

Simultaneous Removal of Caesium and Strontium Ions with Advanced CoPrecipitation Methods and Its Process Intensification

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SUMMARY

- The generation of composite materials by combining natural clinoptilolite and BaSO₄ to remove ¹³⁷Cs and ⁹⁰Sr simultaneously.
- Improvement solid/liquid separation degree with the help of fast sedimentation of composite coagulants for waste volume reduction, which facilitates waste encapsulation for safe long-term waste management.
- The process intensification of the proposed method by using an agitated tubular reactor for enhanced ion removal while reducing plant footprint, cost and waste generation.

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1. INTRODUCTION

Continuous population growth and the resulting increasing energy demand make nuclear energy a promising candidate among alternative energy sources to meet global energy needs, reduce carbon emissions, and minimise global warming effects [1, 2]. Nuclear energy provides safe, green and efficient energy by reducing more than a thousand tons of CO₂ emissions per year, and its safety and sustainability are expected to increase with the new reactor design that can reduce dependence on the uranium fuel cycle and sustain nuclear energy [3, 4]. However, the key challenge is the generation of radioactive waste that poses an inherent hazard and must be managed properly without any interaction with humans and the environment. Especially, radioactive wastewater is of radiological concern and is produced at almost each stage of the nuclear fuel cycle (front-end and back-end) [5]. A larger volume is expected to be generated when the uranium fuel is irradiated and reaches end-of-life in the reactor core, and is then reprocessed to recover fissile material [5, 6]. The reprocessing process generally produces a highly radioactive waste solution containing fission products, which can be considered a significant source of nuclear waste, excluding the fuel itself. Moreover, nuclear accidents are other main contributors to the increasing volume of radioactive wastewater, particularly when using water to cool down the reactor core, as seen at Fukushima Daiichi NPP (2011) [7]. The complexity and mobility of this radioactive wastewater increase the burden on the radioactive waste management process, and appropriate treatment techniques must be chosen according to waste streams.

The main effort in managing radioactive wastewater is to convert dissolved radionuclides into a concentrated solid form using single or combined techniques and then release the treated water back into the environment [8]. Alternatively, diluting the waste solution to the regulatory limit and discharging it into the environment is another option if the initial concentration allows it [9]. The treatment of radioactive wastewater plays a critical role in radioactive waste management because dissolved fission products and actinides are present in the waste solution, which are mobile in the environment and can be taken up by organisms, leading to a radiological hazard [10]. Of these, ¹³⁷Cs and ⁹⁰Sr are the most problematic fission products of spent nuclear fuel due to their half-lives of approximately 30 years, strong ionising radiation emissions, high solubility and mobility, which are responsible for the bulk radioactivity and heat generation in high-level waste [7, 11]. ¹³⁷Cs and ⁹⁰Sr can easily migrate throughout the ecosystems and be taken up by plants and organisms due to their chemical similarities to potassium and calcium, respectively, resulting in accumulation and internal exposure [10, 12, 13].

Therefore, the separation of these fission products from radioactive waste solutions is crucial to reduce radioactivity and waste volume, thereby facilitating the waste management process. However, wastewater containing ¹³⁷Cs and ⁹⁰Sr is difficult to treat, and conventional treatment techniques are not efficient due to their small ionic radii, low charge densities and high solubility [7]. So far, several chemical, physical, biological and combined treatment techniques have been developed to remove ¹³⁷Cs and ⁹⁰Sr ions with or without changing the chemical nature of fission products [8]. Of these, ion exchange or adsorption, and chemical precipitation are probably the most chosen

technologies because they are simple, effective, proven, and low-cost techniques with a wide range of sorbent materials [14-16]. However, these techniques also have disadvantages such as high ionic strength, competing ions, low radionuclide concentration, and secondary waste such as used sorbent material or waste sludge [17, 18]. Furthermore, due to differences in solubility and electrostatic affinity, similar removal efficiencies for these fission products generally cannot be achieved with the same treatment process [17,19]. As a result, simultaneous removal of ^{137}Cs and ^{90}Sr using a single treatment unit is challenging, and novel technologies need to be studied. Therefore, the aim of this thesis is to develop a single treatment process that enables the removal of Cs^+ and Sr^{2+} ions with composite flocs formed by combining clinoptilolite and BaSO_4 , and then to intensify the process using an agitated tubular reactor.

