Conductive polymer–natural clay nanocomposites for efficient heavy metal removal from aqueous solutions

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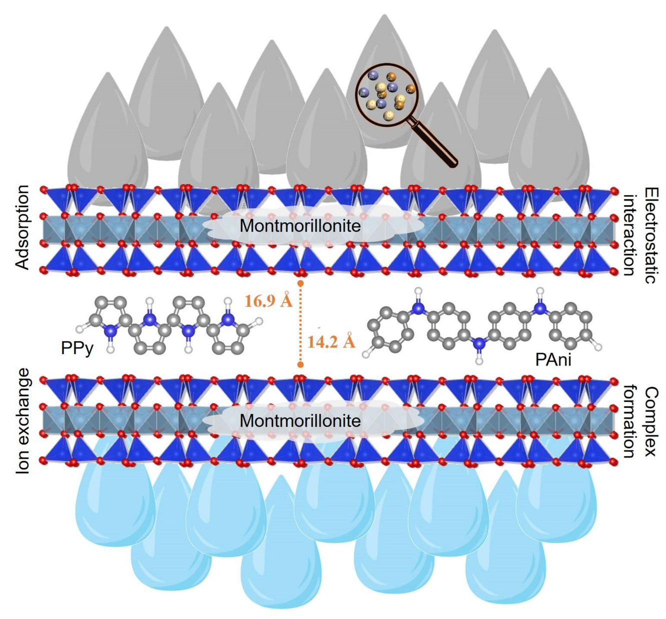
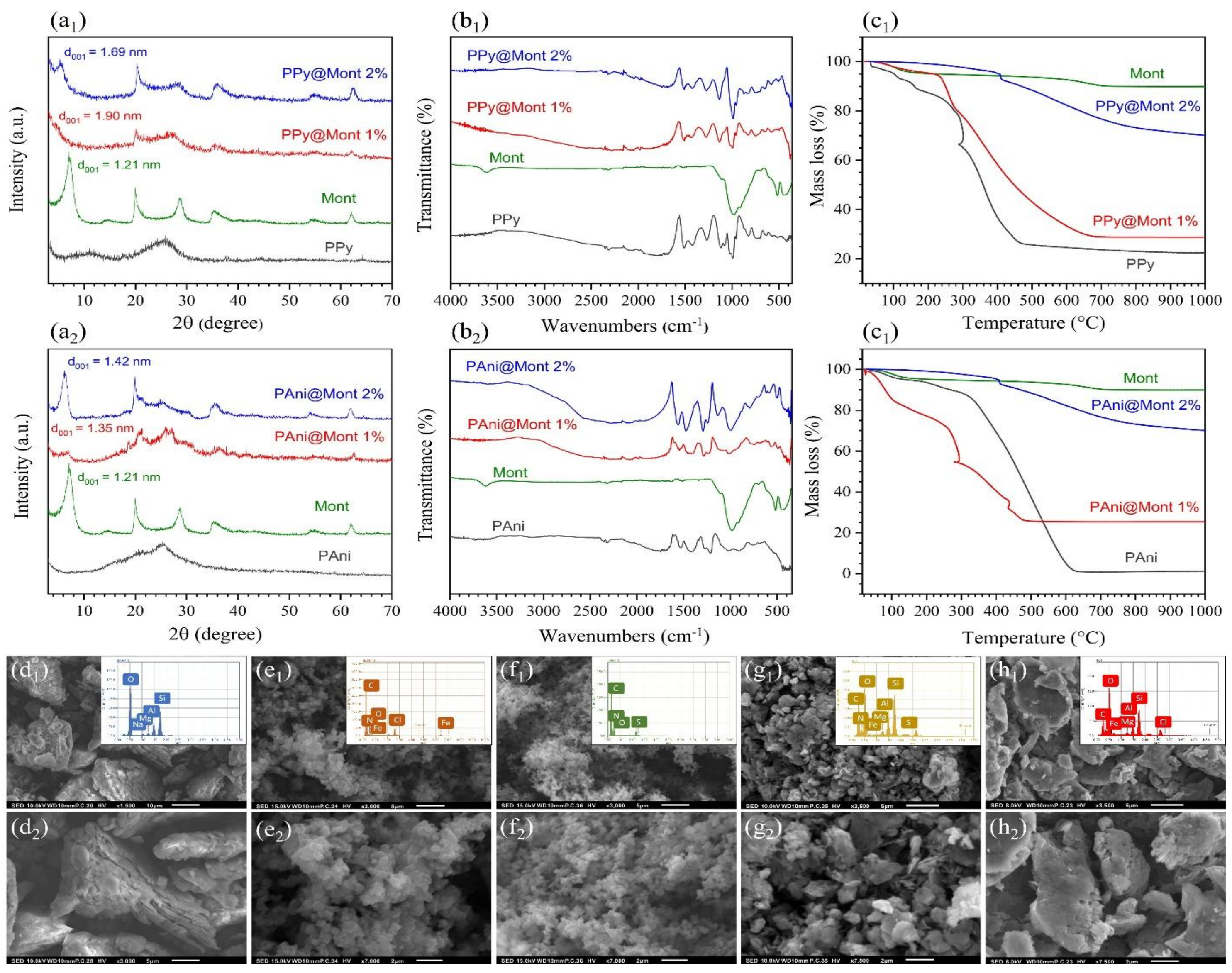


