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Batch adsorption of diesel oil in water using saba banana peel biochar immobilized in teabags

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Abstract

Diesel oil contamination is a threat to environment and human health. Many technologies have been developed to address this issue; however, they are costly to be deployed in real-world oil remediation. Adsorption remains to be one of the most economical methods to remove oil from water. Here, we used banana peel biochar (BPBC) immobilized in teabags as an adsorbent for the removal of diesel oil in water. We investigated the adsorption behavior of BPBC under different conditions, examining the influence of adsorbent loading, pH, salinity, and contact time on its efficiency for removing diesel oil in water. Our results show that the sorption capacity of BPBC is significantly affected by the amount of adsorbent used. Lower biochar loadings enhance the sorption capacity due to greater surface area accessibility, while higher loadings lead to decreased efficiency due to pore blockage and reduced surface exposure. Interestingly, the pH of the solution was found to have minimal impact on the sorption process. This is attributed to diesel oil's hydrophobic and non-polar nature, which leads to its interaction with BPBC being predominantly governed by hydrophobic forces instead of pH-sensitive electrostatic interactions. Salinity emerged as a crucial factor in the adsorption process. An increase in salinity enhances the sorption capacity, likely due to the "salting-out" effect, where higher salt concentrations decrease the solubility of diesel oil, promoting its adsorption onto the biochar surface. Furthermore, the study highlights the importance of contact time, with longer exposure resulting in increased sorption capacity. This trend is explained by the adsorption kinetics, initially characterized by rapid adsorption, followed by a slower, progressive occupation of the biochar's adsorption sites. The kinetic analysis of the process suggests that the pseudo-second-order model is more suitable, indicating a chemisorption mechanism. The Harkins–Jura isotherm model was identified as the best fit for explaining the isotherm behavior, owing to its capacity to account for the heterogeneous nature of the biochar surface and the formation of multiple adsorbate layers. The optimum conditions for maximum diesel oil removal are as follows: BPBC loading of 0.50 g, a solution pH of 5.00, a salinity concentration of 12,656.57 mg/L, and a contact time of 240 min. Under these conditions, BPBC exhibited an adsorption capacity of 19.04 g/g. In summary, our research establishes BPBC, particularly when contained within teabags, as an efficient and practical adsorbent for diesel oil removal in water. Its effectiveness, superior to other biochar, is mainly due to its porosity and hydrophobic properties. These findings not only enhance our understanding of BPBC's adsorption capabilities but also underscore its potential for environmental remediation.

Abstract highlights

- Different environmental conditions affect the sorption capacity of banana peel biochar (BPBC) in teabags for diesel oil removal from water: adsorbent loading, pH, salinity, and contact time.
- The solution environmental conditions were optimized to achieve maximum oil adsorption efficiency.
- Diesel oil adsorption on biochar follows the pseudo-second-order kinetic model and the Harkins-Jura isotherm model.

Keywords: Adsorption, Banana peels, Biochar, Central composite design, Oil spill

Graphical Abstract

Introduction

Environmental pollution, particularly water contamination with hydrocarbons like diesel oil, poses a significant threat to ecosystems and public health [11]. Diesel oil spills in aquatic environments, originating from industrial discharges, transportation accidents, and leakage, are a matter of global concern. These spills result in severe ecological disturbances, affecting both marine and freshwater habitats [15]. The complexity of diesel oil, comprising a mixture of hydrocarbons, makes its removal challenging and essential. Thus, there is a need for efficient and sustainable remediation techniques to reduce the environmental impact of diesel oil contamination [3, 19].

Traditional techniques include mechanical removal [2, 29], chemical degradation [8, 16, 28], and biological treatment [7, 9, 7, 9, 25], each with their inherent limitations such as high costs, low efficiency in low concentrations, and potential secondary pollution. Moreover, chemical and biological techniques are difficult to deploy in actual oil removal operation, while mechanical removal requires large surface areas to ensure separation. These challenges limit their practicability in real-world oil treatment. Previous studies have explored various adsorbents for oil removal, including bentonite [14], graphene oxide [12], and chitosan [13]. However, the high cost of these materials limits their practicality.

Biochar, a carbon-rich material obtained from the pyrolysis of biomass [23], has emerged as a promising solution [6, 26, 27]. It is characterized by its high surface area, porosity, and the presence of functional groups that enhance its adsorption capabilities [17]. The use of saba banana peel, a widely available agricultural waste, for biochar production aligns with the principles of green chemistry and waste valorization. Their high cellulose content and porous structure make them suitable for adsorbing hydrocarbons. The pyrolysis process transforms the organic matter in banana peels into a stable and porous carbon material with a high specific surface area [1, 22]. This porous structure provides ample adsorption sites for diesel oil molecules, effectively removing them from water.

Encapsulating biochar in teabags offers a novel, practical, and user-friendly approach to water treatment, allowing for easy deployment and retrieval in contaminated water bodies. The immobilization of biochar in teabags simplifies the adsorption process, allowing for easy deployment in contaminated water. Teabags containing biochar can be submerged directly into water bodies, making it a user-friendly approach for both laboratory-scale research and potential field applications. This immobilization method combines the advantageous properties of biochar with the convenience of teabags, offering a versatile and sustainable solution for diesel oil removal.

Here, we investigate the effect of batch adsorption parameters on the removal of diesel oil in water using saba banana peel biochar (BPBC) immobilized in teabags. We report the effect of adsorbent dosage, solution pH, salinity, and contact time on the sorption capacity of the biochar. We optimized the solution environmental conditions to achieve maximum removal of diesel oil in water. We also studied the adsorption kinetics and isotherm behavior of BPBC in teabags in removing diesel oil from water.

Methods

Biochar from saba banana peels were produced by slow pyrolysis technique. The produced BPBC was enclosed in teabags for easier application and to prevent the mixing of biochar and water. Afterward, the BPBC-containing teabags was used as an adsorbent for the removal of diesel oil in water. Here, the effect of solution environmental conditions such as initial adsorbent dose, initial pH, salinity, and contact time on the removal of diesel oil via batch adsorption was investigated. Central composite design of experiments was used to optimize the solution environmental conditions. Isotherm and kinetic studies were performed to deduce the adsorption mechanism. Overall, this experimental approach allows us to evaluate the effectiveness of BPBC in teabags as an adsorbent for diesel oil removal.

