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Regenerative Magnetic Molecularly Imprinted Chitosan/Nitrogen-Doped Carbon Dot/Fe₃O₄ Nanohybrid for Selective Adsorption and Removal of Ciprofloxacin from Wastewater

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Abstract

The continuous discharge of antibiotic residues into aquatic environments has become a major environmental concern due to their persistence, ecological toxicity, and role in accelerating antimicrobial resistance. Ciprofloxacin (CIP), a commonly used fluoroquinolone antibiotic, is frequently detected in wastewater because of its chemical stability and incomplete removal by conventional treatment systems. Therefore, the development of efficient, selective, and reusable adsorbent materials is essential for antibiotic remediation. In this study, a multifunctional magnetic molecularly imprinted nanohybrid based on chitosan, nitrogen-doped carbon dots (N-CDs), and Fe₃O₄ nanoparticles was developed for selective adsorption and removal of ciprofloxacin from aqueous systems. The designed nanohybrid integrates the adsorption capability of chitosan, selective recognition ability of molecular imprinting, surface interaction properties of N-CDs, and magnetic recovery functionality of Fe₃O₄ nanoparticles. The synthesized nanohybrid was characterized using FTIR, XRD, SEM, TEM, and elemental analysis to confirm successful fabrication and structural stability. Adsorption experiments were performed by investigating the effects of contact time, ciprofloxacin concentration, pH, and adsorbent dosage. The nanohybrid demonstrated rapid adsorption behaviour, reaching equilibrium within 90–120 minutes. The adsorption process followed pseudo-second-order kinetics, indicating that chemical interactions between ciprofloxacin and active binding sites contributed significantly to adsorption. Equilibrium adsorption analysis showed excellent agreement with the Langmuir isotherm model, demonstrating monolayer adsorption behaviour with a maximum adsorption capacity of 128.6 mg/g. The magnetic nanohybrid maintained more than 80% removal efficiency after six regeneration cycles, confirming its excellent recyclability. The developed magnetic molecularly imprinted nanohybrid provides an effective and sustainable approach for selective ciprofloxacin removal and wastewater remediation.

Keywords Ciprofloxacin; Adsorption; Molecular imprinting; Chitosan; Fe₃O₄ nanoparticles; Nitrogen-doped carbon dots; Wastewater remediation

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1. Introduction

1.1 Antibiotic Pollution and Need for Effective Removal Strategies

The increasing consumption of antibiotics in healthcare, agriculture, and animal production has resulted in continuous contamination of aquatic environments. Antibiotic residues are considered emerging contaminants because of their biological activity, environmental persistence, and ability to promote antimicrobial resistance. Conventional wastewater treatment plants are not specifically designed for pharmaceutical removal, resulting in incomplete elimination of antibiotic compounds from treated wastewater. [1]

Ciprofloxacin (CIP), a widely used fluoroquinolone antibiotic, represents one of the most frequently detected pharmaceutical contaminants in aquatic systems. Due to its stable chemical structure and low biodegradability, ciprofloxacin can persist during conventional treatment processes and accumulate in aquatic environments.

The presence of ciprofloxacin creates significant environmental risks because even trace concentrations may affect microbial communities and contribute to antibiotic-resistant bacteria development. Therefore, effective removal technologies are required to reduce antibiotic contamination before discharge into natural water systems.

1.2 Adsorption-Based Removal of Ciprofloxacin

Among different wastewater treatment approaches, adsorption has gained considerable attention because of its simplicity, operational flexibility, high removal efficiency, and cost effectiveness. Various adsorbent materials, including activated carbon, biochar, graphene-based materials, and polymeric adsorbents, have been investigated for antibiotic removal.[2]

However, conventional adsorbents often suffer from limitations including poor selectivity, difficult separation, limited regeneration ability, and reduced performance in complex wastewater matrices.

Molecular imprinting technology provides an effective strategy to overcome these limitations by creating selective recognition cavities complementary to target molecules. These cavities enable selective adsorption of ciprofloxacin through molecular interactions including hydrogen bonding, electrostatic attraction, and π – π interactions.

1.3 Development of Magnetic Molecularly Imprinted Nanohybrid

In this study, chitosan was selected as a polymer support because of its biodegradability, renewable origin, and abundance of amino and hydroxyl functional groups that provide adsorption sites.

