Evaluation Of Low Coat Bio-Adsorbents For Fluoride Removal From Drinking Water In Kuttanadu, Kerala

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Abstract - Fluoride contamination in groundwater is a major environmental and public health concern in parts of India, especially in Kuttanadu, Kerala. The issue arises from both natural geological sources and the excessive use of phosphate fertilizers. Prolonged exposure to high fluoride levels can lead to serious health problems such as dental and skeletal fluorosis.

This study focuses on developing a low-cost and eco-friendly solution for fluoride removal using bio-adsorbents derived from locally available seaweed. Sargassum was selected due to its high availability and the presence of functional groups that enhance adsorption capacity.

The raw seaweed was processed through washing, drying, and thermal activation to improve its surface area and porosity. These modifications increase the number of active binding sites, thereby enhancing its effectiveness in removing fluoride from water.

Batch adsorption experiments were conducted to evaluate the performance of activated Sargassum in comparison with rice husk ash. Key parameters such as pH, contact time, and initial fluoride concentration were optimized to determine the most effective conditions for fluoride removal.

The study is expected to confirm that fluoride adsorption follows pseudo-second-order kinetics and that activated Sargassum shows higher removal efficiency. This research highlights the potential of seaweed-based adsorbents as a sustainable, cost-effective alternative for water treatment, supporting community-level solutions and promoting a circular economy approach.

Index Terms -Bio-adsorbent, Defluoridation, Sargassum, Groundwater, Kuttanad, Thermal activation, Water treatment, Adsorption kinetics, Sustainable materials, Fluoride removal efficiency.

I. INTRODUCTION

A. Background

Fluoride contamination in groundwater is a widespread environmental and public health concern, particularly in developing countries like India. Fluoride enters water sources through natural geological processes such as the dissolution of fluoride-bearing minerals, as well as anthropogenic activities including excessive use of phosphate fertilizers and industrial discharges. While fluoride in small concentrations (0.5–1.0 mg/L) is beneficial for dental health, prolonged exposure to higher concentrations leads to serious health issues such as dental and skeletal fluorosis.

Conventional methods for fluoride removal, including reverse osmosis, ion exchange, and chemical precipitation, are often expensive, energy-intensive, and require skilled operation. These limitations restrict their applicability in rural and economically weaker regions. As a result, there has been growing interest in developing low-cost, sustainable, and eco-friendly alternatives for water treatment.

In recent years, bio-adsorbents derived from agricultural and marine waste materials have gained significant attention due to their abundance, biodegradability, and cost-effectiveness. Rice husk ash (RHA), a by-product of rice milling, contains high silica content and has shown promising adsorption capabilities. Similarly, Sargassum, a brown seaweed abundantly available in coastal regions, possesses functional groups such as hydroxyl and carboxyl that enhance its adsorption potential.

The comparative evaluation of these two materials provides valuable insights into their efficiency and feasibility for large-scale water treatment applications. Particularly, the superior adsorption capacity of Sargassum highlights its potential as an effective and sustainable bio-adsorbent for fluoride removal.

B. Research Need

The increasing incidence of fluoride contamination in groundwater sources necessitates the development of efficient and affordable treatment methods. In regions like Kuttanadu, groundwater serves as a primary source of drinking water, and elevated fluoride levels have been reported due to both natural and human-induced factors. The lack of accessible and economical treatment technologies further exacerbates the problem, especially in rural communities.

Existing conventional treatment methods are not only costly but also generate secondary pollutants, making them less sustainable in the long term. Therefore, there is a critical need to explore alternative materials that are locally available, low-cost, and environmentally friendly. Agricultural wastes such as rice husk and marine biomass like Sargassum offer promising solutions due to their high adsorption potential and minimal processing requirements.

Despite numerous studies on individual bio-adsorbents, there is limited comparative research evaluating the performance of different materials under similar conditions. Understanding the relative efficiency of rice husk ash and Sargassum is essential for selecting the most suitable adsorbent for practical applications. Additionally, studying the adsorption kinetics, such as the pseudo-second-order model, helps in understanding the mechanism involved in fluoride removal, which is often dominated by chemisorption.

This research is therefore necessary to bridge the gap between laboratory studies and real-world applications by identifying a more efficient, sustainable, and scalable solution. The findings can contribute to improving water quality and safeguarding public health, particularly in fluoride-affected regions.

