**Eco-Friendly Fluoride Adsorption Using Okra Leaves: A Sustainable Approach**

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Abstract

Fluoride is naturally occurring mineral, and its contamination cannot be ruled out. Fluoride contamination in water sources is a critical environmental issue, demanding efficient and sustainable remediation techniques especially in water resource constraint region. The aim of this study is to investigate the potential of leaves from Okra in bioremediating fluoride from water.

Method: Batch adsorption experiments were conducted to study the effect of various parameters on adsorption efficiency of fluoride onto Okra leaves powder. Okra leaves, rich in natural adsorbents like mucilage, were explored for their fluoride-binding properties. The experiment focused on optimizing parameters such as **speed of incubator shaker**, **contact time, adsorbent dose, pH, and initial fluoride concentration** to evaluate the adsorption capacity of leaves. Fluoride-contaminated water was treated in batch reactors, and residual fluoride concentrations were analysed using **spectrophotometric methods (SPADNS method)**

Results and discussion: The results demonstrated a significant reduction in fluoride levels, with a degradation efficiency of **over 80% in optimized conditions**. The study highlights the potential of batch reactors as a scalable and efficient system for bioremediation applications in wastewater treatment, industrial effluent management, and soil remediation. Future research should focus on reactor modifications, microbial strain enhancements, and real-time monitoring to improve process efficiency.

Key word: Bioremediation, fluoride, adsorbents, batch reactor

**Introduction**

Water is an irreplaceable natural resource that supports all living things. Approximately 71% of Earth’s surface is covered with water and out of which only 3% of water is freshwater1,2. Of this freshwater, a substantial portion is trapped in glaciers and ice caps, making it inaccessible for direct human use. Rest 97% of water is saline water which are oceans1,2.

Contamination of freshwater is one of the serious issues with long-term consequences for sustainability. This occurs due to various natural and anthropogenic (human-induced) factors like industrial discharges, sewage and wastewater, agricultural runoff, pharmaceutical and personal care products3.

Fluoride occurs naturally in various water sources and is the major source of contamination4 . Contamination sources are not limited to dissolution of minerals (e.g. fluorite (CaF₂), cryolite (Na₃AlF₆), and apatite (Ca₅(PO₄) ₃F), volcanic activity, and industrial processes etc3.

As per Ministry of Jal Shakti data posted on 24 MAR 2022, Fluoride levels exceeding the permissible limit of 1.5 mg/L have been detected in 370 districts across 23 states5 .

Figure 1 Depicts state wise data of percentage of sample with fluoride concentration above 1.5 mg/L. Source: FLUORIDE IN GROUNDWATER**.** RAJYA SABHA, UNSTARRED QUESTION NO. 1523.

Fluoride is considered as double-sided blade. When in optimum concentration, it works as blessing to treat dental cavities. If the fluoride concentration is high and is exposed to longer duration can leads to fluorosis.

Removal of fluoride is one of the major challenges because it can directly or indirectly affect the quality of water.

**Positive effect of fluoride removal on water:**

1. **Prevention of Fluorosis** – Reduces the risk of **dental and skeletal fluorosis**, which occurs due to excessive fluoride intake 6.
2. **Safer Drinking Water** – Water with fluoride levels maintained within the recommended range (0.7–1.5 mg/L) is safe and beneficial for health7. This helps to avoid **neurological, kidney, and thyroid disorders** linked to high fluoride exposure 8.
3. **Better Agricultural Productivity** – Prevents fluoride accumulation in soil, which can **inhibit plant growth and reduce crop yield**9.
4. **Protection of Aquatic Life** – Prevents excessive fluoride from harming **fish and other aquatic organisms** 10.

**Potential Negative Effects of Fluoride Removal:**

1. **Increased Risk of Tooth Decay** – Fluoride at **optimal levels (0.7–1.2 mg/L)** helps prevent cavities, so complete removal may lead to **weaker dental health** 7.
2. **Higher Water Treatment Costs** – Advanced **fluoride removal methods (adsorption, membrane filtration, electrocoagulation, etc.)** require **costly infrastructure and maintenance** 11.
3. **Nutritional Imbalance** – In some regions, fluoride is a natural **micro-nutrient**, and its removal may require **alternative supplementation** 12.
4. **Challenges in Water Supply Management** – Some water sources have naturally occurred fluoride, and excessive removal may require **reintroducing fluoride** for balance 7.

