

Fabrication of green and powerful magnetic nanocomposite for the removal of oil from seawater: Optimization using Response Surface Methodology

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Abstract: Traditional techniques for adding modifiers to solid support materials are time-consuming and require significant energy and materials. This study focuses on modifying agricultural waste using a quick, simple, and easy solid-phase extraction approach. This work reports the design, fabrication, and laboratory evaluation of Alfalfa straw biomass (Alf. S) decorated with magnetic iron-oxide nanoparticles (Fe₃O₄ MNPs) for oil-water separation. This novel magnetic nanocomposite adsorbent was synthesized via in situ coprecipitation. FTIR, XRD, and SEM characterized the newly developed nanocomposite (Fe₃O₄ MNPs@Alf. S biomass). In this study, the Box-Behnken experimental design (BBD) was used to determine the optimal values of three independent variables affecting oil removal efficiency from seawater: the amount of Fe₃O₄ MNPs@Alf. S biomass, the amount of oil in grams, and adsorption time (min). The maximum adsorption capacity was 1300 mg/g with 300.0 mg of adsorbent, 10.0 mL of used motor oil, and an adsorption time of 1 min. The data also confirm successful fabrication and oil adsorption, as the high R² value and close proximity to R²(adj) indicate that the BBD model was significant.

Keywords: Alfalfa straw, Anchoring process, Biomass, Fe₃O₄ MNPs, RSM

1. Introduction

All living things depend on water to survive. Over the years, water contamination has increased dramatically and is now a major global issue (Abdul Salim et al., 2025; Shekhar et al., 2025). The presence of pollutants, such as organic compounds, in water has become a critical issue today. The volume of greasy wastewater is steadily increasing as industry expands. Because oily wastewater contaminates groundwater, saltwater, and drinking water supplies, it substantially harms ecosystems. This harm can therefore spread throughout the ecosystem (Bolto et al., 2020; Muvel et al., 2025). Oil removal operations have employed several readily available methods, including rapid separation, gravity separation, chemical sedimentation, membrane purification, absorption, and chemical oxidation (Bensadok et al., 2011). Despite their advantages, these treatment procedures have drawbacks, including low efficacy, long operating times, secondary pollution, and high costs (Shokri & Sanavi Fard, 2022). Compared to other methods, adsorption has several advantages, including low capital costs and ease of design. Because of its enormous surface area per unit mass, activated carbon is widely used as an efficient adsorbent in water and wastewater treatment to remove various organic and inorganic contaminants, despite its high cost. Recent studies have focused on using low-cost, eco-friendly materials for water treatment to support sustainability (Abdul Salim et al., 2025; Jain Toshit et al., 2023; Nishi et al., 2025). These materials include agricultural wastes such as fruit peels, cereal husks and straws, crop residues, vegetable peels and residues, sugarcane bagasse, and plant biomass waste (Abdel Rahim, 2025; Al-Najar et al., 2023; Sharma Kavita & Kaur, 2026; Wahi et al., 2013). Alfalfa waste, among agricultural wastes, contains functional groups such as cellulose, hemicellulose, lignin, and residual proteins (Du et al., 2024). Despite their benefits, many natural sorbents exhibit high water absorption, which is linked to their poor



hydrophobicity (water-repelling capacity). Because of this high water uptake, microporous sorbents that lack hydrophobicity are less effective at absorbing oil. Nanoscale materials are expected to have enhanced adsorption capacity and a substantial increase in specific surface area. The functional group composition, surface morphology, active surface area, pore size, and surface interactions of a natural sorbent are additional features closely associated with hydrophobicity (Rahim & Hamdaoui, 2026). Additionally, ferric oxide nanoparticles have been shown to be highly effective adsorbents for removing emulsified oil (gasoline, diesel, and kerosene) from contaminated water (Sarran et al., 2024). Therefore, modifying agricultural wastes with Fe₃O₄ MNPs enhances their oil-removal effectiveness, as the NPs' large surface area enables more active, rapid separation of the adsorbent using a magnetic field.

Synthesizing biomass-based adsorbents for oil spill recovery also offers ecological benefits from a sustainability and climate change perspective. Converting agricultural waste and other biomass materials into efficient adsorbents can help address waste management problems and provide economical materials for ecological rehabilitation. Moreover, the potential of biomass-based sorbents for waste valorization and circular economy initiatives further underscores the need for more sustainable remediation options. Recently, they have been reported as efficient materials for remediating oil spills (Ojo et al., 2025). In this view, the magnetic biomass-derived nanocomposite investigated in the present work can serve as a green technology for oil removal from saline water, since magnetic recovery could allow separation of the adsorbent and its possible reuse.

Researchers often choose the co-precipitation method over other synthesis techniques because it is simple, operates at low temperatures, is affordable, and scales well. Because of their high surface energy, iron oxide nanoparticles tend to agglomerate. Co-precipitation can improve the composite's adsorption efficiency by reducing particle size, ensuring a consistent pore-diameter distribution, and preventing aggregation of Fe₃O₄ MNPs (Abdullah et al., 2019). This study produced Fe₃O₄ MNPs@Alf. S biomass, a nanocomposite of iron oxide and alfalfa waste, using a co-precipitation approach via an anchoring process. This eco-friendly adsorbent successfully remediated oil spills in water. The authors optimized the adsorption parameters using Response Surface Methodology (RSM).