C. Problem Statement

Fluoride contamination in drinking water has emerged as a serious issue affecting millions of people worldwide, with significant impacts on human health. In many parts of India, including rural and coastal regions, groundwater sources contain fluoride concentrations exceeding the permissible limits recommended by the World Health Organization (1.5 mg/L). Continuous consumption of such water leads to irreversible health conditions, including dental and skeletal fluorosis.

Although several treatment technologies are available, their high cost, operational complexity, and maintenance requirements limit their use in low-income and rural areas. This creates an urgent need for simple, cost-effective, and efficient methods for fluoride removal that can be easily adopted at the community level.

Bio-adsorbents such as rice husk ash and Sargassum have emerged as potential alternatives due to their availability and adsorption properties. However, there is a lack of clear understanding regarding their comparative efficiency and practical applicability. Preliminary observations indicate that while both materials are capable of removing fluoride, Sargassum exhibits higher removal efficiency, especially at elevated fluoride concentrations.

The core problem addressed in this study is to evaluate and compare the effectiveness of rice husk ash and Sargassum in fluoride removal from water and to determine why Sargassum performs better. This involves analyzing adsorption capacity, removal efficiency, and kinetics to establish a reliable and sustainable treatment method.

Ultimately, this research aims to provide a scientifically validated solution for fluoride removal that is not only effective but also economically and environmentally viable, thereby addressing a critical gap in water treatment technologies for affected communities.

D. Objectives

The primary objective of this study is to evaluate and compare the performance of low-cost, eco-friendly bio-adsorbents, namely Sargassum seaweed and rice husk, for the removal of fluoride from drinking water, with a focus on developing a sustainable and practical solution suitable for rural regions such as Kuttanad, Kerala. The study aims to understand the adsorption characteristics and efficiency of these materials while ensuring their applicability as an economical water treatment method.

The specific objectives of the study are as follows:

- To prepare and characterise bio-adsorbents from Sargassum seaweed and rice husk through appropriate cleaning, drying, size reduction, and pre-treatment processes to enhance their adsorption properties.
- To conduct batch adsorption experiments using fluoride solutions of known concentrations under controlled laboratory conditions, maintaining a constant adsorbent dosage and varying contact time.
- To investigate the effect of contact time on fluoride removal efficiency in order to determine the optimum time required to achieve maximum adsorption.
- To evaluate and compare the adsorption performance of Sargassum and rice husk under identical experimental conditions to identify the more effective bio-adsorbent.
- To analyze the influence of initial fluoride concentration on the adsorption process and understand the role of concentration gradient in mass transfer.
- To study the adsorption kinetics of fluoride removal and verify the applicability of the pseudo-second-order kinetic model, thereby confirming the mechanism of chemisorption.
- To assess the feasibility of using low-cost and locally available bio-adsorbents for fluoride removal in rural water treatment systems, ensuring environmental sustainability and economic viability.

II. LITERATURE REVIEW

Fluoride removal from drinking water using adsorption techniques has gained considerable attention in recent years due to the limitations associated with conventional treatment methods such as reverse osmosis, ion exchange, and chemical precipitation. Researchers have increasingly focused on the use of low-cost, eco-friendly, and locally available materials, particularly bio-adsorbents derived from natural biomass, agricultural waste, and marine resources. These materials are considered highly effective due to their porous structure and the presence of functional groups capable of binding fluoride ions through various physicochemical mechanisms.

Marine algae, especially species belonging to the Sargassum genus, have been widely studied for their biosorption capabilities. Dobaradaran et al. (2023) investigated the use of Sargassum hystrix biomass for fluoride removal and reported excellent adsorption performance under optimised conditions. The study highlighted that the presence of hydroxyl (–OH), carboxyl (–COOH), and sulfate groups in the algal structure plays a crucial role in fluoride binding through electrostatic attraction and ion exchange mechanisms. The adsorption process was found to be highly dependent on parameters such as pH, contact time, and adsorbent dosage, with maximum removal efficiency reaching nearly 100%. The Freundlich isotherm model provided the best fit for equilibrium data, while kinetic studies confirmed pseudo-second-order behaviour, indicating chemisorption as the dominant mechanism.