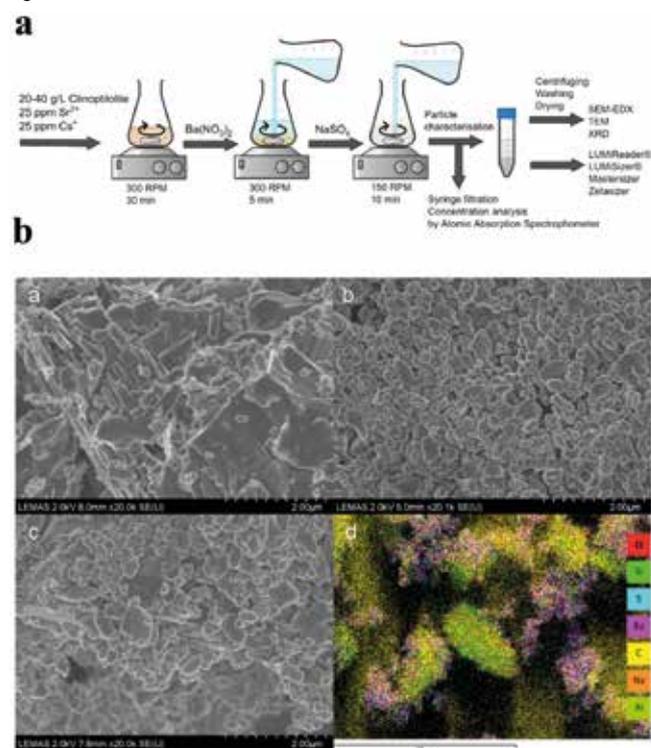


FIGURE 1: a) A schematic of a combined batch experiment. (reproduced from [21]) b) High-resolution SEM for natural clinoptilolite (a), precipitated BaSO_4 (b), composite flocs (c) and EDS image for composite flocs (d) (reproduced from [21]).

2. BATCH AND INTENSIFIED PROCESS FOR Cs^+ AND Sr^{2+} REMOVAL

Most recently, Kivan (2024) [20], in his doctoral thesis at the University of Leeds, studied “simultaneous removal of cesium and strontium ions with advanced co-precipitation methods and its process intensification”, leading to two successive research papers. Firstly, Kivan et al. [21] studied the simultaneous removal of Cs^+ and Sr^{2+} ions through the combination of ion exchange and co-precipitation techniques, utilising zeolite as an adsorbent and barite (BaSO_4) as a co-precipitation agent. In this study, clinoptilolite, one of the natural zeolites with an aluminosilicate structure, was chosen due to being a low cost, abundant, highly

resistant, and selective sorbent material that has been industrially used to treat nuclear cooling pond water at the Site Ion Exchange Effluent Plant (SIXEP) at Sellafield, U.K. [21, 22]. It is noted that clinoptilolite has physicochemical properties that allow higher removal of Cs^+ ions than Sr^{2+} ions due to its ideal Si/Al ratio and pore diameters similar to hydrated Cs^+ ions [21, 23, 24]. Additionally, BaSO_4 is another material used in this study for the co-precipitation of these fission products after the clinoptilolite treatment step [21]. It offers high removal efficiency of Sr^{2+} along with other divalent cations such as Ra^{2+} and is used industrially in the treatment of nuclear wastewater due to its exceptionally low solubility, stability, suitable ionic radii and high density, allowing superior solid-liquid separation degree [25]. Therefore, we synthesised core-shell composite coagulants in a batch system by combining clinoptilolite and BaSO_4 to increase the removal efficiency for both fission products and reduce the waste volume by achieving rapid sedimentation for enhanced dewatering [21].

