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Rimsha Saleem

rimshasaleem453@gmail.com

University of Education

Naeem Abbas

Pakistan Council of Scientific & Industrial Research

Amina Asghar

University of Education

Muhammad Hammad Khan

Pakistan Council of Scientific & Industrial Research

Kainat Fatima

University of Education

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Sustainable Moringa Derived Acrylic acid Based Nanocomposite Hydrogel for Dual Removal of Ionic and Dye Pollutants

Rimsha Saleem¹, Naeem Abbas², Amina Asghar³, Muhammad Hammad Khan⁴, Kainat Fatima⁵

1. Division of science and technology, University of Education, Lahore Pakistan
Email : rimshasaleem453@gmail.com
2. Pakistan Council of Scientific and Industrial research, Lahore Pakistan
Email : naeemchemist@gmail.com
3. Division of science and technology, University of Education, Lahore Pakistan
Email : amina.asghar@ue.edu.pk
4. Pakistan Council of Scientific and Industrial research, Lahore Pakistan
Email : jawad_frc@hotmail.com
5. Division of science and technology, University of Education, Lahore Pakistan
Email : kainatfatima5612@gmail.com

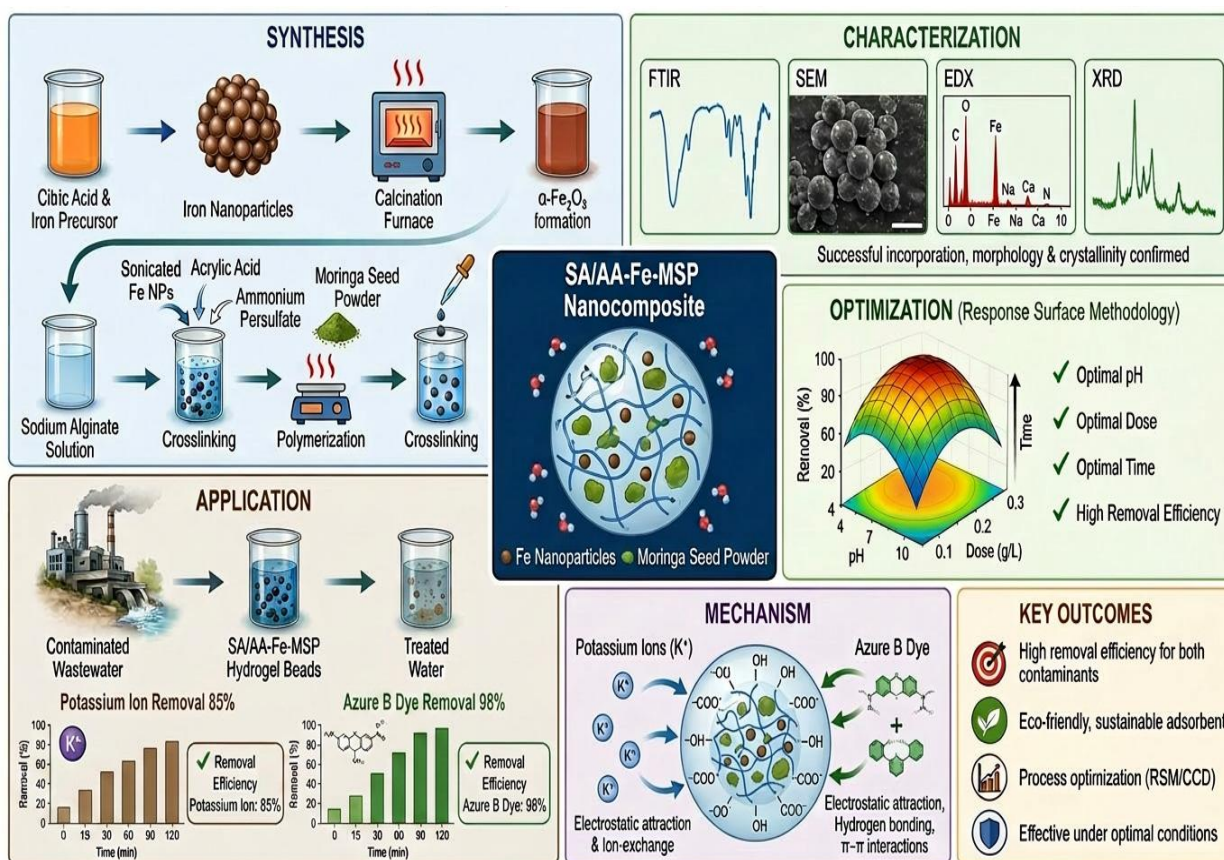
Corresponding author: Rimsha Saleem Email : rimshasaleem453@gmail.com

Abstract

Textile industry wastewater contains hazardous dyes and ionic contaminants that are difficult to remove using conventional treatment methods, highlighting the need for sustainable and efficient remediation materials. In this study, a novel sodium alginate/acrylic acid–iron nanoparticle–Moringa seed powder (SA/AA–Fe–MSP) nanocomposite hydrogel was synthesized for the dual removal of potassium ions and Azure B dye from aqueous solutions. The novelty lies in integrating bio-based Moringa oleifera seed powder with α -Fe₂O₃ nanoparticles within a crosslinked polymeric hydrogel matrix, providing synergistic adsorption and coagulation performance. The composite was prepared through free radical polymerization followed by Ca²⁺ crosslinking and characterized using FTIR, SEM-EDX, and XRD, confirming its functional groups, porous morphology, and crystalline iron oxide phases. Batch adsorption experiments demonstrated effective removal of both pollutants, which was further enhanced by alum-assisted coagulation-adsorption. RSM based on Central Composite Design was employed to optimize pH, dose, alum concentration, and contact time and to evaluate their interactive effects. Maximum removal efficiencies of approximately 85% for K⁺ and 98% for Azure B were achieved. Removal mechanisms involved electrostatic attraction, ion exchange, hydrogen bonding, and surface complexation. Overall, the SA/AA–Fe–MSP hydrogel offers a sustainable approach for effectively treating textile wastewater with complex contaminant characteristics.

Key words:, Azure B dye removal, potassium ions, water treatment.

Graphical abstract



Introduction

In recent decades, water pollution from industrial wastewater has become a serious environmental problem that has a substantial impact on the quality of surface and groundwater globally. Complex chemical mixes found in industrial effluents, such as dyes and inorganic ions, can endanger human health and ecosystems if they are dumped untreated into bodies of water [1]. The textile industry, which uses a lot of water and releases a lot of wastewater during the production and dyeing processes, is one of the biggest causes of this kind of pollution. Textile effluents are challenging to treat using traditional methods alone because of their high chemical oxygen demand (COD), biological oxygen demand (BOD), strong color, changeable pH, and the presence of both organic and inorganic pollutants [2, 3].

The textile industry uses synthetic dyes widely to color garments because of their resilience and vibrant look. Among these, cationic dyes like Azure B are frequently used in the dyeing of synthetic fibers, wool, and silk. But during rinsing and finishing, a sizable portion of these dyes are left unfixed and discharged into wastewater streams [4]. These dye compounds have detrimental ecological effects, such as decreased light penetration in water bodies, obstruction of photosynthesis in aquatic flora, and harmful effects on aquatic creatures, because they are frequently resistant to biodegradation and visible even at low concentrations [5].

Textile wastewater comprises a variety of inorganic ions in addition to dyes, which come from water softening agents used during the process, salts used to improve dye uptake, and dyeing auxiliaries [6]. In example, the use of potassium-based salts during dye fixing and color stabilization can introduce potassium ions. Although potassium is a necessary nutrient in small amounts, high concentrations in wastewater can lead to increased ionic strength and conductivity, which can affect water quality and make downstream treatment more difficult. The effectiveness of biological treatment procedures is also impacted by elevated ionic load [7].

Coagulation, flocculation, sedimentation, oxidation, membrane filtration, and traditional adsorption are examples of effluent treatment techniques that have been extensively researched for the remediation of textile wastewater [8]. Even though these methods are somewhat successful, they frequently have a number of disadvantages, including as high operating costs, the production of secondary waste (sludge), poor selectivity for some contaminants, and decreased effectiveness when simultaneously addressing dye and ionic pollutants. These drawbacks underscore the pressing need for more long-lasting, economical, and multipurpose therapeutic approaches [9].

Nanotechnology has gained significant attention in wastewater remediation due to the high specific surface area, tunable functionality, and enhanced reactivity of nanostructured materials [10]. Iron and iron-based nanocomposites are examples of metal nanoparticles with promising adsorption and catalytic qualities for removing dyes from aqueous solutions. Because of their huge surface area and magnetic separability, iron nanoparticles have proven to be excellent at

decolorizing textile dyes, which can increase treatment efficiency and make recovery and reuse easier [11].

As environmentally benign substitutes for synthetic chemicals, natural adsorbents made from plant materials have also been investigated. Among these, *Moringa oleifera* seed powder has been found to be an inexpensive, biodegradable coagulant and adsorbent with good color removal capabilities. *Moringa* seeds' naturally occurring proteins and functional groups that improve pollutant binding have been found in studies to dramatically lower the color, suspended particles, COD, and turbidity of textile effluent [12, 13]. Because of their high water uptake, abundance of functional groups, and capacity to include nanoparticles and bio-adsorbents, hydrogel-based composites which are made of cross-linked polymer networks offer a flexible platform for pollutant removal. It is possible to chemically modify polymers of sodium alginate (SA) and acrylic acid (AA) to create hydrogels that can adsorb both organic color molecules and ionic ions. The resultant nanocomposite hydrogel beads may be able to more effectively remove both ionic (like potassium) and dye contaminants (like Azure B) from textile wastewater when mixed with iron nanoparticles and moringa seed powder (MSP).