Response Surface Methodology (RSM), a statistical modeling technique, has been widely applied to optimize experimental conditions in numerous studies. RSM mathematical and statistical techniques may be used in process optimization and to compare the relative importance of different contributing factors. Furthermore, the complex nature of the adsorption process necessitates identifying optimal operating conditions to maximize pollutant removal efficiency (Abdel Rahim et al. 2025).

While Fe₃O₄-based biomass adsorbents and RSM-assisted adsorption optimization have been extensively studied, there has been no prior report on the preparation of Fe₃O₄ MNPs@Alf. S biomass for the removal of used motor oil from seawater, studied with RSM-based optimization of the adsorption conditions. The novelty of the present work is thus the integration of these three aspects into a single treatment system: (i) the development of a magnetic nanocomposite using alfalfa straw agricultural waste as a biomass support, (ii) its application for the rapid removal of used motor oil in seawater with facile magnetic separation, and (iii) the systematic optimization of the adsorption parameters using a Box–Behnken design coupled with Response Surface Methodology (RSM). The rapid removal of oil within 1 minute clearly indicates the developed material's practical potential for treating oil-contaminated seawater.

2. Experimental

2.1. Materials

The Alfalfa straw (Alf. S) used in this experiment was sourced from a local farm in the Eastern region of KSA. It was cleaned with distilled water, dried, ground in a mill, and sieved to obtain the fine particles required to prepare the nanocomposite adsorbent (Rahim & Hamdaoui, 2026). Analytical reagent-grade substances were utilized in this investigation. Fe₃O₄ MNPs were prepared using iron (III) chloride (FeCl₃), iron (II) chloride (FeCl₂), and sodium hydroxide (NaOH), which were purchased from Sigma-Aldrich. Used motor oil ($d = 0.91$ g/mL) was collected from a local market in the Eastern region of KSA. A seawater (SW) sample was collected from the Red Sea, KSA. n-Hexane (Sigma-Aldrich) served as an efficient regenerating solvent. Every experiment utilized distilled water.

2.2. Synthesis of the nanocomposite with a time-saving method

Co-precipitation was used to synthesize the nanocomposite Fe₃O₄ MNPs@Alf. S biomass. Typically, a flask containing 0.5 M Fe(III) and 0.25 M Fe(II) was filled with 2.0 g of Alf. S biomass. After adding 5.0 M NaOH solution dropwise to the matrix until the pH reached 11, the beaker was heated to 60 °C for

one hour. Alf. S biomass color changed from green to dark brown, indicating that the anchoring procedure was successful. Subsequently, distilled water was used to wash the Fe_3O_4 MNPs@Alf. S biomass matrix until the pH reached neutrality (Abdel Rahim et al., 2025). After filtering the resultant matrix, the solid particles were collected and dried as shown in Figure 1.

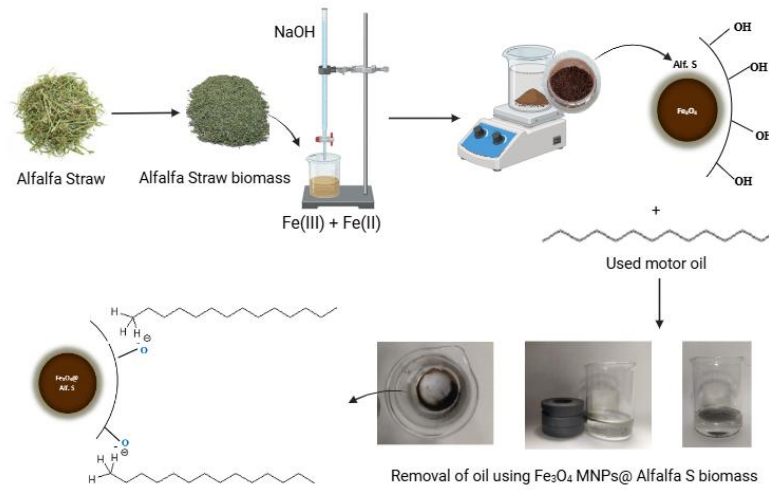


Figure 1. Scheme for laboratory procedures showing the removal of oil using Fe_3O_4 MNPs@Alf. S biomass

2.3. Experimental Design

Response surface methodology includes the Box-Behnken design. To assess three independent variables: weight of Fe_3O_4 MNPs @Alf. S biomass (A), amount of oil in grams (B), and adsorption time (C) (min). RSM was employed to gather mathematical and statistical data. As a result, fifteen experiments were created. X_1 , X_2 , and X_3 are the names of the three important variables. The software package Minitab 17 (USA) was used to define the experimental design and to enhance the system by estimating statistical parameters. The following formula can be used to determine the number of experiments (N) needed to create BBD:

$$N = 2k(k-1) + C_o \quad (1)$$

where k is the number of factors, and C_o is the number of central points (where $C_o=3$). Equation (1) indicates that 15 trials were conducted to evaluate the effects of the three primary independent variables on adsorption efficiency. The quadratic polynomial equation is commonly used to approximate the relationship between the reaction and three significant independent variables, X_1 , X_2 , and X_3 , within a system (Abdel Rahim, 2025).