Initially, BaSO_4 was synthesised following work by Pacary et al. [26], and co-precipitation analysis was performed with the addition of 25 mg/L of Cs^+ and Sr^{2+} ions. Then, an adsorption kinetic study was conducted to analyse clinoptilolite performance in waste solution containing Cs^+ and Sr^{2+} ions together [21]. In the combined adsorption-coagulation study, as seen in Fig. 1, clinoptilolite at different concentrations was mixed with a solution containing 25 mg/L of each fission product, and then BaSO_4 particles were synthesised to obtain composite coagulants [21]. Afterwards, physical characterisation was studied to get the crystal structure and morphology of composites, and sedimentation analyses were performed for the dewaterability degree from the compressive yield stress analysis [21]. According to Fig. 1, SEM images proved that irregular spherical BaSO_4 clusters were observed in high-resolution scanning electron microscopy (SEM), and the friability of clinoptilolite crystals was recorded [21]. In terms of composite coagulants, it was reported that BaSO_4 crystals cover the clinoptilolite surface during coagulation, forming core-shell composites [21]. Furthermore, sedimentation and compressive yield stress analyses revealed that faster sedimentation was observed in composites due to higher BaSO_4 density, increasing sedimentation rate and dewaterability, which in turn reduced the final volume reduction for waste encapsulation [21].

In terms of removal efficiency, adsorption kinetics followed the pseudo-second-order model, showing a rapid adsorption equilibrium reached within 1 h and a higher removal efficiency was achieved for Cs^+ ions (~97%) than for Sr^{2+} ions (~90%), which was attributed to the ideal pore channels of clinoptilolite for hydrated Cs^+ ions [21]. This result can be explained by the high Si/Al ratio of clinoptilolite, where the low framework charge indicates a higher affinity towards monovalent cations (Cs^+) than divalent cations (Sr^{2+}) [27]. In contrast, we studied the performance of BaSO_4 co-precipitation for the simultaneous removal of both ions and, as expected, significantly higher removal was recorded for Sr^{2+} ions than Cs^+ due to the similar ionic radii between BaSO_4 crystals and Sr^{2+} ions [21]. This result supported that simultaneous and effective removal of both ions was not possible using a single clinoptilolite or BaSO_4 . Therefore, combined adsorption was carried out using clinoptilolite and BaSO_4 , and interestingly, a very high removal efficiency was obtained for Sr^{2+} , while a lower

removal was recorded for Cs⁺ ions compared to the single clinoptilolite process [21]. The lower Cs⁺ removal was explained by the lower interaction with BaSO₄ and competition with Ba⁺ ions for clinoptilolite adsorption sites [21, 28].

Thus, we doubled the clinoptilolite concentration to improve Cs⁺ removal, and this increased Cs⁺ removal efficiency a little, but still was not desirable [21]. They then treated natural clinoptilolite with NaCl to increase the exchangeable Na⁺ ions in the clinoptilolite structure, which significantly enhanced the Cs⁺ removal to over 95% and led to the complete removal of Sr²⁺ (>99.9%) [21]. Overall, despite the differences in valence and ionic radii for both ions, they achieved simultaneous removal of Cs⁺ and Sr²⁺ ions in a single batch unit with the composite flocs, as well as faster sedimentation and dewatering, leading to easier waste processing by reducing waste volume [21].

As a next step, the batch combined adsorption-coagulation process was intensified using a plug-flow reactor to increase process safety and efficiency while reducing process footprint, cost and energy consumption [29]. We utilised a pilot-scale Coflore® agitated tubular reactor (ATR) in this study due to its ability to allow the combined adsorption-coagulation process and ease of scalability for industrial application [29]. The mechanism of ATR is mainly based on the lateral shear generated by the inner agitator bar due to the mechanical motion of the reactor body, thereby separating the mixing process from the axial flow [29]. Initially, similar combined batch experiments were performed using natural clinoptilolite and BaSO₄ to allow benchmarking with the ATR study.