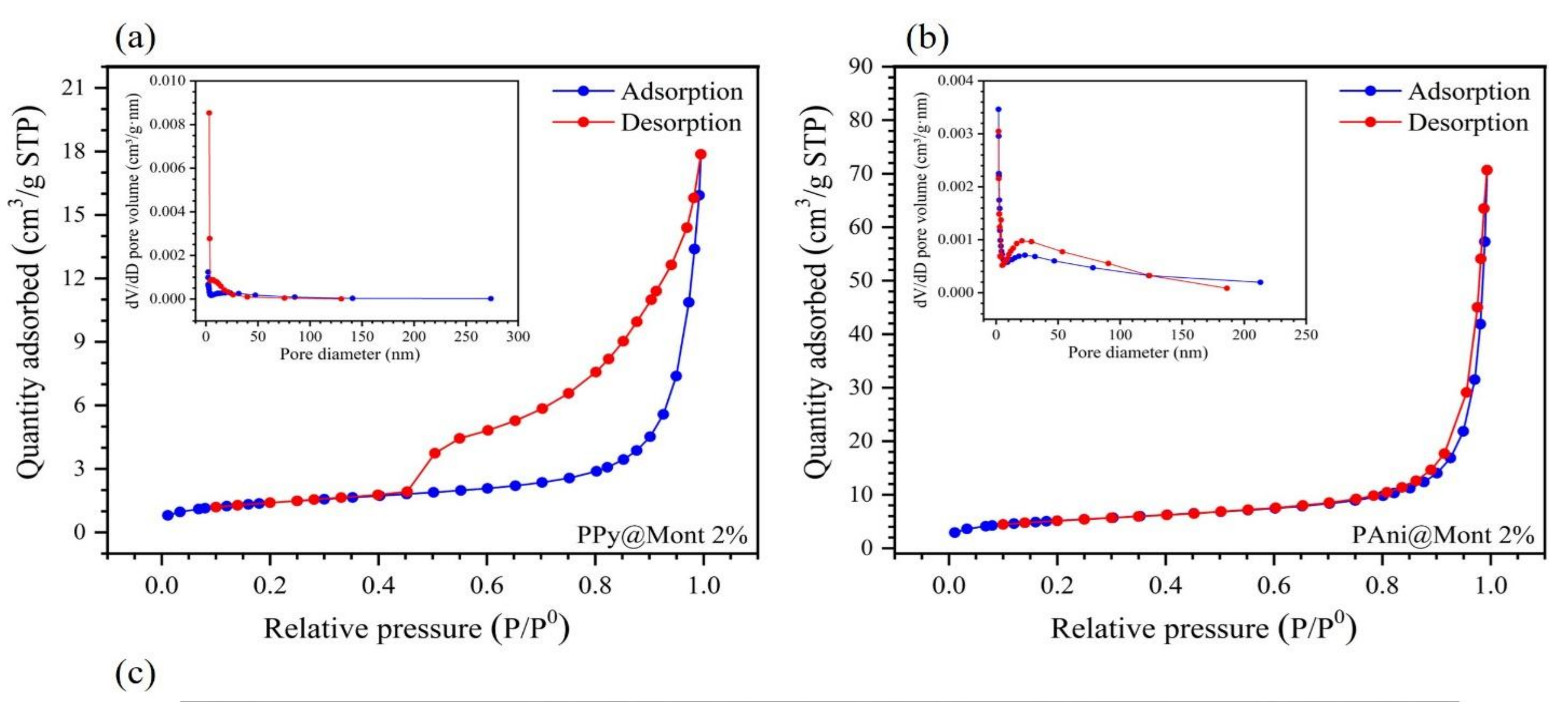
INTRODUCTION

Water contamination is among the most severe environmental concerns worldwide, driven primarily by industrial effluent, agricultural runoff, and inappropriate waste disposal. Among the myriad of pollutants, heavy metals like copper (Cu^{2+}), zinc (Zn^{2+}), and cadmium (Cd^{2+}) are particularly hazardous due to their persistence, bioaccumulative capacity, and widespread ecological and human health effects. As a response to the limitations of conventional treatment methods, noteworthy investigation has been dedicated towards the development of new adsorption technologies using nanomaterials. Out of the numerous nanomaterials that have been considered, conducting polymers (CPs) and clay-based composites were found to be the best contenders for the elimination of heavy metals. CPs like polyaniline (PAni) and polypyrrole (PPy), possess high adsorption capabilities due to their abundant functional groups, like amines and