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Short Note

Optimized Nanocellulose-Based Magnetic Metal-Organic Frameworks for Antibiotic Adsorption: A Cutting-Edge Strategy in Environmental Remediation

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Abstract: The growing threat of antibiotic pollution in water systems demands innovative and sustainable remediation strategies. Nanocellulose-based magnetic metal-organic frameworks (MOFs) represent a cutting-edge solution for the adsorption and removal of antibiotics, leveraging their high porosity, magnetic properties, and environmentally friendly nature. This paper provides an in-depth review of recent advancements in nanocellulose-based MOFs, focusing on their synthesis, adsorption mechanisms, and applications in environmental remediation between 2020 and 2024. By summarizing key studies, we highlight their performance in targeting widely used antibiotics such as tetracyclines and fluoroquinolones. The integration of nanocellulose with MOFs not only enhances adsorption capacity but also offers easy recovery, recyclability, and environmental compatibility. This review explores their adsorption mechanisms, practical applications, and future research directions, contributing to the advancement of scalable and sustainable water treatment technologies.

Keywords: nanocellulose; metal-organic frameworks; water remediation; antibiotic adsorption; environmental sustainability

Introduction

Antibiotic contamination has escalated into a global crisis, with residues from pharmaceuticals increasingly found in water systems. These pollutants accelerate the development of antibiotic-resistant pathogens, posing a serious risk to public health and aquatic life. Conventional remediation technologies—such as chemical oxidation, reverse osmosis, and photocatalysis—are often inefficient, energy-intensive, or economically unsustainable for large-scale deployment [1].

Nanocellulose-based magnetic metal-organic frameworks (MOFs) have emerged as a powerful tool in environmental remediation, offering a unique blend of biodegradability, high surface area, and magnetic separation capabilities. Their synthesis has evolved to create materials that are not only effective in removing antibiotics but also scalable and environmentally friendly. This paper provides an extensive review of recent studies (2020-2024) on nanocellulose-based MOFs, exploring their potential to revolutionize water remediation.

Recent Advancements in Nanocellulose-Based Magnetic MOFs

Nanocellulose-based MOFs are gaining momentum in the scientific community due to their multifunctionality. The combination of nanocellulose's renewable nature with MOFs' highly porous structure results in composites with exceptional adsorption capacities and magnetic properties for efficient separation. Table 1 summarizes key research studies from 2020 to 2024, focusing on adsorption efficiency, antibiotic targets, and practical applications.

Table 1. Recent Studies on Nanocellulose-Based Magnetic MOFs for Antibiotic Adsorption (2020-2024).

Study	Composite Material	Antibiotics Targeted	Adsorption Capacity (mg/g)	Key Features	Reference
Fe ₃ O ₄ /HKUST-1 Magnetic Copper MOF	Fe ₃ O ₄ /HKUST- 1	Ciprofloxacin, Norfloxacin	538 (CIP), 513 (NOR)	High magnetization, 10 reuse cycles, fast kinetics	[2]
Zn-based MOF Hybrid Composites	ROD-Zn1@MF, ROD-Zn2@MF	Multiple antibiotics	High	Dual functionality (removal and detection), stable under acidic and basic conditions	[3]
Magnetic Porous Carbon Composite from MOF	α -Fe/Fe ₃ C	Tetracycline Hydrochloride	99.91% H ₂ BDC recovery	Sustainable synthesis from PET waste, magnetic separability	[4]
ZIF-L/gelatin aerogel	ZIF-L/FGA200	Tetracycline	387.6	High adsorption, excellent recyclability	[5]
Functionalized MIL-53(Fe)	Br-MIL-53(Fe)	Tetracycline	309.6	Strong adsorption, recyclability	[6]
Nanocellulose Scaffolded MOFs	MOFs@NC	Multiple pollutants	High	Prevents agglomeration, mechanical stability	[7]

Adsorption Mechanisms

The efficiency of nanocellulose-based magnetic MOFs in antibiotic adsorption can be attributed to several well-defined mechanisms:

Electrostatic and Hydrogen Bonding: Antibiotics containing charged groups (e.g., carboxyl or amine) form strong electrostatic interactions with MOF surface groups. Simultaneously, hydrogen bonding enhances these interactions, contributing to greater adsorption capacity [3].

π - π Interactions: For aromatic antibiotics like tetracycline, π - π stacking interactions between the MOF's aromatic linkers and the drug molecules significantly increase adsorption affinity. These interactions are key in facilitating the removal of fluoroquinolones and other aromatic antibiotics [5].

Magnetic Separation: Magnetic nanoparticles embedded in the composite allow for rapid separation of the adsorbent from the water using external magnetic fields. This process greatly enhances the practicality of the material for real-world applications [4].

Recyclability and Stability: One of the most significant advantages of nanocellulose-based magnetic MOFs is their reusability. Studies show that these materials can maintain their adsorption efficiency for up to ten reuse cycles with minimal loss in performance, making them highly sustainable [2].

Key Advances in Material Design

Several noteworthy advancements in the design of nanocellulose-based MOFs have been made in recent years:

Sustainable Synthesis Approaches: Using waste products like polyethylene terephthalate (PET) as a precursor for the synthesis of porous carbon composites reduces the environmental impact and cost of material production. This approach also contributes to the circular economy by recycling waste [4].

Nanocellulose Integration for Mechanical Stability: Nanocellulose acts as a support matrix for MOFs, preventing agglomeration and ensuring the material's structural stability during water treatment. This is particularly beneficial in real-world applications where extended exposure to water might degrade less stable materials [7].

Applications and Environmental Impact

Nanocellulose-based magnetic MOFs offer several advantages in environmental remediation:

Sustainability: As both nanocellulose and MOFs can be derived from natural or recycled materials, they offer a green solution for water treatment. Nanocellulose, in particular, is biodegradable, ensuring that the material does not contribute to secondary pollution.

Scalability: Recent studies have shown that the synthesis of nanocellulose-based MOFs can be scaled up for industrial applications, offering potential for large-scale water treatment plants and environmental clean-up operations.

Broad-Spectrum Pollutant Removal: While the primary focus has been on antibiotic removal, nanocellulose-based magnetic MOFs also show potential for removing heavy metals, dyes, and other organic pollutants. This versatility makes them ideal candidates for comprehensive water treatment solutions [1].

Conclusion

Nanocellulose-based magnetic MOFs have emerged as one of the most promising materials for antibiotic adsorption in water remediation. Their high adsorption capacities, coupled with their ability to be easily recovered and reused, make them a sustainable solution for addressing global water pollution. The advancements made in the synthesis and functionalization of these materials over the past five years demonstrate their potential for scaling up and expanding into broader environmental applications. Future research should continue focusing on optimizing their cost-effectiveness, enhancing their recyclability, and broadening their scope of pollutant removal.

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