

## Introduction

Groundwater in Tanzania frequently exceeds the WHO fluoride limit of 1.5 mg/L, with concentrations in some regions surpassing 30 mg/L. Chronic exposure causes dental and skeletal fluorosis and has been associated with impaired neurodevelopment in children.<sup>1,3</sup>

Natural fluoride originates primarily from volcanic and geothermal rock formations, and its removal from groundwater is challenging due to the small ionic size and high hydration energy of  $F^-$ .<sup>2</sup> Conventional techniques—such as bone char filtration and reverse osmosis—are either culturally unsuitable, inefficient at low concentrations, or prohibitively expensive for rural deployment.<sup>3</sup>

This project, part of the **TUDAY (Tanzania–UK Defluoridation by Adsorption and recoveryY)** initiative, develops **metal-loaded ion-exchange resins** to selectively capture and recover fluoride from groundwater. By optimizing adsorption chemistry and integrating community input, the project aims to create a **socially equitable, low-cost, and sustainable** defluoridation system that addresses both technical performance and long-term public health impact.

## Objectives

- Evaluate the fluoride **removal efficiency of metal-loaded chelating ion-exchange resins**.
- Compare **performance under batch and continuous-flow (column) conditions**.
- Assess **adsorption capacity**, regeneration potential, and social acceptance in Tanzanian field settings.

## Methods and Processes

### 1. Adsorbent Selection and Rationale

Three macroporous **cation-exchange resins**—AMPA, IDA, and SULF—were functionalized with  $Al^{3+}$ ,  $Ce^{3+}$ , and  $La^{3+}$  to enhance **fluoride binding**.<sup>4</sup> Each resin–metal combination was synthesized through pH-controlled coordination, washed to remove unbound ions, and analyzed using inductively coupled plasma (ICP) to verify metal loading efficiency.

Batch adsorption and continuous-flow column experiments were conducted using simulant groundwater based on conditions representative of Tanzanian aquifers [4]. The IDA– $Al^{3+}$  resin demonstrated the strongest affinity for fluoride ions, consistent with the Hard–Soft Acid–Base (HSAB) model described by Bhatnagar et al.<sup>2</sup>

### 2. Experimental Workflow

Batch adsorption experiments were conducted using simulant groundwater at **low** ( $\sim 1 \text{ mg L}^{-1}$ ) and **high** ( $\sim 20 \text{ mg L}^{-1}$ ) fluoride concentrations. Samples were equilibrated under constant agitation for 24 h, and residual fluoride concentrations were measured with a **fluoride ion-selective electrode** after filtration. Adsorption capacity ( $q_e$ ) was calculated from mass-balance relationships.

The top-performing resin (IDA– $Al^{3+}$ ) was further tested under **continuous-flow column conditions** ( $10 \text{ mg L}^{-1}$  influent;  $1 \text{ mL min}^{-1}$  flow). Effluent samples were periodically collected to construct **breakthrough curves**, determining mass-transfer behavior and saturation capacity. Post-run, the resin was regenerated with mild acid and evaluated for recovery efficiency and metal stability across cycles.

### 3. Field Engagement and Integration

To ensure that technical solutions align with community needs, a field visit was conducted to the **Nelson Mandela African Institution of Science and Technology (NM-AIST)** and nearby rural Tanzanian communities in **July 2025**. This visit included meetings with local water councils, households, and regional engineers to understand current water infrastructure, fluoride exposure levels, and maintenance challenges.

Community focus groups were used to assess perceptions of existing defluoridation methods. **Bone char** was often viewed as culturally unsuitable due to its animal origin, whereas **ion-exchange resins** were perceived as clean, modern, and easier to maintain. The findings from these engagements directly informed resin design priorities—favoring neutral, regenerable materials and modular column systems—and guided the development of an adoption framework emphasizing affordability, local training, and long-term sustainability.

## Results

### 1. Batch Adsorption Studies

Three ligand–metal combinations (AMPA, IDA, SULF  $\times Al^{3+}$ ,  $La^{3+}$ ,  $Ce^{3+}$ ) were tested under low ( $\sim 1 \text{ mg/L}$ ) and high ( $\sim 20 \text{ mg/L}$ ) fluoride conditions.