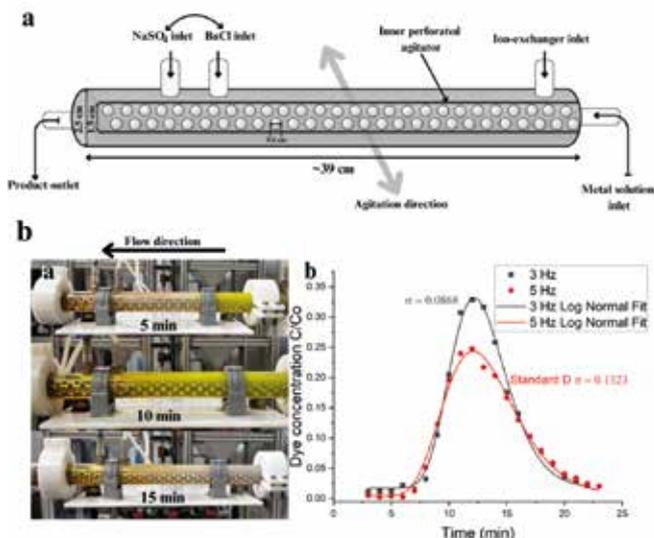


FIGURE 2: a) A schematic illustration of the ATR and its dimensions (reproduced from [29]). b) A plug-flow characteristics of ATR using a dye solution (a) and its residence time distribution (b) (reproduced from [29]).

For process intensification, as given in Fig. 2a, a 39 cm long ATR test tube with a total volume of approximately 150 mL was used during the combined adsorption-coagulation process under the 3 Hz and 5 Hz agitation frequencies, with the residence time adjusted similarly to the batch process (~15 min) [29, 30]. Before the combined process, the ATR plug flow mechanism

was characterised at 3 Hz and 5 Hz by injecting fluorescent dye solution for one minute and then observing the plug flow in the ATR by introducing distilled water [29]. The final dye concentration collected from the ATR outlet was then analysed in a UV spectrometer, and Fig. 2b shows that the residence time distribution at 3 Hz provided a better plug-flow behaviour than 5 Hz due to optimal laminar flow with low axial dispersion [29, 31]. Once the ATR flow was characterised, we repeated the batch combined study with the same ion concentration to compare with the intensified process [29]. In the intensified combined operation, as seen in Fig. 2a, 50 mg/L of mixed metal solution of each ion was injected from the main inlet by adjusting the residence time, similar to the batch operation [29]. Then, clinoptilolite solution was introduced from the second inlet with the same flow rate, followed by NaSO₄ and BaCl₂ dispersion injected from separate inlets [29]. The combined study was conducted at 3 Hz and 5 Hz agitation frequency and then repeated by changing the order of NaSO₄ and BaCl₂ injection as shown in Fig. 2a.

Ion removal efficiency from batch and ATR system is given in Fig. 3, and similar to the previous study, superior Sr²⁺ removal than Cs⁺ removal was observed in all processes [21, 29]. While the composite flocs synthesised in the batch system removed approximately 99.9% of Sr²⁺ ions, the Cs⁺ removal rate was approximately 94.7% due to the different ionic radii of Cs⁺ ions compared to BaSO₄ crystals [29]. It is noteworthy that another natural clinoptilolite was utilised in this study, and therefore, the removal efficiency of the composite flocs was relatively higher than in the previous research, especially for Cs⁺ ions [29]. This is thought to be because the extracted clinoptilolite contains fewer impurities or contamination in its geological structure [21, 29]. We also investigated the competitive effect of Ba²⁺ ions on Cs⁺ removal by injecting NaSO₄ first, reducing the residence time of BaCl₂. They proved that Cs⁺ removal increased above 96% due to the increased interaction between Cs⁺ ions and clinoptilolite adsorption sites, while no improvement was observed in Sr²⁺ removal.

As for ATR removal efficiency, Fig. 3 shows that superior removal efficiency was recorded at 3 Hz agitation frequency for both ions, achieving >94.8% Cs⁺ removal and >99.9% Sr²⁺ removal. When the agitation frequency was increased to 5 Hz, a removal efficiency of >95.7 for Cs⁺ ions and a small increase in Sr²⁺ removal were recorded. We explained that ideal sinusoidal motion at higher agitation could result in better mixing and the formation of smaller composite flocs, which would provide more adsorption sites for target ions [29, 32]. In addition, they studied the Ba²⁺ interference effect in ATR at both agitation frequencies and found that Cs⁺ removal was further improved, achieving more than 96% removal efficiency, proving that Cs⁺ had more opportunity to interact with clinoptilolite adsorption sites [29]. Further increase in Sr²⁺ removal was observed at both agitation frequencies, and almost complete removal (>99.9%) was achieved. Overall, ATR outperformed the batch system in the simultaneous removal of Cs⁺ and Sr²⁺ ions due to superior mixing and mass transfer. It was also stated that it is a promising candidate for the nuclear industry due to its modular, mobile and scalable design that meets the requirements of the process intensification concept and its increased operational flexibility and efficiency.

