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Next-Generation Magnetic Biochar–Silica Nanocomposites for REEs and Radionuclide recovery from complex water systems.

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The global transition toward clean energy technologies has sharply increased the demand for critical metals, particularly rare earth elements (REEs) and uranium. But their co-occurrence in ores such as monazite raises concerns regarding environmental contamination, and the sustainable management of metal-bearing wastes. In this context, the development of durable, low-cost, and environmental friendly materials capable of recovering REEs and Radionuclides from secondary and contaminated sources is essential for advancing circular economy–based remediation strategies. In this study, waste-derived magnetic nanocomposites were synthesized. Biochar produced from sewage sludge as a sustainable carbon substrate was used then biochar was functionalized with nanoscale zero-valent iron (nZVI) to impart magnetic separability and enhance metal-binding affinity. then the composite was further enveloped with a protective silica layer to improve chemical stability and reduce iron leaching under acidic conditions. Effective recovery of Ce, La, Nd and U, with adsorption capacities ranging from 90 to 97 mg g^{-1} at pH 5 demonstrated in Batch adsorption experiments. Under more acidic conditions (pH 3) both magnetic composites exhibited selective uranium uptake, achieving a maximum adsorption capacity of approximately 80-110 mg g^{-1} with maintaining strong resistance to iron leaching.

Structural and surface characterization was performed using FTIR, XRD, SEM, and TEM, including elemental mapping of pristine and spent materials that confirmed the formation of a stable, mesoporous, and magnetically separable composite. TEM imaging and elemental mapping clearly showing morphological integrity of the material and successful adsorption of target metals onto the spent adsorbent surface that is indicating effective surface binding mechanisms. Acid stability tests conducted over time intervals ranging from 10 minutes to 24 hours of pristine composites under low-pH conditions. There are no measurable changes found in pH and electrical conductivity (EC) during the experiments, and no detectable metal leaching occurred that is confirming the structural and chemical stability of both materials in acidic environments. Overall, this approach offers a promising pathway for addressing metal pollution, advancing remediation technologies, and supporting circular economy frameworks in water, soil, and nuclear waste management systems.