- IDA– $Al^{3+}$  exhibited the highest adsorption capacity across both regimes:
    - $q_e = 0.13 \text{ mg/g}$  (low  $F^-$ )
    - $q_e = 4.5 \text{ mg/g}$  (high  $F^-$ )
  - AMPA– $Al^{3+}$  followed closely ( $q_e \approx 3.7 \text{ mg/g}$ ), while  $Ce^{3+}$  and  $La^{3+}$  systems showed negligible uptake.
  - $Al^{3+}$  complexes consistently outperformed  $Ce^{3+}$  and  $La^{3+}$ , validating the Hard–Soft Acid–Base (HSAB) model predicting strong Al–F interactions.
- These results identified IDA– $Al^{3+}$  as the lead candidate for scale-up and further testing. (See Fig. 2A–B: adsorption capacities of low and high fluoride samples.)

### 2. Column (Continuous-Flow) Experiments

- A fixed-bed column packed with IDA– $Al^{3+}$  resin was evaluated under steady influent fluoride concentration ( $10 \text{ mg/L}$ ,  $1 \text{ mL/min}$ ).
- The **breakthrough curve** displayed a distinct sigmoidal shape with a long **mass transfer zone**, confirming strong binding and gradual saturation.
  - **High initial removal efficiency** persisted through the first 90 mL of effluent.
  - Complete saturation occurred at  **$\sim 196 \text{ mL}$** , after which effluent concentration plateaued.
  - The extended adsorption region indicates **diffusion-limited kinetics** and excellent resin stability under flow.

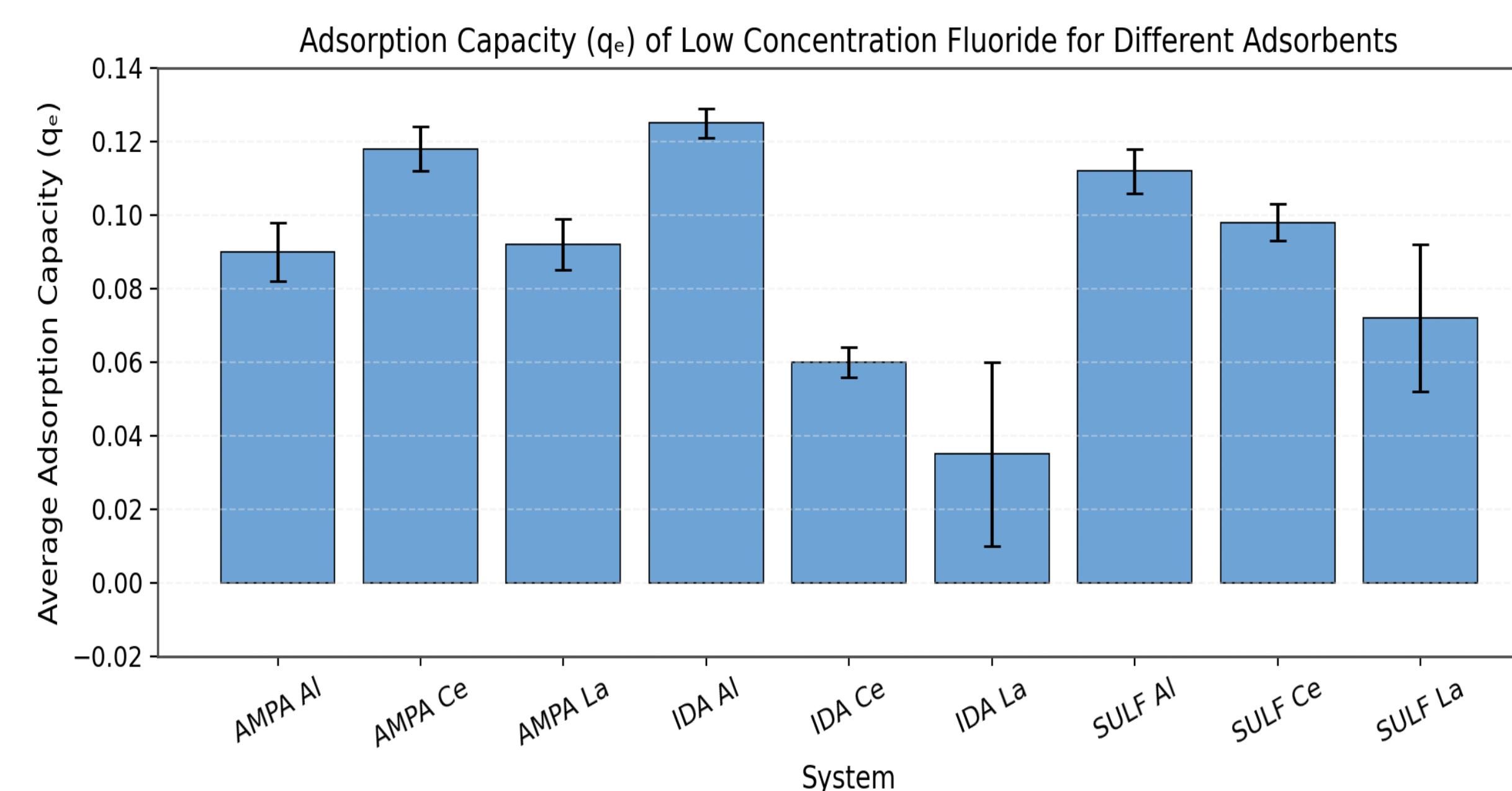
(See Fig. 3: breakthrough profile for IDA– $Al^{3+}$  system.)