Lastly, we also carried out the pressure filtration analysis

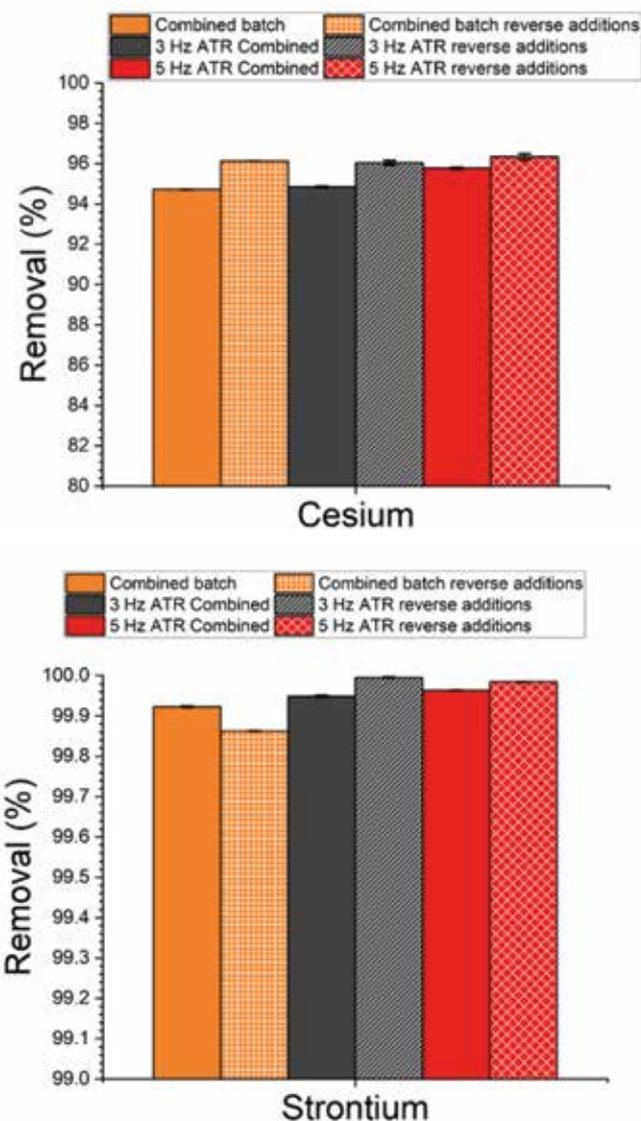


FIGURE 3: Removal efficiencies of Cs⁺ and Sr²⁺ ions from ATR and batch systems at 3 Hz and 5 Hz agitation frequency as well as reverse inlet order (reproduced from [29]).

to study the solid-liquid separation degree of the synthesised composite flocs from both the batch and ATR systems and BaSO₄ precipitates by using the batch HP4750 high-pressure filtration cell (given in Fig. 4) at constant pressure (1-3 bar). We collected and weighed the filtrates to calculate the specific cake resistance and medium resistance according to Darcy's law [29, 33]. Fig. 4 shows the specific cake resistance obtained from the filterability analysis and proves that all suspensions have increased cake resistance with increasing pressure due to denser cake formation at the bottom of the pressure filtration cell [29]. As seen, a high concentration of BaSO₄ precipitate showed a greater resistance at the initial pressure, but composite flocs from the batch system exhibited higher compressibility, especially at the highest pressure [29]. Lower cake resistance was observed in composite flocs obtained from ATR due to the higher density of agglomerates

synthesised at higher agitation [29]. However, the compressibility factor was calculated for all systems, and BaSO₄ precipitates showed an incompressible cake due to high concentration, whereas a greater cake compressibility was observed for composite flocs from both batch and ATR systems, indicating high dewaterability of composite flocs at moderate pressure [29].