Production of biochar from saba banana peels

Initially, the collected banana peels are sliced into small fragments and meticulously washed under running water. They are then dehydrated in an oven at 100 °C for a full day. Post dehydration, these materials are pulverized and filtered through a mesh, segregating particles within the 150 − 300 µm range. Subsequently, 989 g of the preprocessed saba banana peel, or dried banana peel residue, is placed in a custom-built pyrolysis reactor equipped with a temperature control system. This reactor facilitates a slow pyrolysis for 104.2 min at 585.9 °C. These specific pyrolysis conditions are considered ideal for maximizing the yield of biochar from banana peels (Omulo et al., 2019).

Batch adsorption experiments

Batch adsorption experiments were conducted using various concentrations of diesel oil in a water solution. For these experiments, a 250-mL beaker served as the container. In this setup, BPBC was immersed in a beaker filled with 200 mL of the oil–water mix. The mixture was stirred at a constant speed of 200 rpm with a magnetic stirrer. All experiments were carried out at ambient temperature. The stirring speed was consistently held at 200 rpm. The duration of contact between BPBC and the mixture was adjusted between 30 and 240 min, as per the design of the experiment. Following the adsorption process, BPBC was separated from the mixture through centrifugation, and the remaining oil concentration in the solution was measured. The adsorption capacity of BPBC was determined using Eq. 1. As standard practice, each experiment was repeated thrice, and the average results were recorded.

$$\boldsymbol{Sorption\ capacity} = \frac{Mass\ of\ BPBC\ adsorbed - mass\ of\ BPBC}{Mass\ of\ BPBC} \tag{1}$$

Effect of solution environmental conditions on the sorption capacity of BPBC

The research focused on understanding how four factors — adsorbent dosage, initial pH level, salinity, and contact duration — impact adsorption. Design Expert v.13 software (Stat-Ease, USA) was utilized to develop a face-centered central composite design. The range for the initial adsorbent dose (X_1) was set between 0.5 and 2.5 g/L, the initial pH (X_2) was varied from 5 to 9, salinity levels (X_3) ranged from 500 to 45,000 mg/L, and contact time (X_4) spanned from 30 to 240 min. These parameters were chosen to reflect the typical conditions found in different aquatic environments, from fresh to marine waters. The experimental design included six central points, resulting in a total of 30 experimental runs.

In each run, synthetic water contaminated with oil was prepared, adhering to the initial pH and salinity specifications outlined in the face-centered central composite design of experiments (FC-CCD). This involved dissolving precise amounts of NaCl in 200 mL of distilled water, adjusting its pH with 1-M HCl or 1 M NaOH and then adding the necessary quantity of diesel oil to achieve a concentration of 100 mg/L. This mixture was then agitated at 300 rpm for 5 min using a magnetic stirrer, followed by 10 min of sonication in a bath sonicator at room temperature. This prepared mixture was then employed in the adsorption tests. Each experimental run was replicated three times, with the average sorption capacity values being reported. The tests maintained constant conditions for each run: a temperature of 30 °C, an agitation rate of 200 rpm, and an initial diesel oil concentration of 100 mg/L. Table 1 in the study details the various levels used in this research.

Isotherm study

Adsorption experiments following isothermal conditions were conducted using the optimal adsorbent dosage, pH, salinity, and contact time established from the response surface methodology (RSM) experiments. The study varied diesel oil concentrations

Table 1 Levels of the four parameters using face-centered central composite design of experiments (FC-CCD)

Independent variables	Unit	Symbol	Levels		
			− 1	0	+ 1
Adsorbent dosage	g/L	X_1	0.5	1.5	2.5
pH	-	X_2	5	7	9
Salinity	mg/L	X_3	500	22,750	45,000
Contact time	Minutes	X_4	30	135	240

in the synthetic oil-contaminated water (50 mg/L, 100 mg/L, 150 mg/L, 200 mg/L, 300 mg/L, 400 mg/L, and 500 mg/L) for the isotherm analysis.

To prepare the synthetic oil-contaminated water, the optimal initial pH and salinity determined by FC-CCD were used. The process involved dissolving precise amounts of NaCl in 200 mL of distilled water, followed by pH adjustment with 1-M HCl or 1-M NaOH. Subsequently, varying amounts of diesel oil were added to achieve the different oil concentrations in the water. The mixture was then agitated at 300 rpm for 5 min using a magnetic stirrer and sonicated for 10 min at room temperature in a bath sonicator. This prepared mixture was utilized for the adsorption studies.

During each experimental run, both the temperature (30 °C) and the stirring speed (200 rpm) were kept constant. The adsorbent dosage and contact time, as optimized by FC-CCD, were applied. Under these conditions, adsorption was carried out, and the sorption capacity was measured. Each experimental condition was replicated three times, with the average values being recorded. Various isotherm models were applied to analyze which model best fits the experimental data obtained.

Kinetic study

Adsorption experiments were carried out using the ideal adsorbent dosage, pH, and salinity identified through FC-CCD. For the kinetic analysis, a variety of contact times were employed (0.25 h, 0.5 h, 1 h, 1.5 h, 2 h, 2.5 h, 3 h, and 4 h).

The synthetic oil-contaminated water for these experiments was prepared according to the optimal initial pH and salinity determined by FC-CCD. This entailed dissolving suitable quantities of NaCl in 200 mL of distilled water and adjusting the pH with 1-M HCl or 1-M NaOH. Then, a specific amount of diesel oil was mixed in to create different concentrations of oil in the water. This mixture was rigorously stirred at 300 rpm for 5 min using a magnetic stirrer and subsequently sonicated for 10 min at room temperature using a bath sonicator. This prepared oil–water mixture was then utilized in the adsorption tests.

In each experimental run, the conditions—temperature at 30 °C, agitation speed at 200 rpm, and initial diesel oil concentration at 100 mg/L—were consistently maintained. Under these standardized conditions, the adsorption process was executed, and the sorption capacity was subsequently measured. Each test condition was replicated three times, and the average sorption capacities were reported. The sorption data collected before reaching equilibrium were analyzed using the pseudo-first-order and pseudo-second-order kinetic models.

