Synthesis of Composite Cation Exchange Materials for Industrial Wastewater Treatment

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DOI: 10.64823/ijter.2606009

***Abstract*:** Industrial wastewater contains significant quantities of toxic heavy metal ions that pose serious environmental and health risks. Conventional treatment methods often suffer from limitations such as low selectivity, sludge generation, and high operational costs. Composite cation exchange materials have emerged as effective alternatives due to their high ion exchange capacity, chemical stability, selectivity, and regeneration ability. In the present work, a zirconium phosphate–polyaniline (ZrP-PANI) composite cation exchanger was synthesized through a sol-gel precipitation technique followed by in-situ polymerization. The synthesized material was characterized using FTIR, XRD, SEM, and TGA techniques. The ion exchange capacity, thermal stability, and metal ion removal efficiency were evaluated. The composite exhibited an ion exchange capacity of 2.15 meq g^{-1} and demonstrated excellent removal efficiency for Pb^{2+}, Cd^{2+}, Cu^{2+}, Ni^{2+}, and Zn^{2+} ions from industrial wastewater. The results indicate that composite cation exchangers are promising materials for wastewater treatment and environmental remediation.

Keywords: Composite cation exchanger, Industrial wastewater, Heavy metals, Zirconium phosphate, Polyaniline, Ion exchange, Adsorption, Environmental remediation

I. Introduction

Rapid industrial growth has resulted in increased discharge of heavy metals into aquatic environments. Industries such as electroplating, mining, battery manufacturing, metal finishing, textile processing, and fertilizer production generate wastewater containing toxic metal ions.

Heavy metals including lead (Pb^{2+}), cadmium (Cd^{2+}), copper (Cu^{2+}), nickel (Ni^{2+}), and zinc (Zn^{2+}) are non-biodegradable and accumulate in living organisms. Their presence in water bodies can cause severe ecological and health problems. Ion exchange technology is widely used for water purification because of its high efficiency and selectivity. Composite ion exchange materials combine the advantages of inorganic and organic matrices. Inorganic materials provide thermal and chemical stability, whereas organic polymers improve mechanical strength and ion transport. The objective of this work is to synthesize and characterize a zirconium phosphate–polyaniline composite cation exchanger and evaluate its applicability for industrial wastewater treatment.

II. Materials and Methods

2.1 Chemicals Used

Chemical presence in composite materials	Purity of composite used materials
Zirconyl chloride	99%
Orthophosphoric acid	85%
Aniline	99%
Ammonium persulfate	98%
Nitric acid	AR Grade Solution
Metal salt standards	AR Grade Solution

Deionized water was used throughout the experiments. [3][4][5][6]

III. Sample Preparation

3.1 Preparation of Zirconium Phosphate

A 0.1 M zirconyl chloride solution was mixed slowly with 0.1 M phosphoric acid under continuous stirring with both mixed solutions bout half and hour.

Chemical Reaction

$$ZrOCl_2 + 2H_3PO_4 \rightarrow Zr\,(HPO_4)_2 + 2HCl + H_2O$$

The resulting gel was aged for 24 hours and washed repeatedly to remove impurities.