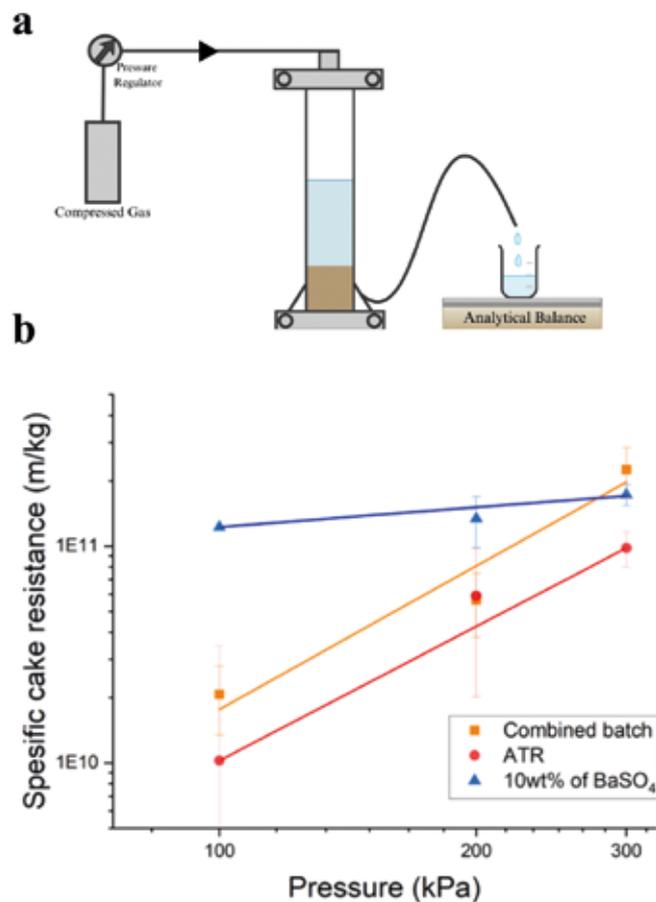


FIGURE 4: a) A schematic representative of a pressure filtration set-up (reproduced from [29]) b) Specific cake resistance for 10 wt% of BaSO₄ precipitates, composite flocs from batch and ATR (reproduced from [29])

3. CONCLUSIONS

In general, the main aim of this PhD research was to simultaneously remove Cs⁺ and Sr²⁺ ions in a single process unit and intensify the process using a plug flow agitated tubular reactor, since dissolved fission products pose a harmful effect for humans and the environment and increase the burden on the waste management plan due to high radiation and heat production. Furthermore, another objective was to understand the solid/liquid separation degree of the synthesised composites by pressure yield stress and pressure filtration analysis for waste volume reduction.

Overall, core-shell composites were synthesised by combining natural clinoptilolite and BaSO₄ in batch and intensified systems, and these composites effectively removed Cs⁺ and Sr²⁺ ions despite the differences in the valence and ionic radii of these ions.

Particularly in this research, it was emphasised that ATR may be used in nuclear cleanup operations for the treatment of radioactive wastewater due to its ideal design and high performance.

Also, this research suggested that highly filterable and compressible composite flocs showed high dewaterability, reducing radioactive waste volume and additives to encapsulate the waste. Interested readers can find more details and additional data for particle characterisation and sedimentation analysis in this research.

