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Effective Adsorptive Removal of SDBS from Aqueous phase Employing Biochar Incorporated Alginate Beads

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Abstract

This study examines the elimination of sodium dodecylbenzenesulfonate (SDBS), an anionic surfactant, from water with a new composite adsorbent prepared from biochar produced from banana peels and calcium alginate (BPBCA) beads. Batch adsorption investigations demonstrated optimal removal (95.55%) at pH 7, utilizing a 0.06g adsorbent dosage, an initial SDBS concentration of 50mg/L, and a stirring duration of 60 minutes, resulting in q_e of 39.85mg/g. The process obeyed pseudo-second-order model and the Langmuir isotherm, exhibiting a q_{max} of 46.51mg/g. Thermodynamic analysis demonstrated spontaneous adsorption, validated by negative changes in Gibbs free energy. The environmentally sustainable composite can effectively remove SDBS from water.

Keywords: Effective Adsorptive Removal of SDBS from Aqueous phase Employing Biochar Incorporated Alginate Beads.

Introduction

Aquatic ecosystem preservation and public health protection depend on wastewater treatment. Wastewater, comprising pollutants such as organic matter, nutrients, heavy metals, surfactants including sodium dodecylbenzenesulfonate (SDBS), and pathogens, is increasingly expanding in volume and complexity due to urbanization and industrial activities[1]. Effective treatment is essential because untreated or insufficiently treated wastewater offers serious environmental concerns, such as eutrophication, oxygen depletion, and toxin bioaccumulation. Owing to their diverse functions, surfactants are widely employed across sectors, including textiles, cosmetics, and papermaking. The existence of surfactants in wastewater causes considerable difficulties for further biological or physicochemical treatment procedures.

Surfactant levels in residential wastewater are usually between 1 and 10 mg/L, however surfactant manufacturing effluent typically has an average of about 300mg/ [2]. Because of their superior cleaning capabilities, anionic surfactants are widely used[3]. However, SDBS in wastewater presents significant environmental risks, including excessive foaming, which disrupts oxygen transfer and harms aquatic ecosystems[4]. When released into natural water bodies, surfactant-rich effluent not only generates increased foaming and less dissolved oxygen, but it also makes other pollutants more soluble[5,6].

Reusing wastewater, especially grey water, is essential to reducing the industrialization-induced depletion of freshwater supplies[7]. Because it contains fewer organics and dangerous microbes, grey water, which makes up 50–75% of household wastewater, is appropriate for a variety of non-potable uses, such as cleaning and irrigation[8,9].

Anionic surfactant concentrations in water are strictly regulated by the World Department of Environment (DOE), with drinking or recreational water not allowed to include more than 0.5mg/L and surface water not allowed to have more than 1.0mg/L[10]. Certain rules draw attention to the possible health hazards connected to the introduction of certain substances into the bodies of humans and animals.

Pathogens, nutrients, and organic materials in gray water hinder its reuse[11]. Effective treatment is essential to produce high-quality water that meets standards for pollutants, including Total Organic Carbon (TOC), nitrates, and phosphates. Surfactants like sodium dodecyl benzene sulfonate (SDBS) pose toxicity risks to humans and wildlife, harming aquatic life and disrupting microbial function, thereby increasing treatment costs[12]. Prolonged exposure to contaminated water can lead to skin irritation and endocrine disruption. Additionally, surfactants can enhance disease persistence by solidifying microbial suspensions, reducing disinfection efficacy[13].

There are a variety of ways for eliminating SDBS from water bodies. Physical, chemical, and biological techniques are frequently employed to remove pollutants from wastewater before it is discharged or reused. Adsorption is the most extensively used approach, as it is both cost-effective and environmentally friendly. In this context, biopolymers were employed to develop novel adsorbents for contaminants[14]. Adsorption is a very effective way to get rid of pollutants in wastewater, especially in comparing with other methods like

coagulation, membrane filtration, or advanced oxidation processes, because it is selective for target pollutants like heavy metals, organic dyes, and surfactants, even at very low levels; it works well in normal conditions without needing a lot of energy or creating secondary sludge, making it cost-effective and good for the environment[15].

Biochar is an effective adsorbent material that utilizes biomass waste, minimizing environmental pollution from biomass byproducts. Its porous structure and large surface area enhance adsorption properties[16]. Additionally, it is durable, improves soil quality when disposed of, and aids in carbon conservation. Biochar is frequently reusable and free from sludge or hazardous residues.

Hydrogel beads, derived from renewable and biodegradable seaweed alginate, are non-toxic and environmentally friendly. They effectively absorb water and adhere to contaminants like heavy metals, dyes, surfactants, and pharmaceuticals due to their carboxyl groups. Their flexibility allows them to be shaped into various forms, such as beads and films, and they are easy to separate after use without causing filter blockages. Additionally, they can be modified with other substances to enhance performance[17].

The aim of this research is to combine the adsorption capabilities of hydrogel with biochar to produce a high-performance, synergistic adsorbent that effectively removes contaminants from wastewater. This study determined that the procedure is environmentally sustainable in two respects: it utilizes banana peel, which is agricultural waste, and it eliminates surfactants. It was incorporated with alginate beads to improve its handling, surface area, and adsorption power.
It merges the benefits of hydrogel's swell ability and structural flexibility with biochar's large surface area. The hydrogel enhances mechanical strength and water retention, while biochar increases contaminant capture efficiency, especially for organics and heavy metals. Additionally, it is easy to separate after use, created from agricultural waste, and biodegradable, making it a cost-effective and sustainable option.

Materials and Methods

Chemicals: All chemicals that were used are of analytical standard. Loba Chemie Pvt. Ltd. supplied chemicals including orthophosphoric acid (88% pure), sodium alginate (91% pure), sodium dodecyl benzene sulfonate (SDBS) (98% pure), calcium chloride (97%) pure, hydrochloric acid (37% pure), and sodium hydroxide (97% pure).

The Instrumentation: A Labman double beam UV-Vis spectrophotometer model LMSPUV 1900 was used in this study to assess the levels of SDBS prior and following adsorption. The FTIR spectra of modified hydrogel beads were examined both before and after adsorption using an ATR-FTIR spectrometer (thermo-fisher scientific Nicole summit x). A Hitachi Flex-SEM 1000 scanning electron microscope was applied to examine the surface morphology of the adsorbent.

