Design and Optimization of Ion-Exchange Technology for Deflouridation of High-Flouride Groundwater in Tanzania

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I. Abstract

Elevated fluoride concentrations occur naturally in groundwater throughout northern Tanzania due to the region's volcanic geology and the East African Rift Valley. As groundwater is the primary source of drinking water for many communities, chronic exposure to elevated fluoride levels has led to an over 75% prevalence rate of dental and skeletal fluorosis, posing a significant public-health and safe-water challenge. To address this issue, this study investigates the design and optimization of a regenerable ion-exchange system to selectively remove fluoride in groundwater in collaboration with the Nelson Mandela African Institution of Science and Technology (NM-AIST) in Tanzania and the University of Leeds in England. My work was two-fold by (1) determining the best resin material with the highest fluoride absorbance and testing it with locally-available alternatives and by (2) optimizing conditions to regenerate resin after fluoride capture for re-use.

A simulated groundwater recipe was refined in order to mimic water conditions in the northern Tanzanian region and multiple different charged resins were assayed for affinity of binding to fluoride ions. The best performing resin, an aluminum-loaded iminodiacetate (IDA-Al) achieved a fluoride adsorption capacity of approximately 4 mg F^{-} g^{-1}–about ten times more than tested local biochars and bone chars. Large-scale column experiments with the resin further demonstrated that increasing column volume significantly enhanced groundwater treatment capacity prior to fluoride breakthrough, supporting our model’s potential for community-scale treatment.

To study resin reuse, regeneration studies evaluated 5 different eluents: bicarbonate, sodium hydroxide, sodium chloride brine, and oxalate. Sodium hydroxide achieved the quickest fluoride recovery from saturated resin (8 mg*mL/L), demonstrating its potential for efficient resin regeneration. Overall, the results demonstrate that regenerable IDA-Al ion-exchange technology is a promising, scalable, and sustainable solution for fluoride removal from contaminated groundwater. Ongoing work focuses on field validation, cost optimization, and pilot-scale deployment in communities surrounding Mt. Meru, Tanzania, to support the development of locally deployable drinking water treatment systems.

II. Introduction and Background

Elevated fluoride concentrations in drinking water is a persistent public-health concern in northern Tanzania, particularly in communities surrounding Mount Meru in the Arusha Region. Groundwater is a principal source of domestic water in Tanzania and supplies more than 80% of daily water production in Arusha; consequently, groundwater quality directly affects drinking-water security for a large proportion of the local population (Bennett et al., 2021; Chacha et al., 2018). Although fluoride can be beneficial to dental health at low concentrations, the World Health Organization (WHO) recommends a maximum concentration of 1.5 mg/L in drinking water. Chronic consumption above this guideline can cause dental fluorosis and, at higher or prolonged exposures, skeletal fluorosis (Bakar et al., 2025, Figure 1).

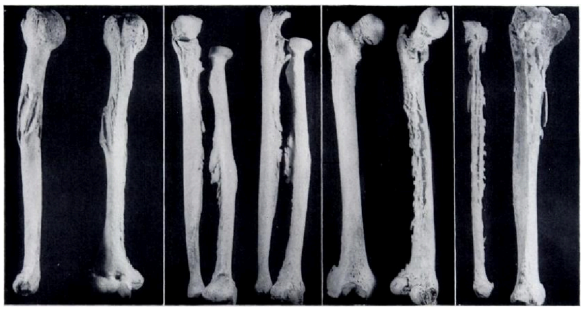

Figure 1. Radiographs illustrating skeletal fluorosis, characterized by abnormal bone thickening, increased density, and irregular bony outgrowths following prolonged exposure to elevated fluoride concentrations in drinking water (Singh et al., 1962).

The fluoride contamination in Arusha is largely geogenic. The region lies within the East African Rift System and is characterized by volcanic aquifers associated with Mount Meru. Weathering and dissolution of fluoride-bearing volcanic minerals, including fluorite and fluorapatite, can release fluoride into groundwater. These processes are promoted by the region's alkaline, sodium-bicarbonate-rich groundwater chemistry and low calcium and magnesium concentrations, which favor continued fluoride dissolution (Bennett et al., 2021; Chacha et al., 2018). Earlier work in Arusha similarly found concentrations as high as 68 mg/L in alkaline volcanic zones and reported that 82% of analyzed groundwater samples exceeded 1.5 mg/L (Chacha et al., 2018).

