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ORIGINAL RESEARCH ARTICLE

Sesbania grandiflora activated carbon as a high-efficiency stable and reusable adsorbent for sustainable fluoride removal

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ABSTRACT

BACKGROUND AND OBJECTIVES: Excess fluoride in groundwater poses environmental and public health risks, causing skeletal and dental fluorosis. Standard defluoridation techniques encounter difficulties concerning their expense, efficiency, and potential for reuse. This study assesses the effectiveness of *Sesbania grandiflora* activated carbon as a reliable and reusable adsorbent for fluoride, emphasizing its characterization, ideal adsorption parameters, and reusability.

METHODS: *Sesbania grandiflora* activated carbon was synthesized and characterized using fourier transform infrared spectroscopy, scanning electron microscopy, energy dispersive x-ray spectroscopy, and x-ray diffraction to assess structural integrity and surface interactions. Batch adsorption experiments were conducted by varying particle size (up to 2.360 millimeter), dosage (2–10 grams), agitation speed (100–500 revolution per minutes), and contact time (up to 140 minutes) to determine the optimal conditions for fluoride removal. Freundlich and Langmuir models were employed to analyze the adsorption isotherms and kinetics. Furthermore, the reusability was tested over five regeneration cycles with 0.1 mole sodium hydroxide.

FINDINGS: Fourier transform infrared spectroscopy revealed interactions between fluoride ions and surface functional groups. The analysis using scanning electron microscopy indicated a porous structure characterized by pore sizes between 0.5 and 5 microns, which exhibited a smoother appearance following adsorption, thus validating the absorption of fluoride. Energy dispersive x-ray spectroscopy showed before treatment, *Sesbania grandiflora* activated carbon had 78.3 percent carbon and 16.5 percent oxygen, while after treatment, carbon increased to 78.8 percent, oxygen to 17.1 percent, and sodium rose to 2.1 percent, with phosphorus and sulphur undetected. X-ray diffraction confirmed that activated carbon from *Sesbania grandiflora* remained mostly amorphous, with crystallinity increasing from 17.2 percent to 17.4 percent. The study revealed that the best adsorption conditions include a particle size of 2.360 millimeters, a dosage of 8 grams, an agitation speed of 300 revolutions per minute, and a contact duration of 120 minutes, which together achieved a fluoride removal efficiency of 89.3 percent. Adsorption followed the Freundlich isotherm (coefficient of determination is 0.9976), suggesting a multilayer heterogeneous adsorption process. Pseudo second order kinetics (coefficnet of determination is 0.9988) confirmed chemisorption as the dominant mechanism. *Sesbania grandiflora* activated carbon maintained 78.3 percent efficiency after five regeneration cycles, demonstrating good reusability.

CONCLUSION: The activated carbon obtained from *Sesbania grandiflora* is an exceptionally efficient and stable adsorbent for fluoride removal in groundwater, offering reusability while preserving its structural integrity and effectiveness. Its potential for scalable, sustainable water treatment warrants further study on scale-up, hybrid integration, and enhanced regeneration techniques.

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49	10	5

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INTRODUCTION

The crust of the earth, the air, the soil, the water, and a range of foods are natural sources of fluoride (Onipe *et al.,* 2020). High concentrations of fluoride in soil from irrigation can lead to reduced fertility and lower agricultural yields. Furthermore, increased fluoride levels in aquatic environments endanger aquatic life, and contaminated groundwater may not unsuitable for domestic purposes. Over consumption of fluoride in food and water can cause dental fluorosis in children, leading to tooth discoloration and pitting. Long-term exposure may result in skeletal fluorosis, damaging bones and joints, and potentially causing hypothyroidism (Mallishery *et al.,* 2020). An excessive amount of fluoride intake can impede iodine absorption, which may lead to hypothyroidism, renal toxicity, compromised kidney function, and neurobehavioral concerns, including a decline in intelligence quotient (IQ), memory issues, and learning challenges (Singh and Singh, 2021). Elevated fluoride concentrations in plants can stunt development, lower agricultural yields, and induce necrosis or discolouration of the leaves, which can upset nearby ecosystems and food sources (Kumari *et al.,* 2024). Fluoride contamination in groundwater is a major issue in Tamil Nadu, particularly in drought-prone districts like Dharmapuri, Krishnagiri (Kavisri and Moovendhan, 2024), and hard rock terrains of Madurai (Thivya *et al*., 2017), where fluoride levels often exceed health limits due to geological factors. Recent assessments show that about 9.04% of groundwater samples in India exceed permissible fluoride limits, with Tamil Nadu among the most affected states. Reports indicate that fluoride levels in Erode and Coimbatore are elevated, contributing to health concerns like dental and skeletal fluorosis, especially in regions where the concentration exceeds the 1 milligram per liter (mg/L) threshold established by the Bureau of Indian Standards (BIS) (Kumar 2021). The Hogenakkal integrated drinking water project, implemented by the Tamil Nadu Water Supply and Drainage Board with funding from the Japan Bank for International Cooperation, provides safe drinking water to affected districts using Cauvery river water (Gousalya *et al*., 2023). Current activities encompass groundwater monitoring, awareness campaigns for the public, and techniques for defluoridation. Nevertheless, enduring challenges call for additional sustainable water management strategies and policy interventions to ensure the protection of public health. The World Health Organization (WHO) recommends a maximum fluoride concentration of 1.5 mg/L in drinking water to prevent health risks. It is vital to decrease fluoride concentrations in groundwater to safeguard environmental integrity and public health. Achieving safe and sustainable groundwater utilization demands the implementation of efficient treatment processes, diligent monitoring, and sound policy frameworks. Various traditional and advanced methods, including precipitation-based and alumina-activated adsorption, have been used for fluoride removal (Wang *et al.,* 2023), reverse osmosis (Ousman *et al.,* 2023), ion exchange (Addar *et al.,* 2024), dialysis by electrodialysis (Imai *et al.,* 2017), precipitation and coagulation (Solanki, *et al.,* 2021), nalgonda method (Divyadeepika *et al.,* 2024), adsorption of bone char (Huyen *et al.,* 2023), adsorption activated carbon (Takmil), nano-separation (Ghomashi *et al.,* 2020), the process of distillation and adsorption to different adsorbents (Iwar and Ugwudike 2022). Among various techniques, adsorbent materials like activated carbon sourced from natural and waste origins have proven to be the most effective in eliminating fluoride ions. The recent studies also showed that the activated carbon derived from materials like lemon peels (Amaibi *et al*., 2024) and hazelnut shells (Al-Musawi *et al*., 2024) has demonstrated effective fluoride removal, with improvements noted through modifications and hybrid treatments (Bakhta *et al*., 2022; Bonyadi *et al*., 2019). A study conducted by Fito *et al*. (2019) and Chukka *et al*. (2022) highlights the significance of enhancing the properties of biomass-derived activated carbon to improve its effectiveness in removing fluoride from water sources, a method that is both highly efficient and cost-effective (Bakhta *et al*., 2022; Chukka *et al*., 2022). The consistent observation across these studies is the importance of enhancing adsorbent properties, such as surface area, functional groups, and pore structure, to improve fluoride removal efficiency in terms of both adsorption capacity and reusability. The choice of fluoride removal technique for groundwater is influenced by several aspects; including fluoride content, water chemistry, cost, and resource availability. Due to their effectiveness and flexibility in different scenarios, techniques such as activated alumina adsorption, reverse osmosis, and ion

exchange are commonly used (Adam *et al.,* 2022). Adsorption techniques are quite successful in eliminating fluoride from groundwater, especially when using activated alumina and bone char (Kennedy and Arias-Paic, 2020). The adsoption techniques have benefits such as ease of use, affordability, and the capacity to treat different fluoride concentration levels. These approaches are flexible and can be adjusted in scale, making them ideal for a wide array of water treatment demands, from small to big (Jayashree *et al.,* 2020). Traditional treatment methods are effective, but adsorption techniques may have higher environmental impacts and operational costs. Adsorption offers a cost-effective, eco-friendly solution for fluoride removal, especially in water-scarce areas. The effectiveness of adsorption is influenced by critical factors such as the characterization of the adsorbent, the design of experimental procedures, the methods of regeneration, and the modeling of kinetics involved in adsorption. Activated carbon from agricultural by-products is a popular choice due to its large surface area and high fluoride removal efficiency. Activated dried palmyrah (*Borassus flabellifer*) nut shells carbon (Senewirathna *et al.,* 2022), date palm (*Phoenix dactylifera*) stems carbon (Bakhta *et al.,* 2022) and raffia palm shell (*Raphia farinifera*) activated carbon-aluminium oxide (Iwar and Ugwudike, 2022) have been investigated for their fluoride-adsorption capacity. *Sesbania grandiflora (*S. *grandiflora)* has been selected as the biomass material for fluoride removal from groundwater due to its exceptional physicochemical properties, widespread availability, and the environmental benefits it offers in comparison to other biomass options. It possesses a highly porous structure and abundant functional groups such as hydroxyl and carboxyl, which enhance its fluoride adsorption capacity (Palodkar *et al*., 2017; Tan *et al*., 2020). Additionally, S. *grandiflora* is a fast-growing leguminous tree that thrives in diverse climatic conditions with minimal agricultural input, ensuring a sustainable and cost-effective raw material supply (Varol and Mutlu, 2023). The use of this biomass is in line with sustainable waste management strategies, as it converts an agricultural byproduct into a beneficial adsorbent while also addressing issues of groundwater contamination (Samimi, 2024; Wang *et al*., 2023). Compared to other biomass sources like sawdust, rice husk, and coconut shell, S. *grandiflora* offers a unique combination of high adsorption efficiency, ease of processing, and renewable biomass production, with a relatively lower lignin content that facilitates easier activation and modification for enhanced adsorption performance (Ratnani *et al*., 2019; Talat *et al*., 2018). Moreover, past studies have highlighted the effectiveness of biomass-based activated carbon in adsorbing fluoride and heavy metals, implying that S. *grandiflora* could be appropriate for similar applications (Niyitegeka *et al*., 2023; Ousman *et al*., 2023; Tefera *et al*., 2020). This study focused on using agriculture-based activated carbon to remove fluoride from groundwater. This task encompassed the preparation of adsorbents, the experimental design, the quantification of adsorption capacity, and the analysis of factors affecting the process through modeling. The main objectives were: i) to prepare activated carbon from S. *grandiflora* wood at various activation temperatures and identify the optimal temperature for maximum surface area and pore volume for fluoride removal; ii) To comprehend the sorption mechanism, the morphology of S. *grandiflora* activated carbon (SGAC) will be analyzed using fourier transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), energy-dispersive x-ray spectroscopy (EDX), and x-ray diffraction (XRD); iii) to conduct batch adsorption studies to determine optimal process parameters (particle size, dosage, agitation speed, contact time) for maximum fluoride removal; iv) to assess maximum adsorption capacity using Freundlich and Langmuir isotherms and determine adsorption kinetics through pseudo-first and second-order models; v) to validate SGAC's fluoride removal efficiency and its effect on other groundwater quality characteristics; and vi) to assess SGAC's ability to regenerate for multiple cycles in order to lower preparation costs. This study was conducted at Kalasalingam Academy of Research and Education (KARE), Tamil Nadu, India, in 2024.