Preparation and Activation of Banana Peel-Generated Biochar (BPB): Biochar, a stable form of charcoal produced from the thermal pyrolysis of biomass, particularly banana peels, is rich in carbon, potassium, chlorine, magnesium, and calcium, with notable surface area and porosity. Its properties, which vary with production temperature, enable both acidic and basic functional groups for effective adsorption[18]. The process involves cleaning, drying, and pyrolyzing banana peels at 450°C with ramp rate 10^{o}C, followed by activation using orthophosphoric acid and further heating, enhancing its adsorption performance[19]. Following the crushing and sieving of dried banana peel biomass through a 0.3 mm sieve, the biochar was activated to enhance its adsorption properties[20]. Five grams of biochar were treated with 50% orthophosphoric acid, heated at 50°C for three hours, and subsequently heated to 600°C in a muffle furnace for two hours. Then cooling, it was washed multiple times with distilled water and dried overnight at 100°C.

Formation of BPBCA Composite Beads: Brown algae are the source of alginate, a naturally present biopolymer that dissolves in water and is made up of alternating blocks of 1-4 α-L-guluronic and β-D-mannuronic acid leftovers. When bivalent ions such as Ca^{2+}, Zn^{2+}, Sr^{2+} and Ba^{2+} are present, this polymer forms hydrogels. This gelation process is mediated by guluronic residues that specifically chelate Ca^{2+} to create the "egg-box" structure[21]. Using a magnetic stirrer, three grams of sodium alginate were dissolved in one hundred milliliters of distilled water and stirred for twenty minutes. After adding one gram of biochar, the mixture continues to blend for a further five minutes. To get ready100 milliliters of clean water were used to dissolve 3.88 grams of .035 M calcium chloride. Add droplets to the calcium chloride solution using a syringe. After allowing it to settle at room temperature for the entire night, the BPBCA beads were filtered the next day, cleaned with distilled water, and allowed to dry naturally[22]. The refrigerator was used to store the dried beads (Figure-1).

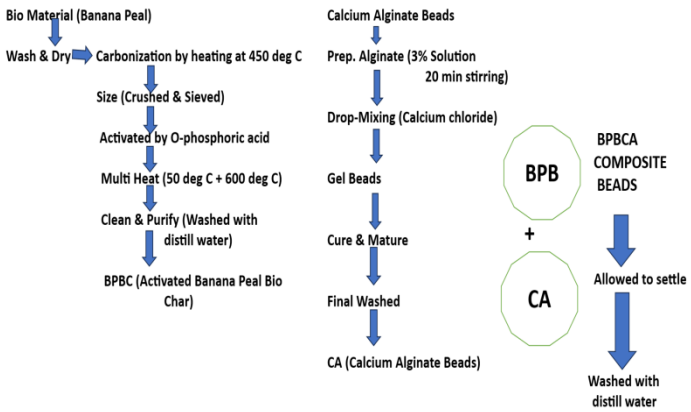


Figure-1: Synthesis flow chart: BPBCA composite.

Batch Experiments: A standard stock solution of SDBS (100 mg/L) was prepared in distilled water. This stock solution was then used to obtain the specified concentrations. In this work, BPBCA adsorbents were utilized in a series of intermittent trials to remove SDBS. 50ml samples were used for the investigations. The investigation focused on a number of variables, including pH levels (2–10), contact length (10 to 60 min), initial concentrations (20–70ppm), amounts of BPBCA beads (0.02–0.1g/50 ml). In addition to this, desorption experiments of the adsorbents were also carried out. While keeping the other values fixed, we optimized each parameter independently. To ensure accuracy, each test was performed three times. To avoid contamination, vessels were thoroughly rinsed with distilled water. The pH was changed by using HCl and NaOH. The percentage removal and adsorption capacity was computed by Equation (1) and (2).

$$q_e = \frac{(C_o - C_e)}{w} \times V \quad (1)$$

$$\% \, r = \frac{Co - Ce}{Co} \times 100 \quad (2)$$

V is the sample volume in liters (L), W is the adsorbent weight in grams, % r is the percentage of SDBS eliminated, q_e is the adsorption capacity in milligrams per gram (mg/g), C_o is the initial concentration, and C_e is the equilibrium concentration. Parts per million (ppm) units were used to measure C_o and C_e.

Swelling or Deswelling of Hydrogels: Spherical hydrogels have the tendency to adsorb an A large volume of water. This causes swelling of the hydrogels, which increases the mass as well as volume of the hydrogels. When hydrogels reach their maximum water absorption, or equilibrium swelling, there is no discernible change in the water intake or volume over time[23]. Deswelling is a reversible process in which hydrogels release adsorbed water while shrinking in volume due to elastic contraction of polymer chains and changes in solvent interactions. The swelling ratio is the change in volume of viscous hydrogels when submerged in fluids or moist environments, which is impacted by elements such as crosslinking, charge density, and polymer concentration[24]. The Swelling Ratio (SR) of hydrogel beads indicates their ability to absorb and retain fluids such as water or physiological buffers.

$$\text{Swelling Ratio} = \frac{(Ws - Wd)}{Wd} * 100 \quad (3)$$

In Equation (3) W_s and W_d are the weight of the swollen and dry hydrogel, Swelling Ratio of BPBCA beads are 144%, it is satisfactory result.

Isothermal Study: The adsorption isotherm graphically depicts how the quantity of adsorbed material varies with concentration, representing equilibrium conditions at a constant temperature. It aids in comprehending the adsorption process, with the mathematical relationship expressed as loading capacity (qe) based on the residual concentration of the adsorbate (Ce) at equilibrium[25].

The Langmuir isotherm assumes that each adsorbent material's surface has a set number of homogenous active sites and adsorbate adsorption is inhibited when these active sites become saturated. As stated in the model, Adsorbate adsorption continues unless a monolayer of adsorption is produced at which time the adsorbent and adsorbate molecules cease to interact[26].

Equation (4) is the model's linearized form, with C_e (mg/L) representing the concentration at equilibrium, q_e (mg/g) representing the quantity of SDBS adsorbed at equilibrium, q_{max} representing the optimal adsorption capacity (mg/g), and K_L representing the Langmuir constant. Consider the intercept $1/q_{max}.K_L$ and the slope $(1/q_{max})$ Equation (4).
The dimensionless parameter (R_L) also called separation factor can be calculated by Equation (6).

The Freundlich isotherm is an equation that describes solute adsorption onto solid surfaces. It is particularly useful for heterogeneous surfaces with changing binding sites, as it shows the link between the quantities of adsorbed and the equilibrium concentration. In Equation (5) C_e (mg/L) is the concentration at equilibrium of solute in the bulk, K_f (mg/g) is the Freundlich constant, This is comparative measurement of the adsorbent's adsorption capability and nf is a constant relating to the heterogeneity of the adsorbent surface.

n_f is typically bigger than one. A value of n_f indicates a good adsorption process. The isotherm constants Kf and nf were determined from the slope and intercept of the plot log qe vs. log Ce. Equation (5)[27]

$$\frac{c_e}{q_e} = \frac{1}{q_{max} \; K_L} + \frac{c_e}{q_{max}} \quad (4)$$

$$log q_e = log K_f + \frac{1}{n_f} log \, Ce \quad (5)$$

$$R_L = \frac{1}{1 + K_L C_o} \quad (6)$$

The Freundlich isotherm constants Kf and nf include all elements influencing the adsorption process, such as adsorption capacity and intensity of adsorption.