Statistical treatment

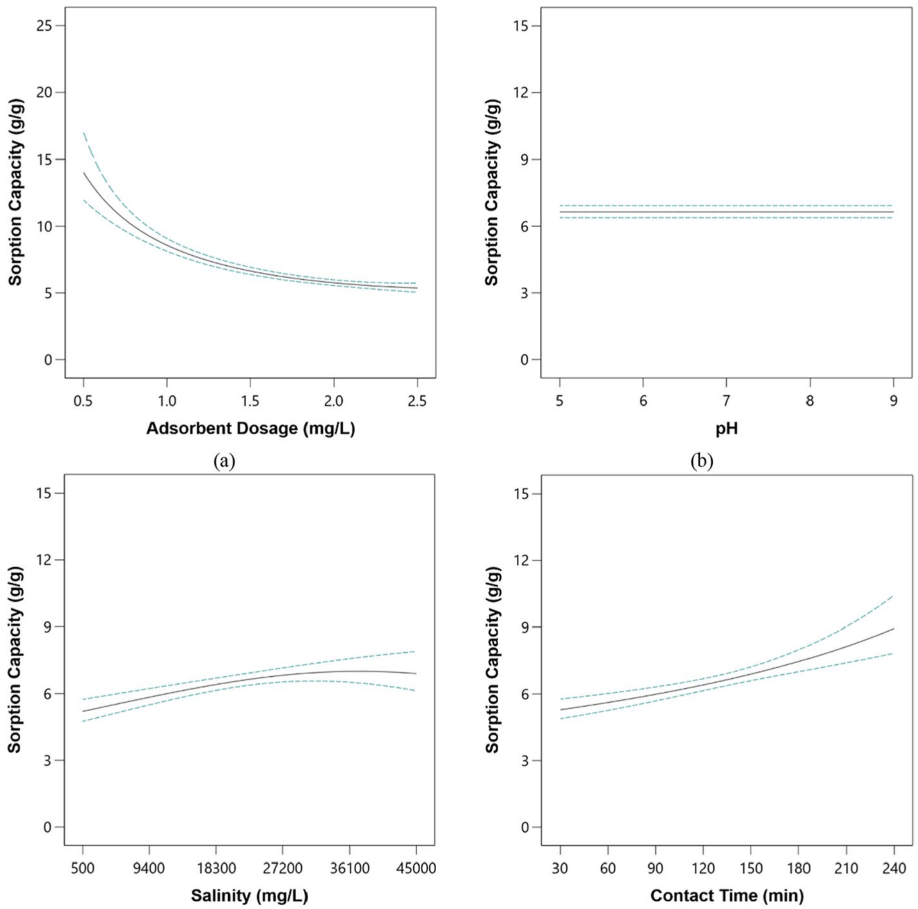
After gathering the experimental data, the sorption capacity is initially modeled using a general polynomial equation. Subsequent to this, an analysis of variance (ANOVA) is carried out to pinpoint which factors significantly impact the sorption capacity. This process includes refining the model by eliminating terms that are statistically insignificant, leading to the derivation of the final model for sorption capacity. Additionally, residual analysis is employed to identify any outliers in the data. The presence of influential data points, which could potentially skew the accuracy of the model, is examined through the use of influence plots. To further understand the impact of the four key parameters (adsorbent dosage, pH, salinity, and contact time) on the sorption capacity of BPBC, contour plots are generated. The final step involves optimization, where the most effective conditions for achieving the highest sorption capacity are determined. All these analytical steps are conducted using Design-Expert v.13 (Stat-Ease, USA).

Results and discussion

Effect of solution environmental conditions

Main effects

Our research focused on how different environmental conditions in a solution affect the sorption capacity of BPBC contained within teabags. The study revealed that the optimal sorption capacity occurs with a 0.5-g adsorbent loading, while the least effective is seen at 2.5-g adsorbent loading. This variation in sorption capacity with different adsorbent doses is statistically significant, as indicated by an ANOVA result showing a *p*-value of 1.3736×10^{-6}. A clear decrease in sorption capacity with increased adsorbent loading is depicted in Fig. 1. The adsorption efficacy is linked to the quantity of biochar available for adsorption, which in turn is determined by the adsorbent dose used. The diesel oil sorption capacity of banana peel biochar immobilized in teabags, and its decrease with increasing adsorbent loading, can be explained by considering several factors inherent to the adsorption process and the physical properties of the materials involved. First, banana peel biochar is a porous material, and its ability to adsorb diesel oil primarily depends on its surface area and pore structure. At lower adsorbent loadings, the available surface area for adsorption is maximized, allowing more diesel oil molecules to adhere to the biochar. However, as the loading increases, the effective surface area available for adsorption decreases. This is because the pores may become clogged, and overlapping of biochar particles can occur, leading to a decrease in the exposed surface area for diesel oil molecules to adhere to. Second, with an increased amount of biochar in the teabags, the diffusion of diesel oil to the internal sites of the biochar can be hindered. The mass transfer resistance increases, which means diesel oil molecules find it harder to reach the inner adsorption sites. This effect is more pronounced in denser packings of the biochar, where the path for the diesel oil to diffuse into the interior of the biochar becomes longer and more tortuous. Third, as the concentration of biochar in the teabags increases, the likelihood of particle agglomeration also rises. This agglomeration



(c) (d)