There has been few research on sustainable, plant-derived hydrogel composites that may concurrently target ionic and dye contaminants in actual textile effluent, despite advancements in nanocomposite adsorbents and hydrogel applications. An innovative method that combines the advantages of each component for improved contamination removal is the incorporation of iron nanoparticles with moringa seed components into a SA/AA hydrogel matrix. Thus, the purpose of this study is to synthesize, characterize, and assess the efficacy of a sustainable SA/AA-Fe-MSP nanocomposite hydrogel for the dual removal of potassium ions and Azure B color from textile effluent.

Materials and Method

Source of Moringa seeds:

Moringa seeds were purchased from a local market in Haroonabad, Punjab, Pakistan.

Synthesis of Iron nanoparticles

Iron nanoparticles were fabricated by using a method aided by citric acid. To put it briefly, 1.5g of iron (III) nitrate nonahydrate were dissolved in 60ml of deionized water. The mixture was then agitated for two hours after the addition of three grams of citric acid. The liquid was stirred until it was homogeneous after the pH was lowered to 10 using sodium hydroxide. It was then heated to 70 °C with continuous stirring to produce a viscous residue, which was subsequently dried at 110 °C to produce a gel precursor. In order to produce α -Fe₂O₃ nanoparticles, the gel was finally calcined for six hours at 400 °C [14].

Fabrication of SA/AA-Fe-MSP nanocomposite

The nanocomposite was synthesized by dissolving sodium alginate (0.4 g) in 40 mL of distilled water under continuous stirring. Subsequently, sonicated Fe nanoparticles (0.75 g), acrylic acid (1 mL), and ammonium persulfate (0.02 g) were added as an initiator. The mixture was heated at 60–65 °C for 1–2 hours under gentle stirring to promote polymerization. After cooling the solution to room temperature, 0.1 g of moringa seed powder was added and the mixture was further stirred for 45–60 minutes to ensure uniform dispersion within the polymer matrix. The resulting solution was then dropped into a 2% CaCl_2 solution to form crosslinked hydrogel beads, which were allowed to stabilize for about 30 minutes. The obtained beads were washed with distilled water and subsequently dried at 40 °C or at room temperature (fig-1).

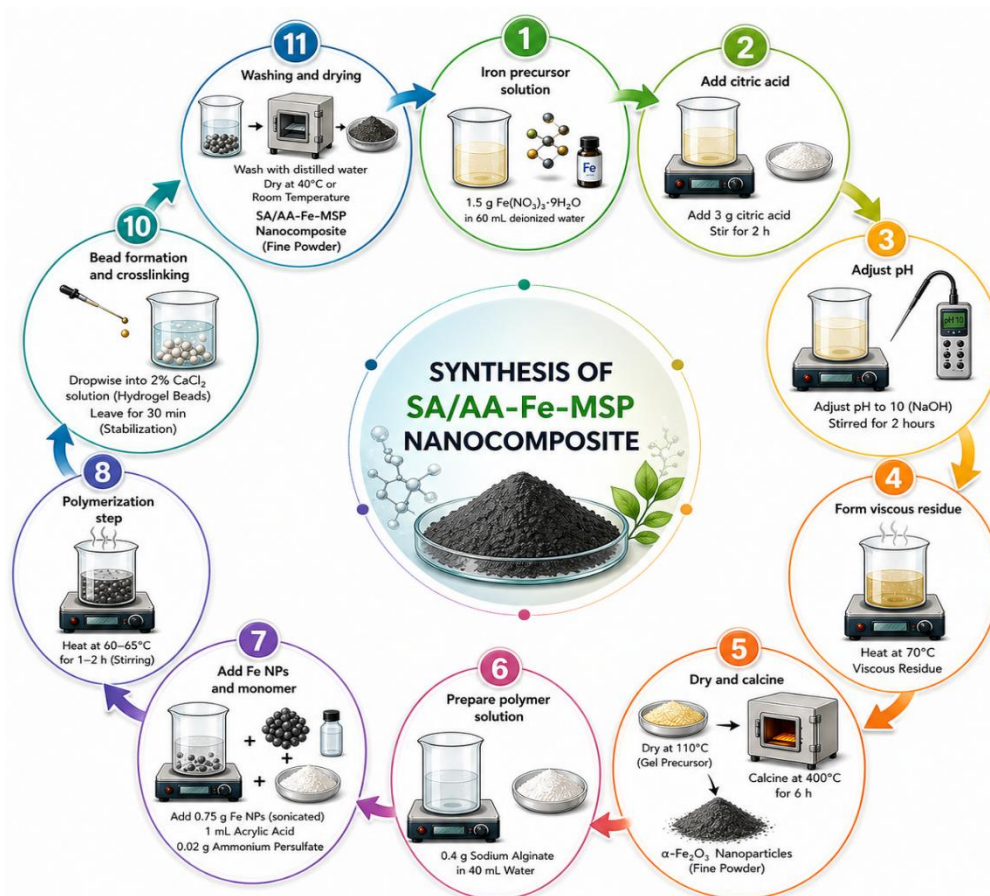


Figure 1- schematic illustration of the synthesis of SA/AA-Fe-MSP nanocomposite

Characterization of SA/AA-Fe-MSP nanocomposite

A structural and morphological investigation was performed following the synthesis of the SA/AA-Fe-MSP nanocomposite. The surface functional groups were identified by FTIR analysis in the 400–4000 cm^{-1} range using TENSOR 27. Nevertheless, their morphology was examined using a SEM (HITACHI S-3400N) attached to an energy dispersive X-ray analyzer

(EDX). The SEM images were produced using a high-performance scanning electron microscope with a high resolution of 20 μ m. The crystalline characteristics of the nanocomposite were then recorded using an X-ray diffractometer (XRD).

Preliminary Analysis for potassium removal

A preliminary batch adsorption study was carried out to evaluate the potassium ion removal efficiency of the synthesized adsorbent prior to optimization through Response Surface Methodology (RSM). For this purpose, a 1000 ppm stock solution of potassium was prepared and subsequently diluted to obtain a working solution of 10 ppm concentration. Thereafter, 50 mL of the prepared potassium solution was transferred into a conical flask, followed by the addition of 0.1 g of the synthesized adsorbent.

The adsorption experiment was performed under batch conditions using an orbital shaker for 4 h to ensure proper interaction between potassium ions and the adsorbent surface. In addition, comparative batch experiments were carried out using different combinations including composite with potassium solution, alum with potassium solution, and alum-composite with potassium solution in order to evaluate their adsorption performance. These comparative tests were conducted to investigate the effect of alum and composite on potassium ion removal efficiency, as improved removal was observed through the combined alum-composite system, as presented in fig-2. Alum was used as a natural coagulant to enhance the removal efficiency by promoting coagulation and facilitating the interaction between potassium ions and the adsorbent surface.

After completion of the shaking process, the suspension was filtered to separate the adsorbent particles from the treated solution. The residual potassium ion concentration present in the filtrate was then determined using a flame photometer.

The obtained results demonstrated that the synthesized adsorbent exhibited promising adsorption performance and achieved approximately 75% potassium ion removal under preliminary experimental conditions. The considerable reduction in potassium concentration indicated the presence of effective adsorption sites on the adsorbent surface, which facilitated the uptake of potassium ions from aqueous solution. The enhanced adsorption behaviour may be attributed to electrostatic interactions and ion-exchange mechanisms occurring between the adsorbent functional groups and potassium ions, along with the coagulation effect provided by alum, which further improved the removal efficiency

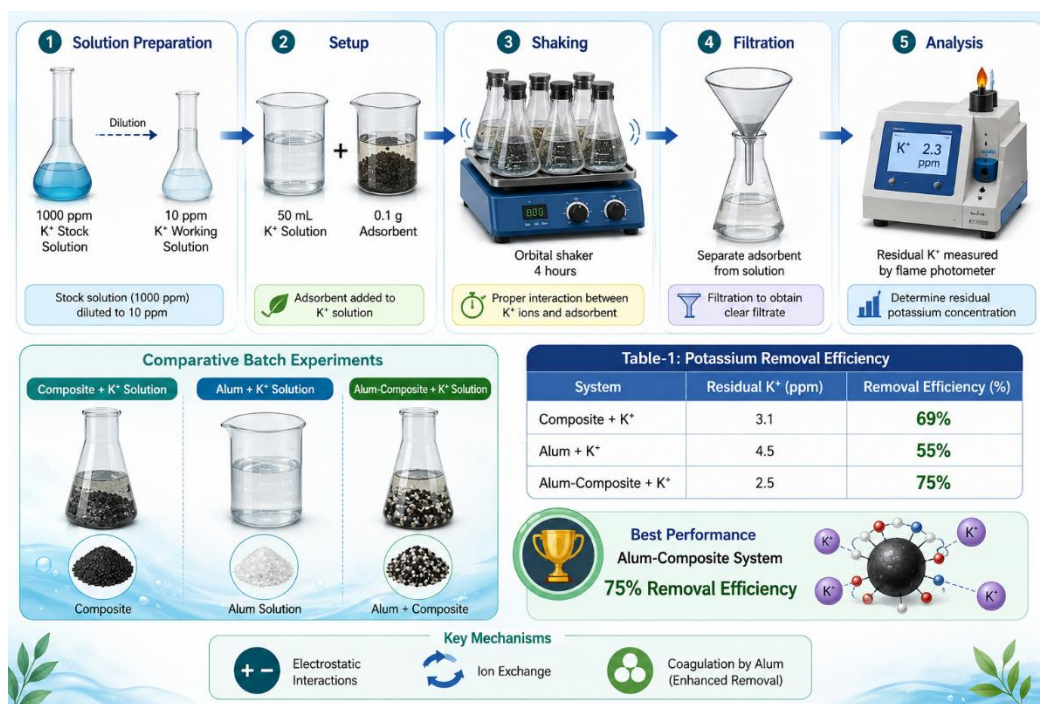


Figure 2-procedure of batch experiment for potassium removal

Preliminary Analysis for Azure B removal

Determination of Azure B Concentration

Azure B dye concentration was determined by constructing a calibration curve using known concentrations of Azure B standard solutions. According to the standard analytical procedure for determining Azure B dye in wastewater samples, the maximum absorbance wavelength (λ_{max}) of Azure B was measured at 647 nm. The absorbance of all samples was recorded using a UV–Visible spectrophotometer (SPECORD 200, Analytic Jena), following the same analytical procedure used previously for phenol analysis.