Similarly, Kanwal et al. (2025) explored the use of biochar derived from Sargassum polycystum, modified with Fe_3O_4 nanoparticles to enhance adsorption efficiency. The modification significantly improved surface area, porosity, and availability of active sites, resulting in fluoride removal efficiencies of approximately 90%. The adsorption followed the Langmuir isotherm model, indicating monolayer adsorption on a homogeneous surface, and kinetic analysis revealed pseudo-second-order behaviour. The study demonstrated that surface modification techniques can substantially improve the performance of bio-adsorbents, making them more suitable for practical water treatment applications.

In addition to marine biomass, agricultural wastes have also been extensively studied as low-cost adsorbents for fluoride removal. Materials such as rice husk, corncob, and tea waste have shown promising adsorption capabilities due to their lignocellulosic composition and the presence of functional groups. Liu et al. (2025) investigated iron–manganese modified corncob biochar and reported enhanced fluoride removal efficiency due to increased surface reactivity and adsorption sites. Similarly, Aboulsoud et al. (2024) demonstrated that tea waste can effectively remove fluoride from wastewater through biosorption mechanisms, highlighting the potential of agricultural residues as sustainable treatment materials. However, these materials often exhibit lower adsorption capacity compared to modified or marine-based adsorbents, indicating the need for further enhancement or activation.

Biochar-based composites have also gained attention for their improved adsorption performance. Yu et al. (2024) developed a modified MgO/biochar composite and reported significant improvement in fluoride removal efficiency due to increased surface alkalinity and adsorption sites. These studies suggest that chemical modification and composite formation can enhance adsorption capacity, although such processes may increase cost and complexity.

Fundamental studies on adsorption mechanisms further support the effectiveness of bio-adsorbents. Bhatnagar et al. (2011) and Mohan and Pittman (2007) provided comprehensive reviews on adsorption-based fluoride removal, emphasising that adsorption efficiency depends on surface area, pore structure, and the nature of functional groups present on the adsorbent. Similarly, Davis et al. (2003) highlighted the role of brown algae such as Sargassum in biosorption processes, attributing their effectiveness to the presence of alginate compounds and active binding sites.

Overall, existing research clearly demonstrates the potential of both marine biomass and agricultural waste materials for fluoride removal from water. However, most studies focus on individual adsorbents or modified materials, with limited emphasis on direct comparison under identical experimental conditions. Additionally, the practical applicability of these materials in rural settings requires further investigation in terms of efficiency, cost, and ease of implementation. This gap highlights the need for comparative studies such as the present work, which evaluates the performance of Sargassum and rice husk as low-cost bio-adsorbents for fluoride removal, aiming to identify a suitable and sustainable solution for drinking water treatment in regions like Kuttanad.

III. MATERIALS USED

A. Sargassum Seaweed

Sargassum seaweed was used as the primary bio-adsorbent in this study due to its high adsorption potential and natural abundance in coastal regions. The biomass was collected from nearby coastal areas and thoroughly washed with distilled water to remove adhered salts, sand particles, and organic impurities. The cleaned samples were then oven-dried at a controlled temperature of 60°C to eliminate moisture content without altering the chemical structure of the material. After drying, the biomass was crushed and sieved to obtain a uniform particle size in the range of 300–600 µm, ensuring consistency during adsorption experiments.

The selection of Sargassum was based on its rich composition of alginate compounds and the presence of various functional groups such as hydroxyl (–OH), carboxyl (–COOH), and sulfate groups, which play a significant role in the adsorption of fluoride ions through electrostatic attraction and ion exchange mechanisms. In addition, the naturally porous structure of the seaweed enhances its surface area, thereby increasing the availability of active adsorption sites. Due to these characteristics, Sargassum is widely recognised as an effective and sustainable biosorbent for water treatment applications.

B. Rice Husk Ash

Rice husk, an abundant agricultural byproduct, was selected as a secondary bio-adsorbent for comparative analysis. It is readily available in rural areas and is often considered a waste material, making it a cost-effective and environmentally friendly option for adsorption studies. The collected rice husk was washed thoroughly with distilled water to remove dust and impurities, followed by drying under controlled conditions to reduce moisture content. The dried material was then ground and sieved to obtain a uniform particle size suitable for batch adsorption experiments.