In order to address this persistent issue, my work, in collaboration with the Nelson Mandela African Institution of Science and Technology (NM-AIST) and the University of Leeds' , is to use chemical techniques by developing a water treatment and purification technology to remove fluoride from groundwater (Figure 2). My research objectives were three-fold:

(1) Design and optimization of an ion exchange system via resin beads that selectively removes fluoride from groundwater.
(2) Develop a sustainable method to regenerate resin for reuse after fluoride saturation.
(3) Conduct a techno-economic analysis to determine feasibility of enabling a large-scale ion exchange vessel on-site in Arusha, Tanzania.

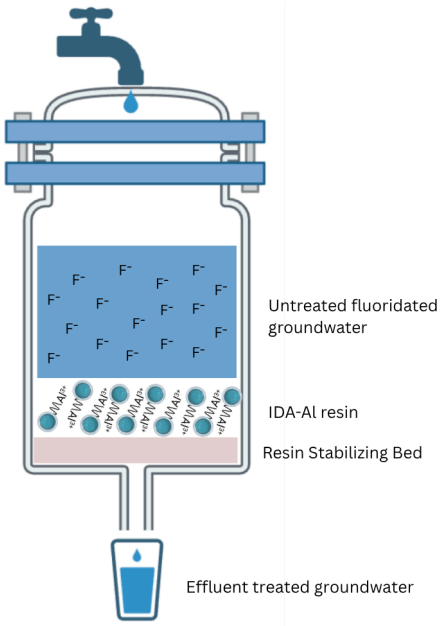

Figure 2: Schematic Model of Ion-Exchange Fluoride Recovery System

III. Methodology

The overall project contains two phases; the first phase involves benchtop research in order to optimize the ion-exchange model for maximum efficiency while the second phase is pilot-scale deployment of the ion-exchange vessel in communities in the Mount Meru region. My summer research primarily focused on completing phase 1.

A. Biochar Comparison Studies

For all experiments, a simulant groundwater was made based on samples of groundwater in Mt. Meru, which consists of competing ions, like Magnesium Sulfate ($MgSO_4$), Sodium bicarbonate ($NaHCO_3$), Potassium Chloride (KCl), etc. Past research conducted by other experimenters involved identified an ion-exchange resin that would selectively and efficiently absorb fluoride in the simulant groundwater; based on these experiments, the IDA-Al^{3+} (Iminodiacetic Acid-Aluminum) chelating resin as the strongest performing fluoride capture technology at both low and high fluoride concentrations compared to other ligand-metal systems. Following resin finalization, I compared the IDA-Al^{3+} resin with naturally occurring local biochar materials; I selected water hyacinth and miscanthus and added a known mass of all three absorbents in different concentrations of simulant groundwater and mixed the suspensions over time. A fluoride absorbent capacity (Qe) was calculated for all the samples both before and after using the equation in Equation 1.

$$q_e = \frac{(C_0 \text{ (initial fluoride concentration)} - C_e \text{ (equilibrium fluoride concentration)})\, V \text{ (solution volume)}}{m \text{ (resin mass)}}$$

Equation 1: Fluoride absorption capacity (Qe)

B. Isotherm Modelling

Using the absorption capacity equation from earlier, batch adsorption isotherm experiments were conducted to quantify the equilibrium fluoride-removal capacity of the IDA-Al Fluoride solutions, which were prepared at a range of initial concentrations using sodium fluoride dissolved in deionized water or simulated groundwater. Equal volumes of each fluoride solution were added to separate containers containing a fixed mass of preconditioned resin. Samples were agitated at room temperature for a standardized contact period sufficient to reach adsorption equilibrium.