Adsorption Test

The adsorption experiments for Azure B dye were performed following the same experimental procedure and operating conditions as described previously for phenol removal. Similarly, batch adsorption experiments involving different treatment combinations (Composite + Azure B, Alum + Azure B, and Alum + Composite + Azure B) were carried out using the same experimental protocol applied in the phenol removal study. These comparative experiments were conducted to evaluate the individual and combined effects of alum and composite materials on Azure B dye removal efficiency. The results demonstrated that the combined system exhibited enhanced dye removal performance due to the synergistic effect of coagulation and adsorption, as presented in Table-1.

Preparation of Azure B Calibration Standards (0.1–5 ppm)

A series of Azure B standard solutions were prepared from a 10ppm stock solution to construct the calibration curve. Different concentrations ranging from 0.1 to 5 ppm were obtained through appropriate dilution of the stock solution. The calibration curve for Azure B dye was constructed using standard solutions (0.1–5 ppm) prepared from a 10ppm stock solution (Fig. 3) and analyzed at 647 nm by UV–Vis spectrophotometry.

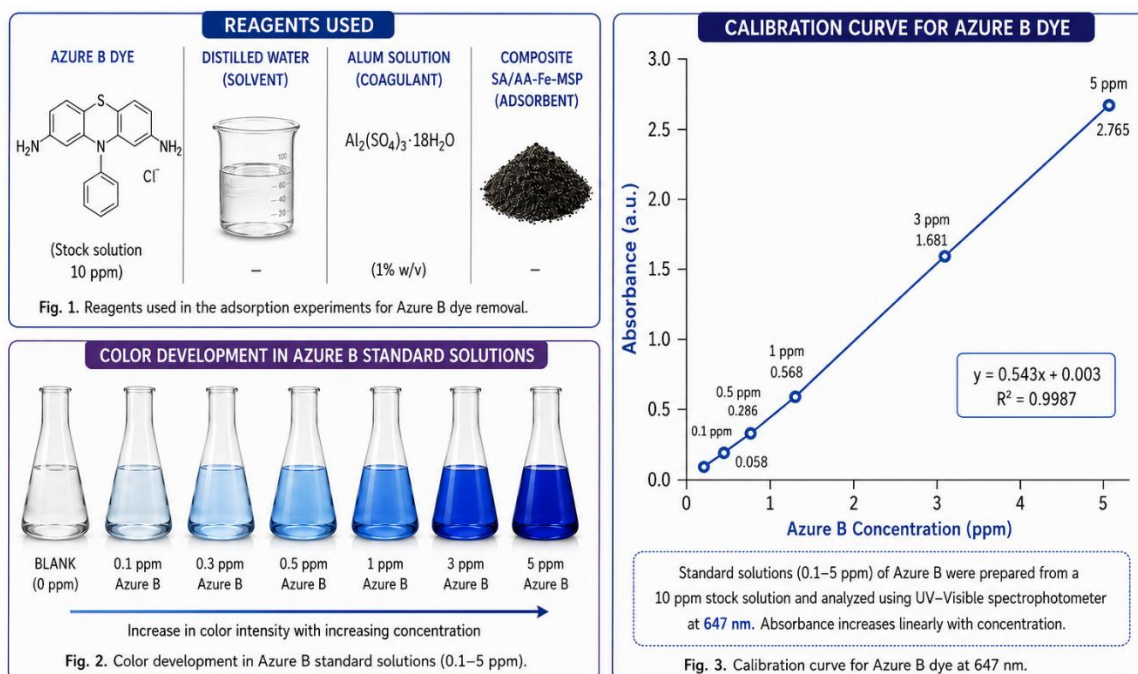


Figure 3-Calibration curve for Azure B showing linear relationship between absorbance and concentration

Table 1- Removal percentage of dye by different treatment conditions

Treatment Condition	Removal Percentage of Dye (%)
Alum + dye solution	60
SA/AA-Fe-MSP + dye solution	85
Alum + SA/AA-Fe-MSP + dye solution	92

Results and Discussion

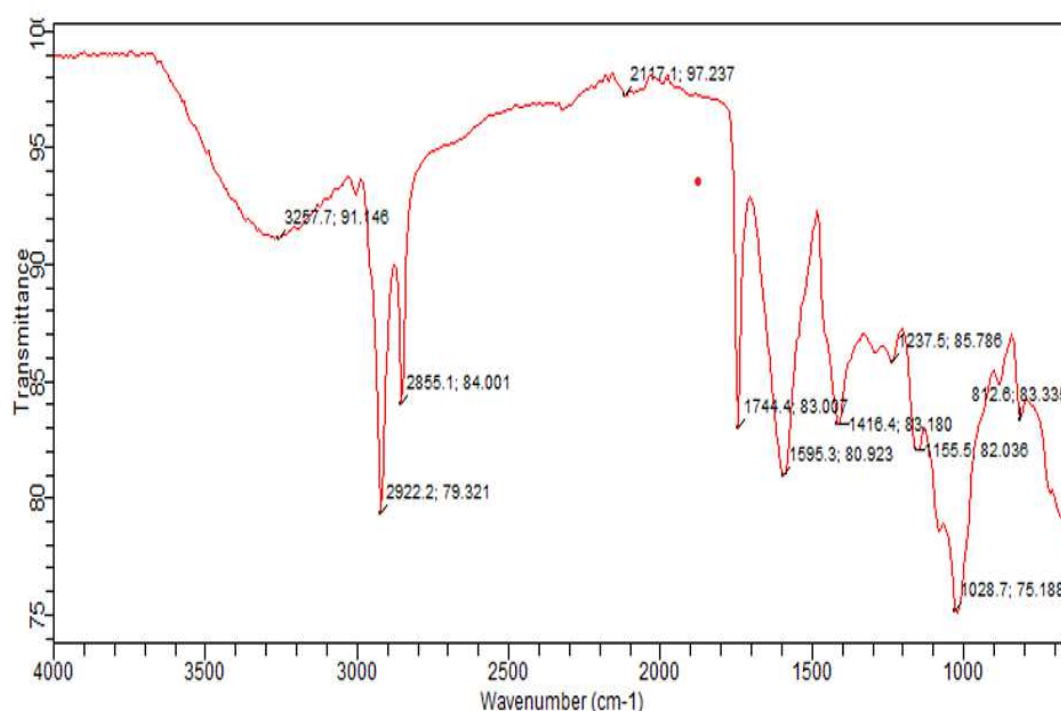
Characterization of SA/AA-Fe-MSP

FTIR of SA/AA-Fe-MSP

The FTIR spectrum of the synthesized SA/AA–Fe–MSP nanocomposite confirms the successful incorporation of all components into a unified structure. A broad peak at 3200–3500 cm^{-1} corresponds to O–H and N–H stretching vibrations, indicating hydrogen bonding from alginate and Moringa seed constituents [15]. The peak at 2920 cm^{-1} is assigned to C–H

stretching of aliphatic chains from acrylic acid. A strong band at 1600–1650 cm^{-1} represents C=O stretching of carboxylate groups, while the peak at 1400–1450 cm^{-1} corresponds to symmetric COO^- stretching, confirming polymerization and crosslinking with Ca^{2+} ions. The band at 1000–1100 cm^{-1} is attributed to C-O-C and C-O vibrations of the polysaccharide backbone [16]. Importantly, the peak at 550–650 cm^{-1} is assigned to Fe-O stretching, verifying the presence of $\alpha\text{-Fe}_2\text{O}_3$ nanoparticles [17]. Overall, the observed peaks and slight shifts indicate strong interactions among polymer matrix, iron nanoparticles, and Moringa seed powder, confirming the formation of a stable nanocomposite as shown in Fig-4.

Figure 3- FTIR analysis of SA/AA-Fe-MSP



XRD of SA/AA-Fe-MSP

The X-ray diffraction analysis of the synthesized SA/AA-Fe-MSP nanocomposite confirmed the successful incorporation of iron nanoparticles within the polymeric matrix. A broad diffraction region observed between $2\theta = 20\text{--}30^\circ$ indicated the semi-amorphous nature of sodium alginate and acrylic acid-based polymer networks [18] (fig-5). The reduction in crystallinity was mainly attributed to the interaction of biopolymeric constituents of Moringa leaf material with the Fe nanoparticles. Furthermore, characteristic diffraction peaks appearing at approximately 29° , 31° , 34° , 38° , 45° , 65° , and 78° suggested the presence of crystalline $\alpha\text{-Fe}_2\text{O}_3$ phases within the composite structure [19]. The nanoscale nature and good dispersion of Fe-NPs throughout the hydrogel matrix were shown by the sharp but low-intensity peaks. Furthermore, the lack of further impurity peaks demonstrated the nanocomposite's purity and

effective production. Overall, the XRD pattern confirmed the development of a stable semi-crystalline SA/AA-Fe-MSP nanocomposite with crystalline iron oxide domains and amorphous polymeric properties.

