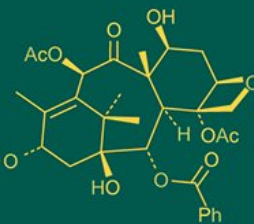
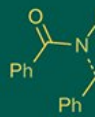


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## Sustainable fluoride removal from water using banana leaf-derived adsorbents

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### Abstract

Drinking water can excess contain fluoride, either from geogenic or anthropic sources, causing dental and skeletal fluorosis. In fluoride endemic locations, defluoridation is essential, however, it implies the usage of expensive methods with complex equipment, for instance, coagulation-precipitation, ion exchange and membrane filtration processes. Bioadsorption, a green and cheap technique of using natural materials for fluoride removal can serve as a possible tool for addressing the problem. The present research focuses on the effectiveness of banana leaf powder and banana leaf biochar in fluoride removal.

The present study included comparison of the efficiency of the removal of fluoride from water using banana leaf powder, banana leaf biochar and alum. Ion-selective electrodes were used for fluoride determination, while the experiments were related to the adsorption of fluoride from aqueous solutions containing varying concentrations of the substance. The results show that banana leaf biochar has the maximum fluoride removal efficiency.

The characterization of the bioadsorbents has been done in terms of pH value, point zero charge and FTIR spectroscopy. The results show that banana leaf powder and biochar have functional groups such as -OH groups that help in fluoride adsorption. The study reports that banana leaf biochar can be used as a sustainable, efficient and inexpensive method of fluoride removal, proving to be useful in resource-poor countries

**Keywords:** Banana leaf biochar, bioadsorption, defluoridation, fluoride, FTIR, ion-selective electrode, sustainable

### Introduction

Fluoride is a native element commonly present in several aquifers such as groundwater, surface water and even certain bottled waters. Its presence in aquatic domains predominantly springs from the regular weathering and dissolution of fluoride-rich minerals like fluorite and apatite (Onipe *et al.*, 2021) [21]. Fluoride burden in groundwater is fundamentally of geogenic origin, resulting from the interaction of water with fluoride-laden rocks, comprising granites rich in hornblende, biotite and muscovite near volcanic regions (Hanse *et al.*, 2019) [8]. Groundwater carries fluoride through pore spaces within these rocks, with dissolution, ion exchange and desorption processes playing crucial roles in fluoride convemimg. Further human activities can exacerbate fluoride levels in water bodies. The chemical characteristics of aquifers, particularly the weathering of silicate minerals, nitrate oxidation and sulfate dissolution, contributing to the natural enrichment of fluoride (Yidana *et al.*, 2012) [30]. The interplay of hydrological cycle significantly impacts fluoride concentrations, with stagnant or slow-moving water bodies often evincing elevated fluoride levels due to limited dilution.

In addition to aqueous sources, fluoride can accumulate in crops, fruits and animal-derived food products through soil absorption or consumption of contaminated fodder (Han *et al.*, 2021). In affected areas, excessive fluoride intake may lead to severe health complications, including dental and skeletal fluorosis. The World Health Organization (WHO, 1997) emphasized the narrow limit between beneficial and harmful fluoride levels in drinking water, recommending a maximum permissible limit of 1.5 mg/L to avoid adverse effects (Amereih *et al.*, 2013) [1]. Depending on the fluoride concentration, water quality can be grouped as very good (<1 mg/L), moderate (1-1.5 mg/L), or very poor (>1.5 mg/L), corresponding with the standards set by WHO (1997). Several analytical techniques have been engaged for detection of fluoride levels in water. Colorimetric test strips, widely used