Following equilibration, the resin was separated from the solution and the final fluoride concentration was measured using a fluoride ion-selective electrode. Prior to analysis, samples were mixed with total ionic strength adjustment buffer (TISAB) to control solution pH and ionic strength and to minimize interference from multivalent ions. The resulting absorption capacity (Qe) and final fluoride concentration (Ce) were fitted into adsorption-isotherm models including the Langmuir, Freundlich, and Redlich-Peterson models. Model fit was mathematically evaluated using the coefficient of determination (R^2) to identify the model that best describes fluoride absorption by the resin. Modelling allows us to better understand how fluoride is absorbed chemically.

C. Elution and Regeneration Analysis

The primary goal of the resin is being able to regenerate it after it's saturated with fluoride so it can be reused sustainably. Saturated resin was retained in the column and exposed to a series of regenerant solutions to evaluate their ability to desorb fluoride and restore adsorption capacity. Sodium bicarbonate, sodium hydroxide, sodium chloride brine, and oxalate solutions were screened as potential regenerants because they can alter solution pH, ionic strength, or competitive-ion concentrations and thereby promote fluoride release from the resin.

Each regenerant was pumped through the saturated resin column at a controlled flow rate. Eluents were collected in sequential fractions, and the fluoride concentration in each fraction was measured using a fluoride ion-selective electrode after addition of TISAB. Fluoride elution profiles

were generated by plotting fluoride concentration against cumulative eluent volume. Total fluoride recovered during regeneration was calculated by summing the fluoride mass present in all collected fractions:

D. Large Column Scale-up

While most IDA-Al ion-exchange resin experiments were evaluated in a 5mL column, I also conducted a 20-fold large-scale fixed-bed column experiment to evaluate the performance of IDA-Al ion-exchange resin under conditions that were more representative of the practical groundwater treatment. A larger column was packed with a known mass of resin and operated using fluoride-contaminated groundwater at a controlled flow rate. The column influent fluoride concentration was measured before treatment, while effluent samples were collected at regular intervals throughout the experiment.

Breakthrough was defined as the point at which effluent fluoride exceeded the selected treatment target, such as the World Health Organization drinking-water guideline of 1.5 mg/L. The total volume of water treated before breakthrough was used to estimate the practical treatment capacity of the resin bed. These results were compared with small-column experiments to determine how column dimensions, resin mass, bed depth, and flow conditions affected fluoride removal and breakthrough behavior during scale-up.

E. Technoeconomic Analysis

A technoeconomic analysis was conducted to estimate the feasibility of implementing an IDA-Al ion-exchange system for on-site groundwater defluoridation in Arusha, Tanzania. The analysis incorporated treatment performance data from the large-scale column experiments, including fluoride adsorption capacity, treated-water volume before breakthrough, resin mass, and regeneration frequency.

Capital expenditures were estimated for the equipment required to construct and operate the treatment system, including the ion-exchange vessel, IDA-Al resin, pumps, tubing and fittings, pH and fluoride ion-selective electrode probes, and installation. Operating expenditures included regeneration chemicals, replacement resin, pumping requirements, water used during regeneration and rinsing, and routine monitoring. Costs were obtained from supplier quotations or published pricing and converted into a total estimated system cost.

Overall, each step of the experimental process is modelled in Figure 3.

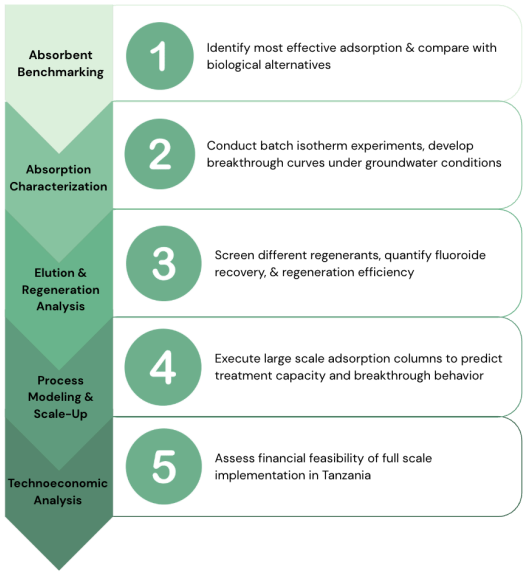

Figure 3: Experimental workflow used to evaluate and scale ion-exchange technology for fluoride removal from groundwater