MATERIALS AND METHODS

Materials

Wood from S. *grandiflora*, commonly known as Agathi in Tamil Nadu, was collected in Silamalai, Theni, Tamilnadu, India. The wood measured 15 centimeters (cm) in height and 7.3 cm in average diameter. S. *grandiflora* featured slender branches and a sparse canopy, characterized by deeply

wrinkled, yellowish-brown bark. Cows are fed leaves to produce more milk. Used as a vegetable are the leaves, flowers, and fruit of S. *grandiflora*. High-purity analytical grade chemicals intended for immediate application were sourced from Merck Biopharma in India and employed to analyze various properties of groundwater. Chemical solutions were prepared using double-distilled water to analyze the materials.

Preparation of S. *grandiflora activated carbon*

S. *grandiflora* wood was collected from the local region, cut the wood materials into small pieces, and then dried in the sun for 2 hours (h) to remove surface moisture content. The selection of S. grandiflora's stem for activated carbon production in this study is based on its elevated lignocellulosic content, which contributes to increased carbon yield and porosity, both vital for the adsorption of fluoride. Additionally, its lower extractive content compared to leaves or roots minimizes interference in adsorption efficiency. Evidence from studies suggests that activated carbon obtained from stems has a superior surface area and a variety of functional groups that are beneficial for the fluoride removal. Its structural stability also ensures better regeneration potential, making it a sustainable choice for water treatment applications (Kumar *et al.*, 2019). According to earlier studies, the production of activated carbon from wood generally occurs at temperatures between 500 and 1000 degrees Celsius (°C) (Ratnani *et al.,* 2019). This study also obtained the activated carbon from the S. *grandiflora* wood at the temperatures of 500, 550, 600, 650, 700, and 750 °C in 2 h of contact time, of which the study found the maximum pore size and number of pores at 650 °C. The Brunauer-Emmett-Teller (BET) surface area of SGAC was found to be maximum at 650 °C with 1236.3 square meters per gram (m^2/g) and the pore volume corresponding to a surface area is 0.85 cetimeter cubes per gram (cm^3/g)**,** when compared to the surface area of SGAC at other temperatures (which was not shown in this study). This study employed several process parameters to maximize the removal of fluoride from groundwater using SGAC that had been produced at 650 °C. The preparation of activated carbon from S. grandiflora generally involves the removal of its bark, as it contains elevated amounts of extractive compounds that may hinder the effectiveness of adsorption. The mass of the dried plant samples is approximately 430 grams per kilogram (g/kg) of fresh stem material, based on the moisture content at the time of experiment.

Material characterization

i. Fourier transform infrared spectroscopy: FTIR was utilized to know the various functional groups available in SGAC for removing fluoride in groundwater. Once the SGAC powder was finely ground, it was blended with dry potassium bromide (KBr) in a proportion of 2 mg to 200 mg. Using Perkin Elmer Spectrum 100 FTIR spectrophotometry, the sample was scanned across a wavelength (WL) of 400–4000/cm.

ii. Scanning electron microscope: Among the various tools available, the SEM stands out as a highly valuable resource for the examination and analysis of the morphological traits of microstructures. The beam voltage from 500 to 2,000 volt (V), magnifications from 250 to 65,000, and resolution of 3 nanometer (nm) at 1,000 V were used to capture the microphotographs of the prepared SGAC. Different resolutions of SEM images were obtained using FE-SEMs from the ZEISS 200 High-Resolution instrument.

iii. Energy dispersive x-ray: EDX, an elemental analysis method, is utilized to ascertain the specific elements within SGAC and their corresponding atomic percentages. Each component within SGAC possesses a unique atomic structure, allowing for a specific arrangement of peaks in its x-ray spectrum. This spectrum was captured using a two-dimensional VANTEC-500 detector made by BRUKER EDX.

iv. X-ray diffraction: XRD is a technique used to determine the crystalline or amorphous structure of a sample. When an x-ray beam hits an atom of the SGAC, and the angles and intensities of the diffracted beams are measured produce a three-dimensional (3D) electron density map, which illustrates the molecular structure and the locations of atoms within the material. This investigation, XRD data from 0° to 80° were collected using a Bruker D8 ADVANCE ECO instrument with copper (Cu) K-alpha (Kα) radiation (wavelength lambda (λ) = 1.54060 Å) in a coupled Two Theta/Theta mode.

Collection of groundwater sample

Samples of groundwater were obtained from five different locations on the KARE campus in Krishnankoil, using a secure, insulated container. The collected groundwater samples were taken to the

Table 1: Characteristics of groundwater sample collected from the KARE campus

S.N.	Parameters	Observed value	BIS (IS 10500:2012)
1	pH	6.9	6.5-8.5
2	Total dissolved solids, mg/L	426.87±18.05	500
3	Total hardness, mg/L	432.62±14.28	200
4	Calcium, mg/L	98.45±4.68	75
5	Magnesium, mg/L	31.26±2.54	30
6	Sodium, mg/L	195.76±7.89	200
7	Potassium, mg/L	8.66±0.85	12
8	Chloride, mg/L	235.74±8.23	250
9	Sulphate, mg/L	195.84±6.52	200
10	Nitrate, mg/L	38.32±3.05	45
11	Fluoride, mg/L	2.50±0.14	1.0
12	Iron, mg/L	0.67±0.04	0.3

Table 2: Experimental design of different process parameters for the removal of fluoride from groundwater using SGAC

S.N.	Particle size (mm)	Adsorption dose (mg/L)	Agitation speed (rpm)	Contact time (min.)
1	0.425	2	100	60
2	0.600	4	200	80
3	1.180	6	300	100
4	2.360	8	400	120
5	4.750	10	500	140

laboratory and kept in a refrigerator at 5 °C to test the quality of the groundwater. Five of these samples were further analyzed to determine the effectiveness of fluoride removal, as well as to measure other groundwater characteristics such as potential of hydrogen (pH), total dissolved solids (TDS), total hardness (TH), calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), chloride (Cl_2), sulphate (SO_4), nitrate (NO_3), and iron (Fe). Table 1 displays the average characteristic values of groundwater samples taken from five locations, along with the corresponding BIS standard limits. All selected quality characteristics in the groundwater were determined following the American Public Health Association (APHA), American Water Works Association (AWWA), and Water Environment Federation (WEF) guidelines (APHA, 2017).

Methods

Sorption experiments

Batch adsorption experiments were used to adsorb fluoride onto SGAC, in order to carry out the adsorption test and evaluate the efficacy of SGAC in fluoride removal from groundwater, 250 milliliters (mL) of a groundwater sample was placed in a magnetic stirrer apparatus. Particle size in millimeter (mm), adsorbent dosage in gram (g), agitation speed in revolutions per minute (rpm), and contact time in minutes (min.) were the chosen process parameters for eliminating fluoride from groundwater against the initial fluoride concentration of 2.5±0.14 mg/L, pH of 6.9, and room temperature of 27 °C. A series of batch studies were performed with various process parameters to determine the best value. Following this, an equilibrium study was executed using the optimal parameters across different contact times until reaching equilibrium contact time. The SGAC and fluoride mixed solution was transferred to the filter unit for filtering using Whatman filter paper No. 41 as the filter media, following the specific contact time of 60 min. in the batch study and different contact times in the equilibrium study, when the SGAC and fluoride adsorbate came into contact with one another. Table 2 outlines the experimental design for various process parameters aimed at the removal of fluoride ions from groundwater utilizing SGAC. The percentage of fluoride removed from groundwater by SGAC was calculated, using Eq. 1 (Durairaj, 2024):

$$\text{Percentage reduction} = \frac{(C_i - C_f)}{C_i} \times 100 \quad (1)$$

Where, C_i represents the fluoride concentration in groundwater (mg/L) before treatment using SGAC and C_f represents the fluoride concentration in

groundwater (mg/L) after treatment using SGAC.

Particle size (Palodkar *et al.,* 2017) was selected based on available sieve sizes, agitation speed (Chandraker *et al.,* 2021) based on the magnetic stirrer range, and adsorption dosage (Iwar and Ugwudike 2022) and contact time (Amaibi *et al.,* 2024) based on prior studies on fluoride removal. SGAC efficacy was assessed by measuring fluoride concentration and other groundwater characteristics in treated water, APHA guidelines (APHA, 2017).