Kinetic Study: The investigation of the rate at which solute molecules (adsorbate) travel from a liquid state to the surface of a solid (adsorbent) and the amount of time needed to attain equilibrium is known as adsorption kinetics[28]. It is an important characteristic for assessing adsorbent performance and developing large-scale adsorption systems. Adsorption kinetics is investigated using linear or non-linear models. The model that best captures the process is determined using the degree of fit index[29]. The following models can be used to calculate the kinetics of adsorption onto the surface of BPBCA:

$$log(q_e - q_t) = log q_e - \frac{k_1 t}{2.303} \quad (7)$$

$$\frac{t}{q_t} = \frac{1}{k_2 \, q_e^2} + \frac{t}{q_e} \quad (8)$$

In Equation (7) and (8) q_e is adsorption capacities of SDBS (mg/g) at equilibrium and K_1 is the first order rate constant in min^{-1}, k_2 is the second order rate constant in L/mg min, t is the contact time in min, and qt is the adsorption capacity (mg/g) at time t (min).

Thermodynamics of Adsorption: Adsorption thermodynamics explains the spontaneity, energy changes, ΔS^0, ΔH^0, and ΔG^0as well as nature of molecules attaching to a surface. Thermodynamics are used to calculate key parameters such as $\Delta G^{0,}$ Gibbs Free Energy, ΔH^0 Enthalpy, and ΔS^0 Entropy to determine if the process is feasible, the type of forces involved, and how temperature affects it[30].

$$\log K_d = \frac{\Delta S^o}{2.303R} + \frac{-\Delta H^0}{2.303RT} \quad (9)$$

$$\Delta G^o = \Delta H^o - T\Delta S^o \quad (10)$$

In the Equation (9) and (10), ΔS^0 represents the change in entropy, ΔH^0 denotes the enthalpy change, and ΔG^0 signifies the Gibbs free energy change, which is computed using Equation (10). Equation (9) illustrates a linear correlation between $\log K_d$ and 1/T, where the value of $\Delta S^0$is derived from the intercept, and ΔH is also determined using the slop.

Results and Discussion

Characterization: SEM Analysis: The BPBCA beads were examined using SEM both before and after they were treated with SDBS to see how their surface characteristics had altered. The BPBCA beads' surface morphology was considerably changed by SDBS adsorption[31]. Before adsorption, the surface of BPBCA was rough, porous and wrinkled, as seen in Figure-2(a). The cross-linked network structure and the presence of hydrophilic groups give the BPBCA beads their rough surface and porosity[32]. The smoother surface indicated that the SDBS molecules had been adsorbed onto the BPBCA beads Figure-2(b). A coating of adsorbed SDBS molecules covers the surface, and many of the pores are either fully or partially filled. The creation of a coating layer and the decrease in pore gaps suggest that the adsorbate has taken up residence in these sites. Overall, the distinct difference between the compact, covered treated surface and the porous untreated surface attests to the successful adsorption that has occurred on the BPBCA beads.

FTIR Analysis: Before adsorption, BPBCA's FTIR spectrum shows a broad band about 3231 cm^{-1}, showing hydroxyl (-OH) stretching vibrations, mainly derived from calcium alginate and biochar surface functional groups. A small signal at 2040 cm^{-1} reveals overtone vibrations, whereas another peak at 1539 cm^{-1} shows aromatic C=C stretching from the biochar[33]. Intense peaks at 1089 cm^{-1} and 1005 cm^{-1} reveal C-O stretching from alcohol, ether, or ester groups, which increases adsorption activity. Additionally, the band at 665 cm^{-1} indicates bending vibrations from aromatic ring structures or skeleton deformations (Figure-3a).

After SDBS adsorption, the spectrum shifts indicate a positive interaction between the adsorbent and the adsorbate. The -OH stretching peak movements from 3231cm^{-1} to 3218cm^{-1}, indicating hydrogen bonding between BPBCA and SDBS's sulfonate groups. New peaks at 1584cm^{-1} and 1411 cm^{-1} suggest aromatic vibrations[34]. Peaks at 559 and 1021 reveal the presence of a sulfonate group and demonstrate chemical alterations caused by interaction between BPBCA and SDBS[35]. Similarly peak shifts from 2049 to 2161, this shows an interaction between the aromatic ring of BPBCA and SDBS[36] (Figure-3b).

These spectral changes indicate that the adsorption of SDBS onto BPBCA involves multiple interaction mechanisms. The primary mechanisms include electrostatic attraction between sulfonate groups of SDBS and positively charged sites on BPBCA, hydrogen bonding between –OH groups and sulfonate ions, and hydrophobic interactions between alkyl chain of SDBS and the carbon-rich biochar surface. Presence of aromatic ring of biochar and SDBS suggested Pi-pi stacking mechanism of adsorption. These interactions improve the adsorption performance and stability of the BPBCA adsorbent (Figure-3a and 3b).

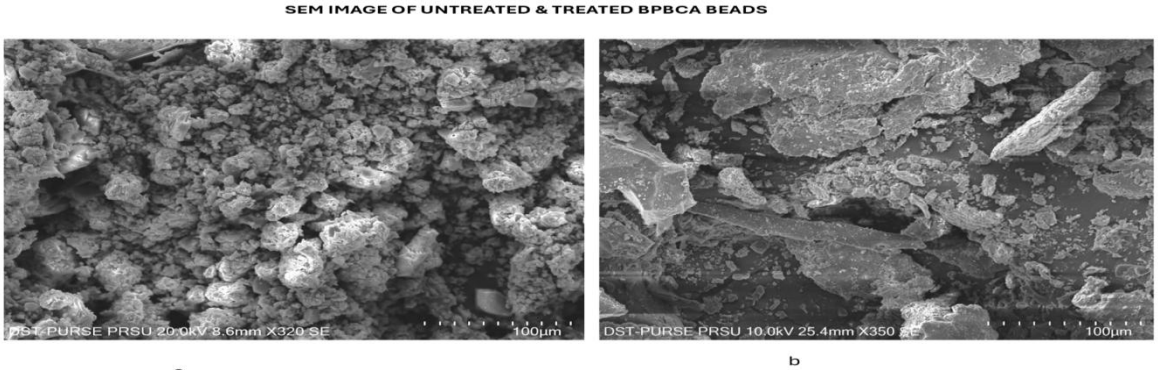


Figure-2: SEM image of BPBCA beads (a) Untreated BPBCA beads (b) Treated BPBCA beads.