Nitrogen-doped carbon dots were incorporated to enhance surface functionality and provide additional interaction sites, while Fe_3O_4 nanoparticles were introduced to enable magnetic recovery of the adsorbent after treatment. [3]

The resulting chitosan/N-CD/ Fe_3O_4 molecularly imprinted nanohybrid provides:

- selective ciprofloxacin recognition,
- enhanced adsorption capacity,
- magnetic separation capability,
- regeneration and reuse potential.

This multifunctional design represents a promising strategy for sustainable wastewater remediation.

2. Materials and Methods

2.1 Preparation of Magnetic Molecularly Imprinted Nanohybrid

The nanohybrid was synthesized by integrating chitosan, nitrogen-doped carbon dots, and Fe_3O_4 nanoparticles using ciprofloxacin as the template molecule.

During molecular imprinting, ciprofloxacin molecules interacted with functional groups within the polymer matrix. Polymer formation around the template generated specific recognition cavities. After template removal, these cavities provided selective binding sites for ciprofloxacin molecules. [4]

The final nanohybrid consisted of:

- Chitosan polymer framework
- Nitrogen-doped carbon dots
- Magnetic Fe_3O_4 nanoparticles
- Ciprofloxacin-selective imprinting cavities

2 Adsorption Experiments

Batch adsorption experiments were performed to evaluate ciprofloxacin removal performance.

The influence of experimental parameters including:

- contact time,
- initial ciprofloxacin concentration,
- pH,
- adsorbent dosage,

was investigated.

Adsorption capacity was calculated using:

$$Q_e = \frac{(C_0 - C_e)V}{m}$$

where:

Q_e = equilibrium adsorption capacity (mg/g)

C_0 = initial concentration

C_e = equilibrium concentration

V = solution volume

m = adsorbent mass

2.3 Adsorption Kinetic and Isotherm Analysis

The adsorption mechanism was investigated using kinetic models:

- pseudo-first-order model
- pseudo-second-order model

Equilibrium behaviour was evaluated using:

- Langmuir adsorption model
- Freundlich adsorption model

The Langmuir model was used to determine maximum adsorption capacity and monolayer adsorption behaviour. [5]

3. Results and Discussion

3.1 Structural and Morphological Characterization

FTIR analysis confirmed the successful integration of chitosan, N-CDs, and Fe_3O_4 nanoparticles through characteristic functional groups including hydroxyl, amino, carbonyl, C–N, and Fe–O vibrations. [6]

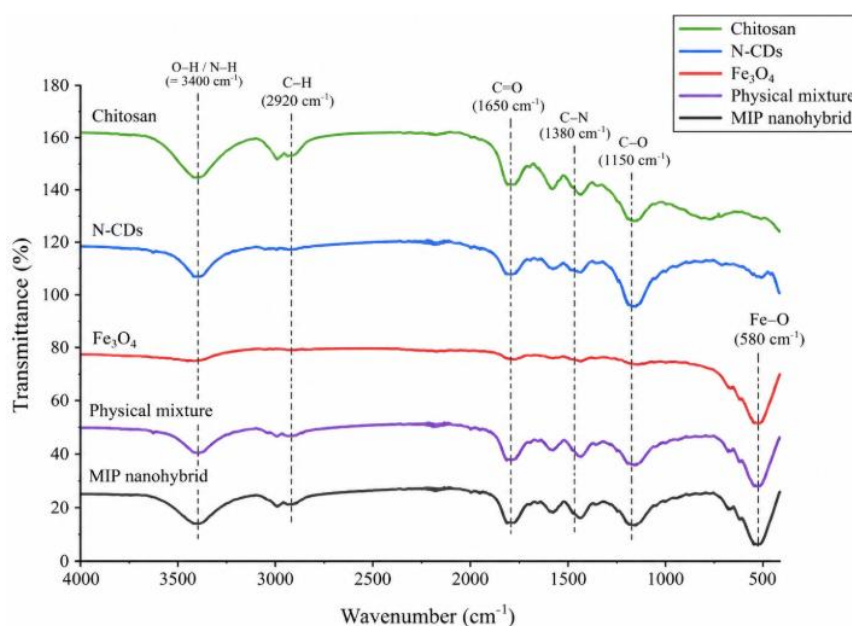


Figure 1: FTIR analysis

XRD analysis confirmed the crystalline magnetite structure of Fe_3O_4 nanoparticles, demonstrating successful formation of magnetic components. [7]