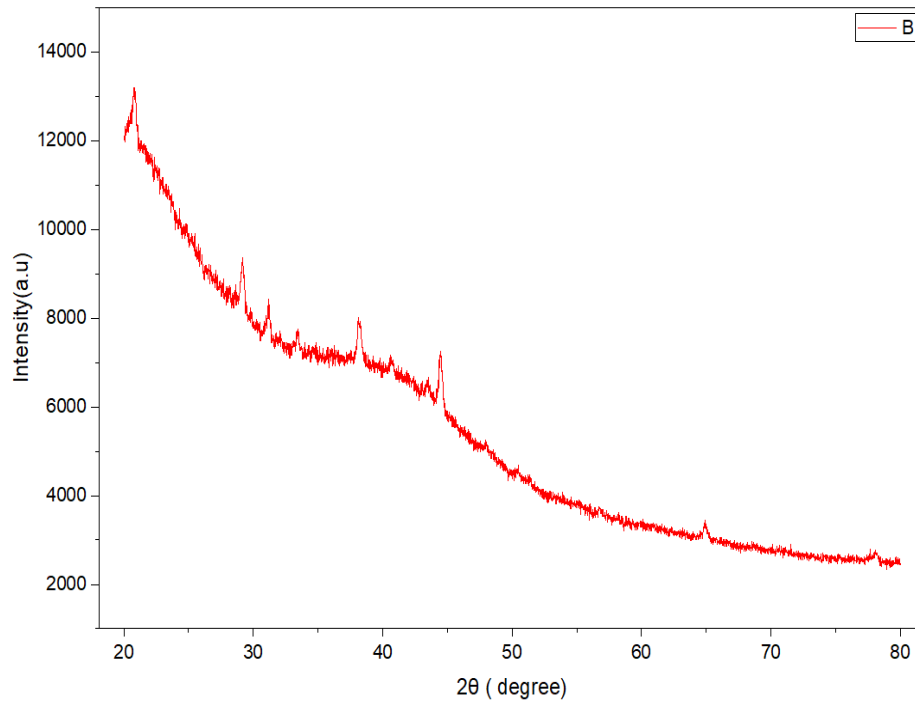


Figure 4- XRD analysis of SA/AA-Fe-MSP

SEM of SA/AA-Fe-MSP

The SEM micrograph of the synthesized SA/AA-Fe-MSP nanocomposite demonstrated the successful formation of a compact and heterogeneous surface morphology with well-integrated structural features as shown in fig-6. The image revealed the uniform incorporation of iron nanoparticles and Moringa seed powder within the sodium alginate/acrylic acid polymeric matrix, indicating effective interaction among all composite constituents [20]. The surface appeared rough and porous with irregularly distributed particles, which is favourable for adsorption applications due to the availability of abundant active binding sites. Moreover, the presence of interconnected structures and stable surface texture suggested successful crosslinking and polymer network formation after CaCl_2 treatment. The morphology also indicated that the polymer matrix effectively stabilized the embedded nanoparticles, preventing excessive particle accumulation and promoting good dispersion throughout the composite. Overall, the SEM analysis confirmed the successful fabrication of a stable hybrid bio-nanocomposite with suitable surface characteristics for efficient wastewater treatment and contaminant removal applications [20].

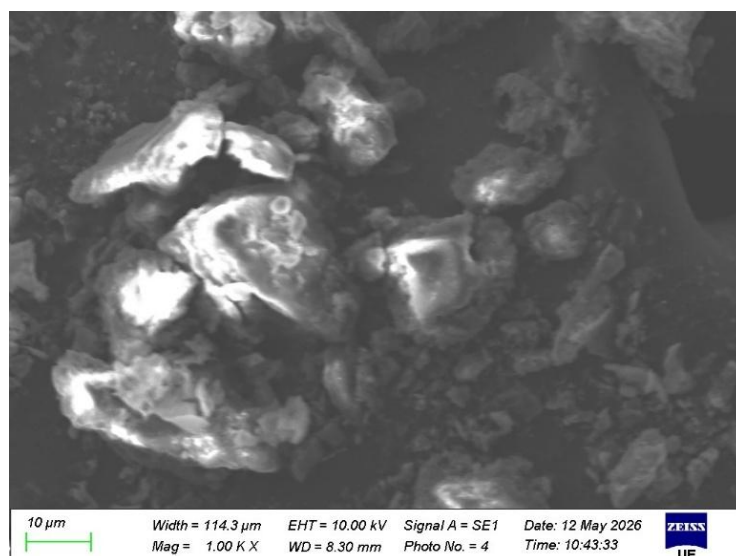


Figure 5- SEM analysis of SA/AA-Fe-MSP

EDX of SA/AA-Fe-MSP

The EDX analysis of the synthesized SA/AA-Fe-MSP nanocomposite confirmed the successful formation of the hybrid composite through the presence of major constituent elements as shown in fig-7 (table-2). Strong peaks of carbon (52.2 wt.%) and oxygen (42.6 wt.%) verified the existence of the sodium alginate/acrylic acid polymeric matrix and oxygen-containing functional groups. The presence of calcium (2.6 wt.%) indicated successful CaCl_2 crosslinking during hydrogel formation [21]. Minor peaks of silicon, sulfur, chlorine, aluminum, copper, and zinc further confirmed the incorporation of inorganic components within the composite structure. Moreover, the elemental distribution and absence of significant impurities suggested the successful fabrication of a stable organic inorganic nanocomposite suitable for wastewater treatment applications [22].

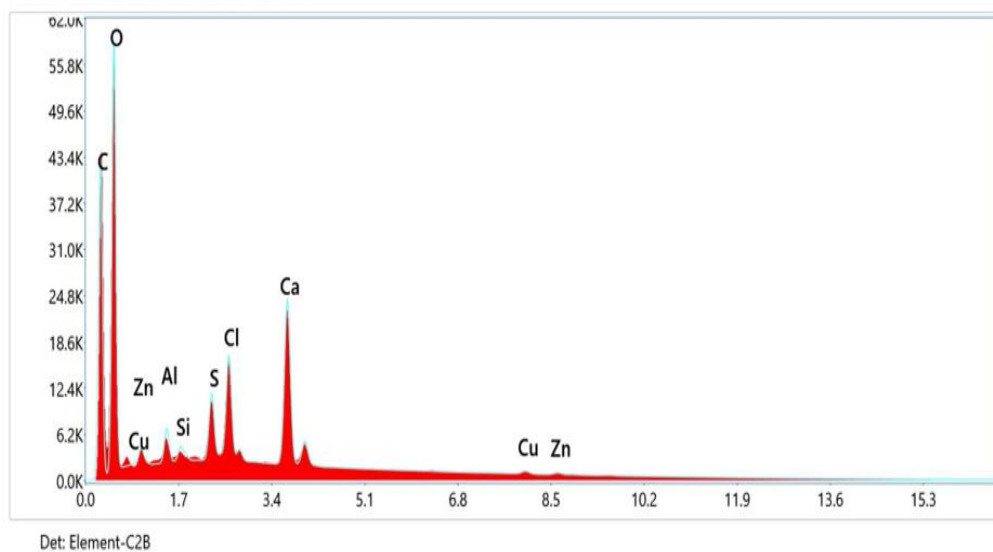


Figure 6- EDX analysis of SA/AA-Fe-MSP

Table 2-Elemental proportion obtained by EDX spectra of SA/AA-Fe-MSP

Element	Weight %	Atomic %
C	52.2	60.8
O	42.6	37.3
Al	0.4	0.2
Si	0.1	0.1
S	0.6	0.3
Cl	1.1	0.5
Ca	2.6	0.9
Cu	0.1	0.0
Zn	0.1	0.0
Total	100	

Response 1 (Removal percentage of Potassium)

ANOVA and modal fitting for potassium removal

Selecting the best-fitting model is essential before figuring out the ideal circumstances since it ensures the correctness of both experimental and anticipated data. ANOVA is a statistical method for determining which experimental conditions significantly affect response and which variables have little to no impact [23] as shown in table-5. Based on the results of the experiment, a model summary statistics (MSS) test was performed on the removals described in table-3.

The model summary statistics (MSS) analysis (table-4) indicated that the quadratic model was the most suitable model for potassium ion removal. The quadratic term exhibited an F-value of

8.48 with a p-value of 0.0007, demonstrating a significant improvement over the lower-order models. In contrast, the cubic model showed an F-value of 3.62 and p-value of 0.0437; however, it was aliased and therefore could not be accurately estimated. Consequently, the quadratic model was selected for further optimization and statistical analysis using Response Surface Methodology (RSM).

The ANOVA results presented in table-5 revealed that the developed quadratic model was statistically significant with an F-value of 4.58 and a p-value of 0.0024. Among the investigated parameters, pH (A) significantly affected potassium removal with an F-value of 9.32 and p-value of 0.0076, while the interaction between pH and shaking time (AD) also showed a significant influence ($F = 8.82$, $p = 0.0090$). Furthermore, the quadratic term of shaking time (D^2) was highly significant with an F-value of 29.98 and p-value < 0.0001 , indicating the strong contribution of shaking time toward the adsorption process. The model exhibited an R^2 value of 0.8003, suggesting good agreement between experimental and predicted data. Additionally, the adequate precision value of 7.2819, which was greater than 4, confirmed an adequate signal and demonstrated that the model could effectively navigate the design space for potassium ion removal.