### 3. Community Feedback and Field Insight

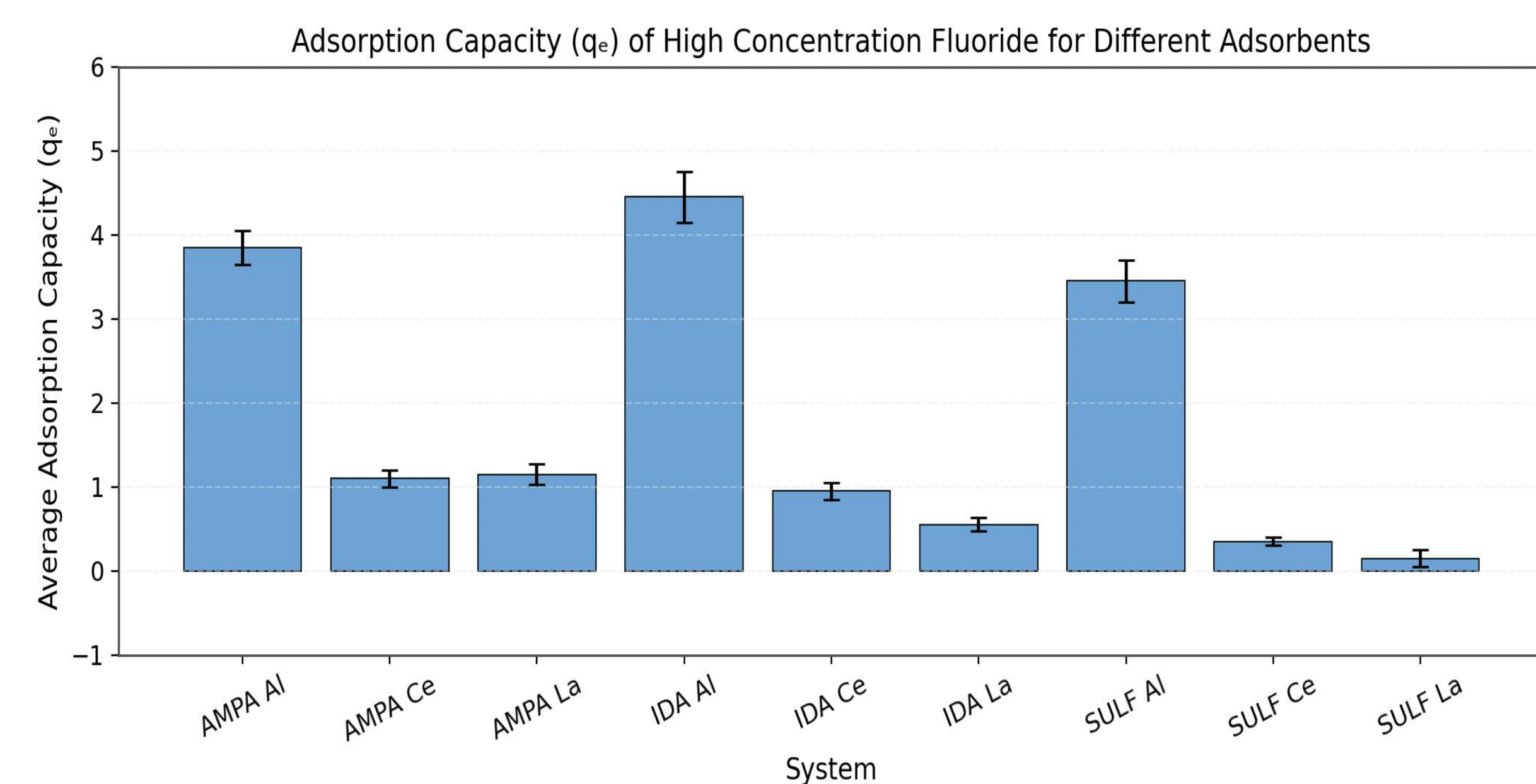
During the July 2025 field visit to NM-AIST and surrounding villages, focus groups discussed technology acceptance.