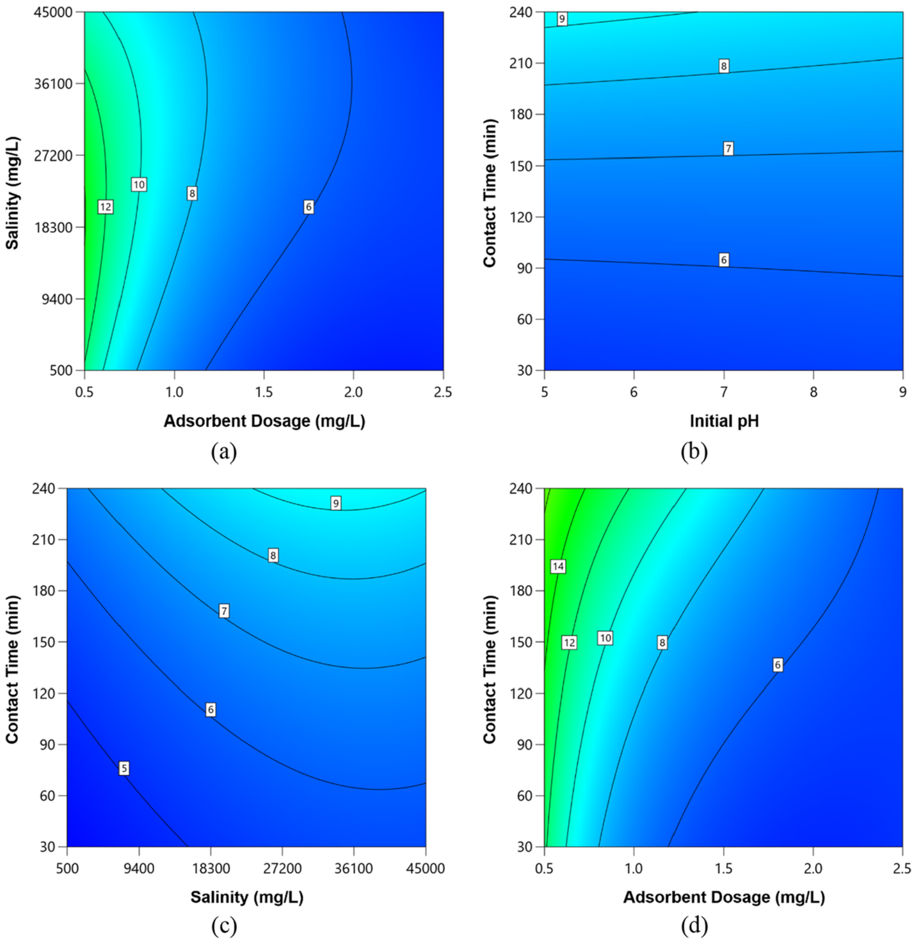
Fig. 1 Main effects of the adsorption parameters on the sorption capacity of BPBC immobilized in teabags: (**a**) adsorbent dosage, (**b**) initial pH, (**c**) salinity and (**d**) contact time

can further reduce the effective surface area available for adsorption and can also limit the accessibility of oil to the active sites on the biochar. Lastly, each biochar particle has a finite number of sites where diesel oil can adsorb. At lower loadings, these sites are readily available, but as the amount of biochar increases, the proportion of these sites that can interact with diesel oil diminishes due to overlapping and aggregation of particles. This leads to a situation where adding more biochar does not proportionally increase the amount of diesel oil that can be adsorbed.

The sorption capacity of BPBC does not exhibit significant variations with changes in pH (Fig. 1b). Diesel oil is a hydrophobic, non-polar organic compound. Its interaction with adsorbents like biochar is primarily governed by hydrophobic interactions and van der Waals forces, rather than electrostatic interactions which are more sensitive to pH changes. Therefore, the sorption capacity of BPBC for diesel oil is likely to be less influenced by the pH of the solution, as these fundamental interactions do not significantly vary with pH. Moreover, banana peel biochar is primarily composed of carbonaceous material, which is relatively inert and does not have functional groups that respond significantly to changes in pH, at least in the range typically encountered in environmental applications. The hydrophobic surface of the biochar favors the adsorption of non-polar substances like diesel oil, a process not greatly affected by the aqueous phase's pH. The sorption mechanism is likely dominated by physical adsorption (physisorption), which involves weak van der Waals forces. This type of interaction is less sensitive to changes in pH compared to chemical adsorption (chemisorption), where bond formation and the presence of functional groups are more critical and can be influenced by pH.

In our study, three distinct salinity levels were used: 500 mg/L, 22,750 mg/L, and 45,000 mg/L. The findings indicated that sorption capacity was at its lowest at a salinity of 500 mg/L and peaked at 45,000 mg/L, as shown in Fig. 1c. The significance of salinity in influencing the adsorption process is statistically validated by ANOVA, which yielded a p-value of 0.0017. A trend of increasing sorption capacity with rising salinity levels is clearly demonstrated in Fig. 1c. There are several factors that contribute to the enhancement of the biochar's adsorption ability at higher salinity levels. A primary factor is the "salting-out" effect. In aqueous solutions, the presence of salts can reduce the solubility of non-polar organic compounds like diesel oil. This phenomenon occurs because the salt ions tend to attract water molecules, reducing their availability to interact with non-polar molecules. As a result, diesel oil molecules are effectively pushed out of the solution and onto the surface of the biochar, enhancing the sorption capacity. Increasing salinity can modify the interactions between the biochar surface and diesel oil. Salts can influence the surface charge and hydrophobicity of the biochar. In this case, this can lead to an increased affinity of the biochar for non-polar substances like diesel oil, thereby increasing the sorption capacity.

Figure 1d shows how sorption capacity tends to rise as contact time rises. It indicates that longer contact times result in greater adsorption of diesel oil into the BPBC ($p = 1.0982 \times 10^{-6}$). This behavior is typical in adsorption phenomena and can be explained through a combination of physicochemical processes and kinetic factors. Adsorption is a time-dependent process. Initially, when BPBC is exposed to diesel oil, the available active sites on the biochar are abundant, and the rate of adsorption is high. Over time, as these sites are progressively occupied, the rate of adsorption slows down. However, the total amount of diesel oil adsorbed continues to increase until equilibrium is reached. This initial rapid phase followed by a slower approach to equilibrium explains the increase in sorption capacity with time. The sorption of diesel oil onto BPBC involves two primary diffusion steps: external (film) diffusion and internal (particle) diffusion. Initially, diesel oil molecules quickly migrate from the bulk solution to the biochar surface (external diffusion). Over time, the molecules begin to diffuse into the internal pores of the biochar (internal diffusion). This internal diffusion is usually slower and continues over a longer period, contributing to the increased sorption capacity with more extended contact time. Also, BPBC has a porous structure with a high surface area, allowing for multiple layers of diesel oil molecules to adsorb onto and within its structure. Initially, the outermost surfaces and larger pores are occupied. With prolonged contact, diesel oil molecules penetrate deeper into smaller pores, increasing the overall sorption capacity as more of the biochar's internal surface area becomes utilized.



