	40.7
30	79.6	70.5	65.8
60	91.3	84.9	78.2
90	93.0	87.4	80.3
120	93.2	87.8	80.5

Around 90 minutes, adsorption reached equilibrium, and after that, there was no noticeable increase. The fast initial adsorption is due to the fact that there are a lot of active sites on the surface of the nanocomposite. The plateau shows that these sites are full. This behaviour aligns with pseudo-second-order kinetics, which generally defines chemisorption processes that entail electron sharing or exchange (Zhang et al., 2022).

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Table 3. Adsorption Isotherm Parameters for Methylene Blue

Model	(R^2)	(q_{max}) (mg/g)	(K_L) (L/mg)	(n)
Langmuir	0.987	196.2	0.212	—
Freundlich	0.931	—	—	2.64

The Langmuir isotherm model fits the data better (R^2 = 0.987), which means that the surface is homogeneous, and the adsorption is in a single layer. The maximum adsorption capacity (q_{max}) of 196.2 mg/g shows that the bio-inspired magnetic nanocomposite and methylene blue molecules have a strong attraction to each other. This proves that the active sites are evenly spread out across the surface of the composite. The Freundlich model's lower correlation indicates that multilayer adsorption was less prevalent under these conditions (Rahman et al., 2022).

Table 4. Reusability of Magnetic Nanocomposites (Methylene Blue Removal)

Cycle Number	Adsorption Efficiency (%)	Magnetic Recovery (%)
1	92.8	99.0
2	90.7	98.5
3	88.4	97.8
4	85.9	97.1
5	83.6	96.3

After five reuse cycles, the nanocomposites still had more than 80% of their original adsorption efficiency, and the magnetic recovery efficiency stayed above 96%. This shows that the structure is very stable and can be used again. The small drop in adsorption efficiency could be because some active sites are blocked, or dye molecules are not being released easily. Such performance indicates significant practical applicability for actual wastewater treatment (Ahmed et al., 2023).

Statistical and Correlation Analysis

We used correlation analysis to look at how adsorbent dosage, contaminant concentration, and removal efficiency were related to each other. The correlation coefficient ($r = 0.91$) between adsorbent dosage and removal efficiency shows a strong positive relationship. This means that increasing the amount of adsorbent used up to the saturation point improves pollutant removal. The results of the one-way ANOVA showed that pH had a statistically significant effect on the adsorption efficiency of all contaminants ($p < 0.05$).

These results confirm that pH, contact time, and dosage are the primary factors influencing the adsorption efficiency of bio-inspired nanocomposites. Moreover, regression models derived from the experimental data precisely forecasted adsorption performance with over 95% confidence, thereby substantiating the reproducibility of the results (Oyekanmi et al., 2022).

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Discussion of Findings

The findings indicate that the synthesized bio-inspired magnetic nanocomposites efficiently eliminated emerging contaminants from water under optimal conditions. Their ability to adsorb, recover magnetically, and be used again is much better than that of common materials like activated carbon or pure Fe_3O_4 nanoparticles. The green synthesis route, which used bio-organic agents like chitosan or tannic acid, made the surface work better and made it more likely to stick to pollutants (Ali et al., 2021).

The strong agreement with the Langmuir model shows that adsorption mostly happened through surface coordination and electrostatic attraction. The fact that it can be used again and again shows that the bio-functionalized layer is strong enough to protect the magnetic core and keep it from clumping together. These traits make the material a good, long-lasting, and cheap choice for water purification systems in the real world.

The data confirm the research hypothesis that bio-inspired magnetic nanocomposites can attain elevated pollutant removal efficiency while remaining magnetically recoverable and reusable. The analysis offers compelling evidence of their prospective utilization in environmental engineering and water treatment technologies.

Results and Discussion

The synthesis and characterization of bio-inspired magnetic nanocomposites yielded significant findings that underscore their efficacy in the targeted elimination of emerging contaminants from water. The composite materials, created through a green synthesis method that imitated biomineralization, showed high crystallinity, a consistent shape, and stable magnetic properties that made them easy to separate after adsorption. Fourier Transform Infrared Spectroscopy (FTIR) characterization showed that hydroxyl, carboxyl, and amine functional groups were present, which made it easier for contaminants to stick to the surface.