$$Y = \beta_o + \sum_{i=1}^n \beta_i X_i + \sum_{i=1}^n \beta_{ii} X_i^2 + \sum_{i=1}^{n-1} \sum_{j=i+1}^n \beta_{ij} X_i X_j + \varepsilon \quad (2)$$

In this equation, Y represents the projected yield (% adsorption), β_o denotes the constant, β_i signifies the first-order coefficient, β_{ii} indicates the second-order coefficient, and β_{ij} refers to the interaction term. X_i and X_j represent the encoded values of the examined variables, whereas n denotes the number of independent variables.

2.4. Adsorption of oil using Fe_3O_4 MNPs@Alf. S biomass

The following process was used to remove oil from seawater (SW): A 20.0 mL water sample was mixed with the appropriate amount of oil in a 50 mL beaker. Because oil has a lower density than water, an oil layer quickly formed on the water. Next, the oil/water mixture was gently covered with the adsorbent Fe_3O_4 MNPs@Alf. S biomass according to the parameters mentioned in Tables 1 and 2. After removing the adsorbent from the mixture using a permanent magnet, it was dried in an oven at 50°C and

weighed. The oil adsorption capability of Fe₃O₄ MNPs@Alf. S biomass was calculated using weight measurements, with known volumes of the examined oil and their respective weights determined from density values. The following equation is used to quantify the oil adsorption capacity:

$$Q_{oil} = \frac{m_s - m_i}{m_i} \quad (3)$$

where Q_{oil} is the adsorption capacity for oil (mg/g), m_s is the weight of wet adsorbent after draining (g), and m_i is the initial weight (g) of the dried adsorbent before adsorption. All adsorption experiments were conducted in triplicate, and the results are expressed as mean $\pm$ standard deviation.

Table 1. Presents the values and ranges of the variables used in the BBD for oil adsorption using Fe₃O₄ MNPs@Alf. S biomass

Factor	min.	max.
Wt. of Fe ₃ O ₄ MNPs@Alf. S biomass (mg)	100	500
Amount of oil (expressed in mL)	1	10
Time of adsorption (minutes)	1	30

Table 2. Experimental design in terms of actual factors affecting the adsorption of oil on Fe₃O₄ MNPs@Alf. S biomass (n = 3)

No.	Weight of adsorbent (mg)	Time (min)	Amount of oil (mL)
1	300	1.0	10.0
2	300	15.5	5.5
3	500	30.0	5.5
4	300	1.0	1.0
5	300	15.5	5.5
6	300	15.5	5.5
7	100	15.5	10.0
8	500	15.5	1.0
9	500	1.0	5.5
10	500	15.5	10.0
11	300	30.0	10.0
12	100	1.0	5.5
13	300	30.0	1.0
14	100	30.0	5.5
15	100	15.5	1.0

2.5. Recycling of Fe₃O₄ MNPs@Alf. S biomass

The reusability of Fe₃O₄ MNPs@Alf. S biomass is one of its exceptional characteristics. n-Hexane was selected for its strong affinity for nonpolar hydrocarbon oils. Upon completion of adsorption, the Fe₃O₄ MNPs@Alf. S biomass composite was magnetically extracted and subsequently regenerated using hexane. Afterward, the adsorbent was washed with distilled water and dried at 60 °C before reapplication. Four recycling experiments were conducted during this cycle under optimal experimental conditions. The Fe₃O₄ MNPs@Alf. S biomass adsorption capability was quantified after each precipitation (Mottaghi et al., 2021).

2.6. Characterization of the nanocomposite

Fe₃O₄ MNPs@Alf. S biomass was characterized both before and after the Fe₃O₄ MNPs anchoring process using a variety of analytical techniques. In this work, Fourier transform infrared (FTIR) spectra were recorded for chemical characterization using a Thermo Scientific Nicolet 380 spectrometer over the range 400–4000 cm⁻¹. The crystal structure of Fe₃O₄ MNPs@Alf. S biomass was investigated using a Cu source ($\lambda = 1.5406 \text{ \AA}$) to examine powder X-ray diffractograms in the 20–80° range using an X'Pert PRO 30–40–60 diffractometer, a JEOL JSM-6000 plus SEM, and a ZEISS LEO SUPRA 55 for scanning electron microscopy (SEM).

