

Supplementary Materials

Synthesis and application of $\text{Fe}_3\text{O}_4\text{--ZrO}_2$ magnetic nanoparticles for fluoride adsorption from water

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Energy-dispersive X-ray spectroscopy (EDS)

Elemental composition of M1, M2, and M3 adsorbents were examined using EDS. The elemental analysis of M1 adsorbent confirmed the presence of Fe, Zr, and O, corresponding to the equimolar binary oxide formulation (Figure S1). The relative intensities of Fe and Zr are consistent with the 1:1 molar ratio. For M2 the increased intensity of the Zr peak compared to Fe reflects the higher zirconia content in the 1:2 formulation (Figure S2). In the case of M3 adsorbent, the dominant Zr signal and reduced Fe content are in agreement with the 1:4 Fe:Zr molar ratio, confirming the progressive zirconia enrichment (Figure S3).

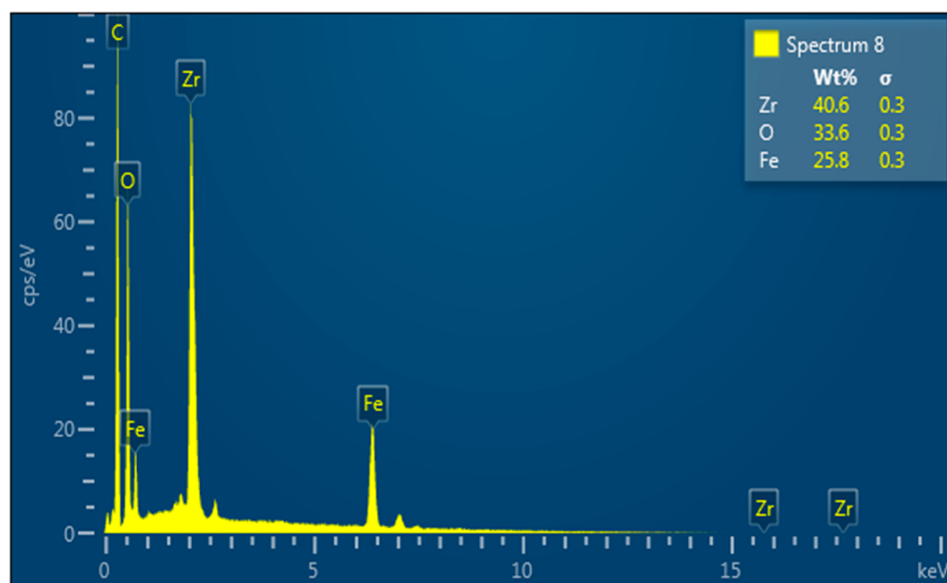


Figure S1. EDS spectrum of composite M1 ($\text{Fe}_3\text{O}_4\text{:ZrO}_2 = 1\text{:}1$)

