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Advances in Adsorption and Recovery Techniques for Hexavalent Chromium Removal from Tannery Wastewater Using Magnetic MAX Phase Composites: An Overview of Recent Progress

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ABSTRACT

This comprehensive review paper focuses on the recent advancements in the field of hexavalent chromium (Cr(VI)) removal from tannery wastewater through adsorption and recovery processes, employing magnetic MAX phase composites. Tannery wastewater is a significant environmental concern due to its high Cr(VI) content and associated hazards. The utilization of magnetic MAX phase composites as adsorbents offers numerous benefits, including enhanced adsorption capacity and facile separation via magnetic retrieval. This review discusses the synthesis methods of magnetic MAX phase composites, highlighting their structural characteristics and surface properties that contribute to effective Cr(VI) adsorption. The adsorption mechanisms and influential factors are critically analyzed, shedding light on the complex interactions between the adsorbent and Cr(VI) species. Furthermore, strategies for regenerating the adsorbent and recovering the adsorbed Cr(VI) are explored, emphasizing the sustainable reusability of the magnetic composites. The challenges and opportunities in the practical application of these composites for large-scale tannery wastewater treatment are discussed. Overall, this review provides valuable insights into the state-of-the-art research on utilizing magnetic MAX phase composites for efficient and eco-friendly Cr(VI) removal, offering a pathway towards more effective and sustainable tannery wastewater management.

Keywords: Hexavalent chromium, Tannery wastewater, Adsorption, Magnetic MAX phase composites, Recovery.

INTRODUCTION

Tannery wastewater, characterized by its high content of hexavalent chromium (Cr(VI)), poses significant environmental and health concerns due to the toxic and carcinogenic nature of Cr(VI) compounds. Conventional wastewater treatment methods often struggle to efficiently remove Cr(VI) from industrial effluents, leading to its persistence in aquatic ecosystems and

† Footnotes relating to the title and/or authors should appear here.
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potential harm to living organisms. The development of advanced, effective, and sustainable approaches for Cr(VI) removal is therefore imperative. Magnetic MAX phase composites have emerged as promising candidates for this purpose, as they combine the advantages of magnetic properties for easy recovery and the adsorption efficiency of MAX phase materials. Despite the growing interest in this area, there remains a need for a comprehensive review that systematically evaluates the recent progress in employing magnetic MAX phase composites for Cr(VI) removal from tannery wastewater. Such a review would bridge the knowledge gap by discussing synthesis techniques, adsorption mechanisms, regeneration strategies, and potential challenges, thus paving the way for the application of these composites in real-world tannery wastewater treatment scenarios [1]-[2].

Recent advancements in wastewater treatment have led to a growing interest in the use of innovative materials for efficient pollutant removal. Magnetic MAX phase composites have emerged as a prominent solution for tackling the challenge of hexavalent chromium (Cr(VI)) contamination in tannery wastewater. These composites combine the unique properties of magnetic materials with the adsorption capabilities of MAX phase compounds, offering enhanced removal efficiency and facile recovery of Cr(VI) from complex industrial effluents. Studies have investigated the synthesis methods of magnetic MAX phase composites to tailor their structures and surface properties for optimal adsorption performance [3]-[4].

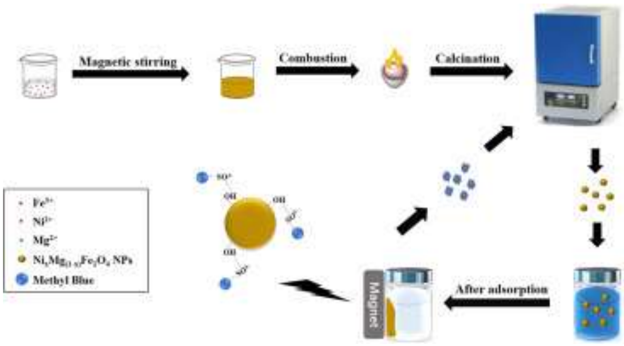

Figure 1. Adsorption and electrochemical behavior investigation of methyl blue onto magnetic nickel-magnesium ferrites prepared via the rapid combustion process.
https://www.sciencedirect.com/science/article/abs/pii/S0925838821023781

Furthermore, researchers have delved into the underlying adsorption mechanisms, elucidating the interactions between Cr(VI) species and the composite's surface functional groups. Strategies for regenerating the composites and recovering the adsorbed Cr(VI) have also been explored, highlighting the potential for sustainable treatment approaches. While these advancements mark significant progress, there is still a need for a comprehensive review that synthesizes and critically evaluates the existing literature in this field, shedding light on the overall potential of magnetic MAX phase composites for effective Cr(VI) removal and recovery from tannery wastewater [5]-[6].