- **Bone char** was viewed as unsustainable due to reliance on animal byproducts and cultural resistance.
- **Ion-exchange resins** were perceived as cleaner, modern, and more easily maintained at community scale.

These findings support the long-term viability and social compatibility of resin-based fluoride treatment systems in Tanzanian rural contexts.



**Fig 2A.** Adsorption capacity ( $q_e$ ) of low-concentration fluoride ( $1 \text{ mg L}^{-1}$ ) across ligand–metal resin systems. IDA– $Al^{3+}$  shows the highest capacity, followed by SULF– $Al^{3+}$  and AMPA– $Ce^{3+}$ .



**Fig 2B.** Adsorption capacity ( $q_e$ ) of high-concentration fluoride ( $20 \text{ mg L}^{-1}$ ). IDA– $Al^{3+}$  maintains the greatest adsorption ( $\sim 4.4 \text{ mg g}^{-1}$ ), confirming strong Al–F binding under higher loads.

## Discussion

The superior performance of the IDA– $Al^{3+}$  resin demonstrates that metal-chelated ion-exchange materials can offer a scalable and sustainable pathway for fluoride remediation in resource-limited settings. Its strong binding affinity and extended breakthrough profile highlight both thermodynamic stability and kinetic resilience under continuous operation—key requirements for real-world implementation in rural Tanzanian groundwater systems.

From a **technical perspective**, these findings validate the potential of functionalized resins as an alternative to traditional adsorbents like bone char or activated alumina, which are limited by regeneration cost and social acceptability. Future work will focus on optimizing column design for field-scale deployment, improving resin regeneration cycles, and quantifying selectivity against co-existing ions (e.g., sulfate, phosphate) that affect adsorption in natural groundwater.<sup>3</sup> The integration of this system into modular community-scale filtration units could enable decentralized water treatment adaptable to local flow rates and chemical conditions.

From a **social and non-technical standpoint**, the use of synthetic polymer resins aligns with the TUDAY initiative’s goal of ensuring not only chemical efficacy but also cultural and economic sustainability. Unlike bone-based materials, the IDA– $Al^{3+}$  system avoids ethical and cultural concerns while maintaining affordability through reusability. Partnering with Tanzanian engineers and community organizations will be critical to co-develop resin production and maintenance frameworks that foster local ownership and long-term viability.<sup>4</sup>

Looking forward, the methodology developed here can extend beyond fluoride to other priority contaminants such as arsenic or nitrate by tailoring ligand–metal pairs for selective adsorption. The adaptability of the resin synthesis process enables broader environmental applications, from groundwater purification to industrial wastewater recovery. Ultimately, this study advances both the **scientific foundation and social translation** of sustainable water treatment technologies, bridging the gap between laboratory performance and community impact.

## Conclusion

This study identifies IDA– $Al^{3+}$  as the most effective fluoride adsorbent among nine tested metal–ligand resin systems, exhibiting superior performance in both low- and high-concentration conditions and demonstrating strong breakthrough behavior under continuous flow. These results validate the promise of **metal-chelated ion-exchange resins** as scalable, regenerable, and socially acceptable solutions for rural groundwater defluoridation.<sup>5</sup>