3. Results and discussion

3.1. SEM analysis for morphological characterization

SEM was used to examine the morphology of Alfalfa straw biomass, Fe_3O_4 nanoparticles, and the adsorbent Fe_3O_4 MNPs@Alf. S nanocomposite. Figure 2a shows the SEM image of Alf. S, which shows a rough and fibrous surface structure typical of lignocellulosic biomass and provides a favorable surface for the deposition of nanoparticles. The Fe_3O_4 nanoparticles are mainly spherical or quasi-spherical in shape (Figure 2b). Figure 2c depicts the morphological changes of Fe_3O_4 MNPs@Alf. S nanocomposite after the deposition of Fe_3O_4 nanoparticles on the surface of Alfalfa straw biomass. It demonstrates the successful incorporation of nanoparticles into the biomass matrix. The resulting surface changes may provide more active sites and improve the composite's surface characteristics, which could enhance its adsorption performance.

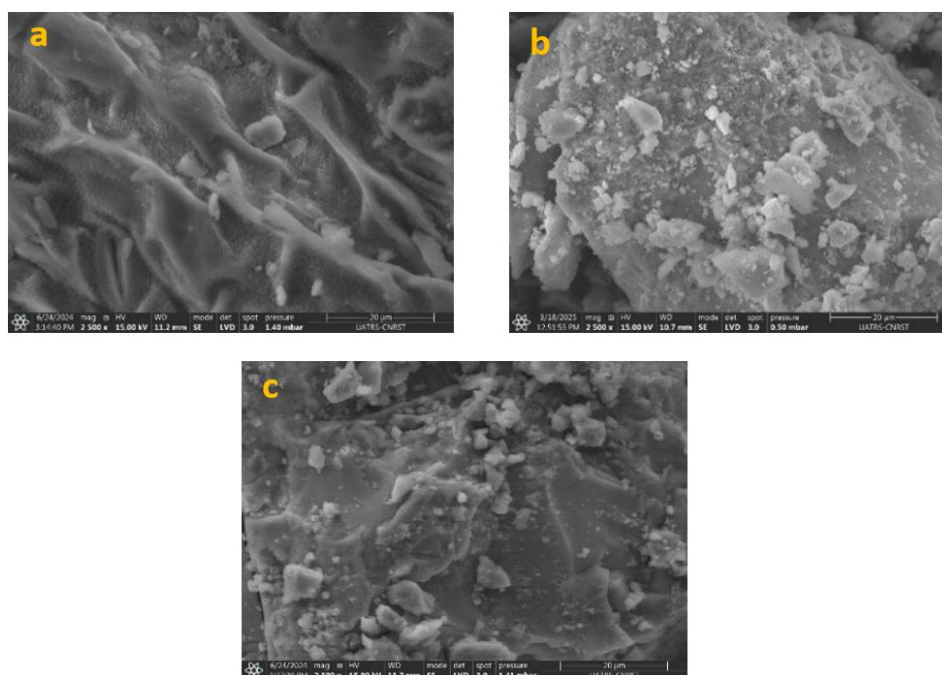


Figure 2. SEM images for (a) Alfalfa straw biomass, (b) Fe_3O_4 MNPs, and (c) Fe_3O_4 MNPs@Alf. S biomass

3.2. FTIR analysis for Chemical characterization

The FTIR spectra in Figure 3 also support functionalization of the alfalfa biomass with Fe_3O_4 nanoparticles. The characteristic vibration band related to the Fe–O bond at 541.27 cm^{-1} (Abdel Rahim et al., 2020), which corresponds to Fe_3O_4 , appears in Fe_3O_4 MNPs@Alf. S confirms the anchoring process. The characteristic absorption bands associated with cellulose, hemicellulose, and lignin, such as O–H and C–H at 3310.40 , 2917.76 , and 2849.37 cm^{-1} , respectively, and C–O–C at 1151.73 cm^{-1} in Alf. S (Du et al., 2025) decreased the intensity of the spectrum of Fe_3O_4 MNPs@Alf. S. Variations in the position or intensity of these peaks in the nanocomposite indicate chemical interactions between the Alf. S biomass and the nanoparticles, and hence impregnation and functionalization.

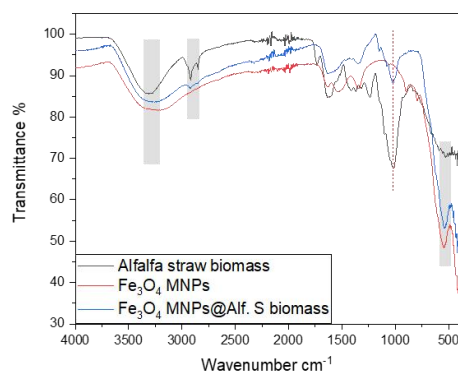


Figure 3. FTIR spectra for Alfalfa straw biomass, Fe₃O₄ MNPs, and Fe₃O₄ MNPs@Alf. S biomass

3.3. XRD analysis for structural characterization

Both SEM and FTIR analyses provide clear evidence of nanoparticle impregnation and chemical interactions in the Fe₃O₄ MNPs@Alf. S. Nonetheless, other characterization techniques, such as XRD, can be employed to assess the degree of crystallinity and the chemical states of the nanoparticles, as well as those of the biomass and Fe₃O₄ MNPs (Figure 4). Fe₃O₄ is the primary crystalline phase in the sample, according to the XRD pattern of Fe₃O₄ MNPs—the Fe₃O₄ MNPs@Alf. S nanocomposite's XRD pattern revealed a cubic spinel structure with distinct peaks at $2\theta = 30.3, 35.4, 44.2, 52.6, 57.4,$ and 62.8 . Based on the 2θ values and relative intensities of Fe₃O₄ reported in the literature, the peaks are indexed as (220), (311), (400), (422), (511), and (440) (Rahim & Hamdaoui, 2026). The efficacy of the suggested approach is confirmed by compelling evidence that the Fe₃O₄ MNPs@Alf. S adopt the crystalline form of Fe₃O₄ MNPs.