For initial screening, provide a visual estimation of fluoride levels by comparing color changes with a reference scale (Barghouthi and Amereih, 2017) [3]. Ion-selective electrodes (ISEs) are picked due to higher accuracy, although they are relatively expensive (Mondal, 2021) [16]. The process of reducing superfluous fluoride content from drinking water, known as defluoridation, is essential in regions facing elevated natural fluoride burdens or human-induced pollution. In fluoride endemic regions, instant execution of defluoridation strategies is imperative (Wang *et al.*, 2023) [27]. The Nalgonda technique, a widely adopted community-level solution in India developed by NEERI, involves chemical precipitation using aluminum sulfate and lime, with or without phosphate additives (Nawlakhe and Paramasivam, 1993) [20]. Advanced procedures like reverse osmosis (RO) and nanofiltration (NF) utilize semi-permeable membranes to physically separate fluoride based on ionic size and charge, whereas electrodialysis (ED) uses electrical potential to achieve ionic separation (Jagtap *et al.*, 2012) [9]. Ion exchange and adsorption processes are also employed, using specially designed resins or contact beds to selectively extract fluoride ions from water (Yang and Dluhy, 2002; Jamwal and Slathia, 2022) [11, 29]. Bioadsorption has appeared as a particularly attractive approach due to the abundance, restorability and low toxicity of natural biomaterials. Hydrogel beads containing *Zingiber officinale* rhizome extract have achieved up to 98.5% removal efficiency (Srivastava *et al.*, 2020) [25], while *Elettaria cardamomum* and *Coriandrum sativum* seeds also exhibit significant adsorption potential (Santhi *et al.*, 2005; Moradi *et al.*, 2020) [18, 23]. Powdered leaves of *Ocimum sanctum* and ash from *Syzygium cumini* have shown significant fluoride binding capacities, with optimal performance observed at pH ranges near neutrality (Bayu *et al.*, 2022; Tirkey *et al.*, 2020) [4, 26]. The banana plant (*Musa acuminata*) holds particular interest as a bioadsorbent due to its global availability and complex applications. Banana peels, rich in starch, lignin and protein, serve as compelling natural adsorbents for fluoride removal (Fadaei, 2019) [6]. These biopolymers increase fluoride uptake through surface interactions and ion exchange. Banana leaves exhibit notable antioxidant activity, due to the presence of polyphenol oxidase and flavonoids, which protect the plant against oxidative stress (Karpagavalli *et al.*, 2023) [12]. Biochar derived from agricultural waste is another sustainable alternative for fluoride adsorption. Compared to conventional activated carbon, biochar is less energy-intensive and utilizes renewable feedstocks. Biochars made from coffee grounds, rice husks and banana leaves offer promising results due to their high surface area, porosity and functional group diversity, which facilitate effective fluoride binding (Santos *et al.*, 2023; Kumar *et al.*, 2023; Kumar *et al.*, 2021) [13, 14, 24]. These findings highlight the potential of natural and modified bioadsorbents as viable solutions for fluoride remediation, aligning with global efforts toward eco-friendly and cost-efficient water purification technologies.

## Materials and Methods

### Place of experiment

The study was carried out in the Animal Health Laboratory of I.C.A.R.- R.C.E.R., Patna.

### Study design

Fluoride adsorption was studied within batch experimental settings to determine the capability of Banana leaf powder

and biochar for defluorination. For control purposes, distilled water (100 mL) was served as a negative control while alum was employed as a positive control at 300 ppm concentration. The fluoride containing water in the group subjected to treatment involved administering different doses of banana leaf powder and biochar at concentration of  $1 \times 10^4$  to  $20 \times 10^4$  ppm as per the procedure outlined by Mondal (2017) [17]. All treatments were conducted at an established contact period of 60 minutes to allow the adsorption of fluoride ions on the surfaces of the absorbents. The amount of fluoride ions in the treated water samples was examined both prior and after carrying out the process using a fluoride selective electrode (ISE). The effectiveness of each treatment was examined by comparing the quantities of fluoride remaining with their original concentrations, and calculation of the removal percentage of fluoride and adsorption capacity was done. The experimental groups and treatment parameters included in the study are summarized in Table 1.

### Collection of sample

Approximately 1 litre of water was collected in separate clean plastic bottles from five distinct water sources located in Sheikhpura.

### Measurement of fluoride

Fluoride concentration in serum and urine was quantified using an ion-selective electrode (ISE) method (Bard and Faulkner, 2001) [2]. The system employed an Orion 96-09 fluoride-selective electrode and mV meter (Thermo Fisher Scientific, USA). To ensure consistent ionic strength and pH, all standards and samples were mixed with Total Ionic Strength Adjustment Buffer (TISAB) in a 1:1 ratio. A calibration curve was generated using sodium fluoride standards (0.1-20 µg/mL), and sample readings were taken after 1-2 minutes of stabilization.

### Collection of banana leaves

Raw waste banana leaves (*Musa acuminata*) were collected from the ICAR-Research Complex for Eastern Region (ICAR-RCER), Patna Campus.

### Procurement of alum

The alum used in this study was procured from local market.

### Preparation of banana leaf powder (BLP)

Raw banana leaves (*Musa acuminata*) were washed sequentially with tap and deionized water to remove adhering impurities. The leaves were dried in a hot-air oven at 50 °C for 12 h, followed by drying at 60 °C for 24 h to ensure complete moisture removal. The dried material was ground into a fine powder using a grinder and stored in airtight containers until further use (Mondal, 2017) [17].