Adsorption isotherms

An isotherm model was used in this study to determine the maximum fluoride removal efficiency of SGAC in groundwater. Utilizing data from the equilibrium study, the model was formulated with an emphasis on the optimal process parameters, including particle size, adsorbent dosage, agitation speed, and contact duration. The equilibrium study was carried out for various contact periods starting from the beginning against all other optimum process parameters. The equilibrium adsorption capacity (q_e) milligrams per gram (mg/g) was calculated using Eq. 2 (Fuentes Gandara *et al.,* 2024). The effectiveness of the Langmuir and Freundlich isotherm models, both of which are frequently employed, was evaluated against equilibrium data to determine their suitability for fluoride removal from groundwater using SGAC. The equations of the Langmuir and Freundlich isotherm models are presented using Eqs. 3 and 4 (Fuentes Gandara *et al.,* 2024):

$$q_e = \left(\frac{C_i - C_e}{m}\right) x\, V \quad (2)$$

The Langmuir isotherm equation is presented as:

$$\frac{C_e}{q_e} = \frac{1}{K_L q_m} + \frac{C_e}{q_m} \quad (3)$$

The Freundlich isotherm equation is given by:

$$\ln q_e = \frac{1}{n}\ln C_e + \ln K_F \quad (4)$$

Where, K_L is the Langmuir isotherm constant liters per milligram (L/mg), K_F is the Freundlich isotherm constant liters per gram (L/g), n is the adsorption intensity constant varied from 0 to 1, C_e is the equilibrium concentration (mg/L) of fluoride in groundwater, q_m is the maximum adsorption capacity (mg/g) of SGAG for the removal fluoride in groundwater, q_e is the equilibrium absorptivity capacity (mg/g) of SGAG for the removal and volume of groundwater treated for this study is in L.

Kinetic model

One adsorbate concentration is considerably higher than the other adsorbate concentration in a pseudo first-order reaction, the overall behavior of the reaction approximates that of a first-order reaction. The pseudo first order kinetic, using Eq. 5 (Samimi *et al.,* 2024):

$$\ln \frac{(q_e - q_t)}{q_e} = -K_1 t \quad (5)$$

Where, q_t and q_e are the amounts of adsorbate adsorbed at any given time, t and at equilibrium, respectively. The $\ln \frac{(q_e - q_t)}{q_e}$ against time (t) plot yields the value of the kinetic rate constant of pseudo first order K_1. The chemical sorption, referred to as, between the adsorbent and adsorbate. The pseudo second order kinetic model provides a comprehensive forecast of the behavior across the full spectrum of adsorption. Under these circumstances, the adsorption rate depends more on the adsorption capacity than the adsorbate concentration. The pseudo second order reaction, using Eq. 6 (Samimi *et al.,* 2024):

$$\frac{t}{q_t} = \frac{1}{K_2 q_e^2} + \frac{t}{q_e} \quad (6)$$

The plot between $1/q_t$ and t will reveal the pseudo second order adsorption process' rate constant K_2.

Analytical statistics

Using Minitab 21, the standard deviation is calculated to measure the dispersion of data points around the mean. The coefficient of determination (R^2) is used in regression analysis to determine how well the independent variable(s) predict the dependent variable, with values closer to 1 indicating a better fit.

RESULTS AND DISCUSSIONS

Characterizing activated carbon, conducting adsorption studies, and performing isotherm analysis are essential components in the treatment of water. Activated carbon is widely used due to its

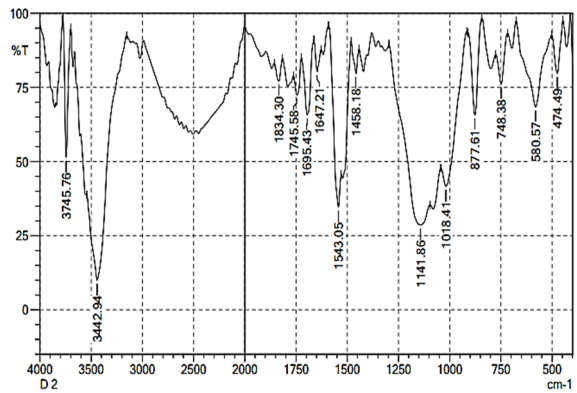

Fig. 1(a)

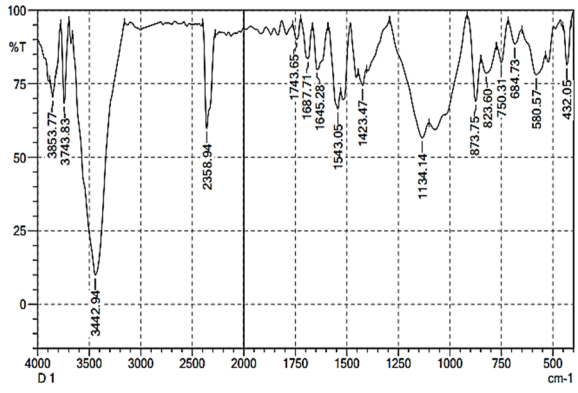

Fig. 1(b)

Fig. 1: FTIR spectrum for SGAC before (1a) and after (1b) removal of fluoride from groundwater

large surface area and porous structure. FTIR, SEM, EDX, and XRD are key for determining the physical and chemical properties of SGAC. The process of adsorption extracts fluoride from groundwater by attaching it to the adsorbent, rendering it a highly effective and affordable method for purification. Isotherm studies help understand SGAC adsorption capacity and behavior, optimizing its use for fluoride removal and improving water purification for safer drinking water.

Characterization of activated carbon

From both structural and chemical viewpoints, the attributes of the materials analyzed in this study correspond with or bolster the findings of other studies. FTIR analysis revealed hydroxyl and carboxyl groups, facilitating fluoride adsorption through electrostatic interactions (Niyitegeka *et al.,* 2023; Palodkar *et al.,* 2017). The characteristics observed in the XRD results revealed a small rise in crystallinity, thereby confirming the presence of additional active sites for fluoride binding (Varol and Mutlu, 2023; Tefera *et al.,* 2020). EDX and SEM characteristics, showing increased oxygen content and a highly porous structure, are consistent with other studies, verifying fluoride uptake and entrapment (Solanki *et al.,* 2021; Zhang *et al.,* 2019; Samimi, 2024; Wang *et al.,* 2023).

Fourier transform infrared spectroscopy

The FTIR spectra of the produced SGAC materials were obtained between 400 and 4000/cm, highlighting structural modifications and the identification of functional groups. Figs. 1a and b, show the FTIR spectra of SGAC before and after fluoride was removed from groundwater, respectively. It can be shown from Fig. 1a that the C=C stretch on SGAC was 1423.47/cm before treatment and moved to 1458.58/cm following groundwater fluoridation (Fig. 1b). After fluoride was removed from groundwater, Nandiyanto *et al.* (2019) found the C=C stretch at a peak value of 1834.30/cm, which reflects the functional group of transition metal carbonyls and five-membered ring anhydrides. The findings revealed C=C stretching at 1637.98/cm with a noticeable increase in the strength of the C=C peak both prior to and following the removal of fluoride from groundwater (Yang *et al.,* 2023). The SGAC spectrum showed consistent peaks before and after treatment at 3442.94/cm, corresponding to O-H stretch and H-bonded vibrations in alcohols and phenols. Peaks at 1734 and 1169/cm were attributed to C-O-C and carbonyl group vibrations. The C-H bent bond vibrations in alkenes were observed at 873.75/cm before fluoride removal from groundwater using SGAC (Fig. 1a). Bakhta *et al.,* (2022) synthesized activated carbon was found to include C=O stretches in the 1500 to 1600/cm range for fluoride removal. The C=O of carboxylate groups was identified at 1543.05/cm. There were variations in peak strength both before and after the fluoride removal process, but the peak range itself remained stable. After treatment with SGAC, these vibrations shifted to 877.61/cm (Fig. 1b). The peak value of 1543.05/cm, falling within the medium N-O symmetric stretch range for nitro chemicals, demonstrated no change pre- and post-treatment.

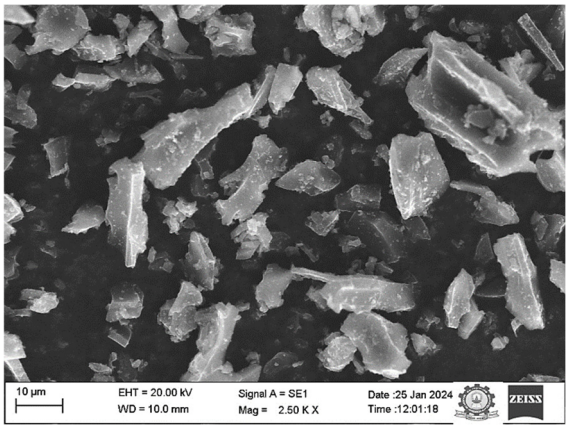

Fig. 2(a)

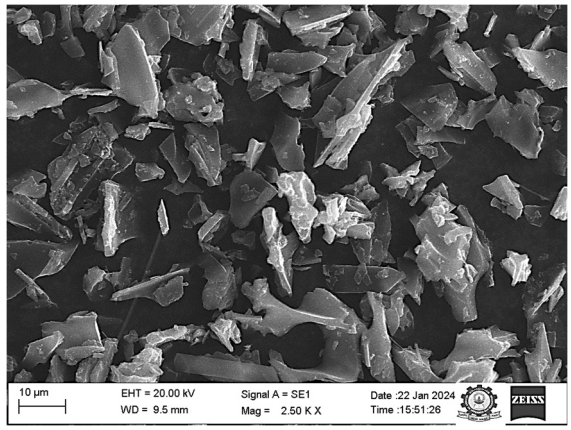

Fig. 2(b)

Fig. 2: SEM image of SGAC before (2(a)) and after (2(b)) removal of fluoride from groundwater

The decomposition of hemicellulose in S. *grandiflora* produces volatile matter, which may be responsible for the O-H stretching observed in SGAC (Varol and Mutlu 2023).