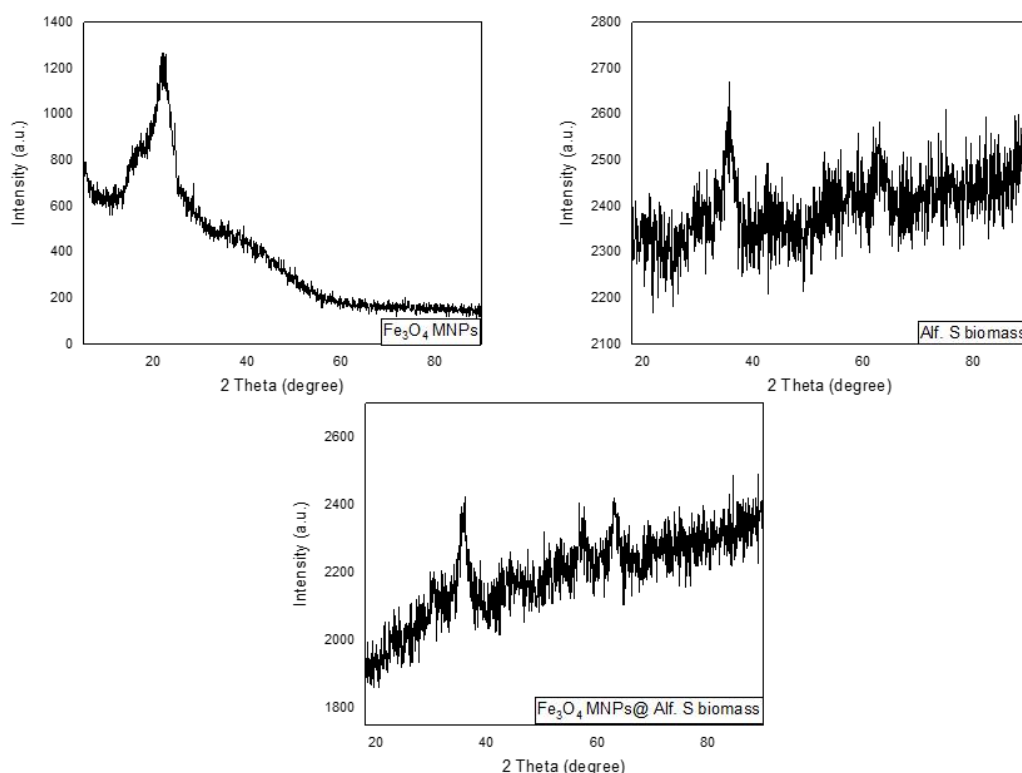


Figure 4. XRD patterns for Alfalfa straw biomass, Fe₃O₄ MNPs, and Fe₃O₄ MNPs@Alf. S biomass

3.4. Statistical analysis

A statistical evaluation of the experimental data is essential to ascertain the optimal conditions for oil adsorption within the specified parameter range. The regression equations characterizing the correlation

between oil adsorption and the independent variables were constructed using RSM. The regression equation for this experiment is articulated in terms of the coded values as follows:

$$\begin{aligned}
 & \text{Adsorption capacity (mg / g)} \\
 & = 0.586 + 0.0416 \text{ conc.} + 0.00039 \text{ wt of phase} - 0.0145 \text{ time} \\
 & - 0.00186 \text{ conc.} * \text{conc.} - 0.000001 \text{ wt of phase} * \text{wt of phase} \\
 & + 0.000756 \text{ time} * \text{time} + 0.000096 \text{ conc.} * \text{wt of phase} - 0.00100 \text{ conc.} * \text{time} \\
 & - 0.000029 \text{ wt of phase} * \text{tim}
 \end{aligned} \tag{4}$$

The analysis of variance (ANOVA) results shown in [Table 3](#) demonstrate the statistical significance and adequacy of the developed quadratic model. The ANOVA test indicated that the entire model was significant ($F = 8.96$, $p = 0.013$). The lack-of-fit was not statistically significant ($F = 1.82$, $p = 0.374$), indicating the model was adequate for the experimental domain studied. The Box–Behnken response surface model was statistically fitted to the oil adsorption capacity of Fe_3O_4 MNPs@Alf. S biomass and the effects of the experimental parameters investigated were explained ([Khoshraftar et al., 2023](#)).