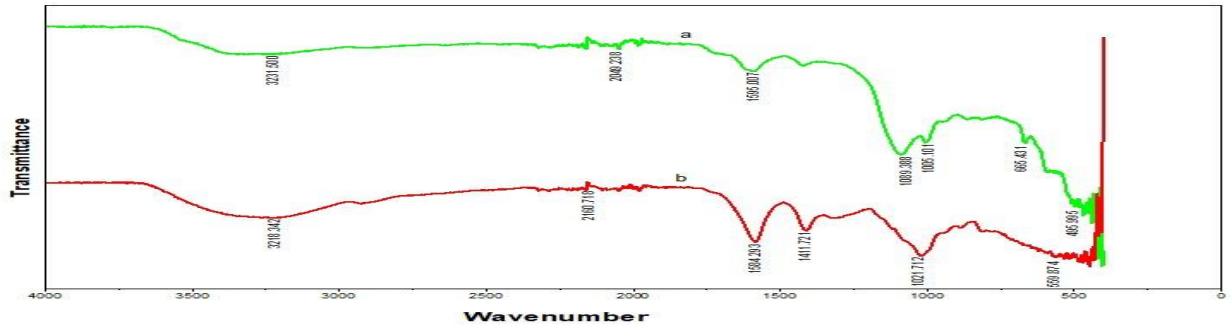


Figure-3: FTIR spectra of (a) BPBCA beads before SDBS adsorption (b) BPBCA bead after SDBS adsorption.

Calibration: The calibration curve for SDBS suggests a strong linear correlation between concentration and absorbance. The calibration curve is acceptable for quantitative analysis. In order to accurately identify unknown amounts of SDBS in experimental samples by comparing their absorbance0 values to this standard curve, this calibration curve is required.

Impact of pH: The pH effect on Sodium dodecylbenzene sulfonate (SDBS) removal via adsorption is mostly governed by the adsorbent's surface charge and the surfactant's ionic state. SDBS, as an anionic surfactant, is usually more effectively removed at lower pH levels of the adsorbent's Zero-point Charge (PZC)[37].

The solution's pH has an important influence on the adsorption of the anionic surfactant SDBS onto BPBCA beads with a point of zero charge (PZC) of 8.5 (Figure- 4). In the case of pH 7, the surface of BPBCA gets more positive due to the protonation of functional groups such as amino and hydroxyl groups, resulting in maximum removal efficiency and adsorption capacity for negatively charged SDBS molecules; however, after pH 7, the net positive charge decreases and the surface becomes less positive, reducing adsorption[38].

The removal of SDBS by BPBCA beads is mainly governed by pH-dependent electrostatic attraction. When the pH of the solution is maintained below the Point of Zero Charge (8.5), the adsorbent's surface functional groups, such as amino and hydroxyl group, experience a net positive charge. SDBS, an anionic surfactant with a negative charge, is strongly attracted to these positive sites on the bead surface.

This "opposites attract" mechanism results in maximum removal efficiency at 7; however, increasing the pH above 8.5 causes the surface to become negative, resulting in electrostatic repulsion and decreased adsorption. FTIR spectroscopy revealed that the presence of an aromatic ring in both the adsorbate and the adsorbent indicated an adsorption mechanism based on pi pi stacking. Adsorption capacity gradually diminishes when the pH goes above 8.5. The adsorption capacity of the BPBCA beads under investigation in this study reaches its maximum at pH = 7 (Figure-5B).

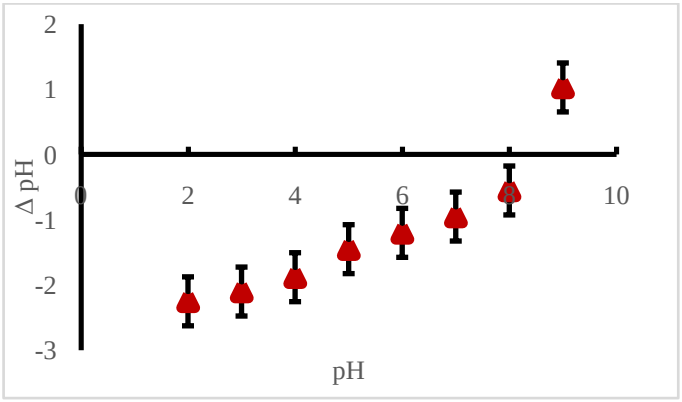


Figure-4: Zero-point charge of BPBCA.

Impact of Initial Concentration: Elevating the initial concentration of Sodium Dodecyl Benzene Sulfonate (SDBS) typically diminishes removal efficiency (percentage) while boosting the quantity adsorbed per unit of adsorbent (capacity), due to increased competition among pollutants for finite active sites[39]. At an initial concentration of 50mg/L, a optimal adsorption capacity of 39.85mg/g and a percentage removal of 95.66 were reported. When the SDBS concentration reaches 50 ppm, the surface sites become saturated; further concentration increases result in a relatively stable adsorption process (Figure-5A).

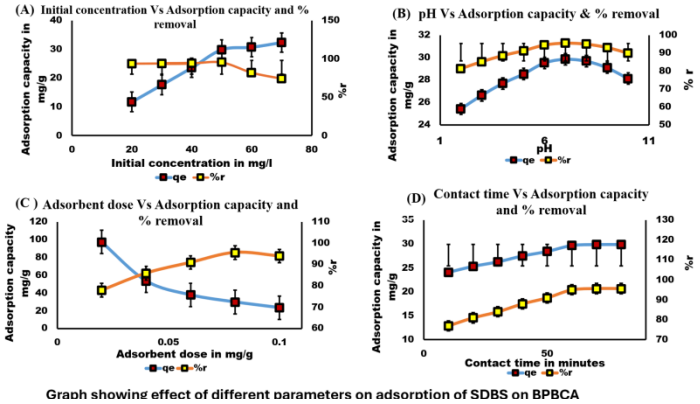


Figure-5: The adsorption capacity of SDBS on BPBCA Beads was measured in mg/g and percent removal at various pH, concentration, adsorbent dose, and stirring times.

Impact of Adsorption Dose: Raising the adsorbent dosage often improves the effectiveness of Sodium dodecylbenzene Sulfonate (SDBS) removal. This is due to the greater number of active adsorption sites and surface area available for SDBS molecules to attach. Even though as the dosage increases, overall elimination increases[40]. The results show that increasing the adsorbent dosage initially enhances the adsorption process, the optimal removal happens at 0.06g/50 ml of adsorbent dose (Figure-5C). A greater dose increases adsorption by creating more active sites. However, saturation causes a drop in adsorption above 0.06 g.