Scanning electron microscopy

The surface morphology of the activated carbon was examined using SEM, with images taken at a magnification of 1,200 times using the ZEISS 200 High-Resolution FE-SEM instrument. The SEM pictures of SGAC used to remove fluoride from groundwater are displayed in Figs. 2a and 2b. Prior to treatment, SGAC displayed an increased quantity of pores, which was corroborated by the darker coloration seen in the SEM image (Fig. 2a). After fluoride was removed from groundwater, SGAC showed less black colour in an SEM image, indicating the presence of more fluoride on SGAC (Fig. 2b). It is observed from Figs. 2a and 2b that the carbon matrix of SGAC before and after treatment, with the white areas representing the solid surface. The clear distinction observed in the two images implies that fluoride adsorption during the treatment has resulted in a reduction of the pore area. The higher surface area observed in Fig. 2a suggests more active sites for fluoride ions, with areas of higher surface energy being more reactive. The surface in Fig. 2b appears smoother, affecting the chemical bonds and interactions between SGAC and fluoride ions (Chandraker *et al.,* (2021).

Energy-dispersive x-ray spectroscopy

The EDX technique was employed to analyze the elemental composition and chemical properties of the sample. The untreated and fluoride-treated samples had higher concentrations of carbon and oxygen ions than other ions, according to the EDX elemental analysis. Different ratios for the Na, Mg, Aluminum (Al), Phosphorus (P), Sulphur (S), Chlorine (Cl), K, and Ca were also seen in the treated and untreated samples. Table 3 presents the EDX results for SGAC both prior to and following the extraction of fluoride from groundwater.

Table 3 shows the absence of P and S in SGAC after fluoride removal, likely due to the formation of P trifluoride and sulphur hexafluoride. The elemental weight percentage of carbon, oxygen, Na, and Cl_2 increased, likely because elements like Al and Ca precipitate and are removed, raising the relative concentration of remaining soluble elements. Following SGAC treatment, the elemental weights of Al, K, and Ca were reduced due to the development of insoluble fluoride compounds, with K experiencing a comparatively minor decrease. Mg content remained stable as SGAC did not interact significantly with Mg ions. An increase in fluoride signal strength was observed in the treated samples, implying that fluoride ions might be displacing oxygen-containing ions (OH^-) on the adsorbent surfaces.

X-ray diffraction

X-ray radiation spectra can help identify whether the adsorbent possesses a crystalline or amorphous structure. Figs. 3a and 3b, respectively, display the peak values obtained from the XRD on SGAC for the removal of fluoride from groundwater. WL used for the XRD experiment was 1.54060 angstrom (Å).

Table 3: EDX for SGAC before and after removal of fluoride from groundwater

Element	CK	OK	NaK	MgK	AlK	PK	SK	ClK	KK	CaK
Before treatment with SGAC										
Weight percent (%)	78.3	16.5	0.6	0.5	0.4	0.4	0.2	0.3	1.3	1.6
After treatment with SGAC										
Weight %	78.8	17.1	2.1	0.5	0.3	-	-	0.6	0.3	0.3

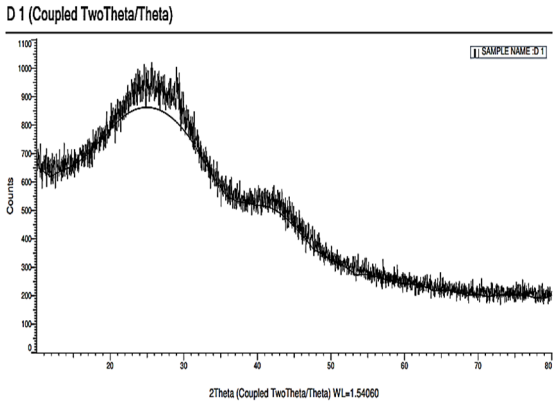

Fig. 3(a)

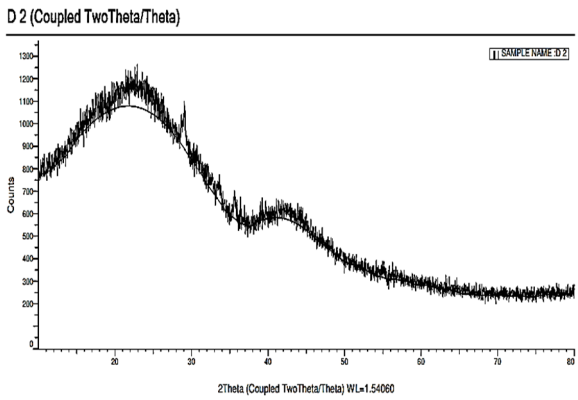

Fig. 3(b)

Fig. 3: XRD image of for SGAC before (3(a)) and after (3(b)) removal of fluoride from groundwater

Before treatment, the XRD pattern of SGAC shows four separate peaks at different 2 teta (θ) angles: Peak 1 has a 2θ angle of 17.561°, Peak 2 has a 29.561° angle, and Peak 3 has a 25.628° angle (Fig. 3a). The presence of Peaks 1 and 2 implies the likelihood of more distantly spaced diffraction peaks, which could signify the existence of several phases with similar lattice properties or a phase characterized by a significant degree of crystallinity. Peak 2 at 2θ = 29.061° in Fig. 3b may reflect a new lattice plane or crystallographic phase, or it may suggest a distinct crystalline structure or orientation in the material. At 2θ = 35.628°, there appears to be another separate diffraction peak, potentially associated with a different crystalline phase or lattice plane (Fig. 3b).

The XRD pattern shows that before treatment, 17.2% of the SGAC structure is crystalline, while 82.8% is amorphous (Fig. 3a). Fluoride removal resulted in a slight increase in crystalline content by 0.2%, and a corresponding decrease in amorphous content by 0.2% (Fig. 3b). The crystallinity rose slightly from 17.2% to 17.4%, and the amorphous content decreased from 82.8% to 82.6%. These slight modifications suggest that the adsorption of fluoride had a minimal effect on the overall structure of SGAC. The resilience of both crystalline and amorphous components implies that the adsorption process does not undermine the structural integrity of SGAC, highlighting its capability for several recycling cycles without notable loss of quality. The enhanced fluoride removal efficiency of *Sesbania grandiflora* activated carbon is attributed to its structural and chemical characteristics, as confirmed by FTIR, XRD, EDX, and SEM analyses. The identification of hydroxyl and carboxyl functional groups through FTIR indicates their role in promoting fluoride adsorption through both electrostatic interactions and ligand exchange mechanisms (Niyitegeka *et al*., 2023; Palodkar *et al*., 2017). XRD revealed a predominantly amorphous structure with a slight crystallinity increase (17.2% to 17.4%) post-adsorption, ensuring more active sites for fluoride binding (Varol and Mutlu, 2023; Tefera *et al*., 2020). After treatment, EDX results indicated a rise in oxygen levels from 16.5% to 17.1% and detected sodium at 2.1%, which points to the processes of ion exchange and fluoride uptake (Solanki *et al*., 2021; Zhang *et al*., 2019). SEM confirmed a highly porous structure as 0.5–5 micrometers (μm) pore size, with surface smoothing post-adsorption, verifying fluoride entrapment (Samimi, 2024; Wang *et al*., 2023). The

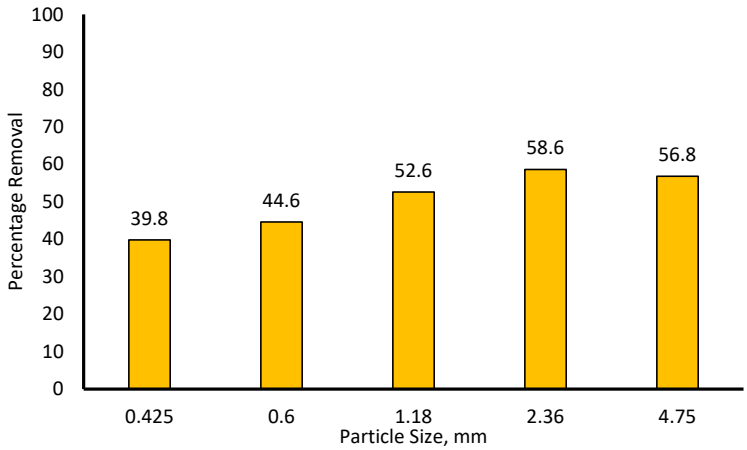

Fig. 4: Removal of fluoride from groundwater using SGAC for various particle size

combination of these features boosts adsorption efficiency, stability, and reusability, establishing Sesbania grandiflora as a viable and eco-friendly option for defluoridation material.

Adsorption study of SGAC

Wood-activated carbon, derived from biomass, is an effective adsorbent for pollutants in water and wastewater due to its high surface area, porosity, and renewability. This sustainable adsorbent aids in water purification and waste reduction, making it an excellent choice for locations with a surplus of wood waste. This study examined the impact of factors such as particle size, adsorbent dosage, agitation speed, and contact time on fluoride adsorption from groundwater by SGAC. This study did not concentrate on the effects of pH and temperature, as modifying pH could result in chemical contamination, and heating groundwater for public use is not a practical solution. Given that groundwater is frequently utilized for household needs, it is crucial to ensure it is treated to minimize contamination.

Effect of particle size

Fig. 4 shows fluoride removal from groundwater using SGAC at particle sizes ranging from 0.425 to 4.750 mm. Fluoride reduction was quantified with a 2 g dosage of adsorbent, an agitation speed set at 100 rpm, and a contact duration of 60 minutes. Results indicated that fluoride removal increased as particle size grew, with maximum sorption achieved at 2.360 mm. No significant difference was observed between the particle sizes of 2.360 mm and 4.750 mm. The maximum fluoride removal percentages were 39.8, 44.6, 52.6, 58.6, and 56.8% for particle sizes of 0.425, 0.600, 1.180, 2.360, and 4.750 mm, respectively. Consequently, the optimal particle size for achieving the highest fluoride removal, which is 58.6%, was found to be 2.360 mm. Wang *et al.* (2023) developed an Fe-La composite adsorbent with a specific surface area of 1113.13 m^2/g for simultaneous phosphate and fluoride removal using a one-pot hydrothermal technique. Wang *et al.* (2023) showed that the highest fluoride removal was achieved with SGAC, which had a surface area of 1236.3 m^2/g. Adsorbents that feature smaller pore sizes and a limited range of pore sizes present a wealth of active adsorption sites along with a high surface area-to-volume ratio. Nonetheless, this can restrict the adsorption of larger fluoride ions, which may lead to a decrease in their overall effectiveness (Kumari *et al.*, 2019).