imines, that afford active spots for the adsorption of metal ions. Here, PPy and PAni composite materials intercalated with montmorillonite (PPy@Mont and PAni@Mont) are prepared and assessed for the efficient elimination of the heavy metals Cu^{2+}, Zn^{2+}, and Cd^{2+} from wastewater. By systematically examining the impacts of adsorbent amount, primary heavy metal concentration, and temperature on adsorption capacity (Qe) and percent removal, this investigation aims to explicate the adsorption mechanisms and optimize the performance of these hybrid composites.

STRUCTURAL AND MORPHOLOGICAL CHARACTERIZATION



Structural, thermal, and morphological characterization of bare montmorillonite, PPy, PAni, and their polymer@montmorillonite composites: (a1, a2) XRD patterns, (b1, b2) FTIR spectra, (c1, c2) TGA curves, and SEM–EDX micrographs of (d1, d2) montmorillonite, (e1, e2) PPy, (f1, f2) PAni, (g1, g2) PPy@Mont, and (h1,h2) PAni@Mont.



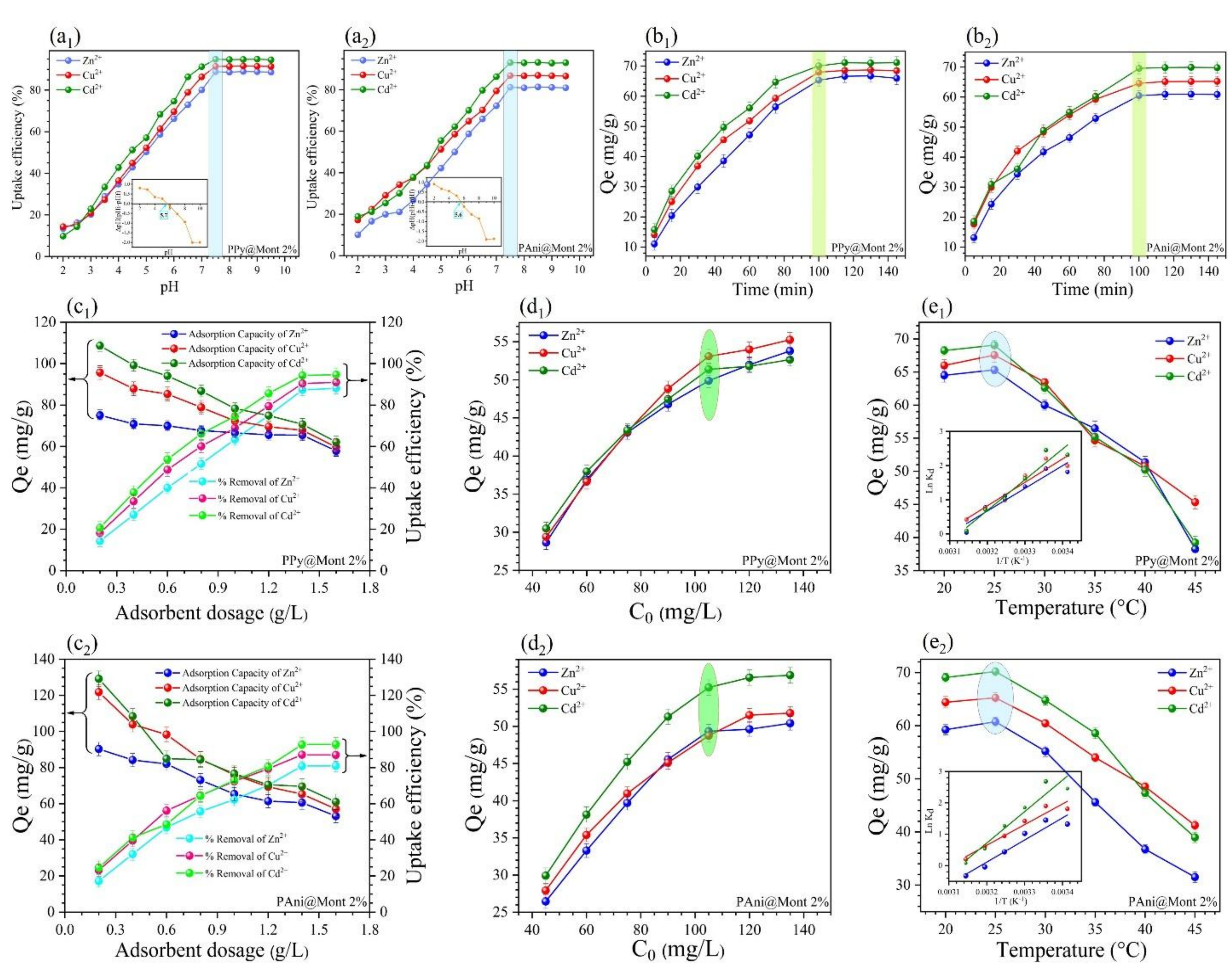
(c)