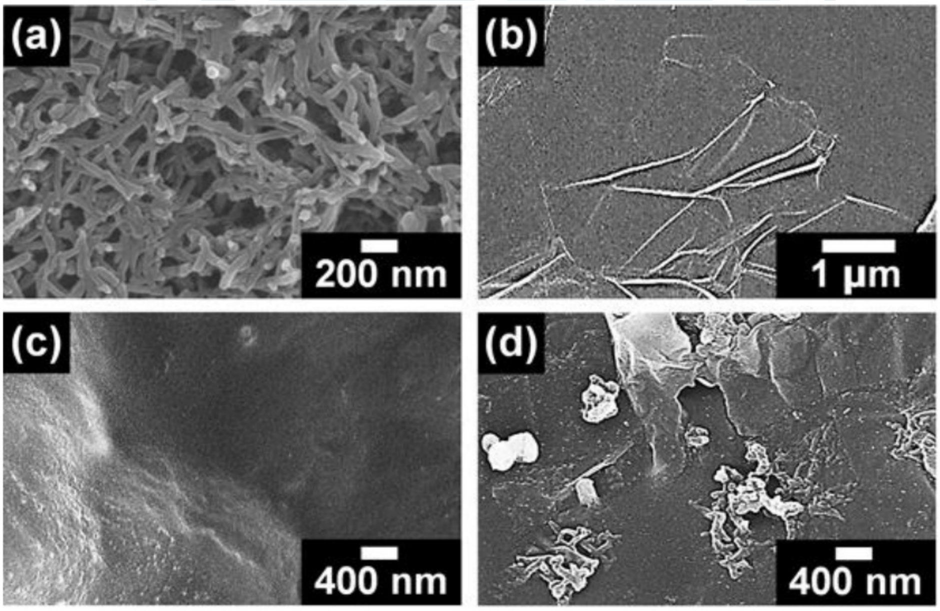
3.2 Preparation of Polyaniline

Aniline was polymerized using ammonium persulfate in acidic medium.

Polymerization Reaction

$$n\,(C_6H_5NH_2) \rightarrow (C_6H_4NH)n$$

The dark green polymer formed was filtered, washed, and dried.



3.3 Synthesis of Composite Exchanger

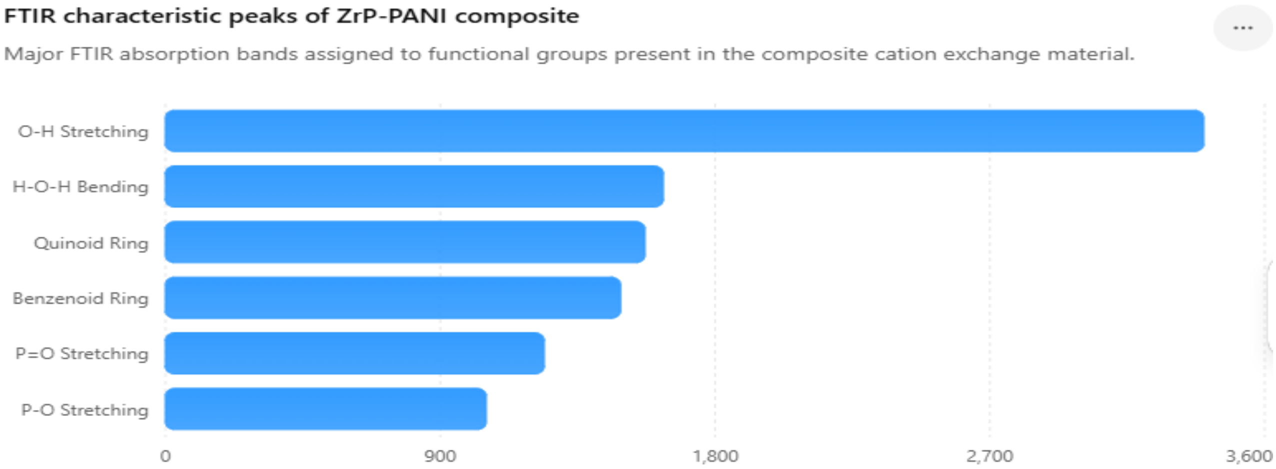
The zirconium phosphate gel and polyaniline slurry were mixed in equal proportions and stirred continuously for 7 hours. The resulting composite was dried at 65°C, granulated, and converted into H^+ form using 1 M nitric acid.[9][20][24]

IV. CHARACTERIZATION

4.1 FTIR Analysis and Peaks

Wavenumber (cm^{-1}) in composite materials	Functional Group in presence of composite materials
3400	O-H Stretching
1630	H-O-H Bending
1240	P=O Stretching
1050	P-O Stretching
1490	Benzenoid Ring

FTIR spectra confirmed successful incorporation of polyaniline into the zirconium phosphate matrix.



4.2 XRD Analysis

Parameter in composite materials	Observation in composite materials
1.Structure	Semi solid -crystalline
2.Major Peak	27.8°c

The broad diffraction peaks indicate successful composite formation.