Table 3. The analysis of variance (ANOVA) results

Source	DF	Sum of Squares	Mean Square	F-value	p-value
Model	9	84.6909	9.4101	8.96	0.013
Linear	3	67.8742	22.6247	21.53	0.003
Initial oil concentration	1	1.7749	1.7749	1.69	0.250
Adsorbent dose	1	66.0813	66.0813	62.89	0.001
Contact time	1	0.0180	0.0180	0.02	0.901
Quadratic	3	15.0615	5.0205	4.78	0.063
Initial oil concentration ²	1	0.4789	0.4789	0.46	0.530
Adsorbent dose ²	1	12.5091	12.5091	11.90	0.018
Contact time ²	1	2.1550	2.1550	2.05	0.212
Two-way interactions	3	1.7552	0.5851	0.56	0.666
Initial oil concentration × Adsorbent dose	1	0.0697	0.0697	0.07	0.807
Initial oil concentration × Contact time	1	0.1910	0.1910	0.18	0.688
Adsorbent dose × Contact time	1	1.4945	1.4945	1.42	0.287
Error	5	5.2539	1.0508	—	—
Lack-of-fit	3	3.8439	1.2813	1.82	0.374
Pure error	2	1.4100	0.7050	—	—
Total	14	89.9448	—	—	—

3.5. Surface Plots for Adsorption Capacity Values

This section contains three 3D surface plots depicting the relationship between adsorption capacity and the following parameters: adsorbent weight, adsorption time, and oil amount. Adsorption capacity normally increases over time, as expected, because adsorbate particles move randomly toward active sites. However, at higher concentrations, saturation is reached, and the adsorption capacity is also saturated. The findings indicate that time and concentration are key factors governing the adsorption features. The system needs sufficient time to reach maximum adsorption. This plot should analyze the relationships among adsorption capacity, adsorbent weight, and oil concentration. Adsorption capacity also tends to increase with adsorbent weight, since more active sites are exposed. However, at high concentrations, saturation can occur ([Sidik et al., 2012](#)). The three surface plots show how operational parameters affect the hybrid material's adsorption capacity, including time, oil concentration, and adsorbent weight ([Figure 5](#)). Changes in adsorption capacity with contact time and oil concentration may reflect the availability and accessibility of adsorption sites and the transport of oil molecules to the active sites of Fe_3O_4 MNPs@Alf. S biomass composite. In adsorption processes, initial adsorption is usually rapid because of the large number of available adsorption sites, but the rate decreases as these sites become progressively occupied. Also, as the adsorbent amount increases, more adsorption sites become available, and the adsorption rate increases. However, adsorption capacity per unit mass of adsorbent may not increase proportionally with adsorbent dose due to free sites and overlapping or aggregation of adsorption sites ([Al-Najar et al., 2023](#); [Sidik et al., 2012](#)). The interaction graphs show the combined effect of contact time and adsorbent mass on adsorption capacity. The results indicate that the adsorption

response is sensitive to both variables and that increasing adsorbent mass can enhance the adsorption rate by increasing the number of available adsorption sites. Therefore, the response surface analysis provides important information for identifying an adequate compromise among adsorption efficacy, contact time, and the amount of material used. However, the contact time analysis and RSM optimization serve different purposes. The contact time analysis helps understand the temporal evolution of the adsorption process, while the RSM optimization identifies the combination of operational parameters that maximizes the projected adsorption capacity within the evaluated experimental design space.

The RSM optimization indicated the highest adsorption capacity of 1300 mg/g at 300.0 mg Fe_3O_4 MNPs@Alf. S biomass, 10.0 mL of used motor oil, and a contact time of 1 min. The results showed that the synthesized magnetic biomass-derived nanocomposite achieved a high adsorption capacity under optimal conditions and rapidly recovered used motor oil from saline water. From an operational standpoint, the short optimum contact time is particularly interesting, as rapid oil uptake may reduce treatment time and increase the practical efficiency of the remediation process.