(a) (b)

(c) (d)

Fig. 2 Interaction effects of the adsorption parameters on the sorption capacity of BPBC immobilized in teabags: (**a**) adsorbent dosage and salinity, (**b**) initial pH and contact time, **c** salinity and contact time and (**d**) adsorbent dosage and contact time

Interaction effects

The interaction between adsorbent dosage and salinity (Fig. 2a) plays a critical role in the adsorption process of diesel oil. It has been observed that the maximum sorption capacity is achieved at low adsorbent dosages combined with intermediate salinity levels. It appears that as the adsorbent dosage increases from 0.5 to 2.5 mg/L, the sorption capacity decreases. Also, within a certain range of salinity (roughly 500 to 18,300 mg/L), increasing the salinity leads to an increase in sorption capacity. However, beyond this range, the sorption capacity does not increase significantly with further increases in salinity. At lower dosages of the adsorbent, the available surface area per unit mass of biochar is maximized, allowing more effective contact between the diesel oil and the adsorbent. This ensures that a larger proportion of the biochar's adsorptive sites are available for interaction with the oil molecules, leading to increased sorption efficiency. Intermediate salinity levels contribute to the "salting-out" effect, where the presence of salts in the water reduces the solubility of hydrophobic compounds like diesel oil. This effect pushes the diesel oil out of the solution and enhances its adsorption onto the biochar. However, this effect might not linearly increase with salinity; beyond a certain point, excessive salinity could potentially lead to decreased sorption efficiency due to changes in the solution's properties or the biochar's surface characteristics. The combination of low adsorbent dosage and intermediate salinity creates an optimal environment for diesel oil adsorption. Low dosage ensures ample surface area for adsorption, while intermediate salinity levels increase the oil's propensity to be adsorbed due to reduced solubility. This synergistic interaction maximizes the sorption capacity of the biochar. At higher adsorbent dosages, the risk of pore blockage or agglomeration of biochar particles increases, which can reduce the effective surface area and hinder the adsorption process. Similarly, too high or too low salinity levels might not provide the ideal conditions for the "salting-out" effect to efficiently facilitate adsorption.

The interaction between initial pH and contact time (Fig. 2b) during diesel oil adsorption suggests that the sorption capacity is influenced by how long the biochar is in contact with the diesel oil, and this relationship is consistent across a range of pH values. A longer contact time generally allows for more diesel oil molecules to come into contact with the biochar, increasing the probability of adsorption. The initial rapid phase of adsorption is due to the abundance of available adsorptive sites on the biochar, and over time, as these sites are occupied, the rate of adsorption slows down, but the cumulative amount of oil adsorbed continues to increase until equilibrium is reached. The finding that maximum sorption capacity is achievable at high contact times across all initial pH values suggests that the interaction of diesel oil with the biochar is not significantly affected by the pH of the solution. Diesel oil is a non-polar, hydrophobic substance, and its adsorption onto biochar is likely dominated by hydrophobic interactions and van der Waals forces rather than any acid–base interactions which would be influenced by pH. The apparent pH stability implies that the biochar's adsorptive properties remain effective across a range of pH levels, which is beneficial for applications in different environmental conditions where pH may vary. In practice, this means that when treating diesel oil-contaminated water with biochar, it is more critical to optimize the contact time rather than adjusting the pH of the water. Ensuring that the biochar remains in contact with the contaminated water for a sufficient period is key to maximizing the adsorption capacity.

The interaction between salinity and contact time (Fig. 2c) during diesel oil adsorption, and the observation that maximum sorption capacity is achieved at high contact times, suggests a complex relationship that depends on both these factors. The fact that maximum sorption capacity is found at high contact times indicates that the adsorption process benefits from extended interaction between the biochar and the diesel oil. This duration allows for the thorough diffusion and adherence of diesel oil molecules onto the adsorbent's surface and within its pores. The contour illustrating sorption capacity is curved and decreases with increasing.

salinity levels, suggesting that there is an optimal salinity range for the adsorption of diesel oil. This optimal range represents a balance where the presence of salts in the water helps to push the diesel oil out of the solution (the "salting-out" effect) and onto the biochar. The optimum sorption capacity at intermediate salinity levels indicates that while some salt presence is beneficial for adsorption due to the "salting-out" effect, too much salt can actually hinder the process. Excessive salinity might lead to changes in the solution's physical properties, such as viscosity or ionic strength, which could adversely affect the adsorption kinetics or the biochar's surface characteristics. At high salinity levels, the contour's downward trend suggests a diminished sorption capacity. This could be because high salt concentrations change the solution chemistry to the point where it negatively impacts the adsorption process, perhaps by affecting the diesel oil's state or the biochar's adsorptive properties. In practical terms, for effective diesel oil adsorption, it would be beneficial to maintain a contact time as long as possible within operational constraints and to adjust the salinity to the intermediate level that corresponds to the peak of the curved sorption capacity contour. This would ensure the adsorption process is optimized for maximum oil removal.

For the interaction between adsorbent dosage and contact time (Fig. 2d) during diesel oil adsorption, the maximum sorption capacity is found at high contact times across all adsorbent dosages. The observation that longer contact times lead to higher sorption capacities suggests that the adsorption process is time dependent. This is likely due to the kinetics of adsorption which allow for more diesel oil molecules to be adsorbed onto the biochar as time progresses. Initially, adsorption occurs rapidly due to the abundance of available sites, but over time, these sites become occupied, and the rate of adsorption slows. Nonetheless, the cumulative amount of diesel oil adsorbed increases with time until equilibrium is reached. The finding that sorption capacity decreases with an increase in adsorbent dosage might seem counterintuitive; however, this can occur if there is an overlapping of adsorbent particles at higher dosages, which leads to a reduction in the effective surface area available for adsorption. Additionally, increased dosages can lead to aggregation of adsorbent particles, potentially blocking the pores and reducing the accessibility of the diesel oil to adsorption sites. The curved nature of the sorption capacity contours suggests a nonlinear relationship between adsorbent dosage and contact time. Initially, as the adsorbent dosage is increased, there might be a slight increase in adsorption capacity due to more adsorbent being available. However, beyond a certain point, further increases in dosage lead to a decrease in adsorption capacity due to particle aggregation and pore blockage, as previously mentioned. The decrease in sorption capacity with increased adsorbent dosage indicates that there is an optimal adsorbent dosage that maximizes sorption capacity. This optimal point is likely at a lower dosage, where there is enough biochar to adsorb the diesel oil effectively without causing blockage or significant overlap of adsorbent particles. In practice, this means that for the effective adsorption of diesel oil, it is beneficial to identify an optimal lower dosage of adsorbent that will maximize the available surface area for adsorption and to allow for sufficient contact time to ensure that the maximum amount of diesel oil is adsorbed.