Rice husk primarily consists of cellulose, hemicellulose, lignin, and a significant amount of silica, which contribute to its adsorption properties. The presence of functional groups such as hydroxyl and carboxyl groups enables interaction with fluoride ions, although its adsorption capacity is generally lower compared to marine biomass like Sargassum. Despite this limitation, rice husk remains an attractive adsorbent due to its low cost, easy availability, and potential for modification to enhance its performance.

C. Hydrochloric Acid

Hydrochloric acid was used for the chemical activation of Sargassum biomass to enhance its adsorption efficiency. The acid treatment process involved soaking the dried biomass in a dilute HCl solution for a specified period, which helps in removing impurities, dissolving mineral components, and increasing surface porosity. This treatment also exposes additional functional groups on the surface of the biomass, thereby improving its binding affinity towards fluoride ions.

After acid treatment, the biomass was repeatedly washed with distilled water until a neutral pH was achieved to ensure the removal of excess acid. The treated material was then oven-dried again before being used in adsorption experiments. The activation process significantly improves the adsorption capacity by increasing the number of active sites and enhancing the surface characteristics of the adsorbent.

D. Fluoride Solution

Synthetic fluoride solutions were prepared in the laboratory to simulate contaminated water conditions. Known concentrations of fluoride, specifically 3 mg/L and 5 mg/L, were prepared using standard fluoride salts dissolved in distilled water. These concentrations were selected based on typical contamination levels observed in groundwater sources and to evaluate the performance of the adsorbents under varying conditions.

The prepared solutions were used in batch adsorption experiments to determine the efficiency of fluoride removal by the selected bio-adsorbents. The use of controlled concentrations ensured accuracy and reproducibility of experimental results.

E. Distilled Water

Distilled water was used throughout the experimental procedure for washing, preparation of fluoride solutions, and dilution purposes. The use of distilled water ensured the absence of impurities or interfering ions that could affect the adsorption process and the accuracy of analytical measurements. It also helped maintain consistency and reliability in experimental conditions.

F. Filter Paper

Whatman filter paper was used for the filtration of samples after the adsorption process. It facilitated the separation of adsorbent particles from the treated solution, ensuring that the filtrate was free from suspended solids before analysis. This step was essential to obtain accurate measurements of residual fluoride concentration using spectrophotometric methods.

IV. METHODOLOGY

This study was conducted to evaluate the effectiveness of bio-adsorbents for fluoride removal from groundwater in the Kuttanadu region of Kerala. The methodology consisted of systematic steps, including sample collection, preparation and treatment of adsorbents, batch adsorption experiments, and analytical evaluation.

A. Sample Collection

Groundwater samples were collected from four locations in Kuttanadu, namely Valiyaveedu, Chudukadu, Kallisery, and Kainakary. The samples were obtained from well sources and stored in clean, labelled containers to avoid contamination. A field survey was also carried out to assess the prevalence of fluorosis among local residents, and symptoms were observed in two out of the four study areas, indicating potential fluoride contamination.

B. Preparation of Bio Adsorbent

Sargassum seaweed was selected as a primary bio-adsorbent due to its availability and adsorption potential. The collected seaweed was thoroughly washed with distilled water to remove adhering impurities and salts. It was then oven-dried at 60°C to eliminate moisture content. The dried material was crushed and sieved to obtain particle sizes in the range of 300–600 µm, ensuring uniformity for adsorption studies. Also, collected Rice husk ash suitable for water treatment and sieved to obtain the particle size between 300-600µm, ensuring uniformity for the adsorption studies.

C. Pre-treatment of Adsorbent

To enhance adsorption efficiency, the prepared Sargassum and collected rice husk ash were chemically activated using acid treatment. The material was impregnated with hydrochloric acid (HCl) for 24 hours, which helped in removing residual impurities and increasing surface porosity by activating functional groups. After treatment, the adsorbent was washed repeatedly with distilled water until a neutral pH was achieved, followed by oven drying at 60°C.

D. Batch Adsorption Experiments

Batch adsorption studies were conducted using both Sargassum and rice husk as bio-adsorbents to compare their performance. Fluoride solutions with initial concentrations of 3 mg/L and 5 mg/L were prepared. A constant adsorbent dosage of 12 g/L was maintained throughout the experiments. The adsorption process was studied at varying contact times of 30, 60, 90, and 120 minutes. The influence of adsorbent type and contact time on fluoride removal efficiency was systematically evaluated.