Impact of Stirring Time: The stirring duration, or contact time, is an important parameter in the adsorption of Sodium Dodecyl benzenesulfonate (SDBS) because it influences the rate at which surfactant molecules travel between the adsorbent surface and the solution. The stirring duration, or contact time, is an important parameter in the adsorption of Sodium dodecylbenzene sulfonate (SDBS) because it influences the rate at which surfactant molecules travel between the adsorbent surface and the solution. Adsorption normally enhances with prolonged stirring durations, commencing with a rapid initial phase that declines as equilibrium is approached[41].

Determining the ideal contact duration is critical for kinetic investigations because it maximizes surfactant removal effectiveness and ensures that the system achieves its maximum adsorption before the process slows, at 10 minutes 32.08mg/g, at 20 minutes 33.75mg/g, at 50 minutes 35mg/g, at 60 minutes 39.85mg/g, at 70 minutes 39.85mg/g (the ideal adsorption capacity), and 39.85mg/g at 80 minutes are shown in Figure-5D. This implies that equilibrium is reached after around 60 minutes, and that longer contact times do not increase adsorption capacity. Maximum adsorption occurred at 60 minutes.

Isothermal Analysis: An adsorption isotherm is a useful graphic representation tool for depicting a dynamic equilibrium between the concentration of residual SDBS in the bulk solution and the concentration of retained SDBS at the BPBCA beads interface, while temperature and pH stay constant. The isotherm describes how much adsorbate is distributed across the solid and liquid phases at an adsorption equilibrium for varied initial concentrations.

To validate the Freundlich model and compute the constants, the equation is transformed into its linear form (Equation (5a). It produces a straight line (Figure-6) the slope indicates the value of (1/n) (adsorption intensity). The intercept represents the value of log K_F (adsorption capacity). The parameters K_F and n_f are empirical constants that represent the interaction between SDBS and BPBCA beads at a certain temperature. The Freundlich coefficient, K_F, represents the BPBCA beads adsorption capability. A higher value of K_F suggests a greater affinity or capability for the material being adsorbed.

After plotting $\log c_e$ vs $\log q_e$, A straight line was found with a regression coefficient value of 0.5. With the help of the slope, with the help of the slop, we calculated the value of n_f=3.64, which is greater than 1 and indicates that this adsorption process is favorable[42]. Because values of n_f range from 1 to 10, with larger values indicating stronger and more advantageous interactions. The value of K_F was calculated by intercept and found to be 21.62 mg1-n Ln g^{-1}, indicating higher affinity between SDBS and BPBCA beads.

The Langmuir isotherm is a fundamental surface chemistry isotherm that represents the monolayer adsorption of an adsorbate onto a homogeneous solid surface, assuming that all adsorption spots are comparable and that there are no lateral interactions between adsorbed molecules[43]. According to Equation (4), a graph plot of c_eVsc_e/q_e shows a linear relation with a regression value of 0.99 (Figure-6).

$\frac{1}{q_{max}}$ is the slop and we calculate q_{max} from the graph to be 46.51 mg/g, which is near experimental value 39.85 mg/g, $1/q_{max}$ .K_L, is the intercept and K_L is calculated by the intercept is .713 L/mg. q_{max} is the greatest quantity of an adsorbate that may be absorbed per gram of adsorbent and is represented by this constant. This indicates complete saturation of the adsorbent surface. It measures BPBCA bead's potential to adsorb SDBS. The equilibrium constant K_L is associated with the binding energy or strength of the contact between the BPBCA beads and the adsorbent. It shows the molecules' affinity for the binding sites. Even at low concentrations, adsorption is made simpler by a substance's stronger attraction to the surface. A strong interaction is indicated by a larger K_L, whereas a weak interaction is suggested by a small K_L (Table-1).

We conducted error analysis tests on both models to assess the dependability of experimental data and the validity of the isotherm model using χ^2 as parameters to quantify the difference between experimental and predicted values according to Equation 11. In the isothermal analysis of BPBCA the Langmuir model was found to be the most acceptable because to its lowest χ^2(Table-2).

$$\sum_{i=1}^{n} \frac{(q_{exp} - q_{cal})\hat{}2}{q\ cal} \qquad (11)$$

Table-1: Parameters of isotherm.

Isotherm	Parameters			
Freundlich	n_f=3.64	R^2 =.57	K_f=21.62mg^{1-n} L^n g^{-1}	
Langmuir	K_L=.713L/mg	R^2 =.99	q_{max}=46.51 mg/g	R_L=.0193-0.065

Table-2: Checking applicability of Kinetic and Isotherm model by Chie square test.

Error Analysis	Freundlich	Langmuir	Pseudo First Order	Pseudo Second Order
χ2 Value	9.96	6.79	615.95	1.21

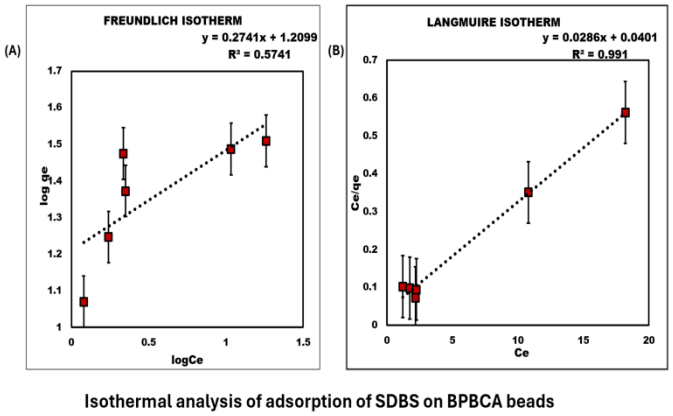


Figure-6: Plot of log q_e versus log c_e (Frendulich Isotherm) for SDS adsorption, Plot of c_e versus $c_e/q_{e,,}$ (Langemuire Isotherm).

Kinetic Analysis: Adsorption kinetics describes how adsorbate is held or released from an aqueous solution at the solid-phase interface. Kinetic adsorption studies look at how quickly an adsorbate moves from the liquid or gas phase to the surface of an adsorbent over time. It is an important tool for determining how quickly equilibrium is reached and recognizing the underlying chemical or physical mechanisms involved[43].

For the pseudo first order reaction, according to Equation (7), a graph of time vs log(q_e-q_t) was drawn for SDBS adsorption on BPBCA beads, with a regression value of 0.95 (Figure-6) and a calculated value q_e of 13.70 mg/g. The data of SDBS adsorption on BPBCA beads is well suited to a pseudo second order reaction. According to Equation (8), q_t is plotted against t/q_t with a high regression value 0.99 and value of q_e was obtained as 42.37 mg/g which is near practical value of 39.85 mg/g (Table-3), (Figure-7). To figure out the applicability of the kinetic model for BPBCA, error analysis test has also been implemented. The error analysis clearly shows that this procedure used a pseudo second order model. The pseudo-second-order (PSO) model has a lower χ^2 (1.21) than the pseudo-first-order (PFO). (Equation 8 and 9). Table-2.