IV. Results & Discussion

A. Biochar Comparison Studies

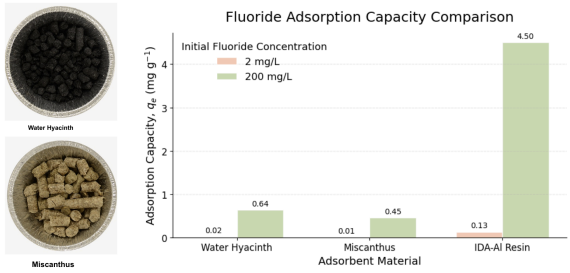

Figure 4: Fluoride adsorption capacities of water hyacinth biochar, miscanthus biochar, and IDA-Al

ion-exchange resin at initial fluoride concentrations of 2 and 200 mg/L

Fluoride adsorption capacities were compared for water hyacinth biochar, miscanthus biochar, and IDA-Al ion-exchange resin at initial fluoride concentrations of 2 and 200 mg/L (Figure 4). At 2 mg/L fluoride, all materials exhibited limited adsorption capacity: water hyacinth biochar adsorbed 0.02 mg F^- g^{-1}, miscanthus biochar adsorbed 0.01 mg F^- g^{-1}, and IDA-Al resin adsorbed 0.13 mg F^- g^{-1}.

Adsorption increased at the higher initial fluoride concentration of 200 mg/L. Water hyacinth and miscanthus biochars achieved adsorption capacities of 0.64 and 0.45 mg F^- g^{-1}, respectively. In contrast, IDA-Al resin reached an adsorption capacity of 4.50 mg F^- g^{-1}, approximately seven times greater than water hyacinth biochar and ten times greater than miscanthus biochar under the same conditions.

B. Isotherm Modeling

Fluoride adsorption by IDA-Al resin was modeled using BET, Redlich-Peterson, Dubinin-Radushkevich (D-R), Langmuir, Freundlich, and Temkin isotherms for both sodium fluoride (NaF) solutions and groundwater samples (Figures 5 and 6). In both matrices, the BET model provided the strongest fit to the experimental data, with (R^2) values of 0.9976 for NaF and 0.9868 for groundwater. The close agreement between the BET model and the measured data indicates that fluoride adsorption was not fully described by a simple homogeneous, single-layer adsorption process.

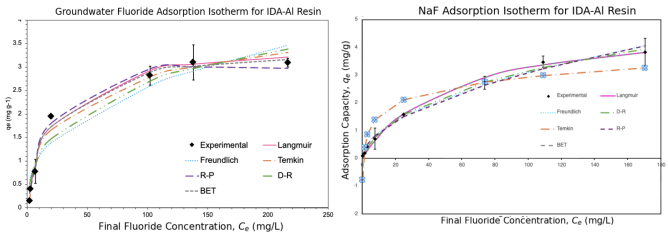

Figure 5. Equilibrium fluoride adsorption isotherm for IDA-Al resin in groundwater and NaF solution.

Model	NaF R^2	Groundwater R^2
BET	**0.9976**	**0.9868**
Redlich-Peterson	0.9892	0.9842
D-R	0.9961	0.9483
Langmuir	0.9948	0.9331
Freundlich	0.9887	0.8569
Temkin	0.8564	0.8749

Figure 6. R-squared values for fitted isotherm models

In comparison, the lower fit of the Freundlich and Temkin models, particularly for groundwater, indicates that a purely heterogeneous empirical model or a model based primarily on changing adsorption energy did not describe the data as effectively.

Groundwater produced a slightly weaker BET model fit ((R^2 = 0.9868)) than the NaF solution ((R^2 = 0.9976)), likely because natural groundwater contains dissolved ions that are absent from a simplified NaF solution. Major ions such as bicarbonate, sulfate, chloride, calcium, magnesium, sodium, and potassium can affect fluoride adsorption by competing for exchange sites, changing ionic strength, or altering fluoride speciation and its interaction with the resin.