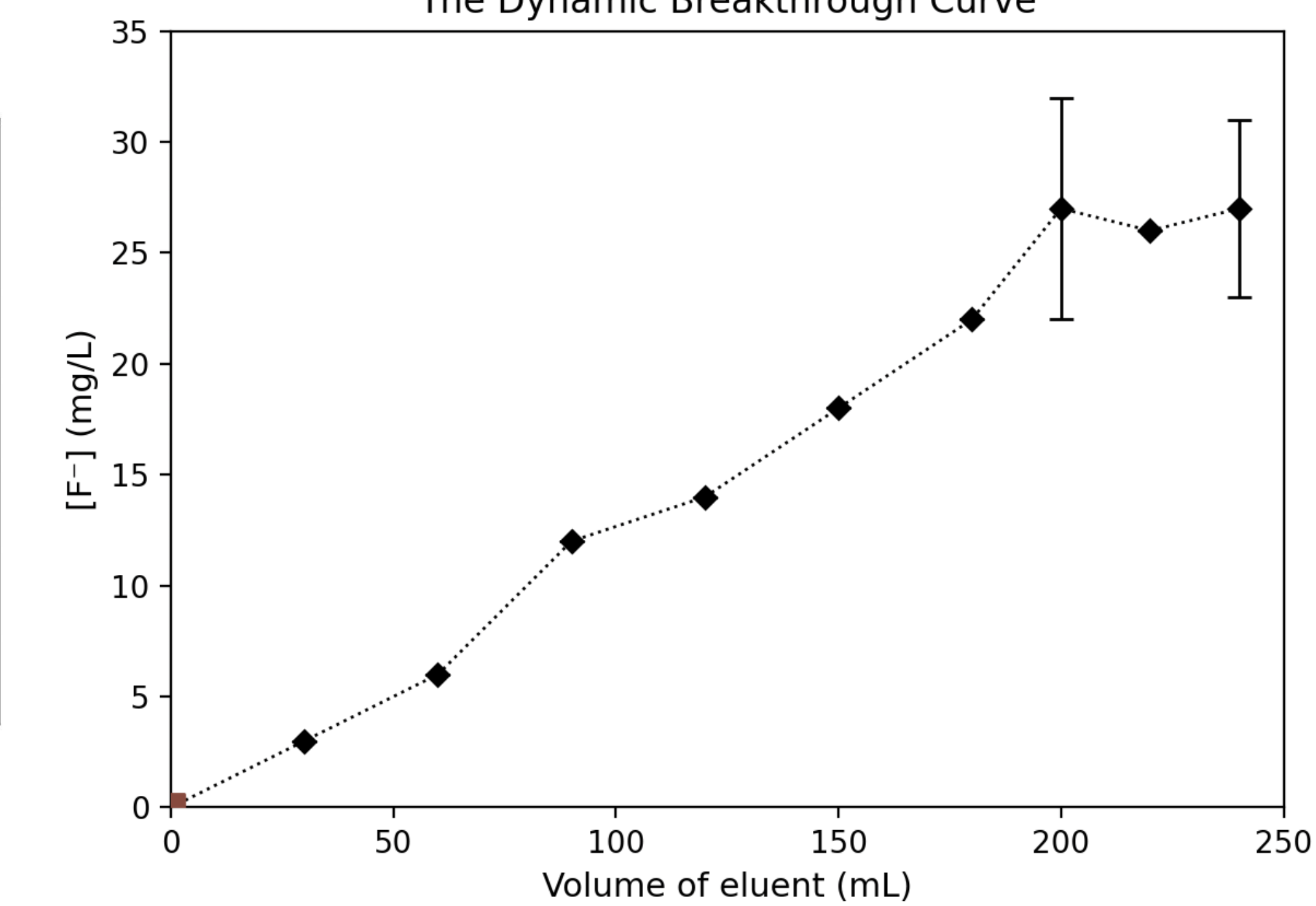
The workflow developed here—from batch testing to column validation—provides a transferable framework for evaluating future ligand–metal combinations. Ongoing work will focus on **field-scale application in Tanzanian water sources**, improving **regeneration efficiency**, and exploring **cross-contaminant selectivity** to extend this approach to other water quality challenges.

## Acknowledgements

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### The Dynamic Breakthrough Curve



**Fig 3.** Dynamic breakthrough curve of IDA– $Al^{3+}$  under continuous flow. Fluoride saturation occurs near 200 mL, indicating efficient uptake and diffusion-controlled kinetics.

## References

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**Fig 1.** Workflow for evaluating metal-loaded chelating resins through batch and column experiments to identify the most effective fluoride adsorbent (IDA– $Al^{3+}$ ).