Material	Montmorillonite	Polypyrrole	Polyaniline	PPy@Mont 2%	PAni@Mont 2%
BET surface area (m^2/g)	81,8531	0,7694	16,4267	4,9112	17,7449
Total pore volume (cm^3/g)	0,110914	0,003199	0,078991	0,023491	0,093435
Average pore diameter (nm)	5,4202	16,6324	19,2347	19,1325	21,0618

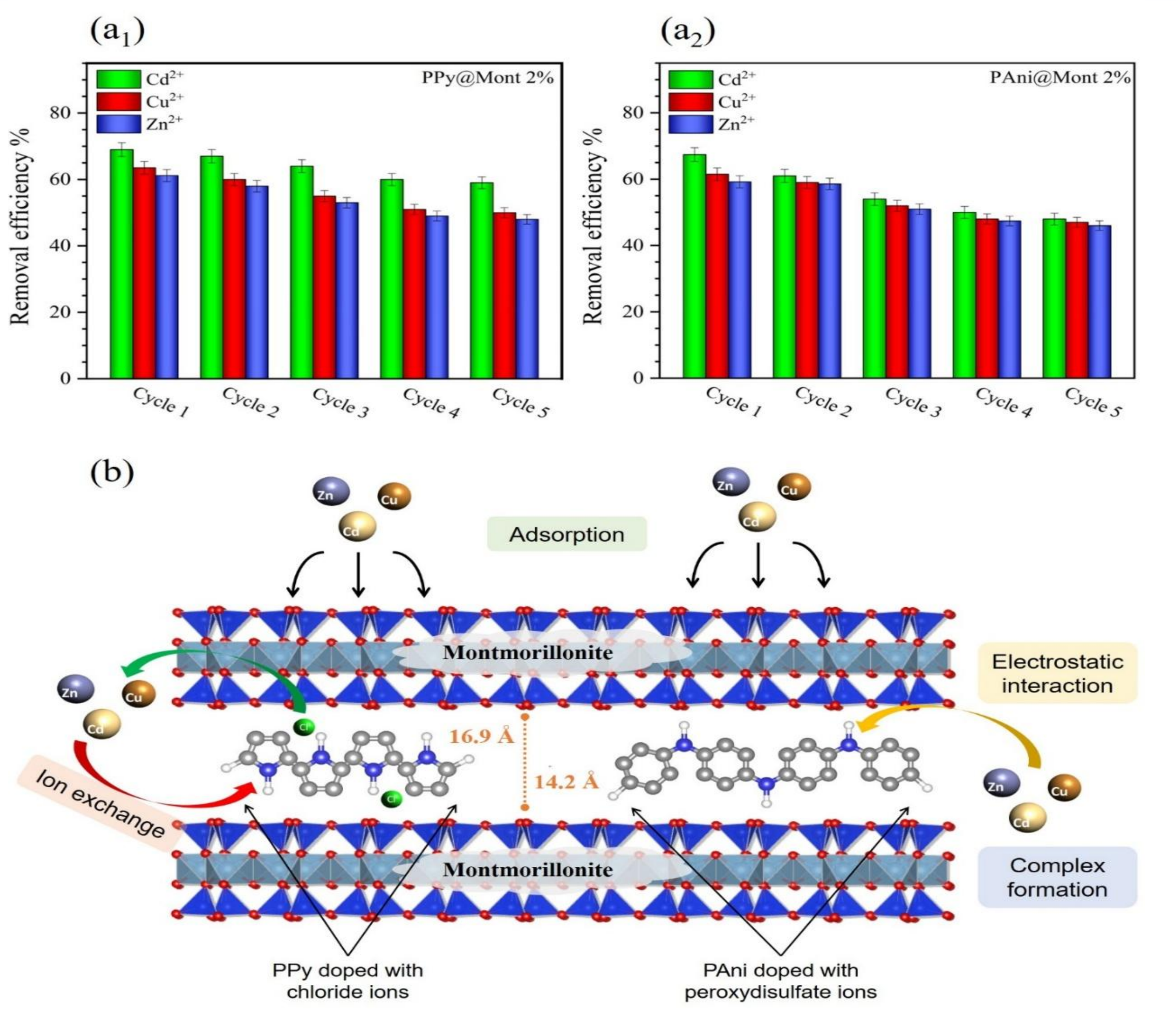
Nitrogen adsorption-desorption isotherms (77 K) and BJH pore-size distribution (inset) of PPy@Mont (a) and PAni@Mont (b). BET surface area, total pore volume, and average pore diameter of pristine Mont, PPy, PAni, and their composites (c).