Effect of dosages

Fig. 5 shows experimental results obtained by varying SGAC dosages between 2, 4, 6, 8, and 10 g for fluoride reduction in groundwater, with optimal conditions of a particle size of 2.360 mm, agitation speed of 100 rpm, 60 min. contact time, an initial fluoride concentration of 2.5 ± 0.14 mg/L, pH of 6.6, and a temperature of 27 °C. The data suggests that at lower dosages, fluoride removal was minimal, whereas it became more effective as the dosage increased. SGAC enhanced fluoride sorption up to an 8 g dosage, and at 10 g, the removal percentage resembled that of the 8 g dosage. The maximum fluoride removal percentages were 58.6, 66.2, 72.1,

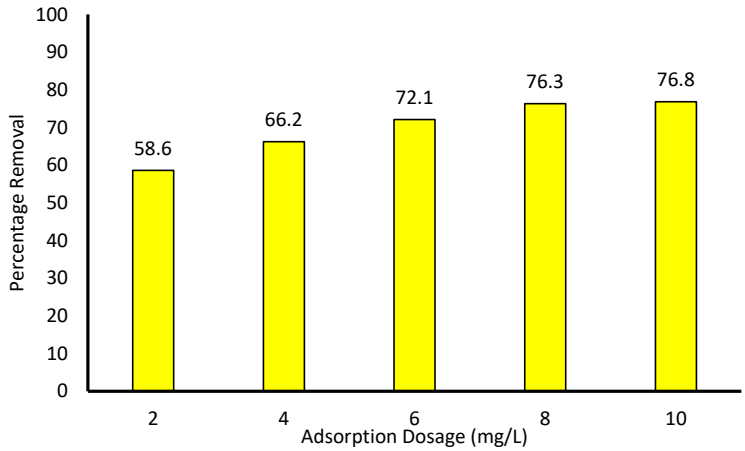

Fig. 5: Removal of fluoride from groundwater using SGAC for various adsorbent dosage

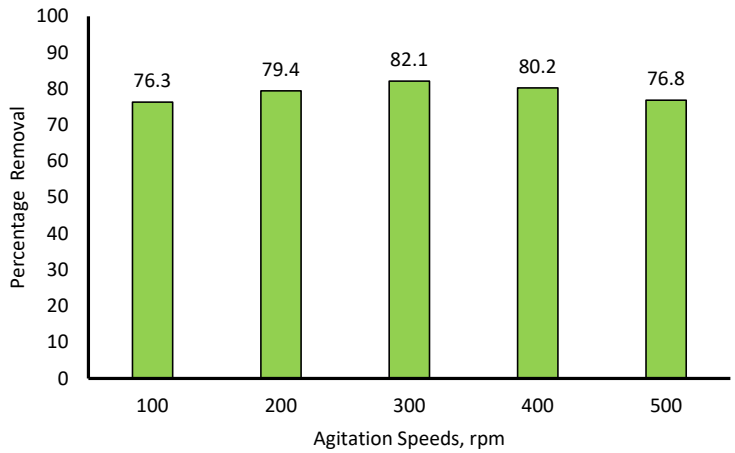

Fig. 6: Removal of fluoride from groundwater using SGAC for various agitation speed

76.3, and 76.8% for dosages of 2, 4, 6, 8, and 10 g, respectively, with the optimal dosage identified as 8 g, achieving a removal of 76.3%. Lower fluoride removal at smaller dosages was due to fewer active binding sites, and higher dosages led to site aggregation, reducing adsorption efficiency (Bhaumik and Mondal, 2016). Hu *et al.* (2018) and Kumari *et al.* (2019) also observed that adsorption increased with higher adsorbent masses. Aligned with these findings, the study indicated that the effectiveness of fluoride removal enhanced with SGAC dosage up to 8 g, but no significant differences were noted beyond that point. As reported by de Carvalho Costa *et al.* (2024), the most effective dosage for the removal of fluoride is 8 g.

Effect of agitation speed

Fig. 6 illustrates fluoride removal from groundwater using SGAC at agitation speeds ranging from 100 to 500 rpm, increasing in 100 rpm increments. The assessment of fluoride concentration reduction was conducted using an ideal particle size of 2.360 mm, a dosage of 8 g, and a contact duration of 60 min. Fluoride removal was minimal at 100 rpm but increased with speed, reaching a maximum of 82.1% at 300 rpm. However, at 400 and 500 rpm, removal efficiency declined due to reduced SGAC-fluoride contact. The maximum fluoride removal percentages at 100, 200, 300, 400, and 500 rpm were 76.3, 79.4, 82.1, 80.2, and 76.8%, respectively. Thus, 300 rpm was identified as the optimal agitation speed for

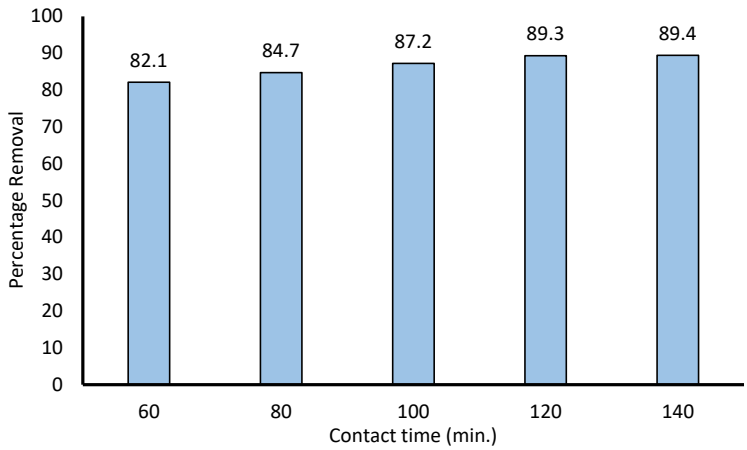

Fig. 7: Removal of fluoride from groundwater using SGAC for various contact time

fluoride removal using SGAC. Due to the agitation speed, fluoride demonstrated improved adhesion to the SGAC surface, which is consistent with the results reported by Iwar *et al.* (2021). The adsorption rate and fluoride ion absorption capacity decreased beyond 650 rpm agitation speed because there was a greater space between the fluoride ions and the adsorbent surface (Bhaumik and Mondal 2016). Conversely, the results of this study utilizing SGAC aligned with the findings of Bhaumik and Mondal (2016), although the agitation speed exceeded 300 rpm. The variations observed in current study compared to previous studies are attributed to the specific properties of the activated carbon chosen for the extraction of fluoride from groundwater.

Effect of contact time

Fig. 7 illustrates the effect of contact time on fluoride removal using SGAC, with durations ranging from 60 to 140 min in 20 min increments. The experiment was conducted at an optimal particle size of 2.360 mm, an 8 g dosage, and an agitation speed of 300 rpm. At the 60 min interval, the fluoride removal efficiency was relatively low; however, it increased with time, achieving its highest level at 120 min. Beyond this duration, no significant gains were noted at 140 min, suggesting that SGAC had fully utilized its fluoride sorption capacity by 120 min. The maximum removal percentages were 82.1, 84.7, 87.2, 89.3, and 89.4% for 60, 80, 100, 120, and 140 min, respectively. Therefore, 120 min was identified as the optimal contact time, achieving 89.3% fluoride removal. The current findings are in agreement with prior studies, notably those by Talat *et al*. (2018), who demonstrated an 86% fluoride removal rate after 60 min using activated carbon sourced from coconut husks at a pH of 5, with an initial fluoride concentration of 10 mg/L. Similarly, Tefera *et al.* (2020) observed 86% fluoride removal at 60 min using avocado seed-derived activated carbon at pH 6. Bonyadi *et al.* (2019) demonstrated that 100 min with *Populusalba* activated carbon (PAC) resulted in 93.37% fluoride removal at 10 mg/L fluoride concentration. The determination of 120 min as the most effective contact time in this study yields significant insights for upcoming groundwater treatment strategies, boosting fluoride removal effectiveness through the use of SGAC.

In this study, the influence of individual factors—namely particle size, dosage, agitation speed, and contact time on the removal of fluoride was analyzed, with all other parameters held constant at their ideal settings. Experimental investigations were conducted to optimize fluoride removal efficiency, determining the ideal conditions as 2.360 mm particle size, 8 g dosage, 300 rpm agitation speed, and 120 min contact time, achieving a maximum fluoride removal of 89.3%. Of all the characteristics examined, agitation speed and contact time were determined to significantly affect adsorption, as they directly improve the interaction between the adsorbent and fluoride ions, leading to increased removal efficiency. The greater removal values observed with optimal contact time (Fig. 7) and

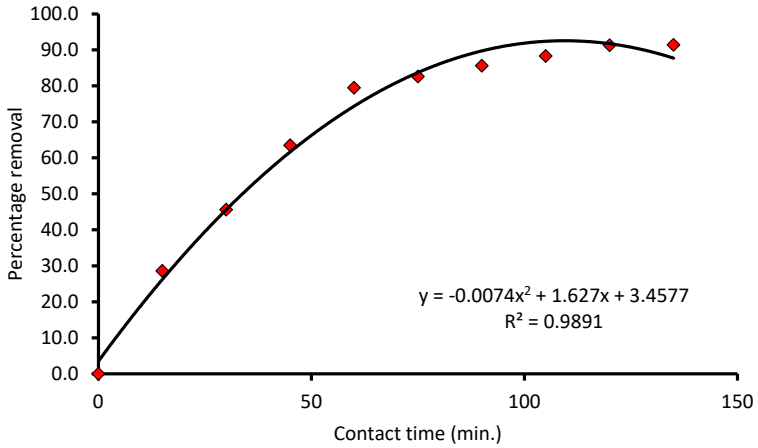

Fig. 8: Removal of fluoride in groundwater using SGAC for the optimum equilibrium data

agitation speed (Fig. 6) compared to the material itself (Figs. 4 and 5) are primarily due to enhanced mass transfer and increased interaction between the adsorbent and adsorbate. Extended contact time enables a greater number of fluoride ions to engage with the active sites on the adsorbent, facilitating equilibrium and enhancing the adsorption capacity. Likewise, elevating the agitation speed improves the distribution of the adsorbent in the solution, thereby minimizing boundary layer resistance and promoting a more uniform engagement between fluoride ions and active sites on the adsorbent surface. In contrast, factors like particle size and adsorbent dosage, while important, may not provide the same level of interaction or mass transfer efficiency, hence their lower impact on removal efficiency compared to contact time and agitation speed.