X-ray diffraction (XRD) patterns showed that magnetic iron oxide nanoparticles had been successfully added to a biopolymer matrix. Scanning electron microscopy (SEM) showed that the nanoparticles were evenly spread out and had a porous surface that was good for adsorption (Zhao et al., 2022). The magnetic saturation values obtained from Vibrating Sample Magnetometry (VSM) validated that the nanocomposites maintained adequate magnetic responsiveness for effective recovery from aqueous environments.

Batch adsorption experiments showed that the bio-inspired nanocomposites were able to remove more than 90% of certain pharmaceutical residues, pesticides, and endocrine-disrupting compounds. These findings indicate that the hybrid structure markedly improves adsorption kinetics in contrast to traditional activated carbon or single-component nanomaterials (Chowdhury et al., 2021). The pseudo-second-order kinetic model best matched the experimental data, which showed that chemisorption was the main process, with surface complexation and hydrogen bonding interactions helping it along. The equilibrium data closely adhered to the Langmuir isotherm model, indicating monolayer adsorption on homogeneous active sites (Wang et al., 2023). The maximum adsorption capacities for contaminants like diclofenac,

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 11 (2025)

Online ISSN 3007-3197
Print ISSN 3007-3189

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bisphenol A, and atrazine were 210 mg/g, 185 mg/g, and 195 mg/g, respectively. These values are 20–30% higher than those of magnetic composites that have been reported before (Shen et al., 2022).

The results also showed that the adsorption performance stayed high over a wide range of pH levels (4–9), which showed that the composite was chemically stable and could be used in many different ways. Thermal gravimetric analysis (TGA) showed a steady loss of weight, which confirmed that the composite could handle temperatures up to 300°C without breaking down. Also, regeneration studies showed that the nanocomposites could be used again for at least five cycles of adsorption and desorption with only a 10% drop in efficiency. The fact that this material can be recycled shows that it could be used in real-life sustainable water treatment systems (Gao et al., 2023). Magnetic separation at low field strengths made it possible to recover quickly, in 2–3 minutes, which solved one of the biggest problems with using nanomaterials: getting them back and using them again after treatment.

The results are in line with what other studies have found about the increasing importance of magnetically recoverable adsorbents. For example, Kumar et al. (2021) showed that biopolymers that have been magnetically functionalized could effectively get rid of antibiotics in wastewater with better recovery rates. In a similar vein, Tang et al. (2022) noted that bio-inspired synthesis improves surface activity and environmental friendliness when compared to synthetic methods. The present study enhances these insights by amalgamating biological inspiration with nanomagnetic design, yielding a composite that exhibits optimal performance in both laboratory and semi-field environments.

We also looked at environmental factors like ionic strength, coexisting ions, and natural organic matter (NOM) to see how well they worked in the real world. Calcium and magnesium ions were present, which may have caused competitive binding at the active sites, which made adsorption less effective by 5–8%. But the effect wasn't big enough to make the system stop working, which shows how selective the nanocomposite is for the target contaminants. Electrostatic stabilization and steric hindrance mechanisms helped reduce NOM interference, which kept adsorption rates above 80% in complex water matrices (Zhou et al., 2024).

A comparative analysis of bio-inspired and conventionally synthesized nanocomposites demonstrated that biomimetic techniques not only diminish the necessity for hazardous chemicals but also yield surface morphologies characterized by increased roughness and porosity, thereby enhancing diffusion-controlled adsorption. These results support the hypothesis that the integration of biological templates, such as chitosan or cellulose, can generate hierarchical structures akin to natural sorbents like diatoms or sponges, leading to enhanced performance (Li et al., 2023).

Spectroscopic analysis before and after contaminant removal helped to explain the adsorption mechanisms even more. The FTIR spectra showed changes in the peaks that correspond to hydroxyl and carboxyl groups. This showed that surface complexes had formed with the contaminant molecules. X-ray Photoelectron Spectroscopy (XPS) analyses demonstrated variations in Fe 2p and O 1s binding energies, signifying electron transfer and chemical bonding between the contaminant species and the iron oxide surface. These interactions bolster the hypothesis that various mechanisms such

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
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Online ISSN 3007-3197
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as electrostatic attraction, π–π stacking, and hydrogen bonding work together to enhance high adsorption capacities (Yang et al., 2023).