Statistical treatment

The significance of different parameters in the oil adsorption process using biochar was analyzed using ANOVA. Accordingly, *p*-values above 0.05 indicate a lack of significant difference within that particular group, whereas *p*-values below 0.05 denote statistically significant results. The ANOVA findings, as presented in Table 2, identified that the primary factors influencing adsorption include the dose of the adsorbent (X_1), salinity (X_3), and contact time (X_4). Additionally, the linear interactions (X_1X_3, X_2X_4, X_3X_4), quadratic (X_1^2 and X_3^2), and cubic effects ($X_1^2X_3$, $X_1^2X_4$, $X_1X_2X_3$) were also significant. Other model terms were deemed to have an insignificant impact on

Table 2 Analysis of variance for the reduced cubic model

Source	**Sum of squares**	**df**	**Mean square**	***F*-value**	***p*-value**
Block	0.0063	2	0.0031		
Model	0.1986	11	0.0181	58.3266	1.8218×10^{-32}
X_1	0.1708	1	0.1708	551.9213	1.3736×10^{-36}
X_3	0.0033	1	0.0033	10.6334	1.6638×10^{-3}
X_4	0.0087	1	0.0087	28.0854	1.0982×10^{-6}
X_1X_3	0.0022	1	0.0022	7.1673	9.0921×10^{-3}
X_2X_4	0.0009	1	0.0009	2.9029	9.2507×10^{-2}
X_3X_4	0.0010	1	0.0010	3.2093	7.7202×10^{-2}
X_1^2	0.0046	1	0.0046	14.7820	2.4895×10^{-4}
X_3^2	0.0033	1	0.0033	10.6515	1.6496×10^{-3}
$X_1X_2X_3$	0.0023	1	0.0023	7.2753	8.6070×10^{-3}
$X_1^2X_3$	0.0025	1	0.0025	7.9846	6.0242×10^{-3}
$X_1^2X_4$	0.0043	1	0.0043	13.8714	3.7382×10^{-4}
Residual	0.0235	76	0.0003		
Lack of fit	0.0111	61	0.0002	0.2211	9.9999×10^{-1}
Pure error	0.0124	15	0.0008		
Cor total	0.2284	89			

the oil adsorption in biochar within teabags and were thus excluded from the cubic model. The refined cubic model, which is used to interpret the experimental data in terms of actual components, is represented in Eq. 2.

$$\begin{aligned}\boldsymbol{Sorption\ capacity}^{-1} = {} & 0.026184 + 0.192349[X_1] - 3.21997x10^{-7}[X_3] - 0.000250[X_4] \\ & - 3.16432 \times 10^{-7}[X_1X_3] + 0.000012[X_2X_4] + 1.94715 \\ & \times 10^{-9}[X_3X_4] - 0.043136[X_1]^2 - 3.60794 \times 10^{-11}[X_3]^2 \\ & - 6.22692 \times 10^{-9}[X_1X_2X_3] + 9.67458 \times 10^{-7}[X_1{}^2X_3] + 6.28347 \\ & \times 10^{-7}[X_1{}^2X_4]\end{aligned} \tag{2}$$

where X_1 = adsorbent dosage (g/L), X_2 = pH, X_3 = salinity (mg/L), and X_4 = contact time (mins).

The coefficients and their respective values in the coded equation provide insights into the impact of each parameter on the overall result. By comparing the coefficients of the factors in the coded equation, the relative importance of these elements can be ascertained. Factors X_3, X_4, X_1X_3, and X_1^2 exhibit negative coefficients, indicating they have opposing effects on the transformed response, while the other factors show positive coefficients. The reduced cubic model detailed in Table 1 is characterized by a notably significant *F*-value of 58.3266 and a very low model *p*-value of 1.8218×10^{-32}. These statistics imply that the chosen reduced cubic model is highly effective in predicting the oil adsorption capacity of biochar within the studied range. The likelihood of achieving such a high *F*-value by chance is only 0.01%, underscoring the model's robustness. Additionally, the lack-of-fit analysis indicates an *F*-value of 0.2211 and a *p*-value of 0.9999, suggesting that the model's lack of fit is statistically negligible. This insignificant lack of fit is beneficial, as it signifies that the cubic model can be confidently used for predicting biochar's sorption capacity.

Generally, a larger coefficient indicates a more accurate fit of the model. In this study, the model's coefficient of determination ($R^2 = 0.8941$) is significantly high, denoting its competency in explaining the variance observed in the experimental data. The coefficient of determination, ranging from 0 to 1, reflects how well a statistical model predicts an outcome, with values closer to 1.00 indicating an excellent match with the experimental data. The model's adjusted R^2 (0.8788) and predicted R^2 (0.8645) are also near 1.00, signifying that the model is not overfitted. The calculated model adequacy value, at 28.4457, which evaluates the signal-to-noise ratio, exceeds 4. This suggests that the cubic model is effective in predicting the response and accurately represents the pure error of prediction within the design space. These results affirm the model's capability to align well with the experimental data.

Optimization of adsorption parameters

The model's high coefficient of determination indicates a strong correlation with the experimental data, signifying its reliability in predicting the sorption capacity of BPBC immobilized in teabags under various solution environmental conditions within the defined design parameters. Due to its robustness, the model is well-suited for optimization studies. Our objective was to enhance the sorption capacity of BPBC, minimize errors in the model, and keep the solution environmental conditions within the boundaries of the design space. We utilized Design-Expert version 13.0 for numerical optimization. The optimal parameters identified for diesel oil adsorption included a BPBC loading of 0.50 g, a pH of 5.00, a salinity level of 12,656.57 mg/L, and a contact time of 240 min. At these conditions, the biochar demonstrated a sorption capacity of 19.04 g/g. Banana peel biochar thus emerges as an exceptional material for oil adsorption in water, exhibiting a high potential for oil sorption under optimal conditions. In contrast, the results from blank and control experiments displayed insignificant oil adsorption/separation.