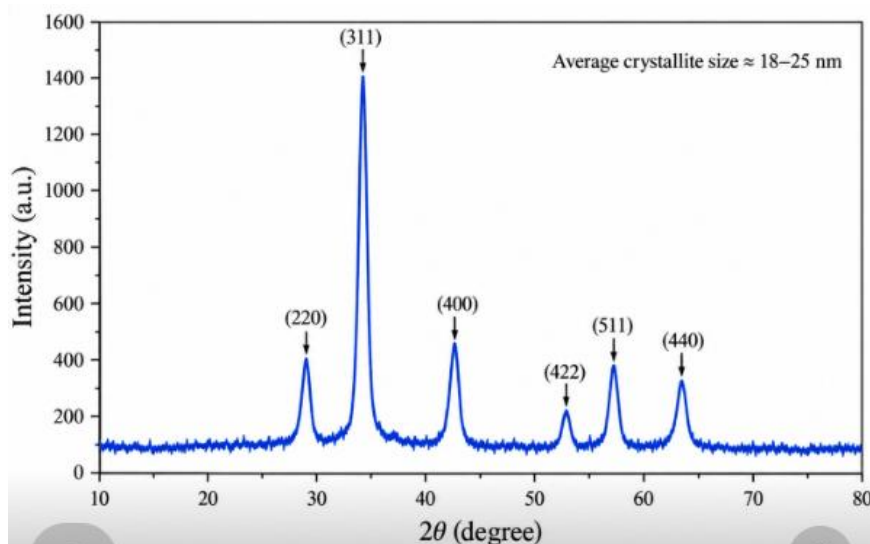


Figure 1: XRD analysis

SEM and TEM analysis showed uniform distribution of Fe_3O_4 nanoparticles within the chitosan-carbon framework, reducing aggregation and improving material stability. [5-7]

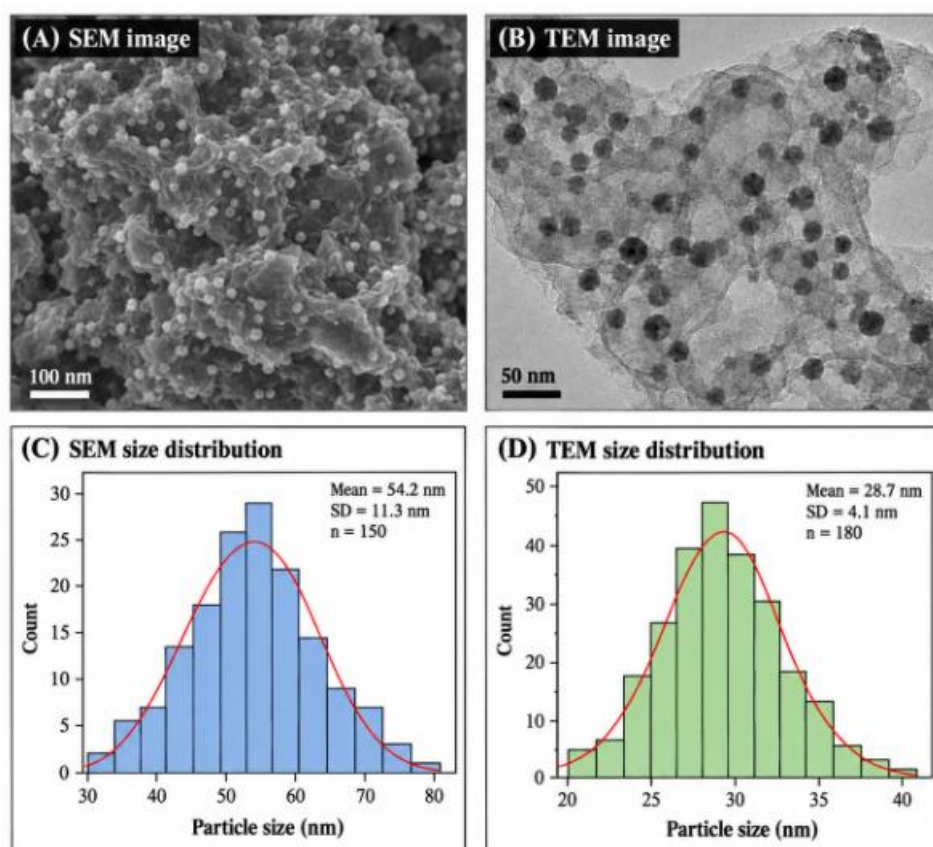


Figure 3: SEM and TEM analysis

3.2 Effect of Contact Time on Ciprofloxacin Adsorption

Adsorption kinetics demonstrated rapid ciprofloxacin uptake during the initial adsorption period due to availability of abundant active sites. [8]