C. Elution and Regeneration Analysis

Four regenerant solutions—bicarbonate, 0.1 M sodium hydroxide (NaOH), oxalate, and sodium chloride (NaCl) brine—were evaluated for their ability to elute fluoride from saturated IDA-Al resin (Figure 7). Oxalate produced the greatest cumulative fluoride recovery, with a reported total recovery of 142.72 mg, and maintained relatively high fluoride concentrations throughout much of the 180 mL elution period. Although oxalate produced the highest cumulative fluoride recovery, it required a substantially larger volume of regenerant and therefore a greater chemical input. This higher chemical demand would increase operating costs and generate a larger volume of regeneration waste, reducing oxalate's practicality for routine treatment. In contrast, 0.1 M NaOH produced the highest fluoride concentrations in the early elution fractions and achieved efficient fluoride removal with a much smaller eluent volume. Therefore,

NaOH was selected as the more practical regenerant overall.

A key limitation of NaOH regeneration is that the alkaline waste stream must be neutralized before disposal. Hydrochloric acid (HCl) would be required to buffer the spent NaOH solution to an appropriate pH, adding a further chemical, cost, and safety consideration to system operation. Nevertheless, the lower NaOH volume requirement and more concentrated initial fluoride recovery make it a preferable regeneration strategy relative to oxalate for a scaled treatment system.

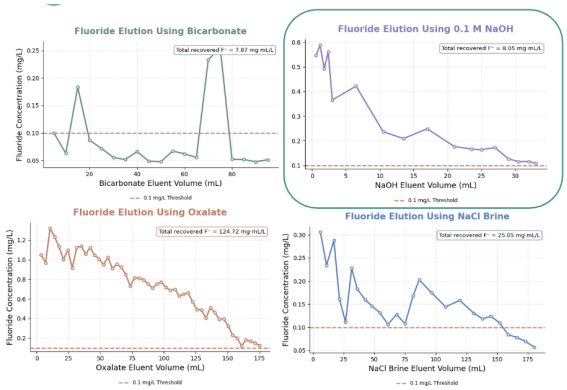

Figure 7: Fluoride elution profiles for saturated IDA-Al resin regenerated with bicarbonate, 0.1 M NaOH, oxalate, or NaCl brine.

D. Large Column Scale-up

The large-scale IDA-Al resin column experiment was done to verify the scalability of the ion exchange model. Results show that it maintained effluent fluoride concentrations below the WHO drinking-water guideline of 1.5 mg/L for approximately 330 mL of groundwater loading (Figure 8). After this point, fluoride concentrations increased rapidly, reaching approximately 250 mg/L as the resin approached saturation. Compared with the small-scale 5 mL column, the larger column treated substantially more groundwater before breakthrough, demonstrating the benefit of increased resin bed volume for practical fluoride treatment.

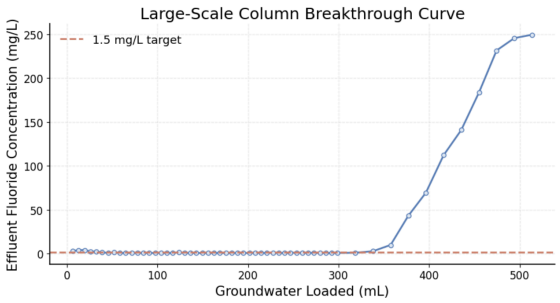

Figure 8: Breakthrough curve for the large-scale IDA-Al resin column (115 mL) treating fluoride-contaminated groundwater

E. Technoeconomic Analysis

Equipment	Units required	Price per unit (£)	Price (£)
Resin (IDA-functionalized, Al-loaded)	0.059 m³	1,000/m³	44
Pumps	2 pumps	5,945	11,891.6
Loading ion-exchange vessel (20 gal / 90 L)	1 vessel	150–350	150–350
pH probe	1 probe	135	135
Fluoride ISE probe	1 probe	434	434
Installation	—	—	4,048–4,108

Note
Shipping costs are not included.
Costs shown in pounds sterling (£).

DISPLAYED TOTAL **£16,673**

Figure 9. Estimated capital expenditure for the loading vessel in a two-vessel ion-exchange defluoridation system.