Table 3-RSM table for SA/AA-Fe-MSP

Run	Factor A:Ph --	Factor B:Alum ml	Factor C:Dose g	Factor D:Shaking time min	Response 1 Removal of K^+	Response 2 Removal of Colour(%)
1	4	8	0.03	120	68.34	58.54
2	9	3	0.03	30	76.91	66.22
3	9	8	0.03	120	75.09	77.56
4	6.5	5.5	0.435	75	82.45	80.98
5	6.5	5.5	0.165	165	46.78	37.65
6	9	3	0.3	30	42.81	70.65
7	6.5	5.5	-0.105	75	76.12	76.54
8	6.5	5.5	0.165	75	81.65	70.86
9	9	8	0.03	30	23.98	28.44
10	4	3	0.03	30	75.09	72.89
11	1.5	5.5	0.165	75	35.98	38.76
12	6.5	5.5	0.165	75	80.78	75.74
13	9	3	0.03	120	76.58	98.66
14	4	8	0.3	30	57.87	58.13
15	6.5	10.5	0.165	75	78.01	79.54
16	6.5	5.5	0.165	-15	18.76	20.64
17	9	8	0.3	30	80.01	69.45
18	4	3	0.03	120	46.65	53.74
19	9	3	0.3	120	79.78	78.54
20	4	8	0.03	30	50.67	49.54
21	4	3	0.3	120	23.91	24.45
22	6.5	5.5	0.165	75	85.02	79.66

23	6.5	5.5	0.165	75	82.98	72.65
24	4	8	0.3	120	45.78	32.54
25	9	8	0.3	120	71.55	80.66
26	6.5	5.5	0.165	75	78.08	75.45
27	6.5	5.5	0.165	75	81.09	71.56
28	4	3	0.3	30	70.61	62.34
29	6.5	5.5	0.165	75	83.67	78.45
30	6.5	0.5	0.165	75	85.19	82.64
31	11.5	5.5	0.165	75	85.79	88.75

Quadratic model was suggested when removal percentage of potassium response was analyzed as shown in table-3.

Table 4- MSS test which predicts Quadratic vs FI as suggested and Cubic vs Quadratic as aliased for potassium removal

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Mean vs Total	1.353E+05	1	1.353E+05			
Linear vs Mean	1693.08	4	423.27	1.01	0.4198	
2FI vs Linear	3051.49	6	508.58	1.30	0.3028	
Quadratic vs 2FI	5322.02	4	1330.50	8.48	0.0007	Suggested
Cubic vs Quadratic	1967.72	8	245.96	3.62	0.0437	Aliased
Residual	543.59	8	67.95			
Total	1.479E+05	31	4770.17			

Table 5- Analysis of variance for potassium removal

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	10066.59	14	719.04	4.58	0.0024	significant
A-Ph	1463.44	1	1463.44	9.32	0.0076	
B-Alum	46.51	1	46.51	0.2963	0.5937	
C-Dose	2.89	1	2.89	0.0184	0.8937	
D-Shaking Time	180.24	1	180.24	1.15	0.2998	
AB	63.40	1	63.40	0.4039	0.5340	
AC	257.36	1	257.36	1.64	0.2186	
AD	1384.77	1	1384.77	8.82	0.0090	

BC	567.04	1	567.04	3.61	0.0755	
BD	470.13	1	470.13	3.00	0.1027	
CD	308.79	1	308.79	1.97	0.1798	
A ²	961.92	1	961.92	6.13	0.0249	
B ²	11.03	1	11.03	0.0703	0.7943	
C ²	41.17	1	41.17	0.2623	0.6155	
D ²	4706.10	1	4706.10	29.98	< 0.0001	
Residual	2511.31	16	156.96			
Lack of Fit	2480.71	10	248.07	48.64	< 0.0001	significant
Pure Error	30.60	6	5.10			
Cor Total	12577.89	30				

As shown in table-5, the value of F in the model is 4.58 which implies that the model is significant.

Fit Statistics

Table 6- Fit Statistics of suggested model

Std. Dev.	12.53	R²	0.8003
Mean	66.06	Adjusted R²	0.6256
C.V. %	18.96	Predicted R²	-0.1393
		Adeq Precision	7.2819

As shown in table-6, the predicted and adjusted R² were in reasonable agreement. Adequate precision having value 7.2819 means that it was greater than 4 so it was desirable.

Final equations in term of coded factors

Potassium removal = +81.90+7.81*A-1.39*B-0.3471*C+2.74*D-1.99*AB+4.01*AC+9.30*AD+5.95*BC+5.42*BD-4.39*CD-5.80*A²-0.6211*B²-1.20*C²-12.83*D²

Where A, B, C, D are Ph, Alum, composite dose and shaking time respectively.

Predicted and actual values report

A plot comparing predicted and actual values is shown in fig-8.

Actual values are those values obtained after performing experiment while predicted values are those suggested by the model.

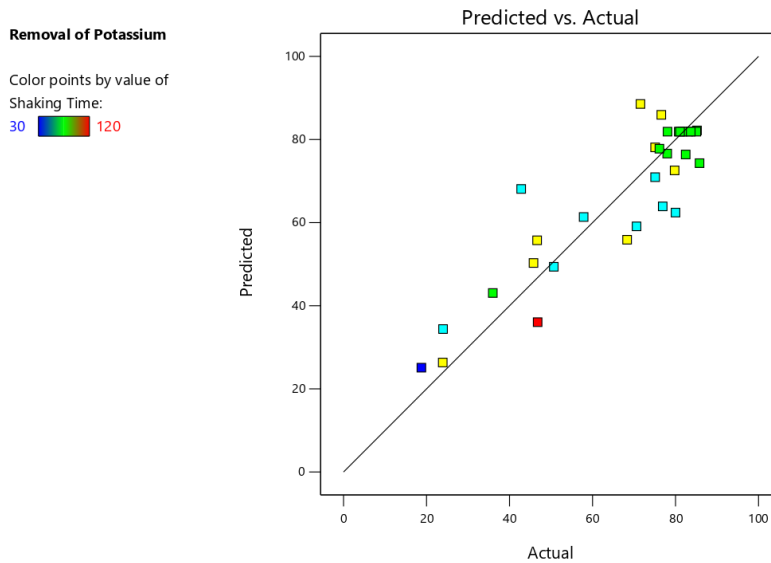


Figure 7- Predicted vs Actual plot of Potassium removal %

Model graphs for removal of Potassium using SA/AA-Fe-MSP

3D response surface and contour plots help identify the ideal circumstances for maximum potassium removal and show the combined impact of process variables. In figure-9(a,b), the interactive effect of pH (A) and alum dose (B) on the response is illustrated through the 3D surface and contour plots. The 3D surface plot shows a gradual increase in removal efficiency with increasing pH and alum dose, reaching a distinct optimum region at intermediate levels, followed by a slight decline at higher values, indicating possible overdosing or destabilization effects. The surface exhibits a pronounced peak, confirming the presence of optimal conditions. The contour plot further supports this trend, displaying a clear color transition from blue (low response) to green and yellow, and finally red (maximum response). The red zone is concentrated in the mid-region of both variables, while blue regions dominate at lower levels. In figure-9(c,d), the combined influence of pH (A) and composite dose (C) is presented. The 3D surface plot demonstrates that the response increases significantly with increasing composite dose, particularly at an optimal pH range, forming a well-defined elevated region. At extreme pH values, the surface slightly declines, indicating reduced efficiency. The curvature of the surface confirms the presence of interaction between the variables. The contour plot shows a progressive color gradient from blue to green and then to bright yellow/red, indicating enhanced removal efficiency. The red region appears at higher composite dose and moderate pH, while lower regions remain blue or green. The elliptical nature of contour lines confirms a strong interaction, suggesting that both pH and adsorbent dosage play a critical role in optimizing adsorption.

The interaction between pH (A) and shaking time (D) is evaluated in fig-9 (e,f). The 3D surface plot indicates that increasing shaking time enhances removal efficiency up to an optimum

duration, beyond which the surface becomes relatively flat, indicating equilibrium conditions. The effect of pH is also evident, with maximum response occurring at favourable pH values. The surface shows a moderate curvature, reflecting interaction between variables. The contour plot exhibits a color transition from blue at lower shaking time and non-optimal pH to green and yellow, with light red zones at optimal conditions. The absence of a highly intense red region suggests a moderate maximum response. In fig-9 (g,h), the combined effect of alum dose (B) and composite dose (C) is illustrated. The 3D surface plot reveals a significant increase in response with increasing levels of both parameters, forming a sharp and well-defined peak region. At higher concentrations, the surface tends to plateau, indicating saturation of the system. The strong curvature suggests a pronounced interaction between variables. The contour plot displays a distinct color gradient from blue (low efficiency) to intense red (maximum efficiency), particularly when both variables are at higher levels. The red region is clearly defined, while lower levels show green and blue shades.

In fig-9 (i,j), the interaction between alum dose (B) and shaking time (D) is presented. The 3D surface plot shows that increasing alum dose improves removal efficiency, especially when combined with sufficient shaking time, after which the surface becomes relatively constant, indicating equilibrium. The surface exhibits mild curvature, suggesting a moderate interaction. The contour plot illustrates a gradual color transition from blue at lower levels to green and yellow at moderate conditions, with limited light red regions at optimal values. The absence of a strong red zone indicates comparatively lower maximum efficiency. The slightly elongated contours suggest a moderate level of interaction between these two parameters.