Equilibrium study

Fig. 8 shows equilibrium study results on the removal of fluoride from groundwater using SGAC for various contact times between 0 and 140 min with an increment of 20 min. The observed percentage decrease in fluoride ion concentration in groundwater occurred at an optimal particle size of 2.360 mm, a dosage of 8 g, and an agitation speed of 300 rpm, evaluated over various contact times. The initial fluoride concentration was 2.5±0.14 mg/L, with a pH of 6.9 and temperature of 27 °C. The findings showed that SGAC removed a small proportion of fluoride at shorter contact times, with removal increasing up to 120 min. Beyond this, no significant difference was observed at 140 min, indicating maximum removal was achieved at 120 min. Fig. 8 also shows that nearly 80% of fluoride removal occurred within the first 100 min. The findings from the equilibrium studies were applied to adjust isotherm and kinetic models, which helped in identifying the maximum adsorption capacity and the rate of fluoride removal by SGAC.

Adsorption isotherms

The adsorption isotherm serves as an essential instrument for demonstrating the sorption capacity of an adsorbent and the underlying mechanisms of the adsorption process. It evaluates the relationship between the amount of fluoride adsorbed at the solid/solution interface and the fluoride concentration remaining in the bulk solution. The equilibrium data collected under ideal conditions through SGAC were analyzed using Freundlich and Langmuir adsorption isotherms to assess fluoride removal from groundwater. Fig. 9(a) presents the Langmuir isotherm model for SGAC, where the K_L value was 3.5982, and the maximum adsorption capacity (q_m), determined by fitting experimental data to linear Langmuir equations, was 0.318 mg/g. The R^2 of 0.9121 indicates that fluoride adsorption was generally favorable. The separation factor (R_L), which determines adsorption type and feasibility, ranges from 0 to 1, confirming a favorable adsorption isotherm. Further analysis of SGAC's effectiveness was conducted using the Freundlich isotherm, which suggests that multilayer adsorption takes place on a heterogeneous adsorbent with adsorption sites

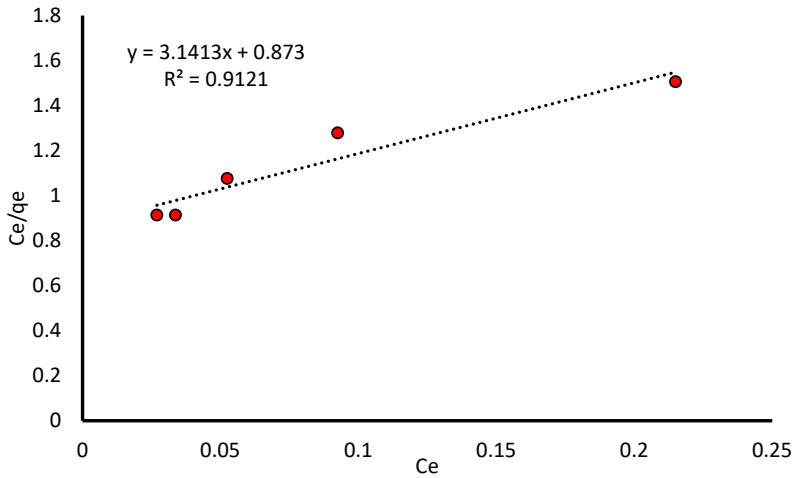

Fig. 9(a)

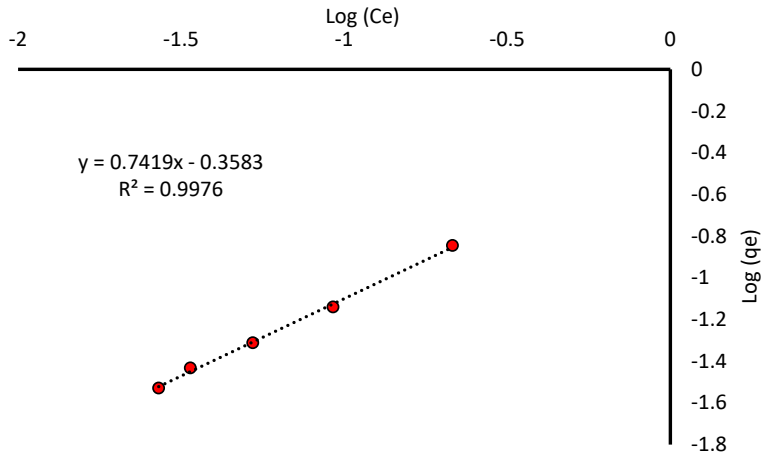

Fig. 9(b)

Fig. 9: Longmuir (9(a)) and Freundlich (9(b)) isotherms for the removal of Fluoride from groundwater using SGAC

that possess varying energy. Fig. 9(b) illustrates the Freundlich isotherm for fluoride removal, showing an R^2 value of 0.9976, with 1/n and K_F values of 0.7419 and 0.6988, respectively. Since 1/n is less than 1, it suggests chemical adsorption rather than a linear process. Comparing Figs. 9(a) and 9(b), the Freundlich isotherm had a significantly higher R^2 value than the Langmuir model, indicating that SGAC exhibits multilayer heterogeneous adsorption, which governs fluoride removal from groundwater.

This study found that the Freundlich isotherm model fits better than the Langmuir model for fluoride removal from groundwater using SGAC due to the heterogeneous nature of the adsorbent surface and the multilayer adsorption process. The Freundlich model is well-suited for illustrating adsorption on surfaces that have varying affinities for fluoride ions, reflecting the highly porous and amorphous structure of SGAC, which includes multiple active sites with distinct energy characteristics (Senewirathna *et al.*, 2022). Unlike the Langmuir model, which assumes a uniform surface with a monolayer of adsorbate, the Freundlich model accommodates the complex interaction between fluoride ions and various functional groups on SGAC, such as hydroxyl and carboxyl groups, resulting in both physical and

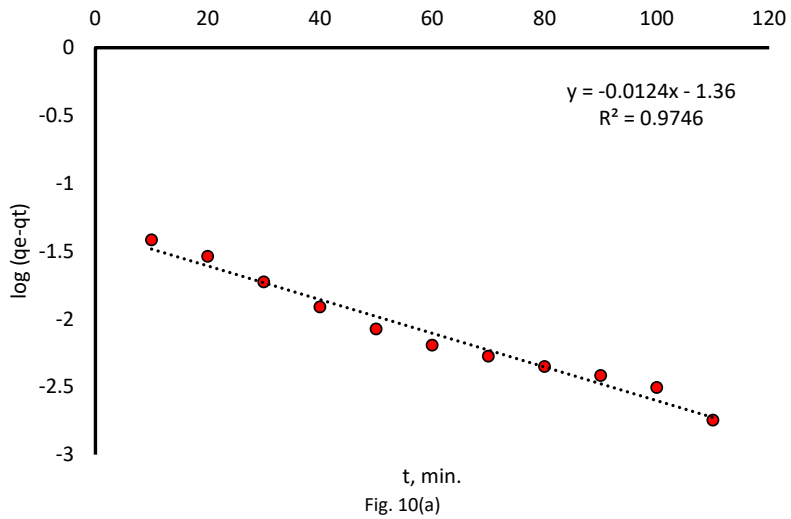

Fig. 10(a)

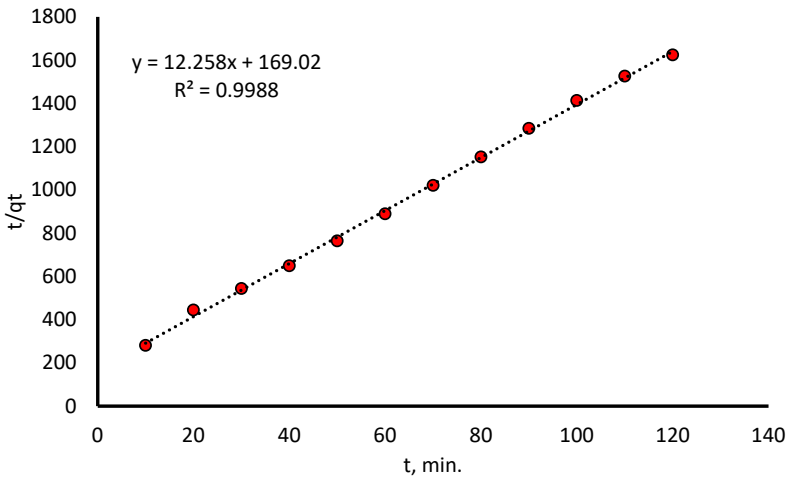

Fig. 10(b)

Fig. 10: Pseudo first order (10(a)) and Pseudo second order (10(b)) kinetic models for the removal of Fluoride from groundwater using SGAC

chemisorptive bonding (Niyitegeka *et al*., 2023). Furthermore, the Freundlich model provides a more precise depiction of SGAC's continuous adsorption capacity, since the fluoride removal does not abruptly level off, facilitating adsorption through multiple phases (Ousman *et al*., 2023). Consequently, the Freundlich isotherm more accurately represents the fluoride adsorption behavior on SGAC, which involves a non-ideal, heterogeneous process rather than the uniform adsorption assumed by the Langmuir model (Solanki *et al*., 2021).