### Preparation of banana leaf biochar (BLB)

Washed and oven-dried banana leaves (*Musa acuminata*) were subjected to controlled pyrolytic combustion at 450-600 °C on a meshed surface. The combustion process was rapidly quenched with water to prevent further oxidation, and the resulting biochar was separated from ash and air-dried for 12 h. The dried biochar was ground into a fine powder and stored in airtight containers for subsequent analyses (Chun *et al.*, 2021) [5].



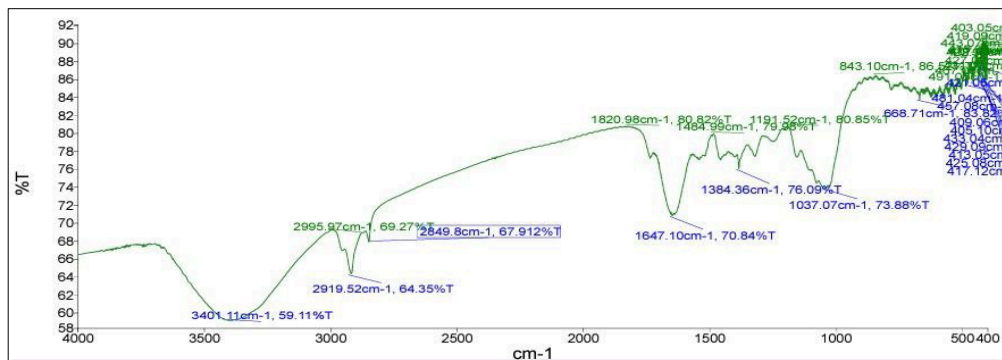


**Fig 2:** FTIR absorbance spectrum of banana leaf biochar

### Adsorption of fluoride

The Adsorption Efficiency (AE) of banana leaf powder, banana leaf biochar, and alum is presented in Table 2, and their fluoride removal performance is illustrated in Figure 3. Banana leaf biochar consistently exhibited higher fluoride adsorption than banana leaf powder across all tested dosages. At  $1 \times 10^4$  ppm, biochar achieved 11.38% fluoride removal compared to 0.00% for leaf powder, while at  $5 \times 10^4$  ppm it was approximately ten-fold more effective (8.00% vs. 0.80%). At higher dosages ( $10^5$ - $2 \times 10^5$  ppm), biochar maintained 1.3-1.7 times greater removal efficiency than leaf powder. Overall, banana leaf biochar demonstrated superior defluoridation potential, although the increase in adsorption capacity diminished with increasing adsorbent dose. The adsorption efficiency of different adsorbents used in the study are listed in Table 3.

### Discussion

Defluoridation of drinking water is essential in fluorosis-endemic regions to reduce fluoride exposure and associated health risks. Although conventional methods such as the Nalgonda technique, which employs alum and lime for fluoride precipitation, are widely used in India, they often involve chemical inputs and sludge management issues (Nawlakhe and Paramasivam, 1993) [20]. Consequently, bioadsorbents have gained attention as economical, eco-friendly, and readily available alternatives for fluoride removal (Yihunu *et al.*, 2019) [31].

In the present study, banana (*Musa acuminata*) leaf powder and biochar were evaluated as bioadsorbents for fluoride removal. Banana leaf biochar consistently exhibited higher adsorption efficiency than banana leaf powder across all tested dosages, indicating that pyrolysis substantially enhanced the fluoride adsorption potential of the biomass. Similar applications of banana-derived adsorbents have been reported previously by Mondal (2017) and Kumar *et al.* (2021) [14, 16].

The superior performance of banana leaf biochar can be attributed to its favorable physicochemical properties. Biochar exhibited a higher pH (9.08) than banana leaf powder (6.36), creating conditions that favor fluoride adsorption (Jain and Singh, 2014) [10]. In addition, the higher adsorption efficiency and adsorption capacity observed for biochar indicate a greater affinity for fluoride ions over the entire dosage range tested.

FTIR analysis further revealed the presence of abundant hydroxyl and other oxygen-containing functional groups on both adsorbents, with biochar exhibiting more prominent absorption bands associated with surface hydroxyl functionalities. These groups provide active adsorption sites

and facilitate fluoride binding through hydrogen bonding, electrostatic interactions, and surface complexation mechanisms (Mondal, 2021) [16]. Furthermore, the pyrolysis process enhances the porosity and surface area of biochar, increasing the availability of adsorption sites and improving fluoride uptake (Santos *et al.*, 2023) [24].