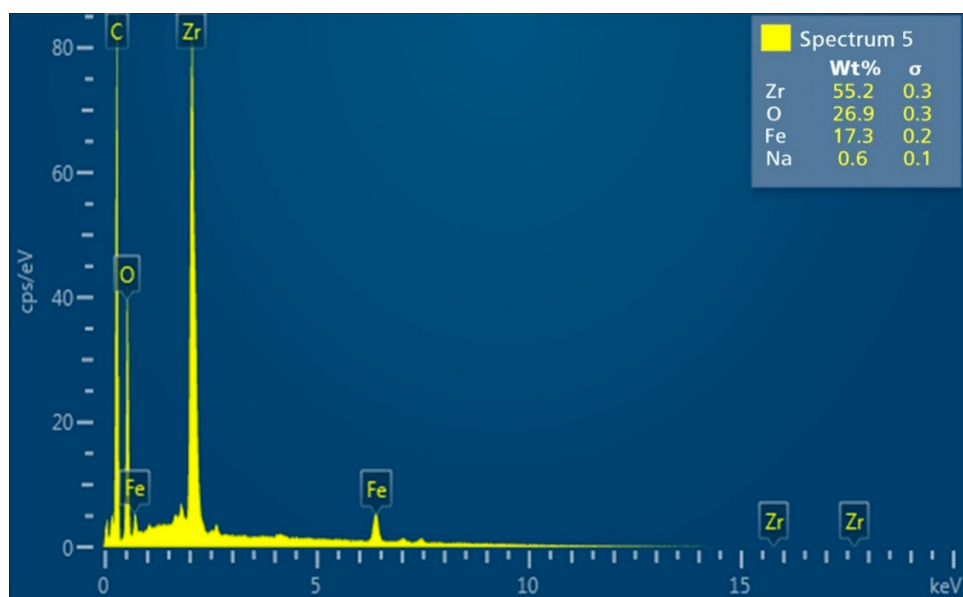


Figure S2. EDS spectrum of composite M2 ($\text{Fe}_3\text{O}_4:\text{ZrO}_2 = 1:2$)

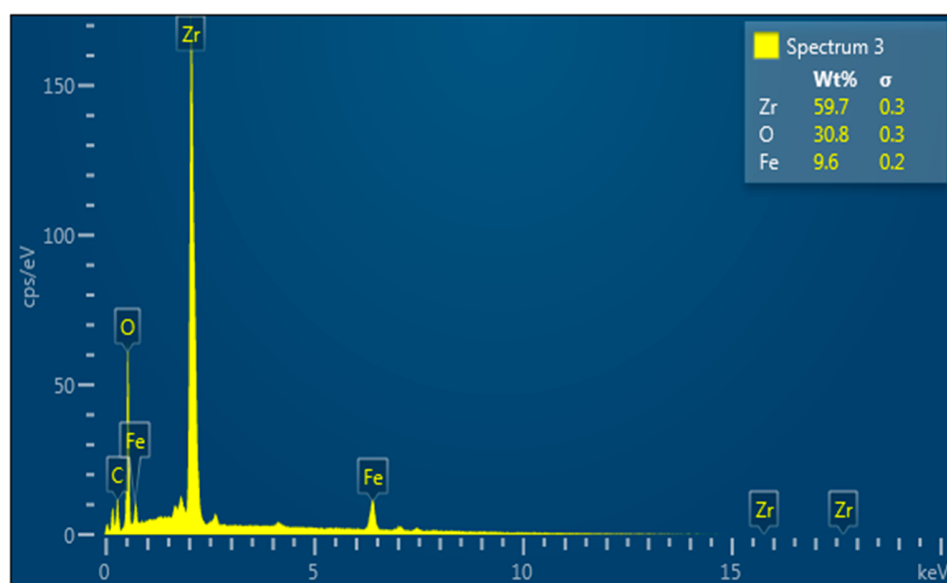


Figure S3. EDS spectrum of composite M3 ($\text{Fe}_3\text{O}_4:\text{ZrO}_2 = 1:4$)

FTIR analysis of M1 adsorbent after ion adsorptions

FTIR spectroscopy was used to confirm the interfering anions' adsorption on the surface of M1 adsorbent. FTIR spectra of the M1 composite before and after ion adsorptions (fluoride, fluoride/phosphate, and fluoride/carbonate) showed no new or distinct bands attributable to F^- ion, which is consistent with the IR-inactive nature of fluoride in this system or its incorporation through weak interactions that are not detectable by FTIR (Figure S4, black and red spectra). The band observed at 1040 cm^{-1} corresponds to the asymmetric stretching vibrations of PO_4^{3-} , indicating successful phosphate binding onto the material's surface (blue spectrum). Additionally, the band near 875 cm^{-1} (out-of-plane bending) confirms the presence of CO_3^{2-} species adsorbed on the surface (green spectrum).