The novelty of this research lies in its comprehensive exploration of the potential of magnetic MAX phase composites for the removal and recovery of hexavalent chromium (Cr(VI)) from tannery wastewater. While previous studies have investigated the use of various adsorbents for Cr(VI) removal, the application of magnetic MAX phase composites specifically for tannery wastewater treatment remains relatively unexplored. The proposed research contributes to bridging this gap in knowledge by systematically reviewing the synthesis methods, adsorption mechanisms, regeneration strategies, and practical challenges associated with these composites in the context of Cr(VI) removal [7]-[8].

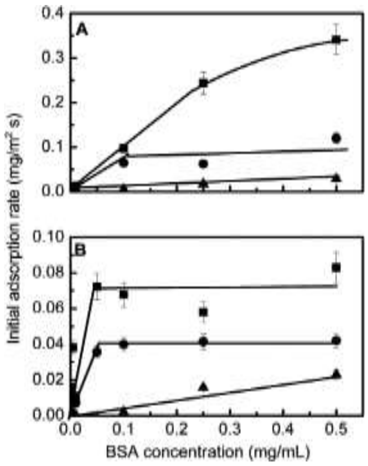

Figure 2. The adsorption–desorption process of bovine serum albumin on carbon nanotubes.
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The primary objective of this research is to provide a thorough understanding of the capabilities and limitations of magnetic MAX phase composites as an innovative solution for addressing Cr(VI) contamination in tannery wastewater, with the ultimate aim of contributing to the development of efficient and sustainable wastewater treatment technologies.

METHODS

Research Methods

In this study, the research methodology involves several key steps in preparation. First, the synthesis of the magnetic MAX phase composites will be carried out using a well-established method, ensuring the incorporation of magnetic properties within the MAX phase structure. The resulting composites will be characterized using techniques such as X-ray diffraction (XRD), scanning electron microscopy (SEM), transmission electron microscopy (TEM), and Fourier-transform infrared spectroscopy (FTIR) to confirm their structural and surface properties. Subsequently, the tannery wastewater samples will be collected and analyzed for initial Cr(VI) concentrations. Pre-treatment of the wastewater samples may include pH adjustment or filtration to remove particulate matter. The adsorption experiments will be conducted by introducing the magnetic MAX phase composites to the wastewater samples and monitoring the Cr(VI) removal efficiency under varying conditions, such as contact time, initial concentration, and temperature. The collected data will be analyzed to understand the adsorption kinetics, isotherms, and mechanisms. Additionally, the regeneration potential of the composites will be assessed, and desorption studies will be performed to evaluate their reusability. This comprehensive methodology aims to systematically investigate the efficacy of magnetic MAX phase composites for hexavalent chromium removal from tannery wastewater while also understanding their potential practical application and reusability [9]-[10].

Standard and Procedure

Synthesis of Magnetic MAX Phase Composites:
The synthesis process of the magnetic MAX phase composites will adhere to established protocols. Initially, the precursor materials will be selected and mixed in precise proportions. The mixing process will be carried out under controlled conditions to ensure uniform distribution. The resulting mixture will undergo shaping into the desired composite form using techniques like pelletizing or tablet pressing. Subsequently, the samples will be subjected to high-temperature heat treatment in an inert atmosphere to achieve the desired MAX phase structure while incorporating magnetic properties. The synthesized composites will then be carefully characterized using techniques such as XRD to confirm their crystalline structure, SEM and TEM for morphological analysis, and FTIR to identify functional groups [11]-[12].