Table-3: Parameters of kinetic analysis

Name of applied model	Kinetic Parameters	Calculated values
Pseudo-first-order model	k_1 (min-1)	0.04
	R^2	0.95
	q_e (mg/g)	13.70
Pseudo-second-order model	k_2 X 10-3 (g/mg min)	0.004
	R^2	0.99
	q_e (mg/g)	42.37
	q_e Experimental (mg/g)	39.85

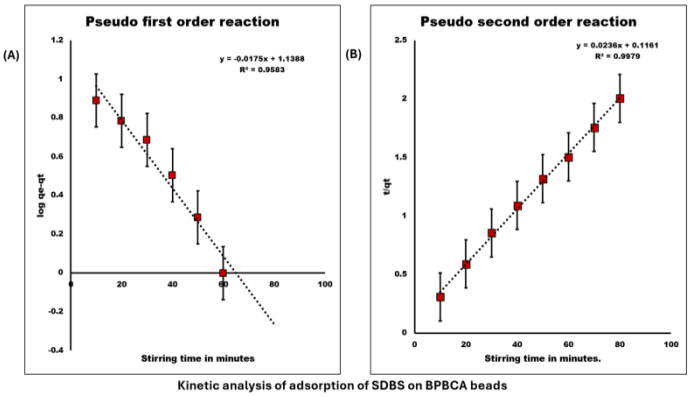


Figure-7: A pseudo-first-order kinetic plot of surfactant adsorption onto an BPBCA and Pseudo-second-order kinetic plot of surfactant adsorption on an BPBCA.

Thermodynamics Analysis: The thermodynamics of adsorption investigates the energy changes and spontaneity of molecules adhering to a surface, characterized by ΔG^0, ΔS^0 and ΔH^0. Plotting log (qe/ce) versus 1/T with the Van't Hoff Equation results in a straight line with a negative slope[44] (Equation 10), from which ΔS^0 is calculated as -0.095 KJ/mol K, indicating reduced molecular randomness. ΔH^0 is determined as -36.08 KJ/mol, signifying an exothermic process[40]. The adsorption of SDBS molecules leads to organized structure on BPBCA beads, with a negative ΔG^0indicating spontaneous adhesion without external energy (Equation 9). As temperature increases, ΔG^0 rises, reflecting decreased spontaneity and thermodynamic favorability (Table-4).

Table-4: Parameters of Thermodynamics.

	ΔGº kJ/mol			
ΔHº kJ/mol	ΔSº kJ/mol K	303	313	323
-36.08	-0.095	-7.2	-6.2	-5.3

Desorption: Desorption is a process that releases, removes, or liberates an adsorbed material from a surface, thereby reversing the adsorption process. It occurs when adsorbed molecules obtain sufficient energy via heat, lowered pressure, or chemical reaction to overcome the binding energy confining them to the surface. Regenerating utilized adsorbents is essential for enhancing the adsorbent's longevity and economic value. Methanol and .1N NaOH were employed as solvents to regenerate the BPBCA beads. Then, sodium dodecyl benzene sulfonate (SDBS) was adsorbed using the regenerated BPBCA beads produced with NaOH. Equations (11) and (12) were used to calculate the desorption efficiency and desorbed quantity.

$$\text{Desorption efficiency (\%)} = \frac{q_{des}}{q} \text{ X } 100 \quad (11)$$

$$q_{des} = \frac{C_f}{m} \text{ X } V \quad (12)$$

Where the amount of adsorbent is m in grams, volume of the NaOH solution is V in liters, C_f is the concentration of SDBS in

milligrams per liter in NaOH solution, and q_{des} is the desorption capacity and q is the adsorption capacity in milligrams per gram. Equations (11) and (12) were used to determine the desorption efficiency and desorbed amount qdes, respectively. During the initial regeneration cycle, qdes was 29.36 mg/g. The qdes value declined to 25.0 mg/g during the second regeneration cycle, and further to 23.9 mg/g in the third. This progressive fall implies that the adsorbent's desorption effectiveness decreases with each regeneration cycle. This is a decent result. As a result, it may be efficiently recycled and used again (Figure-8)

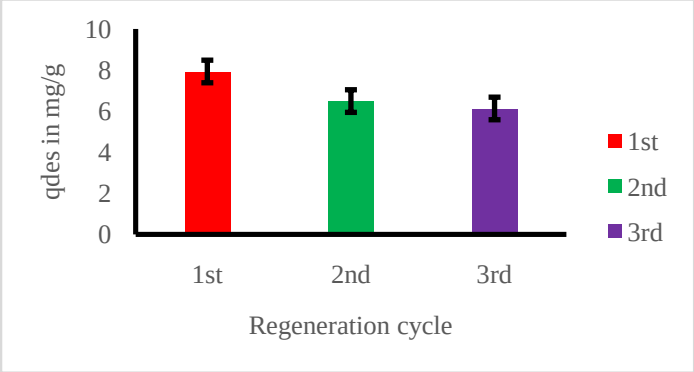


Figure-8: Graph showing relation between regeneration cycle and desorption capacity.

Method validation: Table-5 compares the physicochemical properties of five water samples and assesses the adsorption efficiency of BPBCA (banana peel biochar calcium alginate beads) for the removal of SDBS.

Total Dissolved Solids (TDS) readings ranged from 295 to 360 mg/L, suggesting moderate quantities of dissolved chemicals in water. Conductivity values (620-720 µS/cm) follow a similar trend, indicating the existence of ionic species that enhance electrical conductivity. The pH of the samples ranges from mildly acidic (5.0) to neutral (7.0), which is ideal for adsorption techniques because extreme pH values could negatively impact adsorbent effectiveness.

The initial SDBS concentration in the samples ranges between 6.15 and 7.33. After treatment with BPBCA, the equilibrium concentration (Ce) drops significantly to 0.61 to 0.85 ppm. This huge decrease indicates excellent adsorption capabilities of the composite beads.

The percentage removal (%R) of SDBS ranges between 88% and 91%, indicating consistent high removal effectiveness across all samples. Sample 3 had the best removal efficiency (91%), most likely due to its comparatively low initial TDS and suitable pH conditions, which may improve adsorption interactions. In comparison, Sample 2 has the lowest removal rate (88%), which could be attributed to a slightly higher baseline SDBS concentration or matrix effects.Overall, the findings show that BPBCA is an effective and dependable adsorbent for extracting SDBS from aqueous solutions.