In fig-9 (k,l), the effect of composite dose (C) and shaking time (D) is demonstrated. The 3D surface plot shows a steep increase in response with increasing composite dose and shaking time, forming a prominent peak region before reaching a plateau due to saturation of adsorption sites. The strong curvature indicates significant interaction between the variables. The contour plot displays a clear progression from blue to green, and then to intense red, especially at higher composite dose and adequate shaking time. The red region is well-developed, indicating maximum efficiency, while lower regions remain blue.

Factor Coding: Actual

Removal of Potassium (%)

Design Points:

- Above Surface
- Below Surface
- 18.76  85.79

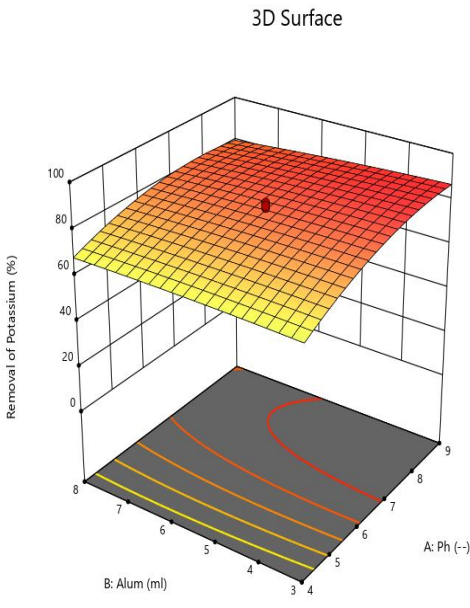
X1 = A

X2 = B

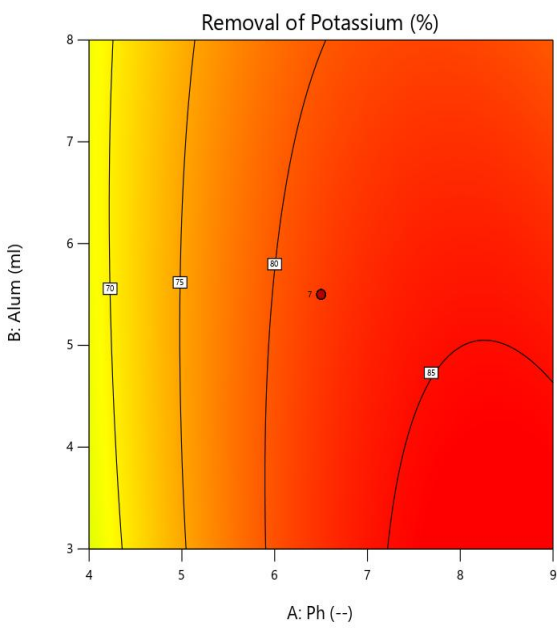
Actual Factors

C = 0.165

D = 75



(a)



(b)

Factor Coding: Actual

Removal of Potassium (%)

Design Points:

- Above Surface
- Below Surface
- 18.76  85.79

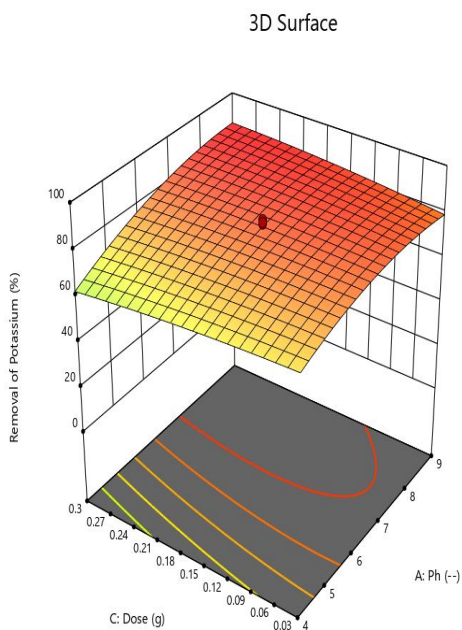
X1 = A

X2 = C

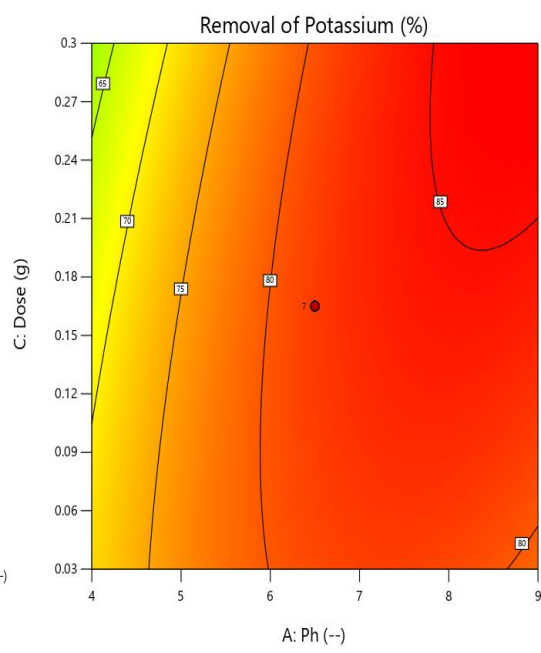
Actual Factors

B = 5.5

D = 75



(c)



(d)

Factor Coding: Actual

Removal of Potassium (%)

Design Points:

● Above Surface

○ Below Surface

18.76 85.79

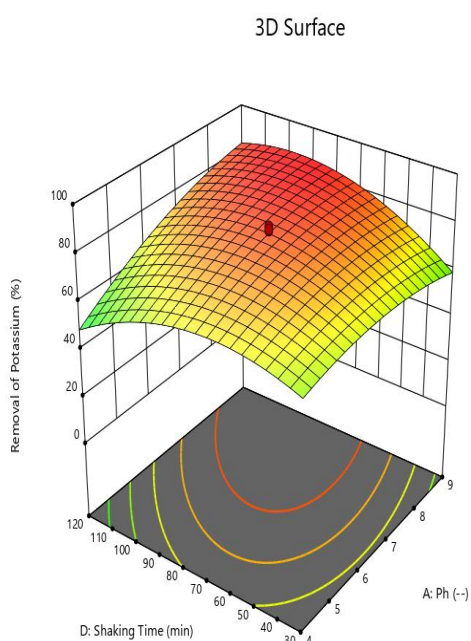
X1 = A

X2 = D

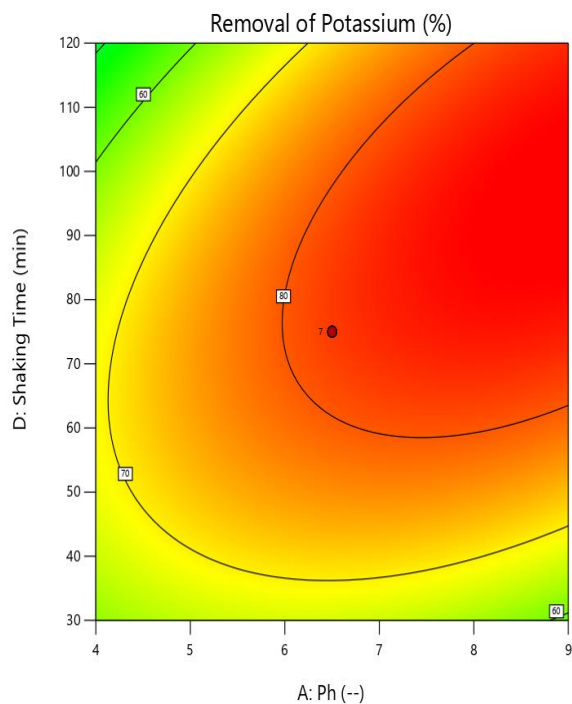
Actual Factors

B = 5.5

C = 0.165



(e)



(f)

Factor Coding: Actual

Removal of Potassium (%)

Design Points:

● Above Surface

○ Below Surface

18.76 85.79

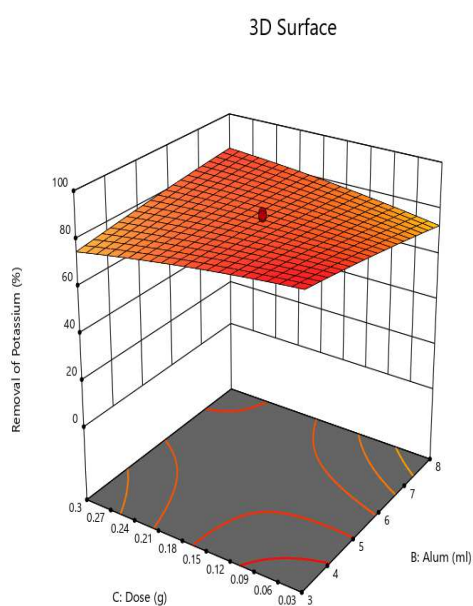
X1 = B

X2 = C

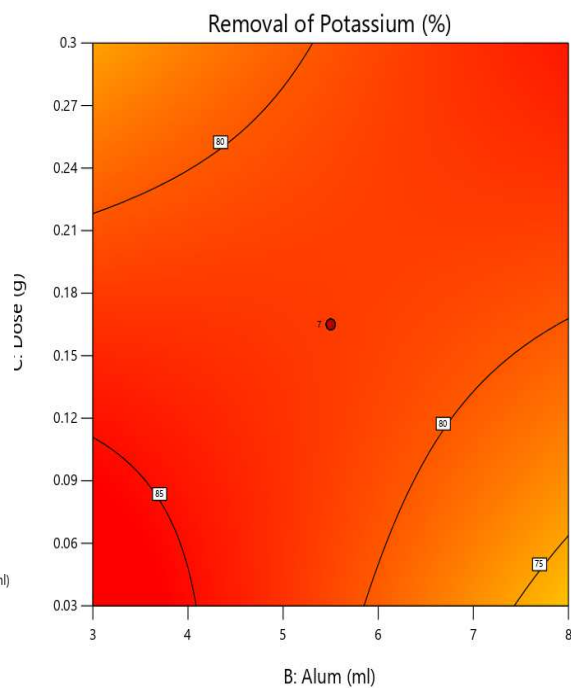
Actual Factors

A = 6.5

D = 75



(g)