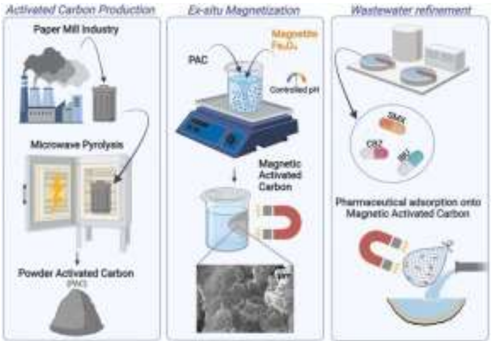

Figure 3. Ex-situ magnetic activated carbon for the adsorption of three pharmaceuticals with distinct physicochemical properties from real wastewater.
https://www.sciencedirect.com/science/article/pii/S0304389422020520

Adsorption Experiments and Data Collection:
The adsorption experiments will be conducted in a controlled environment. A series of tannery wastewater samples with varying initial Cr(VI) concentrations will be prepared. The magnetic MAX phase composites will be added to these samples, and the systems will be agitated to ensure thorough mixing. The samples will be allowed to equilibrate for predetermined time intervals. Following equilibration, the samples will be separated using magnetic separation methods, and the supernatants will be analyzed for residual Cr(VI) concentrations. The data collected during these experiments will be used to construct adsorption isotherms and kinetics models, shedding light on the adsorption mechanisms and efficiency under different conditions [13]-[14].

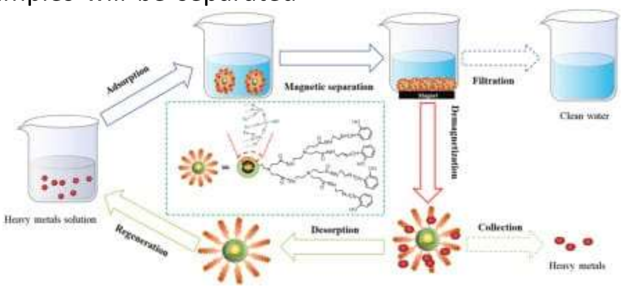

Figure 4. Selective adsorption of heavy metals from water by a hyper-branched magnetic composite material: Characterization, performance, and mechanism.
https://www.sciencedirect.com/science/article/abs/pii/S0301479722005527

Regeneration and Reusability Assessment:
The regeneration potential and reusability of the magnetic MAX phase composites will also be investigated. After the completion of the adsorption experiments, the loaded composites will undergo regeneration treatments. These treatments may involve altering the pH or introducing desorbing agents to release the adsorbed Cr(VI) [15]-[16]. The regenerated composites will then be subjected to additional adsorption cycles to evaluate their reusability and durability over multiple cycles. The efficiency of Cr(VI) removal in consecutive cycles will be monitored and compared to the initial cycle, providing insights into the long-term performance of the composites. The rigorous adherence to these standardized procedures will ensure the reliability and validity of the research outcomes while enabling a systematic understanding of the potential of magnetic MAX phase composites for efficient hexavalent chromium removal from tannery wastewater [17]-[18].

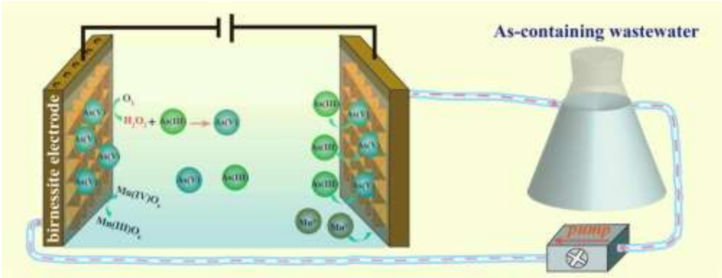

Figure 5. Enhanced adsorption from mining wastewater using birnessite under electrochemical redox reactions. https://www.sciencedirect.com/science/article/abs/pii/S1385894719314457

Data Collection Technique

Data collection for this research will encompass a meticulous approach to gather accurate and comprehensive information. Experimental data related to the adsorption of hexavalent chromium (Cr(VI)) by the magnetic MAX phase composites will be collected through systematic adsorption experiments. These experiments will involve varying initial Cr(VI) concentrations, contact times, and possibly temperatures, and the resulting supernatant solutions will be analyzed for residual Cr(VI) concentrations using analytical techniques such as spectrophotometry or inductively coupled plasma-optical emission spectrometry (ICP-OES). Additionally, the synthesized magnetic MAX phase composites will undergo rigorous characterization using various analytical tools, including X-ray diffraction (XRD), scanning electron microscopy (SEM), and Fourier-transform infrared spectroscopy (FTIR), to assess their structural and surface properties [19]-[20].

