

DOI <https://doi.org/10.30525/978-9934-26-656-0-11>

**A NOVEL MAGNETICALLY RESPONSIVE
FERROCYANIDE/ZIF-8 COMPOSITE
FOR RADIOACTIVE IONS CAPTURE**

**НОВИЙ МАГНІТОЧУТЛИВИЙ КОМПОЗИТ
НА ОСНОВІ ФЕРОЦІАНІДУ/ZIF-8
ДЛЯ ВЛОВЛЮВАННЯ РАДІОАКТИВНИХ ІОНІВ**

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Magnetically responsive sorbents represent one of the most promising classes of materials for water treatment processes. Their advantages include facile and rapid separation, recyclability, and a reduced risk of secondary pollution, which is often associated with the use of conventional powder adsorbents [1, p. 245]. Although bare magnetic nanoparticles possess

the ability to capture certain toxic substances, they tend to agglomerate and oxidize in aqueous media. Consequently, the fabrication of magnetic composites with inorganic or organic coatings is generally required to enhance their physicochemical stability and sorption performance [2, p. 2]. Such materials typically exhibit a “core–shell” architecture, where the magnetic core ensures responsiveness to external magnetic fields, while the shell provides active sorption sites for interaction with aqueous contaminants. Various magnetically responsive materials have been prepared for water pollutant removal: carbon-based sorbents were found to be effective in the elimination of heavy metals [3, p. 22], pesticides [3, p. 25], dyes, organic compounds, and radionuclides [3, p. 29]; magnetic polymers exhibit not only high sorption performance toward dyes and heavy metals, but also efficiency in oil–water separation [4, p. 3]; and magnetic composites with metal-organic frameworks inherit the advantages of both a large surface area and easy recovery in the sorption of a wide range of water contaminants [5, p. 23]. In general, scientific attention and applied interest in magnetic composite materials have been increasing exponentially over recent years [6, p. 66].

In the present study, a novel magnetically responsive material was synthesized via the coordinative immobilization of metal ferrocyanide (FC) structures onto citrate-capped magnetite nanoparticles covered by zeolitic imidazolate framework (ZIF). The resulting FC/Cu_ZIF-8/Fe₃O₄-COOH hybrid combines the unique structural features of metal-organic frameworks (high specific surface area and porosity) with the excellent affinity of ferrocyanides toward metal cations. The porous structure of FC/Cu_ZIF-8/Fe₃O₄-COOH was studied by low-temperature nitrogen adsorption-desorption method. Magnetic composite exhibits a BET surface area (S_{BET}) of 261 m²/g, a micropore area (S_{micro}) and volume (V_{micro}) of 233 m²/g and 0.09 cm³/g, respectively, total pore volume (V_{tot}) of 0.18 cm³/g, and wide pore size distribution. XRD analysis confirmed the successful encapsulation of Fe₃O₄-COOH nanoparticles within the crystalline ZIF-8 lattice and the subsequent formation of the copper FC phase. The diffraction patterns revealed characteristic peaks of magnetite, the SOD-type lattice of ZIF-8, and additional reflections corresponding to mixed metal ferrocyanides. According to the results of XRD analysis, FC/Cu_ZIF-8/Fe₃O₄-COOH hybrid exhibits interconnected cavities (0.46 nm) and channels (0.32 nm) in the crystal structure of FC component, compatible with the size of dehydrated Cs⁺ ions (0.33 nm). Since radionuclides possess the same ionic dimensions as stable cesium ions, synthesized magnetic composite also holds significant potential for the selective capture of radioactive isotopes from aqueous solutions.

The sorption efficiency of FC/Cu_ZIF-8/Fe₃O₄-COOH towards Cs⁺ was investigated in aqueous solutions as a function of solution acidity, contact time, equilibrium adsorbate concentration, and the presence of competing cations. It was found that variations in solution pH from 6 to 9 do not significantly affect the sorptive removal Cs⁺ by FC/Cu_ZIF-8/Fe₃O₄-COOH. Kinetic studies revealed that Cs⁺ removal occurs rapidly, reaching 86 % uptake within the first 10 minutes. The sorption process was found to follow a pseudo-second-order kinetic model, while equilibrium data were best described by the Freundlich isotherm, confirming the interaction of Cs⁺ ions with energetically nonequivalent surface sites of the sorbent and yielding a maximum capacity of 68.6 mg/g. To estimate sorption selectivity of FC/Cu_ZIF-8/Fe₃O₄-COOH toward Cs⁺, competitive studies were carried out from mixed solutions containing excess amounts of coexisting ions (Na⁺, K⁺, or Ca²⁺). The values of Cs⁺ sorption on the magnetically responsive composite and its distribution coefficient reach 54.6 mg/g and 850 mL/g, respectively, and decrease slightly with the increase of coexisting cations concentration in the series Na⁺ < Ca²⁺ < K⁺.

Overall, the synthesized FC/Cu_ZIF-8/Fe₃O₄-COOH composite demonstrates exceptional potential for the selective removal of radioactive cesium, enabled by the precise size-matching between the ferrocyanide lattice and Cs⁺. High distribution coefficients and rapid uptake kinetics, maintained even in the presence of competing ions, confirm the material's structural robustness and chemical affinity. These results highlight a probable pathway for advanced nuclear wastewater remediation, combining high-throughput purification with the benefits of facile magnetic recovery.

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