(h)

Factor Coding: Actual

Removal of Potassium (%)

Design Points:

● Above Surface
○ Below Surface
18.76 85.79

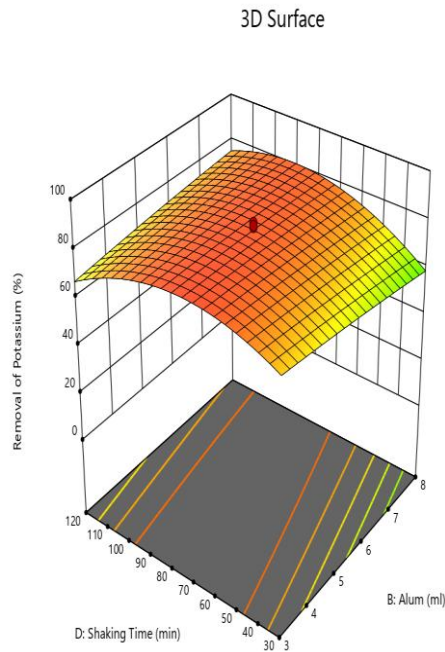
X1 = B

X2 = D

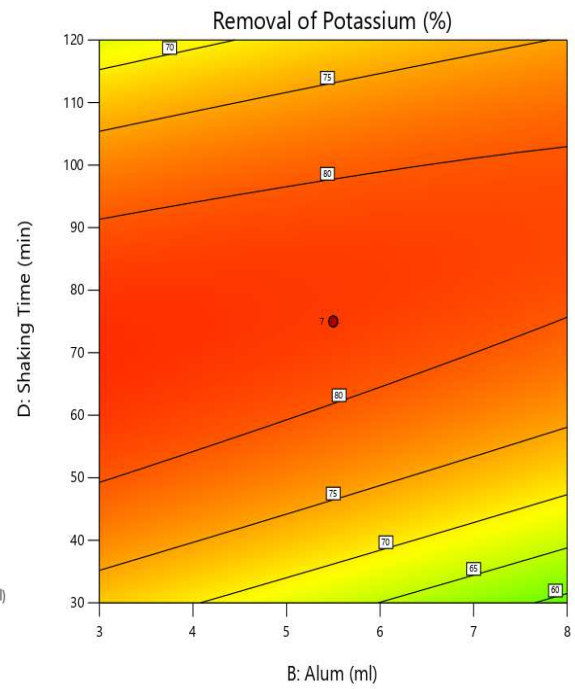
Actual Factors

A = 6.5

C = 0.165



(i)



(j)

Factor Coding: Actual

Removal of Potassium (%)

Design Points:

● Above Surface
○ Below Surface
18.76 85.79

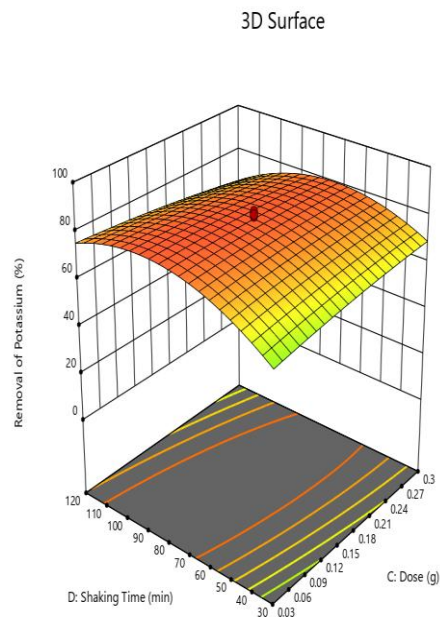
X1 = C

X2 = D

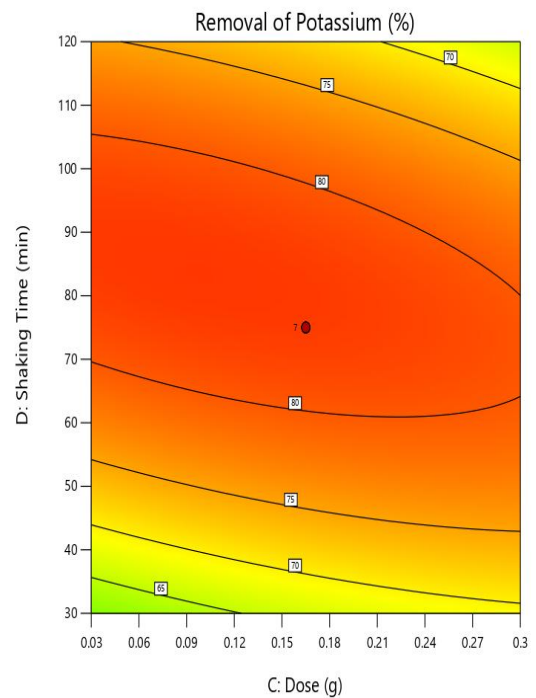
Actual Factors

A = 6.5

B = 5.5



(k)



(l)

Figure 8-3D and Contour plots showing interactive influence of (a, b) pH and Alum (c, d) pH and dose (e, f) pH and shaking time (g, h) alum and dose (i, j) alum and shaking time (k, l) dose and shaking time for potassium Removal

Response 2(Removal percentage of Azure B)

ANOVA and modal fitting for Azure B removal

The MSS results (table-6) indicate that the quadratic model is most suitable for describing Azure B dye removal efficiency. The Quadratic vs 2FI term is highly significant ($F = 38.59$, $p < 0.0001$), confirming that inclusion of quadratic effects significantly improves model performance. The cubic model is aliased ($p = 0.0287$) and therefore excluded, while linear and 2FI comparisons show that increasing model complexity improves fit, with the quadratic model providing the best balance of accuracy and significance. ANOVA results (table-7) further confirm model adequacy. The overall model is highly significant ($F = 29.20$, $p < 0.0001$), indicating strong combined effects of variables on dye removal. Among factors, pH (A) shows the most dominant influence ($F = 98.44$, $p < 0.0001$), followed by alum dose (B), shaking time (D), and several interaction terms (AC, AD, BC, BD, CD). Significant quadratic effects, particularly D^2 ($F = 139.89$, $p < 0.0001$), indicate strong non-linear behaviour. The lack-of-fit is non-significant ($p = 0.0771$), confirming model reliability.

Fit statistics (table-8) show strong model performance with $R^2 = 0.9623$, indicating excellent agreement between predicted and experimental values. The adjusted R^2 (0.9294) and predicted R^2 (0.8083) are in reasonable agreement, confirming model stability. The adequate precision value (20.34) exceeds the threshold of 4, indicating a strong signal-to-noise ratio and good predictive capability. Overall, the empirical model shows strong agreement between actual and predicted responses, confirming its reliability for optimizing Azure B dye removal [23].

Table 6- MSS test which predicts Quadratic vs FI as suggested and Cubic vs Quadratic as aliased for dye removal

Source	Sum of Squares	df	Mean Square	F-value	p-value
Mean vs Total	1.306E+05	1	1.306E+05		
Linear vs Mean	3204.09	4	801.02	2.38	0.0780
2FI vs Linear	3963.35	6	660.56	2.75	0.0407
Quadratic vs 2FI	4348.54	4	1087.14	38.59	< 0.0001 Suggested
Cubic vs Quadratic	364.45	8	45.56	4.22	0.0287 Aliased
Residual	86.30	8	10.79		
Total	1.426E+05	31	4599.37		

Table 7- Analysis of variance for dye removal

Source	Sum of Squares	df	Mean Square	F-value	p-value
--------	----------------	----	-------------	---------	---------

Model	11515.98	14	822.57	29.20	< 0.0001	significant
A-Ph	2773.29	1	2773.29	98.44	< 0.0001	
B-Alum	258.92	1	258.92	9.19	0.0079	
C-Dose	16.58	1	16.58	0.5887	0.4541	
D-Shaking Time	155.30	1	155.30	5.51	0.0321	
AB	117.13	1	117.13	4.16	0.0583	
AC	458.71	1	458.71	16.28	0.0010	
AD	1898.56	1	1898.56	67.39	< 0.0001	
BC	422.61	1	422.61	15.00	0.0013	
BD	228.39	1	228.39	8.11	0.0116	
CD	837.96	1	837.96	29.74	< 0.0001	
A ²	272.54	1	272.54	9.67	0.0067	
B ²	44.44	1	44.44	1.58	0.2272	
C ²	12.61	1	12.61	0.4476	0.5130	
D ²	3941.07	1	3941.07	139.89	< 0.0001	
Residual	450.75	16	28.17			
Lack of Fit	381.94	10	38.19	3.33	0.0771	not significant
Pure Error	68.81	6	11.47			
Cor Total	11966.73	30				

As shown in table-7, the value of F in the model is 29.20 which implies that the model is significant.