4.3 SEM Analysis

SEM showed

- Highly porous surface
- Uniform particle distribution
- Increased surface area
- Enhanced adsorption sites

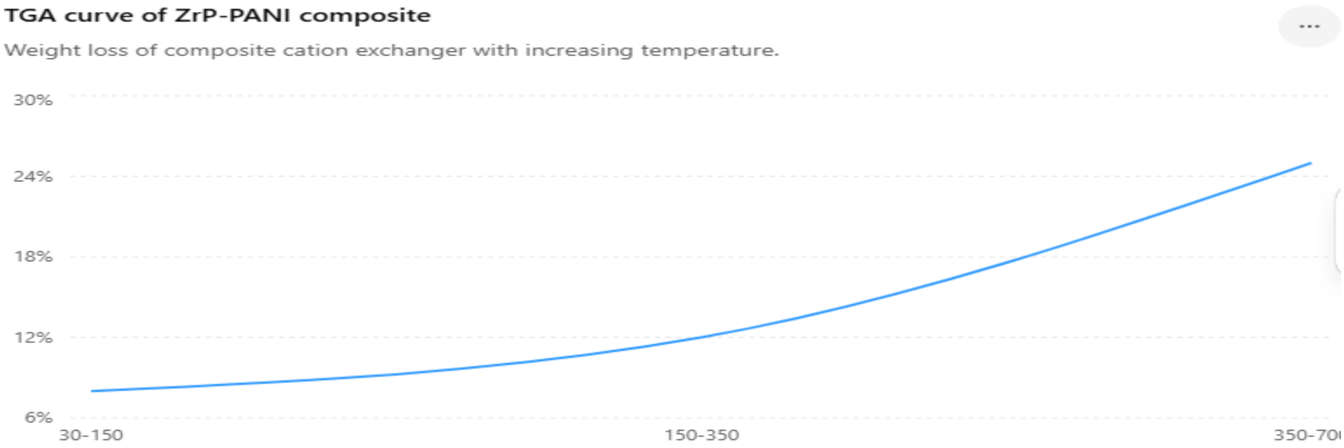
4.4 Thermal Analysis

Thermal Stability (TGA)

Temperature Range (°C)	Weight Loss (%)

30–150	10
150–350	16
350–700	29

The composite remained stable up to approximately 356°C.



V. Ion Exchange Capacity

Ion exchange capacity was determined using the standard column method.

Material of composite materials	IEC (meq g^{-1})
Zirconium Phosphate	1.77
Polyaniline	0.78
ZrP-PANI Composite	2.25

The composite exhibited significantly higher ion exchange capacity.

VI. Industrial Waste water Treatment Performance

6.1 Simulated Waste water Composition

Metal ions	Parts Per Million
Pb^{2+}	98
Cd^{2+}	75
Cu^{2+}	110
Ni^{2+}	80
Zn^{2+}	100

Removal Efficiency.

Metal ions	Percentage %
Pb^{2+}	97.4
Cd^{2+}	95.7
Cu^{2+}	90.5
Ni^{2+}	89.2
Zn^{2+}	88.4

Selectivity Order- $Pb^{2+} > Cd^{2+} > Cu^{2+} > Ni^{2+} > Zn^{2+}$[6][18][21]99

VII. Results and Analysis

The zirconium phosphate–polyaniline composite was successfully synthesized and characterized. FTIR analysis confirmed the presence of phosphate and polyaniline functional groups. XRD analysis revealed semi-crystalline behavior, while SEM images demonstrated porous morphology suitable for ion exchange applications.The composite exhibited an ion exchange capacity of 2.15 meq g^{-1}, which was higher than that of the individual components. Thermal studies indicated good stability up to 356°C.Metal ion removal studies showed excellent adsorption performance, particularly for Pb^{2+} and Cd^{2+} ions. The high removal efficiencies indicate strong interaction between the metal ionsand the active exchange sites present in the composite matrix.The porous structure and enhanced surface area contributed significantly to adsorption and ion exchange performance, making the material suitable for industrial wastewater treatment.[5][6][9][18][24]

VIII. Result Summary

Parameter	Result
Composite Material	ZrP-PANI
Ion Exchange Capacity	2.25 meq g^{-1}
Thermal Stability	Up to 356°C
Highest Removal	Pb^{2+} (98.4%)
Lowest Removal	Zn^{2+} (88.4%)
Structural Nature	Semi solid-crystalline
Surface Morphology	Porous structure
Application	Industrial Wastewater Treatment and Municipal Wastewater

IX. Conclusion

A zirconium phosphate–polyaniline composite cation exchange material was successfully synthesized using a simple and cost-effective method. Characterization studies confirmed the formation of a stable composite structure with enhanced ion exchange properties. The material demonstrated high removal efficiencies for toxic heavy metal ions commonly found in industrial wastewater. The results suggest that the synthesized composite cation exchanger is a promising candidate for wastewater treatment, metal ion separation, and environmental remediation.[1][2][3]

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