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REFERENCES

- [1] Saidi, K. and M. Ben Mbarek, Nuclear energy, renewable energy, CO₂ emissions, and economic growth for nine developed countries: Evidence from panel Granger causality tests. *Progress in Nuclear Energy*, 2016. 88: p. 364-374, <https://doi.org/10.1016/j.pnucene.2016.01.018>.
- [2] Menyah, K. and Y. Wolde-Rufael, CO₂ emissions, nuclear energy, renewable energy and economic growth in the US. *Energy Policy*, 2010. 38(6): p. 2911-2915, <https://doi.org/10.1016/j.enpol.2010.01.024>.
- [3] Wang, S., et al., Economic growth, nuclear energy, renewable energy, and environmental quality: Investigating the environmental Kuznets curve and load capacity curve hypothesis. *Gondwana Research*, 2024. 129: p. 490-504, <https://doi.org/10.1016/j.gr.2023.06.009>.
- [4] Kotov, Y.A., et al., Study on Minor Actinide Incineration in Molten Salt Reactors with Uranium or Plutonium Loadings. *Physics of Atomic Nuclei*, 2023. 86(8): p. 1887-1893, <https://doi.org/10.1134/S1063778823080227>.
- [5] IAEA, Getting to the Core of the Nuclear Fuel Cycle: From the Mining of Uranium to the Disposal of Nuclear Waste. 2013: IAEA.
- [6] Corkhill, C. and N. Hyatt, *Nuclear Waste Management*. 2018: IOP Publishing.
- [7] Lehto, J., et al., Removal of Radionuclides from Fukushima Daiichi Waste Effluents. *Separation & Purification Reviews*, 2019. 48(2): p. 122-142, <https://doi.org/10.1080/15422119.2018.1549567>.
- [8] Ma, H., et al., Radioactive Wastewater Treatment Technologies: A Review. *Molecules*, 2023. 28(4), <https://doi.org/10.3390/molecules28041935>.
- [9] İnan, S., Inorganic ion exchangers for strontium removal from radioactive waste : a review. *Journal of Radioanalytical and Nuclear Chemistry*, 2022. 331(3): p. 1137-1154, <https://doi.org/10.1007/s10967-022-08206-3>.
- [10] Zhang, X., P. Gu, and Y. Liu, Decontamination of radioactive wastewater: State of the art and challenges forward. *Chemosphere*, 2019. 215: p. 543-553, <https://doi.org/10.1016/j.chemosphere.2018.10.029>.
- [11] İnan, S. and Ü. Hiçsönmez, Adsorption Studies of Radionuclides by Turkish Minerals: A Review. *Journal of the Turkish Chemical Society Section A: Chemistry*, 2022. 9(2): p. 579-600, <https://doi.org/10.18596/jotcsa.1074651>.
- [12] Rai, H. and M. Kawabata, The Dynamics of Radio-Cesium in Soils and Mechanism of Cesium Uptake Into Higher Plants: Newly Elucidated Mechanism of Cesium Uptake Into Rice Plants. *Frontiers in Plant Science*, 2020. 11(528), <https://doi.org/10.3389/fpls.2020.00528>.
- [13] Sharma, S., Uptake, Transport, and Remediation of Strontium, in *Strontium Contamination in the Environment*, P. Pathak and D.K. Gupta, Editors. 2020, Springer International Publishing: Cham. p. 99-119.

REFERENCES (CONT.)