The composites were prepared via in situ polymerization, yielding materials with advanced physicochemical properties. Characterization through XRD, FTIR, and SEM confirmed the successful composite formation, with uniform dispersion of polymer matrices on the montmorillonite surface.

APPLICATION TO WATER TREATMENT



Adsorption behavior and thermodynamic analysis of Zn^{2+}, Cu^{2+}, and Cd^{2+} on PPy@Mont and PAni@Mont composites: (a1, a2) Effect of pH on the percent removal (%) (Inset: plot showing the point of zero charges), and effect of (b1, b2) contact time, (c1, c2) adsorbent dosage, (d1, d2) preliminary heavy metal concentration, and (e1, e2) temperature on the adsorption capacity (Qe, mg/g) (inset: Van't Hoff plots).



Reusability performance of PPy@Mont and PAni@Mont composites over five adsorption-desorption cycles for Cd^{2+}, Cu^{2+}, and Zn^{2+} ions (a1, a2), and representation of suggested adsorption mechanisms involving electrostatic interaction, ion exchange, and metal-ligand complexation between metal ions and CP@Mont composites.

CONCLUSION

Successful synthesis and examination of PPy@Mont and PAni@Mont composites were conducted in this research and were demonstrated as effective adsorbents for the deletion of Zn^{2+}, Cu^{2+}, and Cd^{2+} in water systems. Structural and morphological validations through the application of XRD, FTIR, SEM-EDX, and TGA confirmed that the intercalation of the conducting polymer into the montmorillonite matrix had boosted the stability and adsorptive capability of the composites. Batch adsorption experiments validated that both PPy@Mont and PAni@Mont exhibited high adsorption capacities, with optimal performance at pH 7.5, an equilibrium contact time of 110 minutes, and a temperature of 25 °C. The adsorption capacities at 25 °C were found to be 57.8 mg/g (Zn^{2+}), 59.9 mg/g (Cu^{2+}), and 55.2 mg/g (Cd^{2+}) for PPy@Mont and 58.5 mg/g (Zn^{2+}), 57.8 mg/g (Cu^{2+}), and 61 mg/g (Cd^{2+}) for PAni@Mont. The slightly higher affinity of PAni@Mont for Cd^{2+} may be attributed to stronger electrostatic and coordination interactions with its nitrogen-rich polymeric structure.