E. Filtration and Fluoride Analysis

After the adsorption process, the treated samples were filtered using Whatman filter paper through manual filtration to separate the adsorbent particles from the aqueous phase. The residual fluoride concentration in the filtrate was measured using a spectrophotometer, ensuring accurate determination of removal efficiency.

F. Adsorption Kinetic Study

After the adsorption process, the treated samples were filtered using Whatman filter paper through manual filtration to separate the adsorbent particles from the aqueous phase. The residual fluoride concentration in the filtrate was measured using a spectrophotometer, ensuring accurate determination of removal efficiency.

V. RESULTS AND DISCUSSION

A. Test Conducted

Water Quality Parameters

The test was conducted to evaluate the water quality.

Table 1. Results

Locality	pH	Turbidity (NTU)	Fluoride (mg/l)	Hardness (mg/l)
Valiyaveedu	7.0	2.2	1.9	130
Chudukadu	6.8	3.0	2.13	240
Kainakary	6.9	3.8	3.49	180
Kallisery	7.1	1.8	1.7	150

Fluoride removal using rice husk (12mg/l)

This table presents the results of fluoride removal experiments using rice husk as a bio-adsorbent at a constant dosage of 12 g/L. Two initial fluoride concentrations were studied: 3 mg/L and 5 mg/L. The contact time was varied from 30 to 120 minutes to observe its effect on removal efficiency.

Table 2. Test Results

Trial	Time	Initial Fluoride (mg/l)	Final Fluoride (mg/l)	Efficiency (%)
1	30	3	1.80	40
2	60	3	1.35	55
3	90	3	1.05	65
4	120	3	1.03	65.6
5	30	5	2.75	45
6	60	5	1.75	65
7	90	5	1.45	71
8	120	5	1.43	71.6

- Effect of Contact Time:

As time increases from 30 to 120 minutes, the final fluoride concentration decreases. Correspondingly, the removal efficiency increases.

- Performance at Lower Concentration (3 mg/L):

Fluoride was reduced from 3 mg/L to 1.03 mg/L at 120 minutes. The maximum efficiency achieved is 65.6%

- Performance at Higher Concentration (5 mg/L):

Fluoride was reduced from 5 mg/L to 1.43 mg/L at 120 minutes. Higher removal efficiency observed, reaching 71.6%. Rapid adsorption occurs in the initial stages (first 30–90 min). After that, the rate slows down due to saturation of adsorption sites.

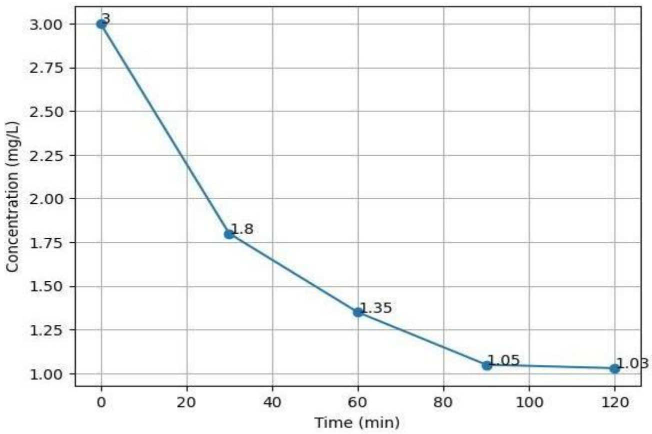


Fig 1: show Concentration v/s time of 3mg/l

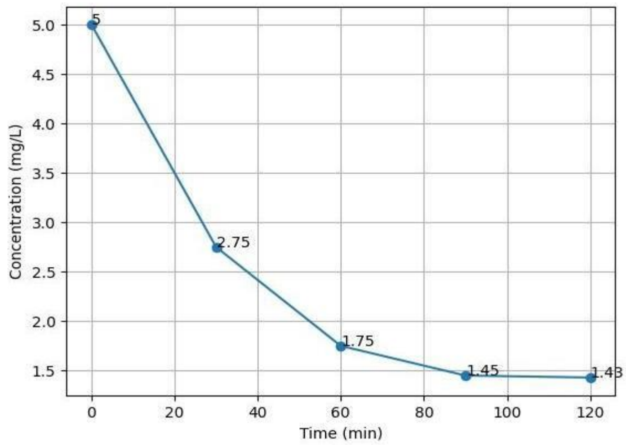


Fig 2: shows Concentration v/s time of 5mg/l

Fluoride removal using Sargassum (12mg/l)

The table shows the biosorption capacity of Sargassum for fluoride removal at a constant dosage of 12 mg/L.

