Ion-exchange-based methods of fluoride extraction from Tanzanian groundwater and the community health issues that stem from overexposure to fluoride

By Chloe Joy Chang

chloejoy.chang@duke.edu

Supervised by Dr. Thomas J. Robshaw (University of Leeds)

Dr. Laura E. Smith (University of Leeds)

Professor Timothy Hunter (University of Leeds)

Professor Revocatus Machunda (Nelson Mandela African Institute of Science and Technology)

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1 Overview

This study was conducted during the summer of 2025 at the University of Leeds in the School of Chemical and Process Engineering under the supervision of Dr. Thomas James Robshaw. It was part of the TUDAY (The Tanzania-UK collaboration on Defluoridation by Adsorption and recoverY) project, aiming to tackle high fluoride concentration levels in Tanzanian groundwater that pose various health threats ranging from bone fluorosis to neurodevelopmental issues amongst the Tanzanian population.

The project aims to design and deploy a technologically and commercially sound solution to the issue of excess fluoride in Tanzanian water in a socially acceptable manner. It works to demonstrate an ion-exchange and precipitation process that will reduce fluoride in groundwater to a safe concentration and, moreover, valorise this fluoride by precipitation as calcium fluoride (fluorite). By understanding public and stakeholder perception of the value and necessity of defluoridation methods, any non-technical barriers were also circumvented to deliver a practical engineering solution. In subsequent work, the feasibility of producing ion-exchange media from locally available biomass (ie, invasive weed species) will also be investigated, reducing the carbon footprint of the process and tapping into local expertise and labor.

2 Introduction

High fluoride concentrations in groundwater are a major public health concern in Tanzania, particularly along the East African Rift Valley, where natural geological processes release fluoride into aquifers. In many regions, fluoride levels far exceed the World Health Organization (WHO) guideline of 1.5 mg/L, with some sources reporting concentrations above 30 mg/L (WHO, 2017; Rango et al., 2012).

Chronic exposure to elevated fluoride is well known to cause dental and skeletal fluorosis, leading to enamel damage, bone deformities, pain, and impaired mobility (Choubisa, 2018). More recently, evidence has highlighted serious neurodevelopmental risks, with studies linking excess fluoride exposure in children to reduced IQ and deficits in memory and cognitive processing (Choi et al., 2012; NTP, 2020). These outcomes are especially concerning in rural Tanzanian communities (this study particularly addressed communities surrounding the Aruhsa, Kilimanjaro areas), where untreated groundwater is often the primary drinking source.

Despite numerous reports of overexposure to fluoride being released, affordable, scalable, and socially acceptable solutions for defluoridation remain limited. Existing methods, such as reverse osmosis and activated alumina, are costly, energy-intensive, or poorly suited to local infrastructure. This research is therefore critical to develop context-appropriate strategies that not only lower fluoride concentrations to safe levels but also support long-term sustainability and protect vulnerable populations from irreversible skeletal and neurodevelopmental harm.

3 Methods

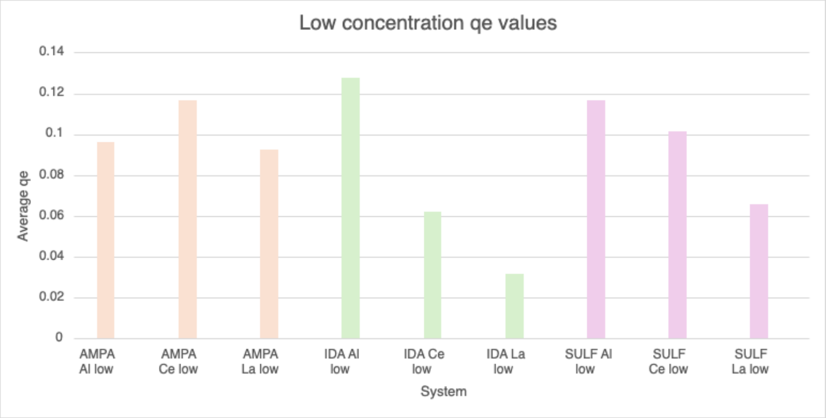
This summer was focused on Phase 1 of the TUDAY project, which was then divided into four work packages combining laboratory investigations with stakeholder engagement. In the first work package, adsorbent chemistry was explored by tailoring ion-exchange resins to the remit of fluoride removal. Different loading metals and functional groups were trialed in order to improve binding capacity and selectivity for fluoride. In the second work package, dynamic operations were investigated to optimize system performance. This involved determining optimum flow rates through breakthrough experiments, screening potential eluant chemicals for effective regeneration, and comparing the performance of a conventional packed column with a process-intensification option using an agitated tubular reactor. The third work package focused on fluoride recovery through valorisation as calcium fluoride (CaF_2). Batch precipitation experiments were performed to optimize pH conditions and experimental setup, and protocols were developed for CaF_2 purity assessment. Large-scale dynamic experimentation was also conducted through a multiphase flow-tracking facility at the University of Leeds, called the Multiform. Finally, the fourth work package addressed non-technical barriers, with efforts directed toward stakeholder mapping and understanding, the development of an engagement strategy, and a review of lessons from prior case studies on the social acceptance of new engineering solutions.