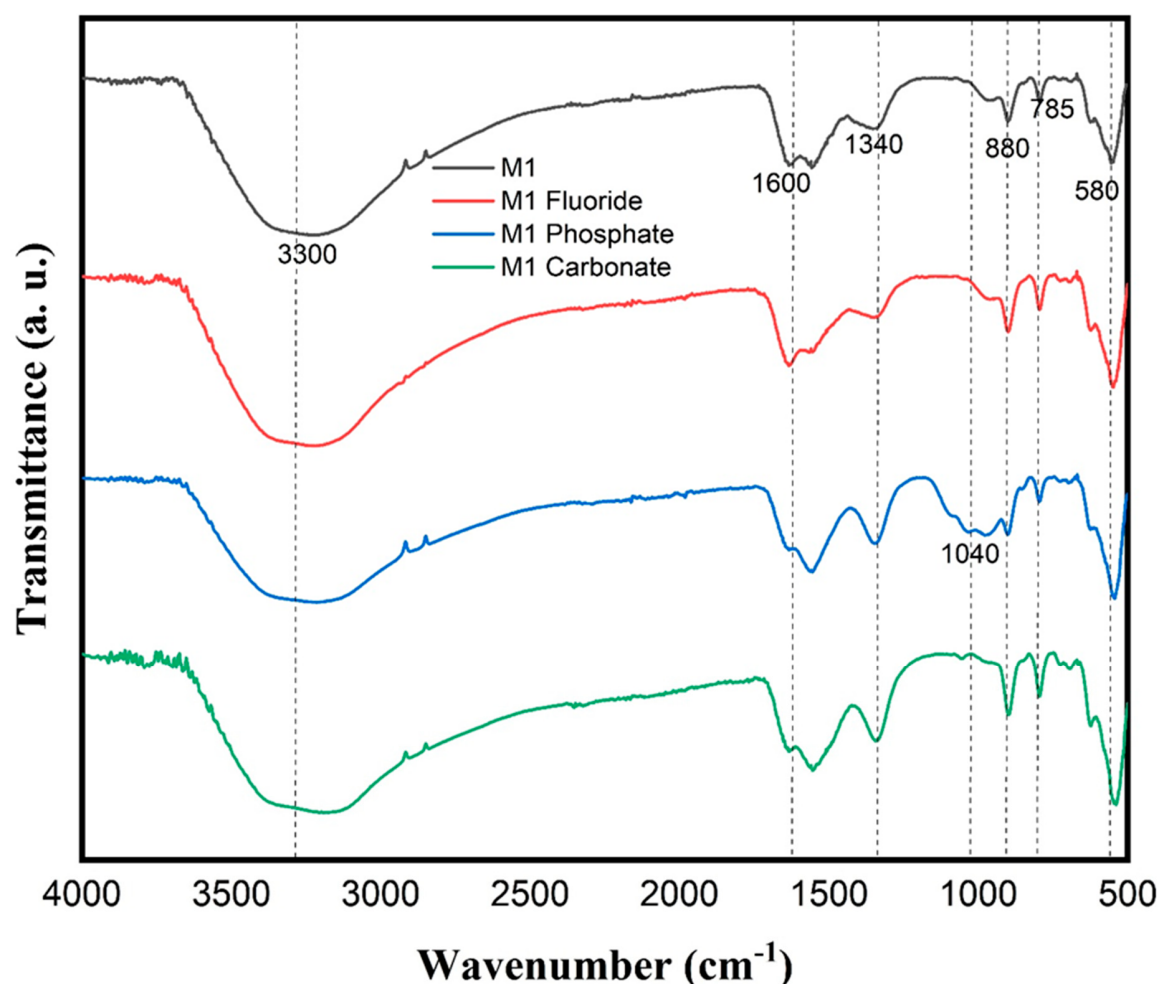


Figure S4. FTIR spectra of the M1 composite before and after ion adsorptions

Reusability of the M1 composite

The reusability of the M1 composite was assessed over four consecutive fluoride adsorption–desorption cycles under identical experimental conditions (initial fluoride concentration = 10 mg/L, adsorbent dose = 50 mg/50 mL, pH = 3, room temperature, 0.5 M NaOH as regenerating dissolution).

Table S1. Adsorption capacity (q_e) and retention percentage of M1 composite over four adsorption–desorption cycles

Cycle	q_e (mg/g)	Retention capacity (%)
1	9.79	100.0
2	4.30	43.9
3	2.40	24.5
4	2.45	25.0