Table 3. Test Results

Trial	Time	Initial Fluoride (mg/l)	Final Fluoride (mg/l)	Efficiency (%)
1	30	3	1.68	44
2	60	3	1.50	50
3	90	3	1.17	61
4	120	3	1.15	61.6
5	30	5	2.40	52
6	60	5	1.50	70
7	90	5	1.20	76
8	120	5	1.18	76.4

- Effect of Contact Time:

As observed in both sets of trials (3 mg/L and 5 mg/L initial concentrations), the removal efficiency increases as contact time progresses from 30 to 120 minutes.

- Initial Rapid Phase:

The maximum rate of adsorption occurs within the first 30 minutes. At this stage, a large number of vacant surface sites on the Sargassum biomass are available, leading to a sharp decrease in fluoride concentration.

- Equilibrium Phase:

After 90 minutes, the efficiency curve begins to plateau. For instance, in the 5 mg/L trial, the efficiency only moves from 76% to 76.4% between 90 and 120 minutes, indicating the system is reaching an equilibrium state.

Fig 3: shows Concentration v/s time of 3mg/l

Fig 4: shows Concentration v/s time of 5mg/l

Efficiency Comparison

The efficiency of adsorbents such as Sargassum and rice husk ash is compared to evaluate their ability to remove fluoride from water. This comparison helps identify the material with better removal efficiency, adsorption capacity, and cost-effectiveness under similar conditions, thereby supporting the selection of suitable and sustainable adsorbents for water treatment.

Sample 1 indicates Rice husk ash.

Sample 2 indicates Sargassum.

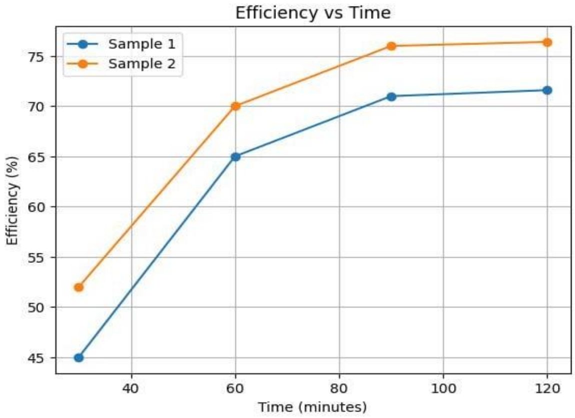


Fig 5**:** Shows the efficiency of Rice husk and Sargassum at 3 mg/l

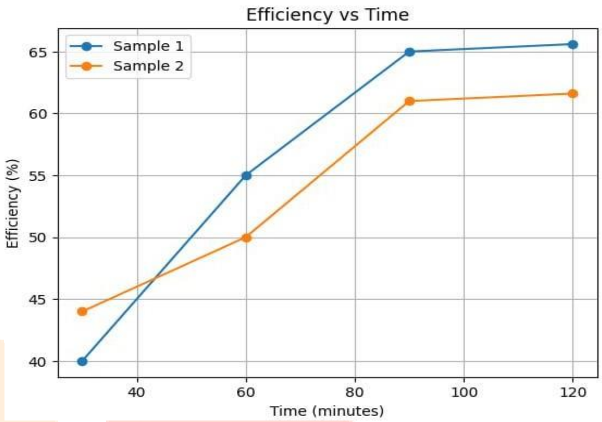
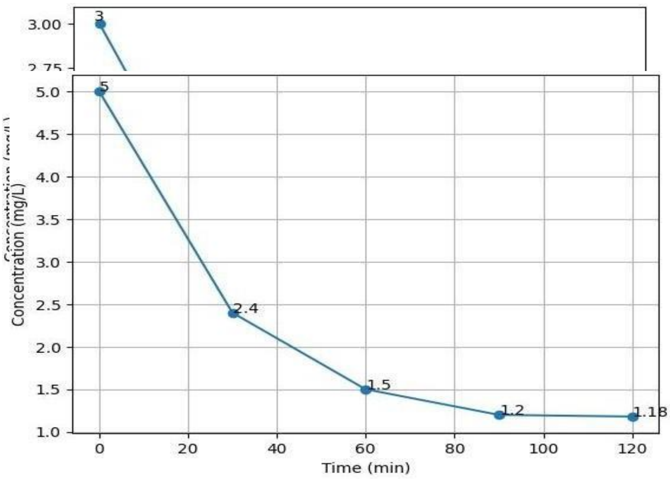