As part of this study, a field visit to Tanzania was undertaken between July 6–10, 2025. This trip was highly focused on examining how the proposed filtration system could be implemented once the laboratory design and chemistry aspects were solidified. Meetings with faculty at the Nelson Mandela African Institution of Science and Technology (NM-AIST), local academics, and community representatives provided valuable perspectives on water management practices, infrastructure limitations, and community priorities. These local interactions highlighted potential non-technical barriers—such as cost, ease of operation, and cultural perceptions of new water treatment technologies—that must be addressed alongside the scientific design. Insights from this engagement directly informed the development of the stakeholder strategy and underscored the importance of aligning technical solutions with local acceptance and long-term sustainability, providing information critical for the fourth "work package" of this phase.

Together, these four strands of laboratory and engagement work, supplemented by direct field interactions in Tanzania, formed the methodological foundation for Phase 1. This integrated approach advanced both the technical optimization and the social feasibility of fluoride defluoridation strategies for Tanzanian groundwater.

4 Results and Findings

Through the analysis of different ion-resin exchange systems, namely AMPA, IDA, and SULF ligands, coupled with Al^{3+}, La^{3+}, and Ce^{3+} ions, we were able to identify the most effective ion-resin combination to use in our column filtration design. The filtration set-ups were tested with both high- and low-fluoride concentration simulated groundwater samples, and the results are summarized in Figures 1 and 2 (see below).



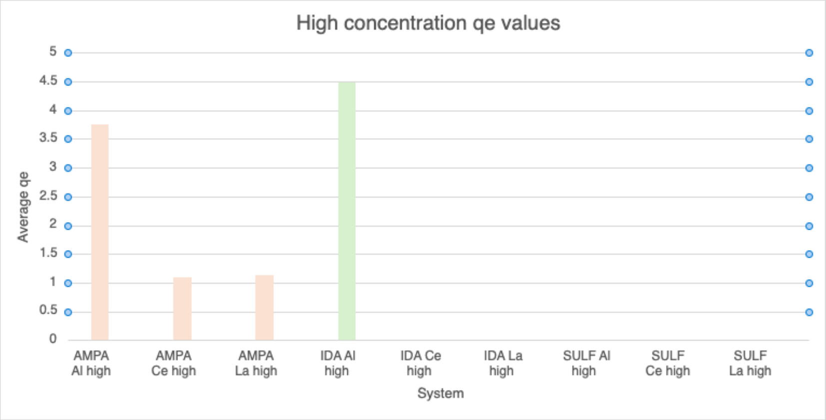


Fig 1 and 2. Bar graph of average qe vs. ion-resin exchange system

At low fluoride concentrations, the qe values across systems were generally modest, with AMPA- and SULF-based resins showing moderate uptake in the range of 0.09–0.12, while IDA–Al^{3+} demonstrated the highest adsorption capacity at approximately 0.13. In contrast, IDA–Ce^{3+} and IDA–La^{3+} exhibited notably lower qe values, indicating poor affinity under these conditions. At high fluoride concentrations, the distinction between systems became much more pronounced. IDA–Al^{3+} outperformed all other combinations with a qe approaching 4.5, while AMPA–Al^{3+} was the next best system at around 3.7. All other systems displayed negligible adsorption, with qe values close to zero.

Taken together, these results highlight IDA–Al^{3+} as the most effective ion-resin system across both concentration ranges. Its consistently superior adsorption capacity suggests strong fluoride affinity and robustness under variable groundwater conditions, making it the most suitable candidate for further development in dynamic column experiments. This laboratory conclusion was reinforced by insights gathered during the Tanzania field visit between July 6–10, 2025, where discussions with community members and local stakeholders revealed significant resistance to the other filtration design option–bone char filtration. As shown in Figure 3, the comparative evaluation between bone char and ion-exchange resins illustrates how both technical performance and community feedback converged to guide our choice of technology. While bone char has moderate adsorption efficiency, it is hindered by poor cultural acceptance, negative social perception, and limited sustainability due to reliance on animal bone supply. In contrast, ion-exchange resins, and particularly IDA–Al^{3+}, demonstrated superior adsorption capacity, high scalability, and crucially, positive reception among Tanzanian stakeholders who perceived them as modern and neutral alternatives. As a result, the IDA–Al^{3+} resin was selected not only on the basis of its superior adsorption performance but also for its alignment with local community values, ensuring that the chosen technology is both technically effective and socially viable for fluoride defluoridation in Tanzania.