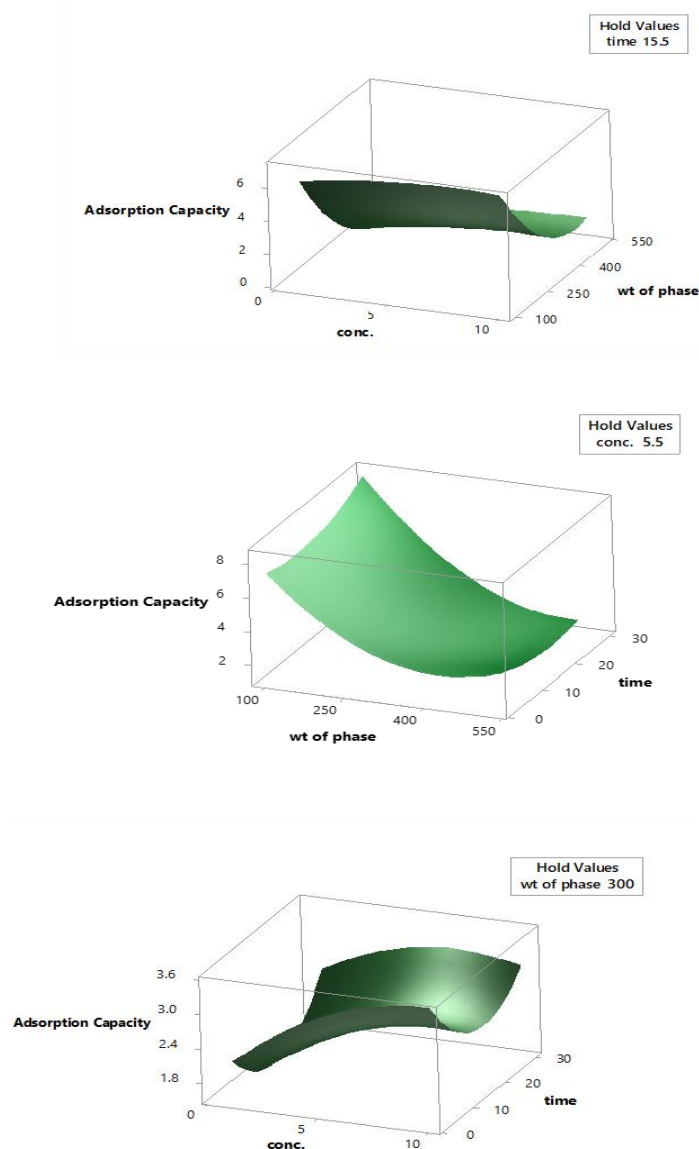


Figure 5. Response surface plots for the interactions of oil adsorption by Fe_3O_4 MNPs@Alf. S biomass from seawater ($n = 3$)

3.6. Validation of the RSM model and experimental -predicted response relationship

The predictive capability of the developed RSM model was verified by comparing experimental and predicted adsorption capacity values. The model showed good agreement between experimental and predicted responses, with $R^2 = 0.95596$ and $\text{adj } R^2 = 0.95257$ (Figure 6). The RSM optimization identified the optimal conditions as 300.0 mg of Fe_3O_4 MNPs@Alf. S biomass, 10.0 mL of used motor oil, and a contact duration of 1 min, with a predicted adsorption capacity of 1300 mg/g. The optimal conditions were experimentally evaluated, and the adsorbent prepared under these conditions was employed in the recycling tests. The statistical significance of the model ($p = 0.013$) and the agreement between the predicted and experimental responses confirmed the applicability of the constructed RSM model in the experimental domain under study.

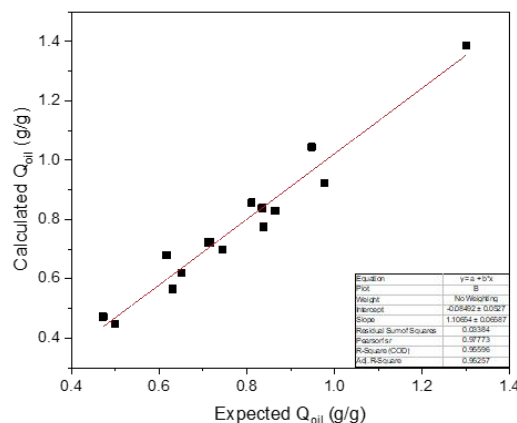


Figure 6. The relationship between the experimental and expected adsorption capacity values

3.7. Recycling of Fe_3O_4 MNPs@Alf. S biomass

The optimum conditions for recycling Fe_3O_4 MNPs@Alf. S biomass for oil adsorption were at 300.0 mg adsorbent, 10.0 mL of used motor oil, and a contact time of 1 min. The oil capacity of Fe_3O_4 MNPs@Alf. S biomass only slightly decreased after each cycle, as Figure 7 illustrates. Since no weight loss was seen following each regeneration cycle, this suggests that Fe_3O_4 MNPs@Alf. S biomass can be reused repeatedly and has a strong structure. The Fe_3O_4 MNPs@Alf. S biomass composite's magnetic characteristics allow for simple separation and reuse, which makes scale-up easier even if the adsorption studies were conducted in batch mode. The adsorption capacity dropped after the fifth cycle. After the adsorption studies, a permanent magnet was used to separate the Fe_3O_4 MNPs@Alf. S biomass adsorbent from the solution. By dividing the mass of recovered adsorbent by the initial mass used, we calculated the magnetic recovery yield (MRY). In our studies, we recovered 0.293 g of adsorbent from an initial 0.3 g, yielding an MRY of 97.67%. This illustrates the material's reusability across several adsorption cycles and the efficiency of magnetic retrieval. Additionally, it demonstrates that magnetic separation is similar to that of other metal-based composites documented in the literature (Xiong et al., 2025). The Fe_3O_4 MNPs@Alf. S biomass composite supports a circular-economy approach and improves overall environmental performance because it can be reused and regenerated without loss of performance.