Kinetic study of adsorption

Time-sensitive analyses were undertaken to identify the step that governs the rate and to elucidate the adsorption mechanism. In this study, fluoride removal was tested against optimal process parameters such as particle size, adsorption dosage, agitation speed, contact time, and initial concentration. To determine the equilibrium time for fluoride removal from groundwater using SGAC, the kinetics of adsorption were analyzed. The maximum removal in the first 60 min was due to fluoride adsorption onto the active surface and greater pore availability on SGAC (Fig. 10(a)). The removal percentage decreased as contact time progressed from 60 min, reaching equilibrium at 120 min with maximum fluoride removal of 91.5%. To ascertain the adsorption mechanism for

fluoride removal with SGAC, the equilibrium data was fitted using two models: pseudo first order and pseudo second order. The experimental data were analyzed using both linear representations of the pseudo first-order and pseudo second-order kinetic models. Figs. 10(a) and 10(b) show the pseudo first order and pseudo second order kinetic models, respectively. The R^2 values obtained from the pseudo second order model (0.9988) were greater than those from the pseudo first order model (0.9746) for fluoride removal using SGAC. Notably, there was a stronger correlation (0.08157 mg/g) between the experimental and computed q_e values for the pseudo second order model than for the pseudo first order model (0.04365 mg/g). Additionally, the constants K_1 and K_2 were found to be 0.0124 and 0.8886, respectively, indicating that the pseudo second order model had a greater rate constant than the pseudo first order model.

Fito *et al.* (2019) found the Freundlich isotherm (R^2 = 0.98) best fitted experimental data for *Catha edulis* stem activated carbon at room temperature, pH 2, 1.5 g in 100 mL, and an initial fluoride concentration of 30 mg/L, indicating a multilayer adsorption process. Tefera *et al.* (2020) determined the Langmuir model fitted experimental data well, with a maximum adsorption capacity of 1.2 mg/g. Bakhta *et al.* (2022) confirmed similar results using activated carbon for fluoride removal. The study conducted by Al-Musawi *et al*. (2024) on magnetized hazelnut shell activated carbon revealed that the pseudo-second-order kinetic model was particularly revealing, with the kinetic process being governed by intra-particle and liquid film diffusion mechanism. The Langmuir model fit the data well, with a monolayer adsorption capacity of 0.3065 mg/g and R^2 = 0.93 (Niyitegeka *et al.*, 2023). Amaibi *et al.* (2024) found the Langmuir isotherm (maximum adsorption capacity of 0.02 mg/g, R^2 = 0.992) best fitted data for lemon peel activated carbon. This study determined that the rate and capacity of adsorption on activated carbon are influenced by surface area, pore architecture, and the presence of active functional groups on the surfaces. Furthermore, raw materials, such as wood, coconut shell, or coal, impact surface chemistry and porosity, affecting adsorption behavior. It is vital to comprehend these factors in order to modify the characteristics of activated carbon for better fluoride removal, underscoring the necessity for detailed characterization and tailored solutions for specific water treatment applications.

Verification of experimentation

The percentage removal of fluoride from groundwater also affects the other parameter concentration in groundwater. This study examined the changes in the concentration of various parameters in groundwater through the use of SGAC, as well as the effectiveness of fluoride removal from groundwater. The maximum removal efficiency of other water quality characteristics was assessed at the optimum particle size of 2.36 mm, adsorption dosage of 8 g, agitation speed of 300 rpm, and contact time of 120 min. In Table 4, the maximum percentage of fluoride removal, along with other groundwater quality characteristics, is displayed for SGAC, with the exception of pH. The pH was improved from 6.9 to 7.4 after treatment with SGAC, which showed that it was within the standard limit as prescribed by the BIS standard.

From Table 4, it may be noted that maximum removal percentages of TDS, TH, Ca, Mg, Na, K, Cl_2, SO_4, NO_3, F, and Fe were found to be 77.20 ± 0.8, 73.80 ± 0.5, 81.90 ± 0.5, 84.10 ± 0.8, 71.90 ± 0.7, 81.60 ± 0.6, 74.90 ± 0.3, 82.50 ± 0.2, 79.80 ± 0.9, 89.30 ± 0.4, and 89.70 ± 0.7 respectively. After the treatment of groundwater with SGAC, the value of all quality characteristics was below the standard limit of BIS. The findings from the validation test suggest that the most effective conditions for fluoride removal from groundwater involve a particle size of 2.36 mm, an adsorption dosage of 8 g, an agitation speed of 300 rpm, and a contact time of 120 min. Additionally, these parameters enhanced all aspects when SGAC was applied at a pH value of 7.4.

Regeneration test

This study ultimately focuses on understanding how expended SGAC can be reused. The regeneration capacity of SGAC for the removal of fluoride was evaluated using 0.1 mole (mol) sodium hydroxide (NaOH) (Tan *et al.*, 2020). The desorption procedure began by combining 25 mL of 0.1 mol NaOH with saturated fluoride in SGAC and letting the mixture sit for 90 min. The percentage of material removed from the SGAC in the first cycle was 89.5%, while the percentages in the second, third, fourth, and fifth cycles were 87.3, 85.4, 82.1, and 78.3%, respectively.

Table 4: Percentage removal of all quality characteristics in groundwater using SGAC

S.N.	Parameters	Initial Value* (A)	Final Value+ (B)	Removal Value# (C)	Removal Percentage^ (D)
1	Total dissolved solids, mg/L	426.87	97.33	329.54	77.20±0.8
2	Total hardness, mg/L	432.62	113.35	319.27	73.80±0.5
3	Calcium, mg/L	98.45	17.82	80.63	81.90±0.5
4	Magnesium, mg/L	31.26	4.97	26.29	84.10±0.8
5	Sodium, mg/L	195.76	55.01	140.75	71.90±0.7
6	Potassium, mg/L	8.66	1.59	7.07	81.60±0.6
7	Chloride, mg/L	235.74	59.17	176.57	74.90±0.3
8	Sulphate, mg/L	195.84	34.27	161.57	82.50±0.2
9	Nitrate, mg/L	38.32	7.74	30.58	79.80±0.9
10	Fluoride, mg/L	2.50	0.27	2.23	89.30±0.4
11	Iron, mg/L	0.67	0.07	0.60	89.70±0.7

*Initial Value (A) = Initial concentration of all parameters value in groundwater before treatment using SGAC
+Final Value (B) = Initial concentration of all parameters value in groundwater before treatment using SGAC
#Removal Value(C) = A – B
^Removal Percentage (D) = (C/A) x 100
Note: The average value is presented in columns A, B, and C, and the average percentage removal with the standard error (SE) of the mean is presented in column D for all parameters

With an increase in the number of cycles, the efficiency of desorption decreased. Because the previously adsorbed fluoride in SGAC could not be eliminated during the desorption process, there was a decrease in regeneration. The interaction of fluoride with various functional groups in SGAC plays a significant role in reducing its reusability. The ability of SGAC to be utilized five times for the extraction of fluoride from groundwater indicates that the material demonstrated strong stability throughout the desorption process (Vardhan and Srimurali, 2016). SGAC exhibited good stability for reusability, as evidenced by the fifth cycle desorb of the fluoride concentration of 3.526 mg/L from the absorbed fluoride in SGAC (which was more than the desorbed concentration of 3.526 mg/L). The preparation cost of SGAC decreased fivefold due to its repeated use in removing fluoride from groundwater on five occasions (Zhang *et al.,* 2019). Consequently, the SGAC that is produced can be used effectively to lower the concentration of various water quality parameters in both water and wastewater contexts, as well as to reduce fluoride levels in groundwater.

Enhanced fluoride removal comparison study

Fluoride contamination in groundwater poses health risks, prompting research on activated carbon-based adsorbents. The findings of this study underscore SGAC as a viable, sustainable, and cost-efficient alternative, characterized by enhanced conditions and effective adsorption dynamics. Table 5 compares activated carbon adsorbents from various plant sources. *Cocos nucifera*-based carbon achieved 94.4% fluoride removal (Palodkar *et al.,* 2017), while SGAC reached 89.3% without extensive pore modifications. *Ficus benghalensis*-based adsorbent removed 90% fluoride (George and Tembhurkar, 2018), but SGAC exhibited superior adsorption (R^2 = 0.9976). *Catha edulis* carbon achieved 73% removal at pH 2 (Fito *et al.,* 2019), whereas SGAC reached 89.3% at pH 7.4 with lower dosage, making it a practical solution for large-scale water treatment. In contrast to earlier studies, the current study, reveals that SGAC is capable of attaining similar or greater fluoride removal rates under conditions that are both more practical and cost-effective. Chandraker *et al.* (2021) achieved 92% fluoride removal using sugarcane bagasse-based carbon, while the present study attained 89.3% with a larger particle size (2.360 mm), reducing the need for extensive refinement. According to Chukka *et al*. (2022), the optimization of coconut shell carbon resulted in a 69.5% removal rate. However, SGAC outperformed this by achieving an 89.3% removal rate, highlighting its enhanced effectiveness for drinking water purification. Iwar and Ugwudike (2022) achieved 99.1% fluoride removal with 2.0 mg/g adsorption capacity using response surface methodology (RSM) at 298 K and pH 5, the

Table 5: Comparison of fluoride removal efficiency using various activated carbon adsorbents in different water types