Fig 6: Shows the efficiency of rice husk and Sargassum at 5mg/l

B. Kinetic Model

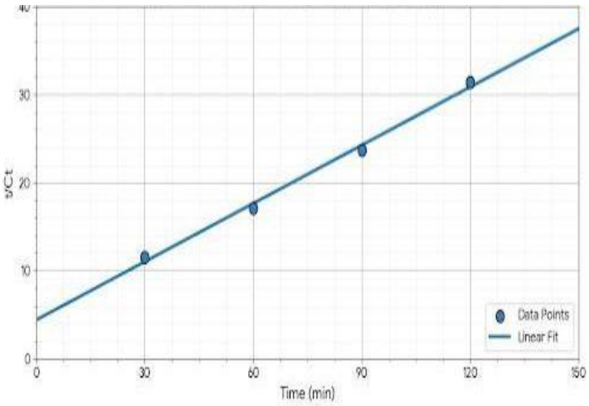
For 3mg/l of fluoride concentration

The pseudo-second-order kinetic model is commonly used to describe fluoride adsorption onto adsorbents such as Sargassum and rice husk ash. It assumes that the process is controlled by chemisorption, involving chemical interactions between the adsorbent surface and fluoride ions. The model indicates that the adsorption rate depends on the availability of active sites and is more suitable for systems with strong bonding compared to the pseudo-first-order model. The linear form of the pseudo-second-order kinetic equation is,



$$\frac{t}{C_t} = \frac{1}{K{C_e}^2} + \frac{t}{C_e}$$

Table 4. Shows 3mg/l initial fluoride concentration



t	Ci	Ce	Ct = $Ci - Ce$
30	3	1.68	1.32
60	3	1.50	1.50
90	3	1.17	1.83
120	3	1.15	1.85

Table 5. Calculation of t/Ct

t	Ct	$\frac{t}{C_t}$
30	1.32	22.73
60	1.50	40
90	1.83	49.18
120	1.85	64.86

Fig 7: Shows t/Ct Graph

From the graph

Slope = $\frac{(64.86-22.73)}{(120-30)}$ = 0.468

Intercept = 22.73 = $(0.468 \times 30) + C$

C = 8.69

Rate constant = $\frac{1}{(8.69 \times 2.14^2)}$

= 0.0251

R^2 = 0.998

From an initial 3 mg/L, about 1.85 mg/L of fluoride was adsorbed. The high R^2 value (0.998) shows an excellent fit with the pseudo-second-order model, indicating chemisorption and confirming the reliability of the results.

Table 6: 5mg/l initial fluoride concentration

t	Ci	Ce	Ct = $Ci - Ce$
30	5	2.40	2.60
60	5	1.50	3.50
90	5	1.20	3.80
120	5	1.18	3.82

Table 7. Calculation of t/Ct

t	Ct	$\frac{t}{C_t}$
30	2.60	11.54
60	3.50	17.14
90	3.80	23.68
120	3.82	31.41

Fig 8: Shows t/Ct Graph

From the graph,

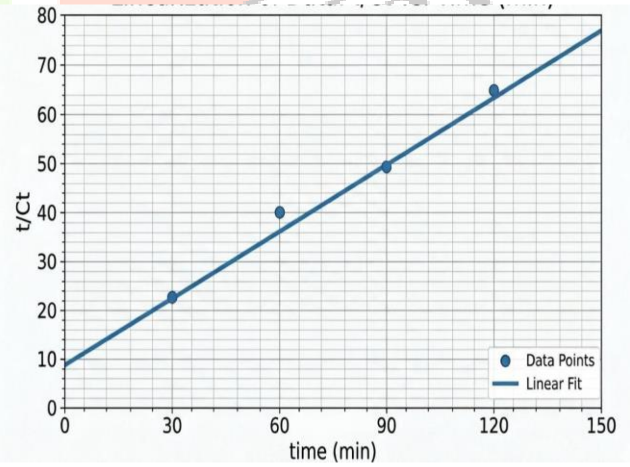
Slope = 0.22

Intercept = 4.405

Rate constant = 0.014

The R^2 value is 0.999

From an initial 5 mg/L, about 3.82 mg/L of fluoride was adsorbed. The high R^2 value (0.999) indicates an excellent fit to the pseudo-second-order model, confirming chemisorption and reliable adsorption performance.