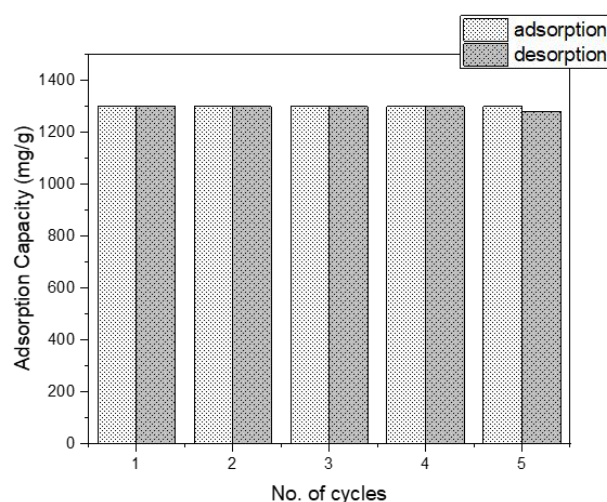


Figure 7. The effect of recycled oil@Fe₃O₄ MNPs@Alf. S biomass on oil adsorption.

3.8. Comparison with literature

Compared with recently used adsorbents, the newly developed nanocomposite Fe₃O₄ MNPs@Alf. S biomass performs better in removing used motor oil from saltwater surfaces (Table 4). Moreover, the data show that the RSM methodology successfully optimized the oil adsorption parameters, yielding a higher adsorption capacity than other natural adsorbents reported in previous studies.

Table 4. Comparison of the adsorption capacity values between Fe₃O₄ MNPs @Alf. S biomass and other natural adsorbents in the literature

Adsorbent	Optimum conditions	Method for evaluation	Adsorption capacity (mg/g)	Ref.
Animal bones (ABs) and anise residues (ARs)	1.0 g adsorbent weight, 200 mg/L of oil at 60 min.	Classical	45 mg/g for ABs, while for ARs 30 mg/g	(Al-Najar et al., 2023)
lauric acid (LA) modified oil palm leaves (OPL _{SLA})	5600 mg/L of oil conc., and 20 min.	Classical	1176 ± 12.92 mg/g	(Sidik et al., 2012)
Yellow horn shell	5 g adsorbent dose, 20 g of oil for 3 h	Classical	0.39–0.61 g/g	(Li et al., 2013)
Lawsonia leaves	0.35 g/L of biomass dose, 1.0 g oil/1 L seawater at 2 min	Classical	1600 mg/g	(Mahmoud et al., 2022)
Fe ₃ O ₄ MNPs@Alf. S biomass	300.0 mg of Fe ₃ O ₄ MNPs @Alf. S biomass, 10.0 mL of used motor oil for 1 min.	RSM	1300 mg/g	This study

3.9. Environmental Considerations, Constraints and Scaling up Application

From a practical point of view, the magnetic property of the Fe₃O₄ MNPs@Alf. S biomass is a major advantage for recovery from the treated saltwater. An external magnetic field can recover the discarded adsorbent after oil adsorption, thereby avoiding conventional filtration or centrifugation and facilitating solid-liquid separation. However, under real oil-spill conditions, high salinity, high oil concentrations, suspended particles, and natural organic matter may alter the adsorbent's dispersion and separation behavior, affecting magnetic recovery. Therefore, although the nanocomposite's magnetic properties suggest it can be recovered from contaminated seawater, additional pilot-scale studies under realistic oil-spill conditions are needed to quantitatively evaluate the process's feasibility and the efficacy of magnetic recovery.

In addition, the environmental management of the adsorbent after use should be explored in detail. Collect and properly treat the oil-loaded adsorbent rather than releasing it into the environment to reduce the risk of secondary pollution. The nanocomposite's stability also affects desorption of adsorbed oil pollutants and leaching of iron species into the treated water. Further investigations are needed to assess the nanocomposite's long-term stability, metal leaching, regeneration efficiency across multiple cycles, and the safe disposal or valorization of the spent adsorbent. However, regeneration and reuse could reduce waste and improve overall process sustainability. Moreover, the proposed method could be scaled up from laboratory tests to real oil spill cleanup. However, challenges may arise in handling oil-loaded biomass, mass transfer, adsorbent recovery and regeneration, large volumes of contaminated seawater, and the design of efficient magnetic separation systems. Future pilot-scale studies should consider these challenges before large-scale environmental applications.

4. Conclusion

This study reports the development of a novel, solvent-free nanocomposite adsorbent composed of Alf. S-coated magnetic nanoparticles (Fe_3O_4 MNPs@Alf. S biomass). This new adsorbent is an eco-friendly nanocomposite with a strong affinity for removing oil from seawater. The Response Surface Methodology was used to analyze the adsorption data. The results demonstrate the feasibility of synthesizing a novel nanocomposite that holds promise as an adsorbent for marine oil spills. The combination of SEM, FTIR, XRD, and adsorption experiments provides compelling evidence that the hybrid material composed of alfalfa biomass and Fe_3O_4 nanoparticles shows promising potential for environmental applications, particularly in water treatment. Structural and chemical analyses suggest that this material could offer an efficient, cost-effective solution for contaminant removal.

Data Availability Statement

All data generated or analyzed during this study are included in this published article.

Conflict of Interest

The authors declare no conflicts of interest.

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