ROLE OF DIPHENYLAMINE IN THE PREPARATION OF PYROLYSIS OIL–BASED SULFONIC CATION EXCHANGER FOR THE SEPARATION OF TOXIC AND HEAVY METALS FROM WASTEWATER

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Relevance. The rapid growth of industrial activities, urbanization, and technological development has led to a significant increase in wastewater generation containing toxic and heavy metal contaminants. Heavy metals such as lead (Pb), cadmium (Cd), copper (Cu), and zinc (Zn) are among the most hazardous pollutants due to their persistence in the environment, non-biodegradable nature, and ability to accumulate in living organisms. Long-term exposure to these metals can cause severe health problems, including

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neurological disorders, kidney damage, and carcinogenic effects. Consequently, the effective removal of heavy metals from wastewater has become one of the most urgent environmental challenges worldwide.Traditional wastewater treatment methods, including chemical precipitation, membrane filtration, and electrochemical techniques, often suffer from limitations such as high operational costs, generation of secondary waste, and limited efficiency at low metal concentrations. In recent years, ion-exchange and adsorption-based technologies have gained increasing attention due to their high selectivity, operational simplicity, and reusability. In particular, sulfonic cation exchangers are widely recognized for their strong affinity toward metal ions and chemical stability under various conditions.The relevance of this study lies in the development of a novel sulfonic cation exchanger based on pyrolysis oil, a waste-derived and carbon-rich material obtained from the thermal decomposition of organic waste. The utilization of pyrolysis oil contributes to waste valorization and supports the principles of green chemistry and circular economy. Furthermore, the incorporation of diphenylamine as a modifying agent plays a critical role in enhancing the structural and functional properties of the cation exchanger. By improving ion-exchange capacity and adsorption performance, this approach offers an environmentally friendly, cost-effective, and sustainable solution for the separation of toxic and heavy metals from wastewater.

The Purpose of the Study. The primary purpose of this study is to investigate the role of diphenylamine in the synthesis of a pyrolysis oil–based sulfonic cation exchanger and to evaluate its effectiveness in the removal of toxic and heavy metal ions from wastewater. The study aims to clarify the influence of diphenylamine on the chemical structure, functional group formation, and physicochemical properties of the synthesized material.In addition, the research seeks to determine the ion-exchange capacity, adsorption efficiency, and selectivity of the prepared cation exchanger toward common

heavy metal ions, including Pb^{2+}, Cd^{2+}, Cu^{2+}, and Zn^{2+}. Special attention is given to understanding how diphenylamine contributes to the stabilization of the polymeric matrix and enhances the formation of sulfonic acid ($–SO_3H$) functional groups during the sulfonation process.Another important objective of the study is to assess the potential of using pyrolysis oil as an alternative raw material for the production of functional ion-exchange materials. By combining waste-derived resources with chemical modification, the research aims to propose a sustainable strategy for wastewater treatment that reduces environmental impact while maintaining high efficiency. Overall, the study seeks to provide scientific justification for the application of diphenylamine-modified sulfonic cation exchangers in advanced wastewater purification technologies.

Research Materials and Methods. Pyrolysis oil obtained from the thermal decomposition of organic waste materials was used as the primary raw material for the synthesis of the sulfonic cation exchanger. Diphenylamine was selected as a functional modifier due to its aromatic structure and ability to influence polymerization and sulfonation processes. All chemical reagents used in the study were of analytical grade.

The synthesis process involved the controlled polymerization of pyrolysis oil components followed by sulfonation using a suitable sulfonating agent. Diphenylamine was introduced during the synthesis to modify the polymeric structure and enhance the stability of the resulting material. The reaction conditions, including temperature, reaction time, and reagent concentration, were carefully controlled to ensure reproducibility.The obtained sulfonic cation exchanger was washed, dried, and characterized using physicochemical analysis methods. Ion-exchange capacity was determined by standard titration techniques. Thermal stability and structural integrity were evaluated using appropriate analytical methods. Batch adsorption experiments were conducted to investigate the removal efficiency of heavy metal ions from

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aqueous solutions. Metal ion concentrations before and after treatment were measured to calculate adsorption capacity and removal efficiency.

Results and Discussion. The experimental results demonstrated that the incorporation of diphenylamine had a significant impact on the structural and functional properties of the synthesized sulfonic cation exchanger. The presence of diphenylamine promoted the formation of a more stable polymeric network and facilitated the introduction of sulfonic acid functional groups, which are responsible for ion-exchange activity.Ion-exchange capacity measurements revealed that the diphenylamine-modified material exhibited higher capacity compared to samples synthesized without diphenylamine. Adsorption experiments showed efficient removal of Pb^{2+}, Cd^{2+}, Cu^{2+}, and Zn^{2+} ions from aqueous solutions. Among the tested metals, the highest affinity was observed for lead and cadmium ions, which can be attributed to their ionic radius and charge density.The results confirm that diphenylamine plays a crucial role in enhancing adsorption efficiency, selectivity, and stability of the cation exchanger. The use of pyrolysis oil as a precursor further demonstrates the feasibility of producing high-performance materials from waste-derived resources. These findings highlight the potential application of the developed material in industrial and environmental wastewater treatment systems.

Conclusion. This study demonstrates that diphenylamine is a key component in the preparation of pyrolysis oil–based sulfonic cation exchangers for wastewater treatment applications. The incorporation of diphenylamine significantly improves the physicochemical properties, ion-exchange capacity, and adsorption efficiency of the synthesized material.The developed cation exchanger showed high effectiveness in removing toxic and heavy metal ions from aqueous solutions, confirming its potential for practical application in wastewater purification. The use of pyrolysis oil as a raw material contributes to sustainable waste management and supports environmentally friendly technological approaches.Overall, the results indicate that diphenylamine-

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modified sulfonic cation exchangers represent a promising, cost-effective, and sustainable solution for the separation of heavy metals from wastewater, and they may serve as a basis for further research and industrial-scale applications.

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