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Risk management of radionuclide waste from nuclear power plants: Removal techniques and control strategies

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In modern society, the ceaselessly increasing demand for clean energy has spurred the exploration of novel low-carbon technologies. Nuclear power has proven its effectiveness in resolving the energy crisis. With the rapid expansion of nuclear power facilitating humanity's shift towards a low-carbon energy society, proper management of nuclear waste generated by nuclear plants has become crucial for minimizing environmental impacts and alleviating public concerns. To promote the development of removal techniques and control strategies for radionuclides in the wastewater, we have organized a special topic on "Nuclear Environment Advances" in *National Science Open* (NSO). We have invited nine scientists from different fields to present their latest research findings and prospective analyses of radionuclides in the environment systematically.

Continuous attention to nuclear safety, strict regulatory supervision, and enhanced emergency response measures are of great significance for reducing the environmental impact during operation of nuclear plants. Assessing the impacts of radiation on various organisms to understand the toxicity mechanisms, potential health effects, and dose-response relationships related to radionuclide exposure can help assess the potential consequences of radionuclide leakage and providing information for decision making in risk management. Huang *et al*. [1] provide an overview and highlight the importance of environmental toxicology in the risk assessment and management of radionuclides, suggesting that both chemical toxicity and radiotoxicity are indispensable in evaluating the toxicology of radionuclides. Concerned about the absence of environmental pollution standards, they suggest that future research should focus on the long-term impacts of these radionuclides on human health, especially the risks related to low-dose radiation exposure.

In the nuclear fuel cycle, radioactive iodine is one of the major gaseous contaminants due to nuclear energy utilization, posing threats to the environment and public health. Covalent Organic Frameworks (COFs) are as a novel class of crystalline porous materials that has been proven promising for iodine capture. Chen *et al*. [2] systematically analyze the structure-activity relationship of COFs in iodine adsorption by evaluating the critical factors like pore structure, electron-rich groups, and ionic sites influencing adsorption performance.

This research provides crucial insights, guiding the design of more efficient COF materials for capturing and immobilizing radioactive iodine, which is vital for nuclear environmental remediation and fuel cycle management. To truly harness the adsorption performance of radioactive iodine by COF, Han *et al*. [3] synthesize an amine-linked COF, namely TABN-COF, which shows a strong affinity for iodine, with an adsorption capacity of up to 365 mg/g for I^{3-} in the aqueous phase. Besides the COF materials, Zhao *et al*. [4] design and prepare a metal-organic framework (MOF) material, Ce(IV)-MOF-808, which has available Ce(IV) sites, for the efficient removal of IO^{3-}. Ce(IV)-MOF-808 demonstrates outstanding selectivity and one of the highest adsorption capacities (623 mg/g) for the removal of IO^{3-}. More importantly, the uptake performance for IO^{3-} from simulated groundwater is excellent, indicating that Ce(IV)-MOF-808 has highly promising practical applications in the remediation of IO^{3-} from actual radioactive wastes.

f-block elements are the elements in the periodic table that fill the 4*f* and 5*f* subshells, including lanthanide elements and actinide elements. Li *et al*. [5] present an account of the development of hydrophilic ligands in four categories, offering a comprehensive summary of hydrophilic f-block element chelators and propose prospective approaches for ligand development in the future. This review provides a comprehensive overview of hydrophilic f-block element chelators and suggests promising approaches for future ligand development. Uranium, as a key f-block element in nuclear fuel production, holds substantial potential in both nuclear and environmental fields. Extracting uranium from seawater and radioactive waste is essential for the efficient utilization of uranium resources and the protection of the natural environment. Dong *et al*. [6] review the excellent catalytic performance of polymer semiconductors in photocatalytic uranium remediation and clarify their principles. This review explores the mechanisms of uranium removal by these materials under different environmental conditions, highlighting their influence on carrier separation and transport as well as the reduction products of uranium. To practically evaluate the effective capture of soluble UO_2^{2+} ions from complex radioactive wastewater, Lv *et al*. [7] design and prepare a MQ_2-collagen fibers (MoS_2-CF; M = Mo, W; Q = S, Se) composites for U(VI) adsorption. They display higher uranium adsorption performance, with a saturated adsorption capacity (q_e) of 301 mg/g. However, it is still challenging to balance the requirements of high stability and high adsorption capacity in U(VI) adsorption. Thus, Zhang *et al*. [8] fabricate a novel, structurally stable, large-block sponge with super-sized water transport channels (SWTC-PAO sponge) for the recovery of dispersed uranium. In natural seawater, the SWTC-PAO sponge achieves a high uranium extraction capacity of 9.1 mg/g and exhibits a rapid extraction rate. The extensive application potential of the SWTC-PAO sponge in both natural seawater and wastewater renders it a highly promising adsorbent for the recovery of dispersed uranium resources. Technetium-99 (^{99}Tc), which is a byproduct of ^{235}U, commonly exists in the form of pertechnetate anion ($^{99}TcO_4^-$). The $^{99}TcO_4^-$ can effortlessly diffuse into ecological systems, thereby causing difficulties in separation during contaminant treatment. Zhang *et al*. [9] analyze the advantages of porous materials like ionic polymers, COFs, MOFs, and carbon-based materials for $^{99}TcO_4^-$ removal. They emphasize that developing scalable, low-cost, efficient, and recyclable materials is crucial for nuclear waste disposal and the nuclear energy industry's sustainable development, while complying with safety and policy standards.

This focused issue will help contribute to the advancement of research on removal techniques and control strategies for radionuclides waste from nuclear power plants. We believe that this topic will foster the advancement of research associated with alleviating the environmental impact of radionuclides by providing valuable information and perspectives, thereby further facilitating innovation and breakthroughs in this significant area. Additionally, we would like to express our sincere gratitude to the authors, reviewers and editorial staff for their support and contributions.

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