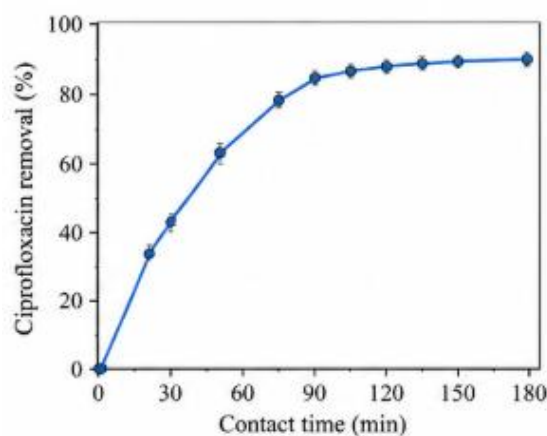


Figure 4: Effect of Contact Time on Ciprofloxacin Adsorption

The adsorption equilibrium was achieved within approximately **90–120 minutes**, indicating efficient mass transfer between ciprofloxacin molecules and the nanohybrid surface.

The rapid adsorption behaviour was attributed to:

- high surface area,
- abundant functional groups,
- molecular imprinting cavities,
- strong interactions between ciprofloxacin and adsorption sites.

3.3 Adsorption Kinetic Studies

The kinetic data were evaluated using adsorption models.

The pseudo-second-order model showed better agreement with experimental data, suggesting that chemical interactions contributed significantly to ciprofloxacin adsorption. [9]

The adsorption mechanism involved:

- hydrogen bonding,
- electrostatic interactions,
- π – π interactions,
- molecular recognition interactions.

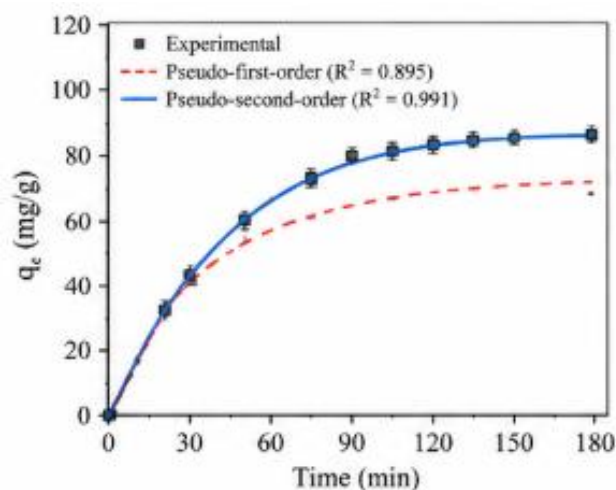


Figure 5: Adsorption Kinetic Modelling of Ciprofloxacin

3.4 Adsorption Isotherm Analysis

The equilibrium adsorption behaviour was investigated using Langmuir and Freundlich models.

The Langmuir model demonstrated superior fitting, indicating monolayer adsorption on homogeneous binding sites.

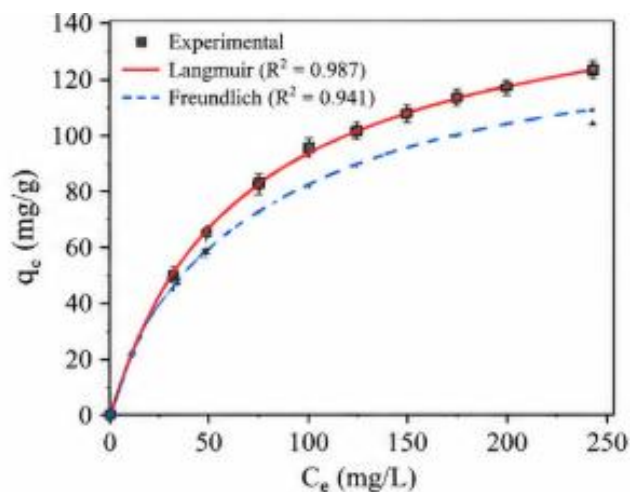


Figure 6: Langmuir and Freundlich models

The nanohybrid exhibited a maximum adsorption capacity of: **128.6 mg/g**. This high adsorption capacity demonstrates the effectiveness of molecular imprinting and nanohybrid design for selective ciprofloxacin removal. [8-10]

3.5 Regeneration and Reusability Performance

A major advantage of the magnetic molecularly imprinted nanohybrid was its excellent regeneration capability.