S.N.	Activated carbon	Types of Water	Botanical Name	Removal Percentage	Characterisation	Duration	Sources
1	Coconut	wastewater	*Cocosnucifera*	Removal efficiency of 94.4%	Activated carbon dose = 2 g, pH = 2 Initial fluoride concentration = 2 mg/L Temperature = 303 K (30°C) Agitation speed = 150 rpm	50 min.	Palodkar *et al.*, 2017
2	Banyan tree leaf	water	*Ficusbenghalensis*	Removal efficiency of 97.0%	Adsorbent dosage = 8 g/L Temperature = 26 °C Adsorption capacity = 2.242 mg/g	90 min.	George *et al.*, 2018
3	Khat	Aqueous solution	*Catha edulis*	Removal efficiency of 73.0%	Adsorbent dose = 1.5 g/100 mL, pH= 2 Initial fluoride concentration = 30 mg/L	60 min.	Fito *et al.*, 2019
4	Bagasse	Drinking Water	*Saccharum officinarum*	Removal efficiency of 82.4%	Adsorbent dosage = 4 g/L, pH=4 Temperature = 26°C Particle Size = 0.225 mm Speed = 100 rpm	24 min.	Chandraker *et al.*, 2021
5	Coconut shell	Groundwater	*Cocosnucifera*	Removal efficiency of 69.5%	Initial fluoride concentration= 50 mg/L Adsorbent concentration = 1 g/100 mL	60 min.	Chukka *et al.*, 2022
6	Palm shell	Groundwater	*Arecaceae*	Removal efficiency of 99.1%	Adsorbent dosage = 2.0 g/L, pH= 5.9 Speed = 250 rpm Initial fluoride concentration = 4.0 mg/L	120 min.	Iwar and Ugwudike, 2022
7	Lemon peels	Drinking water	*Citrus × limon*	Removal efficiency of 94.9%	Adsorbent dosage = 2.5 g/L, pH=7 Speed = 200 Adsorption capacity = 0.02 mg/g Initial fluoride concentration = 1.0 mg/L	100 min.	Amaibi *et al.*, 2024
8	Agathi plant	Groundwater	S. *grandiflora*	Removal efficiency of 86.3%	Adsorbent dose = 8 g, pH = 6.5, Agitation speed = 300 rpm Particle size = 2.36 mm, Initial fluoride concentration = 2.5 mg/L	120 min.	Current Study

Langmuir isotherm had a maximum adsorption capacity of 146.2 mg/g, while SGAC reached 89.3% at a near-neutral pH with a moderate 8 g/L dosage, indicating greater scalability and economic feasibility. Amaibi *et al.* (2024) reported 97.09% fluoride removal using lemon peel carbon within 100 min, slightly higher than SGAC (89.3%), but SGAC exhibited superior reusability and stability, with minimal crystallinity changes (17.2% to 17.4%) and strong adsorption kinetics. In contrast to these studies, SGAC offers a combination of high removal efficiency and improved operational feasibility, positioning it as a practical and sustainable option for water treatment. Compared to previous study results, this study found that SGAC demonstrated efficient fluoride removal (89.3%) under optimized conditions (2.360 mm particle size, 8 g dosage, 300 rpm agitation, and 120 min contact time), ensuring groundwater quality met BIS standards. Structural analysis confirmed fluoride adsorption through FTIR, SEM, elemental variations (EDX), and stable amorphous nature with minimal crystallinity change (XRD). Adsorption followed the Freundlich isotherm (R^2 = 0.9976), indicating multilayer heterogeneous adsorption, while kinetic analysis confirmed chemisorption as the dominant mechanism (pseudo-second-order model, R^2 = 0.9988). In contrast to earlier studies that relied on harsh chemical methods, SGAC demonstrated high efficiency in practical and environmentally friendly conditions, positioning it as a cost-effective, reusable, and scalable option for large-scale fluoride remediation.

Future research directions

The objective of research should be to improve regeneration processes by investigating alternative solvents or cutting-edge techniques that facilitate fluoride recovery and the restoration of SGAC's adsorption capacity following multiple cycles. Pilot-scale trials in various water matrices, with different contamination levels, are essential to assess SGAC performance in real-world applications. These trials will provide insights into SGAC's behavior under diverse environmental conditions and validate its field applicability. Ongoing long-term investigations into SGAC's influence on human health, environmental factors, and its performance across different regions will confirm its safety and scalability.

Practical implications

SGAC presents a promising material for large-scale defluoridation of groundwater, given its cost-effectiveness, stability, and reusability. Improving production and regeneration processes, as well as incorporating SGAC into hybrid systems, will promote sustainability in the removal of fluoride. SGAC's ability to meet drinking water standards makes it a suitable candidate for widespread use in areas with fluoride contamination. The possibility of extensive application provides major enhancements in public health by confronting water pollution issues on a global scale.

CONCLUSION

The findings of the current study clearly indicate that SGAC is a stable and effective material for adsorbing fluoride from groundwater. Initially, SGAC was characterized using FTIR, SEM, EDX, and XRD to analyze its structural, morphological, and elemental composition before and after fluoride adsorption. FTIR analysis identified functional groups such as C=C, C=O, and O-H, which remained present post-adsorption, with peak shifts indicating fluoride binding. SEM images indicated that the SGAC exhibited a highly porous structure prior to adsorption, which transformed into a smoother and denser form following fluoride absorption. According to the EDX analysis, there was a decline in phosphorus and sulfur, while the rise in carbon, oxygen, sodium, and chloride pointed to mechanisms of precipitation and ion exchange. XRD analysis confirmed that SGAC remained amorphous, with a minor increase in crystallinity (from 17.2% to 17.4%), ensuring structural stability. Investigative experiments were undertaken to refine the fluoride removal process, pinpointing the optimal parameters as a particle size of 2.360 mm, an 8 g dosage, a stirring speed of 300 rpm, and a contact time of 120 min, achieving a maximum fluoride removal efficiency of 89.3%. The adsorption process followed the Freundlich isotherm (R^2 = 0.9976), indicating multilayer heterogeneous adsorption, while pseudo-second-order kinetics (R^2 = 0.9988, K_2 = 0.8886) confirmed chemisorption as the dominant mechanism. The Langmuir model provided a maximum adsorption capacity of 0.318 mg/g with a separation factor (RL = 0.5982), indicating a favourable adsorption process. Model validation

showed high predictive accuracy (R^2 = 99.88%, adjusted R^2 = 99.56%, test R^2 = 98.16%) with minimal deviation (S = 1.10561). Further, SGAC's reusability was tested over five regeneration cycles using 0.1 M NaOH, with desorption efficiency declining from 89.5% to 78.3%, indicating strong fluoride interactions with functional groups. Additionally, SGAC-treated water met BIS drinking water standards, with fluoride removal ensuring a final pH of 7.4, making it safe for consumption. Overall, SGAC proves to be a highly efficient, stable, and reusable adsorbent for fluoride removal, with its cost-effectiveness and reusability enhancing its potential for sustainable groundwater treatment applications. To optimize the practical implementation of SGAC, upcoming studies should prioritize scaling production, enhancing desorption techniques, and integrating SGAC within hybrid treatment frameworks. Advanced spectroscopic analysis can provide deeper insights into fluoride binding mechanisms, while pilot-scale trials in diverse water matrices will validate its field applicability. This study is distinguished by its pioneering use of SGAC for fluoride removal, extensive material characterization, exceptional removal efficiency, and the confirmation of a solid adsorption model. With its cost-effectiveness, stability, and sustainability, SGAC presents a promising solution for large-scale groundwater treatment, addressing global concerns over fluoride contamination. Future studies should focus on scaling up SGAC production, enhancing cost-effectiveness, and ensuring suitability for large-scale groundwater treatment. By refining desorption techniques, the reusability of SGAC can be enhanced, contributing to sustainable long-term usage. Future studies should investigate the integration of SGAC within hybrid treatment systems, pairing it with alternative adsorbents or filtration approaches to elevate fluoride removal efficiency across different water types. Surface characterization techniques, such as XPS or NMR, should assist in understanding fluoride binding mechanisms and optimizing surface properties for improved adsorption.

AUTHOR CONTRIBUTIONS

D. Sivakumar conceptualized the study, supervised the study, guided the research process, and contributed to data interpretation, analysis, and report preparation. M. Perarul Selvan conducted the experiments, collected and analyzed the data, and contributed to writing and editing the report. J. Nouri contributed to the study's conceptual framework and provided critical insights for research development. M. Juhi Jabin assisted in experimental setup, data validation, and manuscript formatting. S. Priyanka assisted in statistical analysis, literature review, and final proofreading of the manuscript. G. Madhubala contributed to sample preparation, chemical analysis, and graphical data representation. All authors contributed equally to the completion of the study and approved the final manuscript.

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CONFLICT OF INTEREST

The authors declare that there are no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, were observed by the authors.

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ABBREVIATIONS

%	Percent
°C	Degree Celsius
µm	Micrometers
3D	Three dimension
Å	Angstrom
Al	Aluminum
APHA	American Public Health Association
AWWA	American Water Works Association
BET	Brunauer-Emmett-Teller
BIS	Bureau of Indian Standards
Ca	Calcium
Cl	Chlorine
Cl_2	Chloride
cm	Centimeters
cm^3/g	Cetimeter cubes per gram
Cu	Copper
Cu 2 Theta	Coupled two theta
EDX	Energy dispersive x-ray spectroscopy
F	Fluoride
Fe	Iron
FTIR	Fourier transform infrared spectroscopy
g	Gram
g/kg	Grams per kilogram
h	Hour
IQ	Intelligence quotient
K	Potassium
KARE	Kalasalingam Academy of Research and Education
KBr	Potassium bromide
Kα	K-alpha
L/g	Liters per gram
L/mg	Liters per milligram
m^2/g	Square meters per gram
Mg	Magnesium
mg/g	Milligrams per gram
mg/L	Milligrams per liter
min.	Minute
mL	Milliliters
mm	Millimeter
mol	Mole
Na	Sodium
NaOH	Sodium hydroxide
nm	Nanometer
NO_3	Nitrate
P	Phosphorus
PAC	*Populusalba* activated carbon
pH	Potential of hydrogen
R^2	Coefficient of determination
rpm	Revolutions per minute
RSM	Response Surface Methodology
S	Sulphur
SD	Standard Deviation
SE	Standard Error
SEM	Scanning electron microscopy
SGAC	*Sesbania grandiflora* activated carbon
SO_4	Sulphate
TDS	Total Dissolved Solids

TH	Total Hardness
V	Volt
WEF	Water Environment Federation
WHO	World Health Organization
WL	Wavelength
XRD	X-ray diffraction
λ	Lambda

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