- [14] Şenilâ, M., et al., Removal of Cesium and Strontium Ions from Aqueous Solutions by Thermally Treated Natural Zeolite. *Materials*, 2023. 16(8): p. 2965, <https://doi.org/10.3390/ma16082965>.
- [15] Prajitno, M.Y., et al., The effect of pre-activation and milling on improving natural clinoptilolite for ion exchange of cesium and strontium. *Journal of Environmental Chemical Engineering*, 2020. 8(1): p. 102991, <https://doi.org/10.1016/j.jece.2019.102991>.
- [16] Lee, H.-K., et al., Simultaneous removal of suspended fine soil particles, strontium and cesium from soil washing effluent using inorganic flocculants. *Environmental Technology & Innovation*, 2022. 27: p. 102467, <https://doi.org/10.1016/j.eti.2022.102467>.
- [17] Alby, D., et al., Recent developments in nanostructured inorganic materials for sorption of cesium and strontium: Synthesis and shaping, sorption capacity, mechanisms, and selectivity—A review. *Journal of Hazardous Materials*, 2018. 344: p. 511-530, <https://doi.org/10.1016/j.jhazmat.2017.10.047>.
- [18] Oh, M., et al., Chemical precipitation-based treatment of acidic wastewater generated by chemical decontamination of radioactive concrete. *Journal of Environmental Chemical Engineering*, 2023. 11(5): p. 110306, <https://doi.org/10.1016/j.jece.2023.110306>.
- [19] Agency, I.I.A.E., Handling and Processing of Radioactive Waste from Nuclear Applications, in Technical Reports Series No. 402. 2001: Vienna.
- [20] Kivan, O., Simultaneous Removal of Cesium and Strontium Ions with Advanced Co-Precipitation Methods and Its Process Intensification. 2024, University of Leeds.
- [21] Kivan, O., et al., Removal of cesium and strontium ions with enhanced solid-liquid separation by combined ion exchange and BaSO₄ co-precipitation. *Journal of Water Process Engineering*, 2024. 59: p. 104934, <https://doi.org/10.1016/j.jwpe.2024.104934>.
- [22] Dyer, A., et al., The use of columns of the zeolite clinoptilolite in the remediation of aqueous nuclear waste streams. *Journal of Radioanalytical and Nuclear Chemistry*, 2018. 318(3): p. 2473-2491, <https://doi.org/10.1007/s10967-018-6329-8>.
- [23] Cortés-Martínez, R., M.T. Olguín, and M. Solache-Ríos, Cesium sorption by clinoptilolite-rich tuffs in batch and fixed-bed systems. *Desalination*, 2010. 258(1): p. 164-170, <https://doi.org/10.1016/j.desal.2010.03.019>.
- [24] Kraljević Pavelić, S., et al., Critical Review on Zeolite Clinoptilolite Safety and Medical Applications in vivo. *Front Pharmacol*, 2018. 9: p. 1350, <https://doi.org/10.3389/fphar.2018.01350>.
- [25] Tokunaga, K., et al., Effective removal of iodate by coprecipitation with barite: Behavior and mechanism. *Chemosphere*, 2021. 266: p. 129104, <https://doi.org/10.1016/j.chemosphere.2020.129104>.
- [26] Pacary, V., Y. Barré, and E. Plasari, Method for the prediction of nuclear waste solution decontamination by coprecipitation of strontium ions with barium sulphate using the experimental data obtained in non-radioactive environment. *Chemical Engineering Research and Design*, 2010. 88(9): p. 1142-1147, <https://doi.org/10.1016/j.cherd.2010.01.006>.
- [27] Karmen, M., et al., Natural Zeolites in Water Treatment – How Effective is Their Use, in Water Treatment, E. Walid and C. Rezaul Kabir, Editors. 2013, IntechOpen: Rijeka. p. Ch. 5.
- [28] Lumiste, L., et al., 266034 Removal of Barium From Ground Water Using Clinoptilolite. 2012.
- [29] Kivan, O., et al., Intensified co-precipitation and ion exchange using an agitated tubular reactor (ATR) for enhanced removal of Cs⁺ and Sr²⁺ ions- dataset. *Chemical Engineering and Processing - Process Intensification*, 2024. 207: p. 110077, <https://doi.org/10.1016/j.cep.2024.110077>.
- [30] Tonge, A.S., et al., Coagulated Mineral Adsorbents for Dye Removal, and Their Process Intensification Using an Agitated Tubular Reactor (ATR). *ChemEngineering*, 2021. 5(3): p. 35, <https://doi.org/10.3390/chemengineering5030035>.
- [31] Bianchi, P., J.D. Williams, and C.O. Kappe, Oscillatory flow reactors for synthetic chemistry applications. *J. Flow Chem.*, 2020. 10(3): p. 475-490, <https://doi.org/10.1007/s41981-020-00105-6>.
- [32] Rice, H.P., et al., Physical and numerical characterisation of an agitated tubular reactor (ATR) for intensification of chemical processes. *Chemical Engineering and Processing - Process Intensification*, 2022. 179: p. 109067, <https://doi.org/10.1016/j.cep.2022.109067>.
- [33] Li, Y., et al., Filtration of kaolinite and coal mixture suspension: Settling behavior and filter cake structure analysis. *Powder Technology*, 2021. 381: p. 122-128, <https://doi.org/10.1016/j.powtec.2020.12.050>.