C. Comparison of Adsorbents

A comparative evaluation of the adsorbents indicates that Sargassum consistently outperforms rice husk ash across all key parameters of fluoride removal.

Sargassum exhibits:

- Higher fluoride removal efficiency
- Predominantly chemisorption mechanism
- Greater adsorption capacity
- Strong adherence to pseudo-second order kinetics

- Effective performance even at higher fluoride concentrations

D. Comparison of Cost Analysis

A comparative evaluation of the cost aspects indicates that both Sargassum and rice husk ash are economical adsorbents; however, their cost effectiveness varies based on availability, processing, and performance.

Sargassum shows:

- Low raw material cost in coastal areas, though transport may increase cost inland
- Moderate processing cost due to washing, drying, and grinding
- Lower operating cost due to higher efficiency and faster adsorption
- Lower adsorbent dosage requirement, reducing overall treatment cost
- Better cost efficiency per volume of water treated

In contrast, rice husk ash is extremely low-cost and widely available, resulting in minimal transport and processing expenses. However, its performance in raw form is comparatively lower, often requiring chemical modification to achieve higher efficiency, which significantly increases the overall cost. Additionally, it requires a higher dosage and longer contact time, leading to slightly higher operational costs.

VI. Conclusion

The present study focused on the evaluation of low-cost, eco-friendly bio-adsorbents, namely Sargassum seaweed and rice husk, for the removal of fluoride from drinking water in Kuttanad, Kerala. The investigation was carried out through systematic laboratory-scale batch adsorption experiments, considering key operational parameters such as contact time and initial fluoride concentration, while maintaining a constant adsorbent dosage. The results obtained from the study clearly demonstrate the potential of natural bio-adsorbents as effective alternatives to conventional defluoridation techniques, particularly in rural and resource-limited settings.

The experimental findings revealed that fluoride removal efficiency increased with an increase in contact time for both adsorbents, with a rapid adsorption phase occurring during the initial stages due to the availability of abundant active sites on the adsorbent surface. As the contact time progressed, the rate of adsorption gradually decreased, indicating the progressive saturation of these active sites and the establishment of equilibrium conditions. The optimum contact time was identified to be approximately 90 minutes, beyond which no significant improvement in fluoride removal was observed. This behaviour is consistent with typical adsorption processes governed by surface interactions and diffusion limitations.

A comparative analysis of the two bio-adsorbents indicated that Sargassum consistently exhibited superior adsorption performance compared to rice husk under identical experimental conditions. This enhanced efficiency can be attributed to the presence of a higher density of functional groups such as hydroxyl (–OH) and carboxyl (–COOH), as well as its inherently porous structure, which provides a larger surface area for fluoride binding. The maximum removal efficiency achieved by Sargassum was 76.4% at an initial concentration of 5 mg/L, whereas rice husk showed a comparatively lower efficiency of 65.6% at a 3 mg/L concentration. Furthermore, higher initial fluoride concentrations resulted in greater removal efficiency, which can be explained by the increased concentration gradient that acts as a driving force for mass transfer during the adsorption process.

The kinetic analysis carried out in this study confirmed that the adsorption of fluoride onto both Sargassum and rice husk follows a pseudo-second-order model, indicating that chemisorption is the dominant mechanism controlling the process. This suggests that the adsorption involves chemical interactions between fluoride ions and the functional groups present on the adsorbent surface, rather than mere physical adsorption. The good agreement between experimental data and the kinetic model further validates the reliability and consistency of the obtained results.

Overall, the findings of this study highlight the effectiveness of Sargassum as a sustainable, low-cost, and locally available bio-adsorbent for fluoride removal from drinking water. The use of such natural materials offers significant advantages, including environmental compatibility, ease of preparation, and minimal operational requirements, making them highly suitable for decentralised water treatment applications in rural areas. While rice husk also demonstrated appreciable adsorption capacity, its performance was comparatively lower, indicating the need for further modification or activation to enhance its efficiency.

VII. Acknowledgement

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