Criterion	Bone Char Filtration	Ion-Exchange Resins (IDA-Al^{3+})
Adsorption efficiency	Moderate (dependent on activation method)	High, especially at elevated fluoride
Cultural/religious acceptance	Low – strong skepticism; pork bone concerns in Muslim populations	High – perceived as neutral/synthetic
Social perception	Negative – association with animal products	Positive – seen as modern/innovative
Sustainability	Limited – requires continuous bone supply	Flexible – potential for biomass-derived resins
Scalability	Constrained by material sourcing	High – adaptable to column systems

Fig 3. Comparative assessment of bone char vs. ion-exchange resins based on laboratory performance and community feedback

5 Discussion

The superior performance of the IDA–Al^{3+} resin system can be explained by the underlying coordination chemistry. Fluoride is a hard Lewis base with high charge density, and therefore interacts most strongly with hard Lewis acids such as Al^{3+}. The iminodiacetate (IDA) functional group provides a stable chelating environment that enhances the availability of Al^{3+} for fluoride binding while preventing rapid leaching of the metal from the resin. These conditions create a strong and selective Al–F interaction, reflected in the consistently higher qe values compared to other systems.

In contrast, La^{3+} and Ce^{3+}, while also trivalent cations, have larger ionic radii and lower charge densities than Al^{3+}, resulting in weaker fluoride coordination under similar conditions. Similarly, the AMPA and SULF ligands, although capable of metal binding, appear to provide less stable or less favorable coordination geometries for fluoride capture. The poor performance of these systems at high fluoride concentrations underscores the importance of both metal identity and ligand functionality in designing effective ion-exchange resins. Thus, the observed results align with fluoride's strong preference for Al^{3+} complexation and confirm that IDA–Al^{3+} offers the most chemically robust and scalable platform for further development in column-based defluoridation applications.

Looking ahead, the project's next steps will focus on translating these bench-scale findings into practical, field-ready systems. Phase 2 is likely to involve dynamic column experiments using the IDA–Al^{3+} resin to assess performance under continuous flow and in conditions that more closely resemble Tanzanian groundwater. In parallel, efforts will be directed at optimizing regeneration strategies and evaluating the long-term durability of the resin under repeated adsorption–desorption cycles. Another critical extension of this work will be the valorisation of recovered fluoride through precipitation as calcium fluoride (CaF_2), which has potential applications in metallurgy and ceramics. This circular approach not only prevents secondary waste accumulation but also offers a pathway to offset costs and improve the economic sustainability of defluoridation systems.

Equally important will be the continued integration of social science and stakeholder engagement into the technical design. The Tanzania field visit underscored how non-technical barriers—particularly cultural acceptance and trust in water treatment technologies—can determine the success or failure of implementation. Future project phases will therefore deepen collaborations with local governance structures, water utilities, and community groups to ensure that technical solutions are embedded within culturally acceptable and user-friendly delivery models.

The significance of this research extends beyond engineering feasibility to urgent public health outcomes. High fluoride concentrations in Tanzanian groundwater not only contribute to skeletal and dental fluorosis but also pose risks of neurodevelopmental deficits in children, including reduced IQ and impaired cognitive performance. By advancing a socially viable and scientifically robust defluoridation strategy, this project has the potential to mitigate these long-term neurological harms, protect vulnerable populations, and improve both health and educational outcomes. In this way, the IDA–Al^{3+} resin filtration design represents not only a promising engineering solution but also a critical step toward addressing the intertwined technical, social, and health challenges posed by endemic fluoride contamination.

6 Conclusion

This study identified the IDA–Al^{3+} ion-exchange resin as the most effective system for fluoride removal from simulated Tanzanian groundwater. Laboratory experiments demonstrated its superior adsorption capacity across both low and high fluoride concentrations, significantly outperforming alternative resin–metal combinations. Complementary insights from the Tanzania field visit reinforced this technical decision, as community engagement revealed strong cultural and religious objections to bone char filtration systems, while ion-exchange resins were viewed as socially neutral and acceptable. Together, these findings establish IDA–Al^{3+} as a promising candidate for further development in column-based defluoridation applications.

The integration of chemical optimization with stakeholder perspectives underscores the importance of addressing both technical and non-technical barriers in designing sustainable water treatment technologies. By coupling resin-based defluoridation with the potential valorisation of fluoride as CaF_2, this approach also points toward an economically viable and circular solution. Most critically, the development of a scalable, socially accepted defluoridation system has direct implications for public health in Tanzania, where chronic fluoride exposure continues to drive skeletal deformities, dental fluorosis, and neurodevelopmental deficits in children.

Future work will extend this research into dynamic column trials, regeneration studies, and field-scale validation, with continued emphasis on community partnership and local adaptability. Ultimately, the IDA–Al^{3+} resin system offers not only a pathway to safe drinking water but also a means of safeguarding long-term neurological and skeletal health, thereby advancing both scientific innovation and health equity in fluoride-affected regions.

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