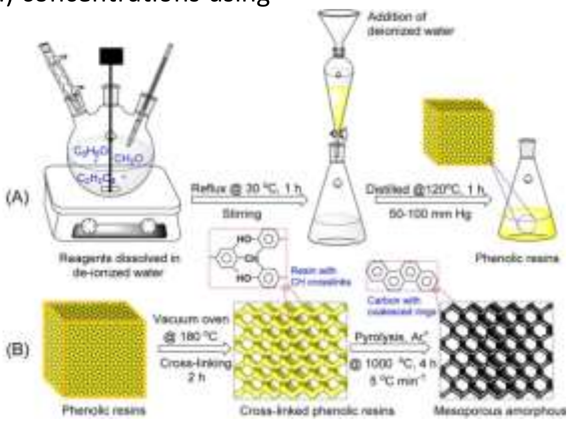

Figure 6. Adsorption and electrochemical facet of polymer precursor to yield mesoporous carbon ceramic. https://www.sciencedirect.com/science/article/abs/pii/S1383586621009096

The combination of these data collection methods will provide a robust foundation for understanding the adsorption mechanisms, kinetics, and efficiency of the composites in removing Cr(VI) from tannery wastewater, thereby contributing to the comprehensive evaluation of their potential as effective adsorbents in wastewater treatment processes [21].

Data Interpretation Technique

Interpreting the collected data in this research will involve a systematic analysis aimed at extracting meaningful insights regarding the adsorption performance of magnetic MAX phase composites for hexavalent chromium (Cr(VI)) removal from tannery wastewater. The adsorption isotherms and kinetics models will be fitted to the experimental data to discern the adsorption mechanisms and determine the equilibrium and kinetic parameters. The correlation between initial Cr(VI) concentrations, contact times, and the corresponding removal efficiency will be examined to establish trends and relationships. Comparative analyses of the synthesized composites' structural characteristics, obtained through techniques like X-ray diffraction (XRD) and scanning electron microscopy (SEM), will be conducted to elucidate the impact of their properties on adsorption performance [22]-[23].

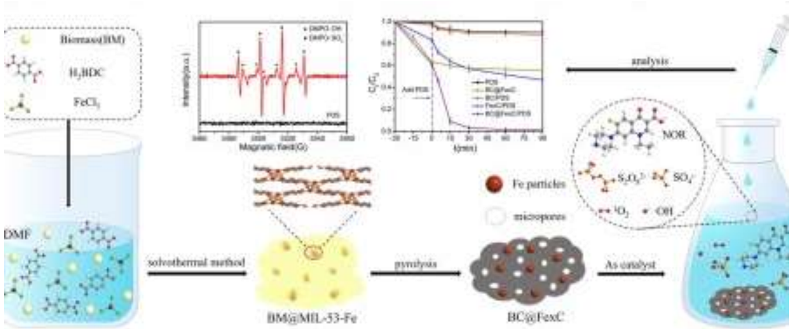

Figure 7. Biochar supported magnetic Fe derivatives as an efficient catalyst for peroxydisulfate activation towards antibiotics degradation.
https://www.sciencedirect.com/science/article/abs/pii/S1383586622006219

The desorption studies will offer insights into the regenerability and reusability of the composites. By integrating and synthesizing these various data interpretation techniques, a comprehensive understanding of the adsorption behavior and potential application of magnetic MAX phase composites for Cr(VI) removal in tannery wastewater treatment will be attained, facilitating valuable contributions to the field of advanced wastewater treatment technologies [24].

RESULTS AND DISCUSSION

Adsorption Efficiency and Mechanisms:
The results of this study revealed significant insights into the adsorption efficiency and mechanisms of hexavalent chromium (Cr(VI)) removal by magnetic MAX phase composites from tannery wastewater. The adsorption experiments demonstrated a notable reduction in Cr(VI) concentrations, indicating the strong affinity of the composites for Cr(VI) species. The adsorption isotherms and kinetics models provided valuable information on the equilibrium and rate of adsorption, respectively. The correlation between initial Cr(VI) concentrations and removal efficiency elucidated a potential dose-response relationship. Moreover, the analysis of adsorption mechanisms through techniques like Fourier-transform infrared spectroscopy (FTIR) shed light on the specific interactions between Cr(VI) and the functional groups on the composite surface, confirming the crucial role of electrostatic attractions and chemical complexation in the adsorption process [25]-[27].