Conclusion

The composite adsorbent produced from banana peel charcoal and calcium alginate beads has numerous benefits for removing SDBS from wastewater. It produces high adsorption (up to 95.55% elimination), is environmentally benign and cost-effective (using agricultural waste and seaweed alginate), and is simple to use, with solid hydrogel beads that do not clog filters. The adsorbent works well at a variety of pH levels, doses, and concentrations, adheres to green chemistry principles (biodegradable, no harmful byproducts), and has the potential to be reused.

Furthermore, it promotes a circular economy by utilizing waste biomass, resulting an appealing solution for industrial and municipal water treatment.

Table-5: Removal Efficiency of SDBS Using BPBCA Adsorbent in Real Water Sample.

Sample No.	TDS(mg/L)	Conductivity(µ/cm)	pH	SDBS Before Adsorption (ppm)	BPBCA (After SDBS adsorption)	
Sample 1	310	690	5	6.34	0.63	90%
Sample 2	348	720	6.2	7.10	0.85	88%
Sample 3	295	715	5.90	6.88	0.61	91%
Sample 4	336	705	7.0	6.15	0.61	90%
Sample 5	360	620	6.50	7.33	0.80	89%

This work investigates the elimination of SDBS from water applying a composite adsorbent composed of calcium alginate beads and biochar produced from banana peels (BPBCA beads). According to the results, this adsorbent is very effective, with a optimal adsorption capacity of 39.85 mg/g and a removal rate of 95.55% under ideal circumstances. The process is affected byfactors i.e. pH, starting concentration, adsorbent dosage, and stirring time. The Langmuir isotherm and pseudo-second-order kinetics govern the adsorption with negative entropy, enthalpy, and Gibbs free energy changes, thermodynamic analysis shows that the adsorption is spontaneous.

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References

1. Zhang, C., Valsaraj, K.T., Constant, W.D. and Roy, D. (1999). Aerobic biodegradation kinetics of four anionic and nonionic surfactants at sub- and supra-critical micelle concentrations (CMCs). *Water Research*, 33, 115– 124.

2. Xu, Y., Zhang, Y., Liu, W., Yin, H., Yang, C., & Chen, J. (2022). Effective treatment of high-concentration SDBS solution by developing a novel integrated technology of foam separation and photocatalysis. *Journal of Environmental Chemical Engineering*, 10(6), 108811.

3. Bautista-Toledo, M. I., Rivera-Utrilla, J., Méndez-Díaz, J. D., Sánchez-Polo, M., & Carrasco-Marín, F. (2014). Removal of the surfactant sodium dodecylbenzenesulfonate from water by processes based on adsorption/bioadsorption and biodegradation. *Journal of Colloid and Interface Science*, 418, 113–119.

4. Tony, M. A. (2022). Low-cost adsorbents for environmental pollution control: A concise systematic review from the prospective of principles, mechanism and their applications. *Journal of Dispersion Science and Technology*, 43(11), 1612–1633.

5. Valizadeh, S., Younesi, H., & Bahramifar, N. (2016). Highly mesoporous K_2CO_3 and KOH/activated carbon for SDBS removal from water samples: Batch and fixed-bed column adsorption process. *Environmental Nanotechnology, Monitoring & Management*, 6, 1–13.

6. Kim, J., Kim, D., Gwon, Y. J., Lee, K. W. & Lee, T. S. (2018). Removal of sodium dodecylbenzenesulfonate by macroporous adsorbent resins. *Materials*, 11(8), 1324.

7. Takayanagi, A., Kobayashi, M. & Kawase, Y. (2017). Removal of anionic surfactant sodium dodecyl benzene sulfonate (SDBS) from wastewaters by zero-valent iron (ZVI): Predominant removal mechanism for effective SDBS removal. *Environmental Science and Pollution Research*, 24(9), 8087–8097.

8. Kamińska, G. & Marszałek, A. (2020). Advanced treatment of real grey water by SBR followed by ultrafiltration: Performance and fouling behavior. *Water*, 12(1), 154.

9. Fountoulakis, M. S., Markakis, N., Petousi, I., &Manios, T. (2016). Single house on-site grey water treatment using a submerged membrane bioreactor for toilet flushing. *Science of the Total Environment*, 551–552, 706–711.

10. Zhu, Y., Zhang, T., Lv, L., Tang, W., Wang, Y., & Tang, S. (2025). Design and synthesis of a macro-porous chitosan-sodium alginate aerogel adsorbent for efficient adsorption of SDBS from aqueous solutions. *Separation and Purification Technology*, 354, 129272.

11. Parhizgar, F., Alishahi, A., Varasteh, H., &Rezaee, H. (2017). Removing sodium dodecyl benzene sulfonate (SDBS) from aqueous solutions using chitosan. *Journal of Polymers and the Environment*, 25(3), 836–843.

12. Wang, A., Zhu, Q. & Xing, Z. (2019). Design and synthesis of a calcium modified quaternized chitosan hollow sphere for efficient adsorption of SDBS. *Journal of Hazardous Materials*, 369, 342–352.

13. Yan, Z., Liu, Y., Chen, Y. & Wang, F. (2025). Bifunctional magnetic chitosan microspheres for simultaneous adsorption of Cu(II) and sodium dodecylbenzenesulfonate (SDBS). *Environmental Research*, 273, 123392.

14. Kahya, N., Kaygusuz, H. & Erim, F. B. (2018). Aqueous removal of sodium dodecyl benzene sulfonate (SDBS) by crosslinked chitosan films. *Journal of Polymers and the Environment*, 26(5), 2166–2172.

15. Krishnan S., Chandran. K. and Sinnathambi C. (2016). Waste water treatment technology used for removal of different surfactants, a comparative review. *International journal applied chemistry*, 12, 727-739,

16. Anas, A. K., Pratama, S. Y., Izzah, A. & Kurniawan, M. A. (2021). Sodium dodecylbenzenesulfonate-modified biochar as an adsorbent for the removal of methylene blue. *Bulletin of Chemical Reaction Engineering & Catalysis*, 16(1), 188–195.

17. Rastogi, P. & Kandasubramanian, B. (2019). Review of alginate-based hydrogel bioprinting for application in tissue engineering. *Biofabrication*, 11(4), 042001.

18. Selvarajoo, A., Muhammad, D., &Arumugasamy, S. K. (2020). An experimental and modelling approach to produce biochar from banana peels through pyrolysis as potential renewable energy resources. *Modeling Earth Systems and Environment*, 6(1), 115–128.