Fluoride removal is essential in areas with high fluoride contamination but should be carefully regulated to maintain safe fluoride levels for health benefits. The choice of removal technique must balance efficacy, cost, and environmental impact to ensure sustainable water treatment solutions.

The purpose of this research is to evaluate Okra leaves as a potential adsorbent for the defluorination. Research highlights the role of various factors, such as pH, contact time, shaker speed, fluoride concentration and adsorbent dose, in fluoride ion elimination.

Why Okra leaves

Okra (*Abelmoschus esculentus*), also known as lady’s finger, is a widely cultivated vegetable known for its nutritional and medicinal properties13. Okra leaves contains polysaccharides and Mucilage which are known for its high adsorption properties14. The negatively charged components in okra leaves interact with positively charged fluoride ions, facilitating effective removal14.

Okra plants have demonstrated the ability to accumulate heavy metals, such as lead, cadmium, and copper from contaminated soil15,16,17.

**Method and methodology:**

**Preparation of Adsorbent**

Okra leaves were collected from farmland near Faridabad. The leaves were washed with tap water three times to remove all the other visible impurities. These leaves are then air dried for 1 week. The leaves were checked if they have churn sound before we crush them. The powder was stored in air light package so that moisture is restricted.

**Preparation of stock fluoride solution**

The stock solution of fluoride is prepared using anhydrous sodium fluoride, procured form Sigma Aldrich (Madrid, Spain). A stock solution of 100 ppm fluoride was prepared by dissolving 221 mg of anhydrous sodium fluoride in 1000 ml of double distilled water. The stock solution is freshly diluted to the desired concentration for each experiment

**Preparation of synthetic water**

A synthetic water was prepared which contains the concentration of 30 mg/L from the same initially a stock solution of fluoride is prepared which will be used for further experiments.

**Procedure for performing the experiment**

The current experiment utilises the SPADNS spectrophotometric method to determine the residual fluoride concentration. The underline principle is that SPADNS reagent (sodium 2-(parasulfophenylazo)-1,8-dihydroxy-3,6-naphthalene disulfonate) forms a red-colored complex with zirconium i.e. Zr–SPADNS complex. When fluoride is added, it will interact with zirconium which is a colour less compound i.e. colorless ZrF₆²⁻ complex

Batch experiments were conducted to optimize conditions such as shaking speed of an incubator shaker, pH (adjust pH using HCl or NaOH), contact time, different concentration of fluoride and doses of okra leaves for maximal fluoride removal.

**Results and Discussion**

**Calibration curve**

A 1000 mg/L stock aqueous solution of Fluoride was prepared. Standard working concentration were obtained by serial dilution of appropriate volume of stock solution, as need for the experiment. Each dilution was observed under UV spectrophotometer at a wavelength where fluoride absorbs highest amount of UV radiation (λmax=570 nm). The linear regression equation obtained was y = -0.1897x + 0.8897, with R2 value of 0.9901. This indicate that it is suitable for quantitative analysis of the analyte in the proposed samples. (figure 2)

Table 1: Provide the parameter and setting used to perform and create a calibration curve

|  |  |
| --- | --- |
| Parameter | Setting |
| Wavelength (nm) | 570 nm |
| Range | 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5 and 4.0 PPM |
| Replicate | 3 |
| Fit type | Linear |
| Min R2 | 0.9901 |

Figure 2: calibration curve for UV-VIS spectrophotometer determination of Fluoride in aq solution (λmax=570 nm)

Adsorption experiments

Batch adsorption experiments were conducted to assess the effect of various operational parameter i.e. adsorbent dose, pH, contact time, temperature, rotation per min. We had studied only one parameter at a time and keeping other parameters as constant.

Effect of pH

Figure 3 showed the adsorption capacity of fluoride on Okra leaves at different pH. The percentage of fluoride absorbed by okra first decrease with increase in pH from 1 to 6 and then increase later from pH 8 to 10. The maximum removal efficiency obtained at pH 7 and 8. The surface charge of the adsorbent site can change with pH (protonation in the acidic medium). At lower pH levels, the surface of the adsorbent might be more positively charged, which can enhance the attraction and adsorption of negatively charged fluoride ions 18.

As the pH increases towards neutral (around pH 7), this positive charge might still be present, facilitating adsorption18. Beyond pH 7, the surface of the adsorbent might become less positively charged or even negatively charged. There is less competition for H+ ions leading to more strong attraction between adsorbent and fluoride ions18.