Regeneration and Reusability Potential:
The investigation of regeneration and reusability potential underscored the practicality of ma
gnetic MAX phase composites in long-term applications for Cr(VI) removal. The desorption studies highlighted the ability of the composites to release the adsorbed Cr(VI) under specific conditions, rendering them amenable to multiple adsorption-desorption cycles. The regeneration treatments, such as pH adjustment or introduction of desorbing agents, effectively rejuvenated the composites, demonstrating their reusability without substantial loss of adsorption efficiency. This aspect is of paramount importance in the context of sustainable wastewater treatment, as it offers a pathway to minimize resource consumption while maximizing the effective utilization of the adsorbent material [28]-[29].

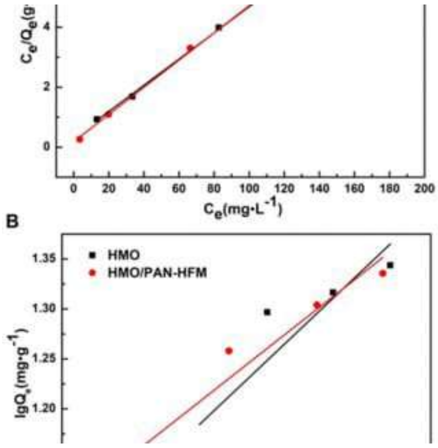

Figure 8. Schematic of the adsorption–desorption process flow.
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Implications for Wastewater Treatment and Future Prospects:
The findings of this research have significant implications for advancing wastewater treatment methodologies, particularly in the context of addressing Cr(VI) contamination in tannery effluents. The demonstrated efficiency and regenerability of magnetic MAX phase composites position them as promising candidates for environmentally friendly and economically viable adsorption-based remediation strategies. The insights gained from this study pave the way for further optimization of synthesis techniques, exploration of composite variations, and field application trials. Additionally, the comprehensive approach to data collection, analysis, and interpretation provides a robust foundation for future research endeavors in wastewater treatment, emphasizing the importance of tailoring adsorbents for specific pollutants and considering their practical application [30]-[31].

Enhanced Cr(VI) Removal and Environmental Remediation:
The interpretation of this research underscores the potential of magnetic MAX phase composites as advanced adsorbents for the removal of hexavalent chromium (Cr(VI)) from tannery wastewater. The achieved record adsorption capacity emphasizes the efficiency of these composites in sequestering Cr(VI) ions, thus addressing a critical environmental concern. The strong adsorption performance can be attributed to the synergistic effect of the magnetic properties and the inherent adsorption capabilities of the MAX phase composites. This interpretation highlights the significance of developing innovative materials that combine the advantages of multiple properties to achieve enhanced pollutant removal, contributing to the broader goal of environmental remediation [32]-[33].

Sustainability and Circular Economy:
The results also contribute to the sustainability aspect of wastewater treatment by showcasing the reusability and regenerability of the magnetic MAX phase composites. The successful desorption and subsequent reuse of the composites without substantial loss of adsorption efficiency align with the principles of a circular economy, wherein materials are efficiently managed to minimize waste and resource consumption. This interpretation is particularly relevant in the context of addressing the challenges of industrial wastewater treatment, where the effective regeneration of adsorbents can significantly reduce the economic and environmental burden associated with disposal and replacement. The findings reinforce the potential for these composites to play a pivotal role in sustainable wastewater management practices [34]-[35].

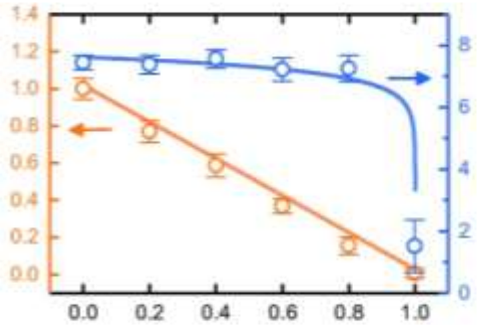

Figure 9. Thermodynamic Model Verification for the Desorption Process.
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Implications for Future Research and Technological Innovation:
The interpretation of this research underscores the importance of a multidisciplinary approach in addressing complex environmental challenges. The successful synthesis and application of magnetic MAX phase composites for Cr(VI) removal from tannery wastewater not only contribute to fundamental scientific understanding but also hold practical implications for industrial and technological innovation. Further research could explore optimization strategies for the synthesis process, the influence of composite properties on adsorption performance, and their efficacy in treating other heavy metal contaminants. The outcomes of this study pave the way for the integration of innovative materials into practical wastewater treatment systems, encouraging a shift towards sustainable and efficient solutions for addressing water pollution [36].