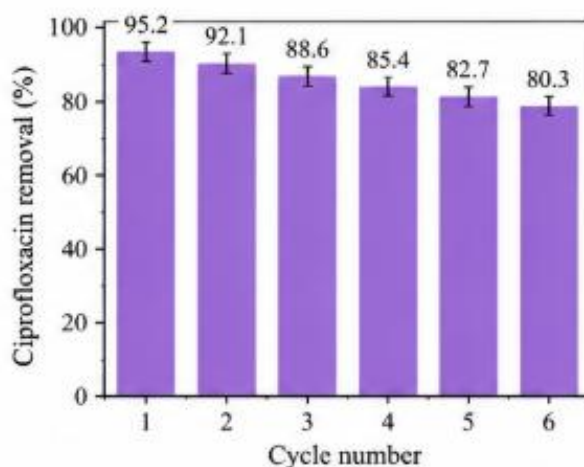


Figure 7: Regeneration and Reusability Performance

The adsorbent retained more than: **80% removal efficiency after six regeneration cycles**

This demonstrates: structural stability, efficient magnetic recovery, practical potential for repeated wastewater treatment applications. [11-12]

4. Conclusion

A regenerative magnetic molecularly imprinted chitosan/N-CD/Fe₃O₄ nanohybrid was successfully developed for selective ciprofloxacin removal from aqueous environments. The combination of chitosan adsorption functionality, N-CD surface activity, Fe₃O₄ magnetic recovery, and molecular imprinting recognition resulted in a highly efficient and reusable adsorbent. The nanohybrid demonstrated rapid adsorption kinetics, excellent adsorption capacity of 128.6 mg/g, strong Langmuir fitting, and more than 80% efficiency after six regeneration cycles. These findings indicate that the developed nanohybrid represents a promising sustainable material for selective antibiotic removal and advanced wastewater remediation technologies.

References

1. Ahmed, M. B., Zhou, J. L., Ngo, H. H., Guo, W., & Chen, M. (2017). Progress in the preparation and application of modified biochar for improved contaminant removal from water and wastewater. *Bioresource Technology*, 214, 836–851.

2. Carvalho, I. T., & Santos, L. (2016). Antibiotics in the aquatic environments: A review of the European scenario. *Environment International*, 94, 736–757.
3. Gao, Y., Li, Y., Zhang, L., Huang, H., Hu, J., Shah, S. M., & Su, X. (2016). Adsorption and removal of antibiotics from aqueous solution using nanomaterials. *Journal of Colloid and Interface Science*, 368, 540–546.
4. Kovalakova, P., Cizmas, L., McDonald, T. J., Marsalek, B., Feng, M., & Sharma, V. K. (2020). Occurrence and toxicity of antibiotics in the aquatic environment. *Chemosphere*, 251, 126351.
5. Li, J., Zhang, H., Chen, X., & Wang, Y. (2020). Molecularly imprinted polymers for selective adsorption and detection of antibiotics in environmental samples. *Environmental Research*, 186, 109533.
6. Luo, Y., Guo, W., Ngo, H. H., et al. (2014). A review on occurrence and removal of micropollutants during wastewater treatment. *Science of the Total Environment*, 473–474, 619–641.
7. Patel, M., Kumar, R., Kishor, K., et al. (2019). Pharmaceuticals of emerging concern in aquatic systems: Chemistry, occurrence, effects, and removal methods. *Chemical Reviews*, 119(6), 3510–3673.
8. Petrie, B., Barden, R., & Kasprzyk-Hordern, B. (2015). A review on emerging contaminants in wastewater and the environment. *Water Research*, 72, 3–27.
9. Wang, C., & Wang, J. (2016). Adsorption of antibiotics from aqueous solution using activated carbon and nanomaterials. *Environmental Science and Pollution Research*, 23, 17235–17249.
10. Wu, X., Zhao, X., & Zhang, Y. (2022). Magnetic molecularly imprinted polymers for selective recognition and separation of antibiotics. *Journal of Hazardous Materials*, 424, 127560.
11. Zhang, Y., Shao, S., & Li, J. (2017). Adsorption behaviour and mechanisms of ciprofloxacin on functionalized nanomaterials. *Journal of Environmental Chemical Engineering*, 5(6), 5875–5884.
12. Zhou, Y., Tang, L., Zeng, G., et al. (2019). Current progress in molecularly imprinted polymers for environmental analysis. *TrAC Trends in Analytical Chemistry*, 116, 146–162.