19. Duwiejuah, A. B., Mutawakil, Z. & Oyelude, E. O. (2025). Eco-friendly banana peel biochar for adsorption of toxic metals from landfill treatment pond leachate. *International Journal of Phytoremediation*, 27(5), 596–605.

20. Bambhaniya, V. U. & Gojiya, M. J. (2025). Biochar production, activation and characterization methods techniques: An integrated review. *International Journal of Environment and Climate Change*, 15(10), 39–56.

21. Segale, L., Giovannelli, L., Mannina, P., &Pattarino, F. (2016). Calcium alginate and calcium alginate–chitosan beads containing celecoxib solubilized in a self-emulsifying phase. *Scientifica*, Article 5062706.

22. Ciarleglio, G., Cinti, F., Toto, E., &Santonicola, M. G. (2023). Synthesis and characterization of alginate gel beads with embedded zeolite structures as carriers of hydrophobic curcumin. *Gels*, 9(9), 714.

23. Shin, S., Kim, S., Hong, S., Kim, N., Kang, J., &Jeong, J. (2025). Tuning the swelling behavior of superabsorbent hydrogels with a branched poly (aspartic acid) crosslinker. *Gels*, 11(3), 161.

24. Prashant, A. & Santosh, A. (2018). Study of swelling behavior and determination of swelling parameters of spherical hydrogels in water. *Journal of Drug Delivery & Therapeutics*, 8(4), 218-222.

25. Thommes, M., Kaneko, K., Neimark, A. V., Olivier, J. P., Rodriguez-Reinoso, F., Rouquerol, J. & Sing, K. S. W. (2015). Physisorption of gases, with special reference to the evaluation of surface area and pore size distribution (IUPAC Technical Report). *Pure and Applied Chemistry*, 87(9–10), 1051–1069.

26. Solińska, A., Rzepa, G. & Marzec, M. (2025). Low-cost halloysite–fly ash composite for the removal of pharmaceuticals, dyes and surfactants from contaminated water. *Journal of Environmental Management*, 389, 126140.

27. Ahmed, T. A., Abdulhameed, A. S., Ibrahim, S., AlOthman, Z. A., Wilson, L. D. & Jawad, A. H. (2023). High surface area mesoporous activated carbon produced from Iraqi reed via pyrolysis assisted H_3PO_4 activation: Box–Behnken design for surfactant removal. *Diamond and Related Materials*, 133, 109756.

28. Kumar, A., Singh, A. K., Singh, K., Mishra, A., Dixit, U., & Agarwal, A. (2025). Removal of sodium dodecyl benzene sulfonate using bagasse fly ash and surface functionalized modified fly ash from aqueous solutions. *Journal of Surfactants and Detergents*, 28(1), 171–188.

29. Musah, M., Azeh, Y., Mathew, J. T., Umar, M. T., Abdulhamid, Z. & Muhammad, A. I. (2022). Adsorption kinetics and isotherm models: A review. *Caliphate Journal of Science and Technology*, 4(1), 20–26.

30. Enache, A.-C., Grecu, I., Samoila, P., Cojocaru, C., & Harabagiu, V. (2023). Magnetic ionotropic hydrogels based on carboxymethyl cellulose for aqueous pollution mitigation. *Gels*, 9(5), 358.

31. Dhahir, S. A., Braihi, A. J. & Habeeb, S. A. (2024). Comparative analysis of hydrogel adsorption/desorption with and without surfactants. *Gels*, 10(4), 251.

32. Ma, C. M., Yang, B. Y. & Hong, G. B. (2021). Husk of agarwood fruit-based hydrogel beads for adsorption of cationic and anionic dyes in aqueous solutions. *Molecules*, 26(5), 1437.

33. Ohemeng-Boahen, G., Sewu, D. D. & Woo, S. H. (2019). Preparation and characterization of alginate-kelp biochar composite hydrogel bead for dye removal. *Environmental Science and Pollution Research*, 26(32), 33030-33042.

34. Alobaidi, D. S. & Alwared, A. I. (2023). Role of immobilized Chlorophyta algae in the form of calcium alginate beads for the removal of phenol: Isotherm, kinetic and thermodynamic study. *Heliyon*, 9(4), e14851.

35. Parreño Jr, R. P. (2023). The correlation of sulfonation reaction kinetics with the degree of sulfonation (DS) and its effects on microstructure and morphology of electrospun fibers for the membrane of fuel cells. *RSC advances*, 13(4), 2523-2529.

36. Foo, K. Y. & Hameed, B. H. (2010). Insights into the modeling of adsorption isotherm systems. *Chemical Engineering Journal*, 156(1), 2–10.

37. He, Z., Li, Y. & Qi, B. (2023). A new and low-cost surface-functionalized corn straw adsorbent for adsorptive removal of sodium dodecylbenzenesulfonate: Adsorbent preparation and adsorption performance. *Separation and Purification Technology*, 309, 122999.

38. Ogawa, T. & Kawase, Y. (2021). Effect of solution pH on removal of anionic surfactant sodium dodecylbenzenesulfonate (SDBS) from model wastewater using nanoscale zero-valent iron (nZVI). *Journal of Environmental Chemical Engineering*, 9(5), 105928.

39. Özdemir, U., Özbay, B., Veli, S. & Zor, S. (2011). Modeling adsorption of sodium dodecyl benzene sulfonate (SDBS) onto polyaniline (PANI) by using multi linear regression and artificial neural networks. *Chemical Engineering Journal*, 178, 183–190.

40. Gao, Q., Chen, W., Chen, Y., Werner, D., Cornelissen, G., Xing, B., Tao, S. & Wang, X. (2016). Surfactant removal with multiwalled carbon nanotubes. *Water Research*, 106, 531–538.

41. Kim, J., Lee, H., Vo, H. T., Lee, G., Kim, N., Jang, S., & Joo, J. B. (2020). Bead-shaped mesoporous alumina adsorbents for adsorption of ammonia. *Materials*, 13(6), 1375.

42. Siyal, A. A., Shamsuddin, R., Low, A., & Hidayat, A. (2020). Adsorption kinetics, isotherms, and thermodynamics of removal of anionic surfactant from aqueous solution using fly ash. *Water, Air, & Soil Pollution*, 231, 509.

43. Almanassra, I. W., Kochkodan, V., Mckay, G., Atieh, M. A. & Al-Ansari, T. (2021). Kinetic and thermodynamic investigations of surfactants adsorption from water by carbide-derived carbon. *Journal of Environmental Science and Health, Part A*, 56(11), 1206–1220.

44. Bhandari, P. S. & Gogate, P. R. (2018). Kinetic and thermodynamic study of adsorptive removal of sodium dodecyl benzene sulfonate using adsorbent based on thermo-chemical activation of coconut shell. *Journal of Molecular Liquids*, 252, 495–505.