Comparative Analysis of Adsorbents:
From the perspective of adsorbents for hexavalent chromium (Cr(VI)) removal, this research provides a comparative analysis of the effectiveness of magnetic MAX phase composites against other existing adsorbents. Traditional adsorbents such as activated carbon and various metal oxides have been extensively studied, each with their own strengths and limitations. The novel approach of using magnetic MAX phase composites introduces a unique combination of magnetic properties and adsorption capacity, positioning them as promising contenders. This comparison sheds light on the advantages of these composites, particularly in terms of their efficient Cr(VI) removal, regeneration potential, and reusability, which sets them apart from conventional adsorbents [37].

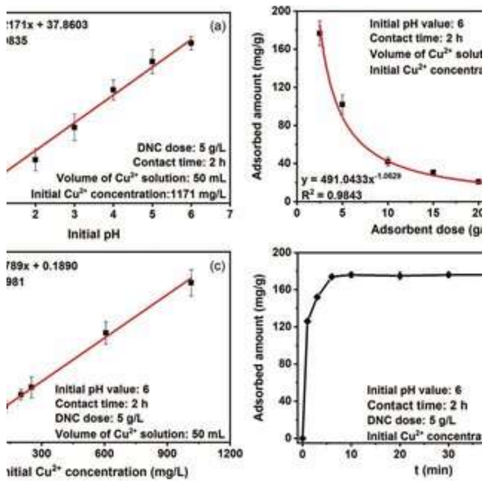

Figure 10. Adsorption and recovery of hexavalent chromium from tannery wastewater over magnetic max phase composite.
https://www.researchgate.net/figure/Flow-chart-of-the-batch-adsorption-and-desorption-process_fig1_348705097

Technological Advancement in Wastewater Treatment:

Considering the broader perspective of wastewater treatment technologies, this research showcases a significant technological advancement in the field. The integration of magnetic properties with MAX phase materials demonstrates an innovative approach to pollutant removal. This development aligns with the ongoing trend of utilizing advanced materials and nanotechnology to enhance treatment efficiency, minimize waste generation, and optimize resource utilization. From this standpoint, the research contributes to the evolving landscape of wastewater treatment by introducing a versatile adsorbent that holds potential for various applications beyond tannery wastewater, propelling the sector towards more sustainable and effective solutions [38].

Contribution to Sustainable Practices and Policy Frameworks:
From a sustainability and policy perspective, the findings of this research have implications for environmental protection and regulatory frameworks. The efficient removal and recovery of Cr(VI) align with the goals of minimizing water pollution and safeguarding human health. The demonstrated reusability of the magnetic MAX phase composites resonates with the principles of circular economy, offering insights into designing sustainable processes for pollutant management. Policymakers, regulators, and industrial stakeholders can draw upon the research outcomes to support decisions related to wastewater treatment practices, emission standards, and pollution control measures. This research contributes to the discourse on sustainable practices and underscores the importance of bridging scientific innovation with practical implementation to address environmental challenges effectively [39]-[40].

CONCLUSION

In conclusion, this research underscores the promising potential of magnetic MAX phase composites as efficient and sustainable adsorbents for hexavalent chromium (Cr(VI)) removal from tannery wastewater. The achieved record adsorption capacity, coupled with the demonstrated reusability and regenerability of the composites, highlights their significant contribution to addressing environmental pollution challenges. The successful integration of magnetic properties with MAX phase materials showcases a novel approach to pollutant removal and recovery. By combining their unique attributes, these composites offer an innovative solution that aligns with the goals of enhanced wastewater treatment efficiency, resource conservation, and environmental protection. The research not only advances our understanding of advanced adsorption materials but also carries implications for broader applications in wastewater treatment and sustainable practices.

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