Kinetic study

We performed a kinetic study on BPBC diesel oil adsorption using the first-order and second-order kinetic models for each diesel concentration (Fig. 3). According to the R^2 value (Table 3), the second-order model offers a better fit to the data points than the first-order model. This suggests that the adsorption process of diesel oil on BPBC is more accurately described by the.

second-order kinetics, which typically implies that the rate of adsorption is proportional to both the concentration of the adsorbate (in this case, diesel oil) and the availability of adsorption sites on the adsorbent (BPBC). The pseudo-second-order model assumes that the rate-limiting step is not diffusion but a chemical process, and the adsorption follows a second-order mechanism. This model is generally applied to processes where the adsorbate concentration is relatively low, and the adsorbent surface has a high capacity for the adsorbate. As such, this model assumes chemisorption, which involves the chemical bonding of adsorbate molecules to the adsorbent surface. This is in contrast to physisorption, which is characterized by weaker physical forces like van der Waals interactions. From the data, equilibrium is reached after 4 h of contact time.

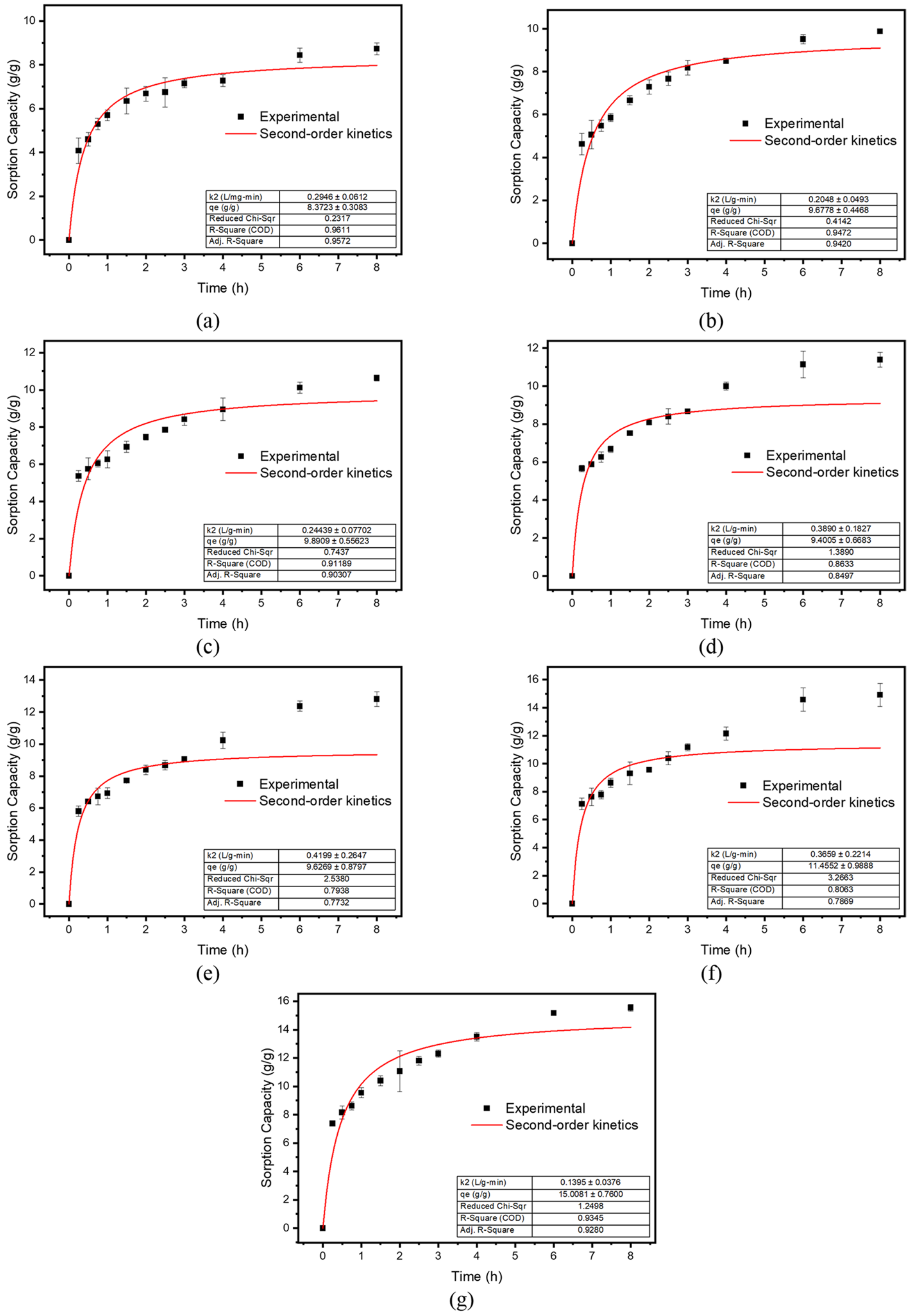


Fig. 3 Kinetic study on BPBC inside teabags for diesel oil adsorption: (**a**) 50 mg/L, (**b**) 100 mg/L, (**c**) 150 mg/L, (**d**) 200 mg/L, (**e**) 300 mg/L, (**f**) 400 mg/L and (**g**) 500 mg/L

Isotherm study

We performed an isotherm study on BPBC, and the results are shown in Fig. 4. It was seen that the best-fit isotherm model is the Harkins–Jura isotherm, with a high model R^2 value of 0.9647. Here, the adsorbent surface is assumed to be heterogeneous, meaning that different sites on the surface have different energies for adsorption. This contrasts with models like the Langmuir isotherm, which assume a homogeneous surface

Table 3 Comparison of BPBC diesel oil adsorption performance against other adsorbents

Adsorbent	Maximum sorption capacity (g/g)	Reference
Biosorbent from teak (*Tectona grandis*) leaves	0.0101	Mathew et al. [21]
Silica-lignin hybrid filler in a natural rubber foam composite	1.36	Mardiyati et al. [20]
Granular biocomposites based on homogenized peat	1.55	Irtiseva et al. [18]
Cornstalk biochar	4.01	Sun et al. [26]
Aluminum soap nanoparticles-lignin powder	5.2	Cui et al. [10]
Superhydrophobic polyurethane sponge coated with oil sorbent derived from textile sludge	13.01	Sarup et al. [24]
Poly (sulfur/soya bean oil)composite adsorbent	14.2857	Bajpai & Dubey [5]
Bamboo-shaped oxidized multi-walled carbon nanotubes in the silica matrix	19.48	AlZubi et al. [4]
BPBC in teabags	19.04	This work