Overall, the results demonstrate that banana leaf biochar is a more effective fluoride adsorbent than untreated banana leaf powder and has considerable potential as a sustainable, low-cost material for water defluoridation.

**Table 1:** Study groups of the experiment

| Group | Treatment                          | Dose/Concentration   |
|-------|------------------------------------|----------------------|
| NC    | Distilled water (Negative Control) | 100 mL               |
| PC    | Alum (Positive Control)            | 300 ppm              |
| T1    | Banana leaf powder/biochar         | $1 \times 10^4$ ppm  |
| T2    | Banana leaf powder/biochar         | $5 \times 10^4$ ppm  |
| T3    | Banana leaf powder/biochar         | $10 \times 10^4$ ppm |
| T4    | Banana leaf powder/biochar         | $15 \times 10^4$ ppm |
| T5    | Banana leaf powder/biochar         | $20 \times 10^4$ ppm |

**Table 2:** Characterization parameters of banana leaf powder and banana leaf biochar

| Parameter         | Banana Leaf Powder | Banana Leaf Biochar |
|-------------------|--------------------|---------------------|
| pH                | 6.36               | 9.08                |
| pH <sub>pzc</sub> | 4.89               | 8.76                |

**Table 3:** Adsorption efficiency (Ae) of different adsorbents

| Adsorbent           | Dose (ppm)       | C <sub>0</sub> (mg/L) | C <sub>e</sub> (mg/L) | Removal (%) | q <sub>e</sub> (mg/g) |
|---------------------|------------------|-----------------------|-----------------------|-------------|-----------------------|
| Alum                | 300              | 1.67                  | 1.32                  | 20.96       | 0.1167                |
|                     | 300              | 2.5                   | 2.3                   | 8           | 0.0667                |
|                     | 300              | 2.6                   | 2.49                  | 4.23        | 0.0367                |
|                     | 300              | 3                     | 2.83                  | 6           | 0.0600                |
|                     | 300              | 3.4                   | 3.1                   | 8.82        | 0.1000                |
| Banana Leaf Powder  | $10^4$           | 1.67                  | 1.67                  | 0           | 0.0000                |
|                     | $5 \times 10^4$  | 2.5                   | 2.48                  | 0.8         | 0.0000                |
|                     | $10^5$           | 2.6                   | 2.32                  | 10.77       | 0.0003                |
|                     | $15 \times 10^4$ | 3                     | 2.6                   | 13.33       | 0.0003                |
|                     | $2 \times 10^5$  | 3.4                   | 2.98                  | 12.25       | 0.0002                |
| Banana Leaf Biochar | $10^4$           | 1.67                  | 1.48                  | 11.38       | 0.0019                |
|                     | $5 \times 10^4$  | 2.5                   | 2.3                   | 8           | 0.0004                |
|                     | $10^5$           | 2.6                   | 2.24                  | 13.85       | 0.0004                |
|                     | $15 \times 10^4$ | 3                     | 2.34                  | 22          | 0.0004                |
|                     | $2 \times 10^5$  | 3.4                   | 2.29                  | 32.65       | 0.0006                |

C<sub>0</sub> = Initial concentration, C<sub>e</sub> = Equilibrium concentration, Removal (%) =  $((C_0 - C_e) / C_0) \times 100$ , q<sub>e</sub> = Adsorption capacity (mg/g)

## Conclusion

The present study demonstrates that *Musa acuminata* leaf-derived bioadsorbents can effectively remove fluoride from contaminated water, with banana leaf biochar exhibiting substantially higher adsorption efficiency than banana leaf powder. The enhanced performance of biochar is attributed to its favorable surface chemistry, greater abundance of oxygen-containing functional groups, and improved porosity generated during pyrolysis. These findings highlight the potential of converting agricultural waste into value-added bioadsorbents for sustainable water treatment applications. Given its low cost, environmental compatibility, and superior fluoride removal capacity, banana leaf biochar may serve as a promising alternative to conventional defluoridation methods, particularly in rural and resource-limited settings. Further studies should focus on optimizing operational parameters, regeneration potential, adsorption kinetics, and field-scale applicability to facilitate its practical implementation in community-based defluoridation systems.

**Conflict of interest:** Authors have no conflict of interest in this study.

**Data availability statement:** The data used to support the findings of this study are included within the article.

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