Additionally, at higher pH levels, competition from hydroxide ions (OH-) can also interfere with fluoride adsorption, as both are negatively charged and can compete for the same adsorption sites.

Figure 3: Effect of pH on Fluoride Removal Efficiency Using Leaf-Based Adsorbent (Okra)

**Effect of Shaker speed on fluoride removal**

Agitation speed is an important parameter because it inflences the distribution of the solute in the bulk solution. In the present study, adsorption efficiency was studied at different speed (100, 125, 150, 175, 200, 300 and 400 rpm). It is clearly visible that fluoride adsorption increases from speed 100 to 200 rpm and from 300 rpm the uptake declines. 200 rpm is the optimum speed for adsorption process. This suggest that there is better adsorption at moderate RPM because it keeps better contact between fluoride ions and adsorbent (figure 4).

At higher speed there is change in kinetics occurs which causes decline in adsorption capacity. With higher speed there is process of desorption occur due to equilibrium18.

Figure 4: Effect of shaker speed on Fluoride Removal Efficiency Using Leaf-Based Adsorbent (Okra)

**Effect of fluoride concentration on fluoride removal**

The fluoride concentration increases, the removal efficiency also increases. At low concentrations (6-10 mg/L), the removal efficiency is lower, indicating less adsorption interaction at lower fluoride availability. It suggests that fluoride ions have **fewer chances to interact** with active adsorption sites on the leaves (figure 5).

At higher concentrations (15-30 mg/L), removal efficiency increases significantly. As concentration increases, **more fluoride ions are available** to bind to adsorbent sites, leading to higher removal efficiency. The trend may eventually **plateau** beyond 30 mg/L, indicating **adsorption saturation.** This means thatthe efficiency **stabilizes at 84.35%.**

Figure 5: Effect of fluoride concentration on Fluoride Removal Efficiency Using Leaf-Based Adsorbent (Okra)

**Effect of contact time** **on fluoride removal**

The effect of contact time is very important parameter. In the initial phase (0-30 min), adsorption is rapid because the sites on the leaves are active and readily available to interact with fluoride ions. The adsorption is slow down from 45 mins (figure 6). This is because of saturation effect of the adsorption sites and desorption effect (fluoride ions are possibly detaching due to extended time)18,19.

Figure 6: Effect of contact time (in mins) on Fluoride Removal Efficiency Using Leaf-Based Adsorbent (Okra)

**Effect in initial dose of Okra leaves**

The absorbent dose of various dosage (10 mg/l to 3000mg/L) was observed. Initially a rapid increase in adsorption was observed with increase in adsorbent dose.

At low doses (10-100 mg/L), the increase in removal is more noticeable. Considering the adsorption sites are limited at low adsorbent dose. As the adsorbent dose increases, more active sites become available, leading to higher removal efficiency. At higher doses (400 mg/L and beyond), the increase in efficiency slows down. After the dose of 800 mg/L there is slight dip in absorption was observed. After a certain dose additional adsorbent does not significantly improve efficiency. This could be due to saturation effect which lead to declining in removal efficiency. This trend can be explained from the fact that there are large number of greater surface area and absorption site available to interact18,20.

Figure: Effect of initial dose of Okra leaves on Fluoride Removal Efficiency

The study evaluated the removal efficiency of fluoride ions using Okra under varying experimental conditions. The results indicate that fluoride removal was significantly influenced by parameters such as **pH, shaker speed, contact time, adsorbent dose, and initial fluoride concentration**. Maximum fluoride removal was observed at **pH 8**, while the lowest removal efficiency occurred at **pH 7**, suggesting that slight alkalinity favours adsorption. The effect of contact time showed that fluoride removal increased initially but reached equilibrium after a specific duration, indicating saturation of active adsorption sites. Furthermore, increasing the adsorbent dose enhanced fluoride uptake, but beyond a certain dosage, no substantial improvement was observed, indicating saturation.

**Future prospects:**

This study explores the bioremediation of fluoride using Okra leaves as a cost-effective and natural adsorbent. Utilizing okra plants for bioremediation purposes can be cost-effective and sustainable compared to traditional remediation techniques. It is a natural, non-invasive approach that does not involve the use of chemicals or heavy machinery, making it an environmentally friendly option.

**Disclosure statement**

*The authors report there are no competing interests to declare*.

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