Equipment	Units required	Price per unit (£)	Price (£)
NaOH (elution chemical)	354 L of 0.1 M / 1.42 kg	£0.50 per kg	£0.71
HCl (neutralization chemical)	354 L of 0.1 M / 1.29 kg	£0.50 per kg	£0.645
Pumps	2 pumps	5,945	11,891.6
Loading ion-exchange vessel (20 gal / 90 L)	—	150–350	150–350
pH probe	1 probe	135	135
Fluoride ISE probe	1 probe	434	434
Installation	—	—	4,048–4,108

Note
Shipping costs are not included.
Costs shown in pounds sterling (£).

DISPLAYED TOTAL **£16,660**

Figure 10. Estimated capital expenditure for the elution and regeneration vessel in a two-vessel ion-exchange defluoridation system.

A preliminary capital-expenditure analysis was conducted to provide stakeholders with a transparent estimate of the equipment and chemical requirements for an on-site ion-exchange defluoridation system in Arusha. The system was designed as a two-vessel configuration: one 20 gal

(approximately 90 L) vessel operates in loading mode to continuously defluoridate groundwater, while a second vessel undergoes fluoride elution and resin regeneration. This arrangement would allow water treatment to continue while the saturated resin is regenerated.

The analysis assumed a 65% resin bed fill, equivalent to 0.059 m^3 of IDA-functionalized, Al-loaded resin per vessel. Daily water demand was estimated at 10-20 L per person for drinking and cooking, corresponding to an estimated 24 people served per system. Capital costs included resin, two pumps, the ion-exchange vessel, pH and fluoride ion-selective electrode probes, and installation. The loading vessel was estimated to require £16,673 in capital expenditure, while the regeneration vessel was estimated at £16,660. The small difference reflects the additional costs of NaOH elution and HCl neutralization chemicals in the regeneration process. Shipping costs were not included.

V. Conclusion & Future Plans

The IDA-Al resin was the most effective adsorbent tested, reaching a fluoride adsorption capacity of approximately 4.5 mg $F^- g^{-1}$ at 200 mg/L fluoride. This was substantially higher than the capacities of water hyacinth and miscanthus biochars, supporting its selection for the remaining treatment experiments. The BET model best described fluoride adsorption in both NaF solution and groundwater, although the groundwater data showed slightly more variability because naturally occurring ions likely competed with fluoride for resin exchange sites. Large-column testing also demonstrated that increasing resin-bed size increased the volume of groundwater treated before fluoride breakthrough occurred.

Oxalate achieved the highest fluoride recovery during regeneration, but its use required a much larger chemical volume. NaOH was therefore identified as the more practical regenerant because it produced efficient fluoride elution with less chemical input. The main limitation is that spent NaOH must be neutralized with HCl before disposal. The preliminary technoeconomic analysis suggests that a two-vessel ion-exchange system could be feasible for small-scale, on-site implementation in Arusha, with one vessel treating groundwater while the second is regenerated.

Future work will focus on repeated loading and NaOH-regeneration cycles to determine whether the resin maintains its fluoride-removal capacity over time. The cost model should also be refined using local prices, shipping costs, maintenance requirements, chemical availability, and wastewater-disposal considerations. Pilot-scale testing with groundwater from communities surrounding Mount Meru will be important for confirming performance outside the laboratory. Finally, stakeholder engagement will be needed to understand household water use, treatment preferences, and practical barriers that could affect adoption of an ion-exchange treatment system.

This research is significant as it goes beyond simply identifying fluoride as a water-quality problem and evaluates a treatment approach under conditions that are closer to real implementation. By comparing low-cost biochars with a higher-performing resin, testing adsorption in groundwater, examining regeneration options, scaling up column treatment, and estimating costs, this project provides a more complete assessment of whether ion exchange can be used in affected communities. The results support IDA-Al resin as a promising option for reducing fluoride exposure in areas surrounding Mount Meru, where groundwater remains an essential drinking-water source.

VI. Acknowledgements

I would like to thank the Laidlaw Foundation as well as the Hart Leadership Program at Duke University, primarily Dr. Lucy Ballard and Dr. Andrew Nurkin for allowing me to travel to England and conduct this research. I am also very grateful for my supervisor, Dr. Thomas Robshaw, for his daily guidance and support throughout the research and experimental process.

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