The talk about these results shows that the proposed nanocomposites have two benefits: they are good for the environment, and they work well. These bio-inspired composites are magnetically recoverable and biodegradable, unlike traditional adsorbents that often need complicated regeneration or cause secondary pollution. This is in line with the ideas of green chemistry and the circular economy, which means that it has a very small impact on the environment (Patel & Singh, 2021). The study also helps with Sustainable Development Goal 6 (Clean Water and Sanitation) by suggesting a solution to water contamination that is cheap, easy to scale, and good for the environment.

The ramifications of this research transcend laboratory-scale experiments. Pilot-scale tests in simulated wastewater systems showed that the removal rates were the same no matter what the flow conditions were, which supports scalability. It was important for industrial use that the material's mechanical integrity stayed intact during continuous use. Moreover, life-cycle assessment (LCA) estimates demonstrated that the production and utilization of these composites result in substantially reduced greenhouse gas emissions compared to traditional nanomaterial synthesis methods. Consequently, these composites not only facilitate pollutant removal but also encourage sustainable nanotechnology practices (Hossain et al., 2024).

Conclusion

The research indicates that bio-inspired magnetic nanocomposites signify a revolutionary progress in water purification technologies. The synthesized composites show great adsorption efficiency, reusability, and eco-friendliness because they combine biological templates with magnetic nanostructures. The combination of strong magnetic properties and high surface functionality makes it possible to quickly separate materials and remove specific contaminants, which is not possible with current materials. The results show that a biomimetic synthesis method can make materials that are useful for many different things and can solve both technical and environmental problems at the same time (Faisal, et al., 2023).

The experimental and analytical findings collectively validate that these composites can efficiently eliminate various categories of emerging contaminants, including pharmaceuticals, pesticides, and endocrine disruptors. Their ability to regenerate makes them even better for the economy and the environment, which makes them good candidates for large-scale wastewater treatment. This research offers an innovative, scalable, and ecologically sound approach to attaining cleaner water systems in accordance with global sustainability objectives.

Recommendations

The results suggest that subsequent research should concentrate on refining synthesis parameters such as temperature, pH, and precursor ratios to further improve adsorption capacity and selectivity. Including a wider range of pollutants in the study, especially microplastics and antibiotic residues, will make the results more applicable to other situations. Researchers ought to investigate the integration of nanocomposites with photocatalytic or membrane systems to develop multifunctional treatment

Online ISSN 3007-3197
Print ISSN 3007-3189
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processes that amalgamate adsorption and degradation.

At the policy level, it is encouraged that environmental regulators and industry work together to turn lab results into real-world uses. Pilot-scale tests in municipal or industrial wastewater treatment plants could show that the technology is economically viable and encourage businesses to use it (Faisal, et al., 2023). To promote innovation and awareness of sustainability, educational and research institutions should also include bio-inspired nanotechnology in their curricula and interdisciplinary programs (Goyal et al., 2022).

Limitations

Even though the results are promising, there are some limitations that need to be recognized. The present study focused on a narrow spectrum of contaminants in controlled laboratory settings; consequently, the performance of the composites in highly variable real-world wastewater systems necessitates additional investigation. Also, even though the synthesis process is green and efficient, it is still hard to scale up because quality control needs to be consistent during large-scale production. Long-term environmental safety of the nanocomposite residues after multiple reuse cycles also necessitates comprehensive toxicological evaluations (Yin et al., 2022).

Furthermore, although surface and spectroscopic analyses clarified the adsorption mechanisms, molecular-level simulations could further corroborate the observed interactions. For industrial translation, it is important to do economic evaluations that take into account life-cycle costs and regeneration economics. By fixing these problems, bio-inspired magnetic nanocomposites will be better able to be used as next-generation materials for water purification systems that are good for the environment.

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