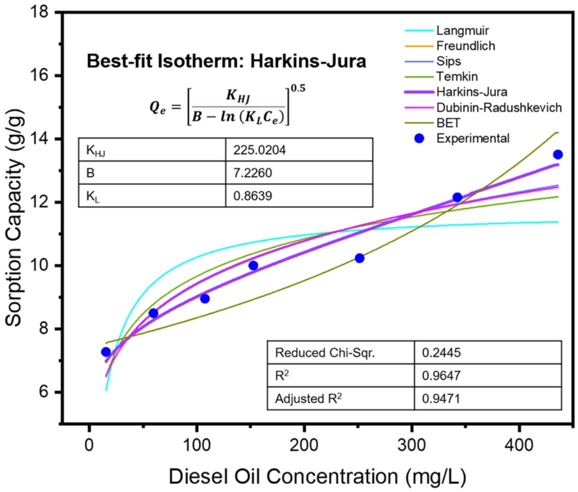


Fig. 4 Isotherm study on BPBC immobilized in teabags for diesel oil adsorption

with uniform adsorption energy. Unlike the Langmuir model, which assumes monolayer adsorption, the Harkins–Jura model allows for the formation of multiple layers of adsorbate molecules. This is more representative of real-world adsorption scenarios, especially for porous materials. The model also assumes that the adsorption energy varies with the degree of surface coverage. As more adsorbate molecules occupy the surface, the average energy of adsorption decreases. Another key feature of the Harkins–Jura model is the consideration of capillary condensation in the pores of the adsorbent. This phenomenon occurs when adsorbate molecules condense inside the capillaries or pores of the adsorbent due to the curvature of the liquid inside these small spaces. The model considers the effect of surface curvature on adsorption, which is particularly relevant for adsorption in fine pores. The curvature of the surface can affect the physical and chemical properties of the adsorbate and the adsorbent.

Adsorption mechanism

Considering that this process follows the pseudo-second-order kinetic model and the Harkins–Jura isotherm model, we can outline a hypothetical mechanism based on the principles of these models. When the teabags containing the biochar are introduced to a diesel oil-contaminated environment, the diesel oil molecules begin to interact with the surface of the biochar. Initially, as there are many available sites, adsorption occurs rapidly. The primary mechanism is likely chemisorption, where diesel oil molecules form a chemical bond with the biochar. This bond might involve sharing or exchange of electrons, indicating a strong interaction between the diesel oil and the biochar. The adsorption may not be limited to a single layer. As the surface sites fill up, additional layers of diesel oil could form on top of the first layer. The biochar, having a heterogeneous surface, provides various sites with different adsorption energies. This heterogeneity could lead to differential adsorption rates across the surface. As more sites become occupied, the rate of adsorption will decrease. This is consistent with the pseudo-second-order model, where the rate of occupation of adsorption sites decreases over time as fewer sites are available. Since the biochar has fine pores, capillary condensation of diesel oil might occur inside these pores, which can enhance the adsorption capacity, especially for heavier fractions of the diesel oil. Eventually, an equilibrium state is reached where the rate of diesel oil molecules adhering to the biochar equals the rate of desorption. At this point, the maximum adsorption capacity under the given conditions is achieved. After reaching equilibrium, the teabags can be removed from the contaminated site. The immobilization of biochar in teabags facilitates the disposal or potential regeneration of the adsorbent.

Comparison with other adsorbents

The efficacy of BPBC in removing diesel oil from water under optimal solution environmental conditions was evaluated against other adsorbents known for diesel oil adsorption. The comparative outcomes are presented in Table 3. Derived from saba banana peels, BPBC demonstrated enhanced effectiveness compared to other biochar, attributed to its porosity and hydrophobic nature. These findings indicate that BPBC is a highly efficient material for diesel oil removal in water.

Conclusions

In this research, we investigated the impact of various solution environmental conditions on the sorption capacity of banana peel biochar (BPBC) contained within teabags. Our findings have yielded several key insights into the adsorption characteristics of BPBC, particularly in the context of diesel oil removal from water. We observed that the sorption capacity of BPBC is notably influenced by the adsorbent loading. At lower loadings, the biochar's surface is more accessible, allowing for greater adsorption. Conversely, higher loadings lead to pore blockage and reduced surface exposure, diminishing the biochar's adsorption efficiency. Interestingly, our results showed that changes in pH had negligible influence on the adsorption process. This can be explained by the nature of diesel oil as a hydrophobic, non-polar compound, whose interaction with BPBC is primarily driven by hydrophobic forces rather than electrostatic interactions, which are more pH-sensitive. Further, our research highlighted the significance of salinity in the adsorption process. The increasing sorption capacity with rising salinity can be attributed to the "salting-out" effect, where higher salt concentrations reduce the solubility of diesel oil, pushing it out of the solution and onto the biochar surface. Additionally, our findings emphasized the importance of contact time in the adsorption process. The sorption capacity increased with longer contact times. This can be explained by the kinetics of the adsorption process, where initial rapid adsorption is followed by a slower, progressive occupation of the biochar's adsorption sites. The optimal conditions determined for the adsorption of diesel oil were found to be a BPBC loading of 0.50 g, a solution pH of 5.00, a salinity concentration of 12,656.57 mg/L, and a contact time of 240 min. Under these specific parameters, the biochar exhibited an adsorption capacity of 19.04 g/g. The pseudo-second-order model provided a better fit to the kinetic data, suggesting chemisorption. The Harkins–Jura isotherm model emerged as the best fit isotherm model. This model's suitability can be attributed to its ability to account for the heterogeneous nature of the biochar surface and the formation of multiple adsorbate layers. In conclusion, our research establishes BPBC as a highly efficient adsorbent for diesel oil removal from water. Its superior performance, as compared to other biochar, is largely due to its porosity and hydrophobic nature. These properties make BPBC contained within teabags not only a practical but also an effective solution for treating diesel oil-contaminated water. This study not only contributes to our understanding of BPBC's adsorption properties but also highlights its potential for environmental remediation applications. Further studies may focus on the effect of other environmental parameters and enabling its scale-up to actual oil spill remediation.

Abbreviations

ANOVA	Analysis of variance
BPBC	Banana peel biochar
FC-CCD	Face-centered central composite design

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Not applicable.

Authors' contributions
All authors contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by JJDU, JMB, ED, KMD, KR, and ECL. The first draft of the manuscript was written by ECL, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets used or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

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