Fit Statistics

Table 8- Fit Statistics of suggested model

Std. Dev.	5.31	R²	0.9623
Mean	64.91	Adjusted R²	0.9294
C.V. %	8.18	Predicted R²	0.8083
		Adeq Precision	20.3439

As shown in table-8, the predicted and adjusted R^2 were in reasonable agreement. Adequate precision having value 20.3439 means that it was greater than 4 so it was desirable.

Final equations in term of coded factors

$$\begin{aligned} \text{Azure B removal} = & +74.91 + 10.75*A - 3.28*B - 0.8313*C + 2.54*D - \\ & 2.71*AB + 5.35*AC + 10.89*AD + 5.14*BC - 3.78*BD - 7.24*CD - \\ & 3.09*A^2 + 1.25*B^2 + 0.6641*C^2 - 11.74*D^2 \end{aligned}$$

Where A, B, C, D are Ph, Alum, composite dose and shaking time respectively.

Predicted and actual values report

The predicted and actual values for Azure B removal showed good agreement, confirming the accuracy and reliability of the developed RSM model for evaluating adsorption performance. The comparative relationship between predicted and experimental responses is presented in fig.10, which demonstrates the satisfactory fitting capability of the proposed model.

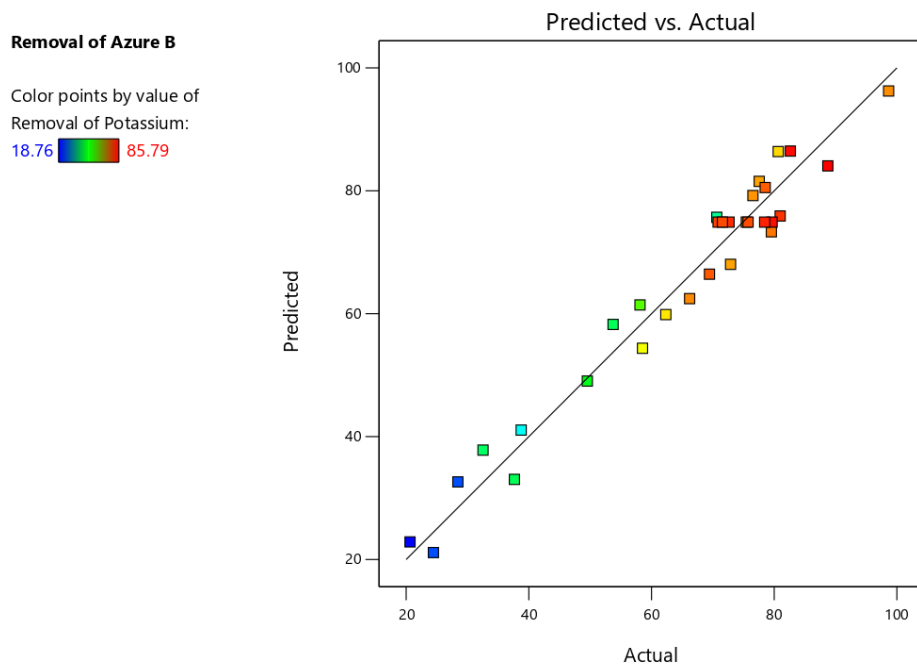


Figure 9- Predicted vs Actual plot of dye removal %

3D and Contour plot analysis for Azure B removal

The 3D response surface and contour plots were used to evaluate the interactive effects of different process variables on the removal efficiency of Azure B dye. These graphical representations helped in understanding the influence of operating parameters as well as their combined interactions on the adsorption performance of the synthesized adsorbent.

Figure-11(a,b) shows the combined effect of pH (A) and alum concentration (B) on Azure B dye removal efficiency while keeping adsorbent dose and shaking time constant. It can be observed from the 3D surface and contour plots that dye removal efficiency increased significantly with increasing pH, whereas alum concentration showed a comparatively smaller effect. The contour plot displayed a gradual color transition from green to yellow regions, indicating enhanced dye removal at higher pH and moderate alum dosage. The elliptical contour pattern further suggested a significant interaction between both variables, confirming that alkaline conditions favoured the adsorption process.

Fig-11(c,d) illustrates the interaction effect of pH (A) and adsorbent dose (C) on Azure B dye removal efficiency at constant alum concentration and shaking time. The 3D response surface showed that increasing pH and adsorbent dose improved dye removal efficiency due to the availability of more active adsorption sites. Similarly, the contour plot exhibited a color variation from green to orange regions, representing higher dye removal efficiency at elevated pH and moderate adsorbent dosage. The contour lines indicated that both parameters positively contributed to the adsorption process. Figure-11(e,f) represents the combined influence of pH (A) and shaking time (D) on Azure B dye removal while maintaining alum concentration and adsorbent dose constant. It was evident from the response surface that dye removal efficiency increased with increasing pH and longer shaking time. The contour plot showed a gradual shift from green to yellow and orange regions, reflecting improved adsorption efficiency under alkaline conditions and extended contact time. The curved nature of the response surface indicated that both variables had an important role in enhancing dye removal efficiency.

Figure-11(g,h) demonstrates the interaction effect of alum concentration (B) and adsorbent dose (C) on Azure B dye removal efficiency at fixed pH and shaking time. The 3D surface plot revealed a slight increase in dye removal efficiency with increasing adsorbent dose, while alum concentration exhibited a comparatively lower effect within the studied range. The contour plot mainly consisted of green and light yellow regions, indicating moderate changes in removal efficiency. The nearly uniform contour pattern suggested that the interaction between alum concentration and adsorbent dose was less significant. Figure-11(i,j) shows the combined effect of alum concentration (B) and shaking time (D) on Azure B dye removal efficiency while keeping pH and adsorbent dose constant. The response surface indicated that increasing shaking time positively affected dye removal efficiency, whereas alum concentration contributed moderately to the adsorption process. In the contour plot, the gradual color transition from green to yellow regions represented improved dye removal efficiency with increasing contact time. The contour pattern suggested a moderate interaction between the studied parameters.

Figure-11(k,l) illustrates the interaction between adsorbent dose (C) and shaking time (D) on Azure B dye removal efficiency at constant pH and alum concentration. The 3D response surface demonstrated that dye removal efficiency gradually increased with increasing shaking time and moderate adsorbent dose. Likewise, the contour plot exhibited green to yellow-orange regions, indicating enhanced adsorption performance at higher contact times. The smooth curvature of the response surface suggested a positive interaction between adsorbent dose and shaking time, resulting in improved removal of Azure B dye from aqueous solution.

Factor Coding: Actual

Removal of Azure B (%)

Design Points:

● Above Surface

○ Below Surface

20.64 98.66

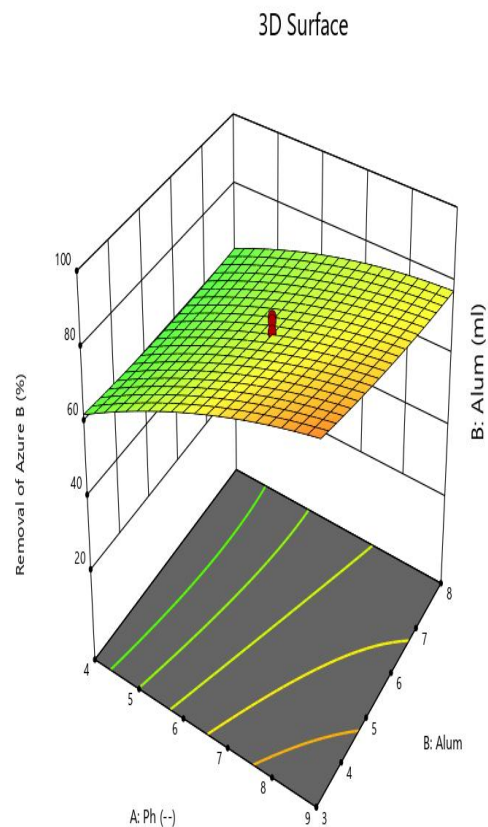
X1 = A

X2 = B

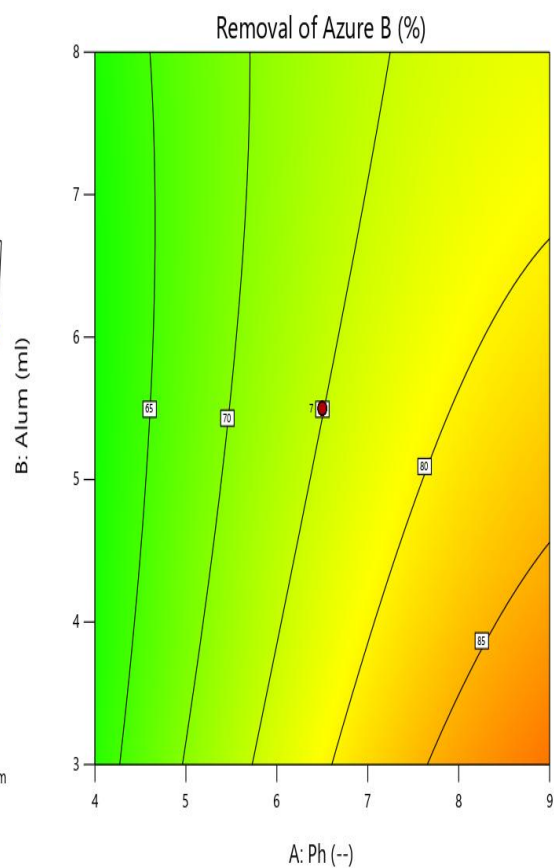
Actual Factors

C = 0.165

D = 75



(a)



(b)

Factor Coding: Actual

Removal of Azure B (%)

Design Points:

● Above Surface

○ Below Surface

20.64 98.66

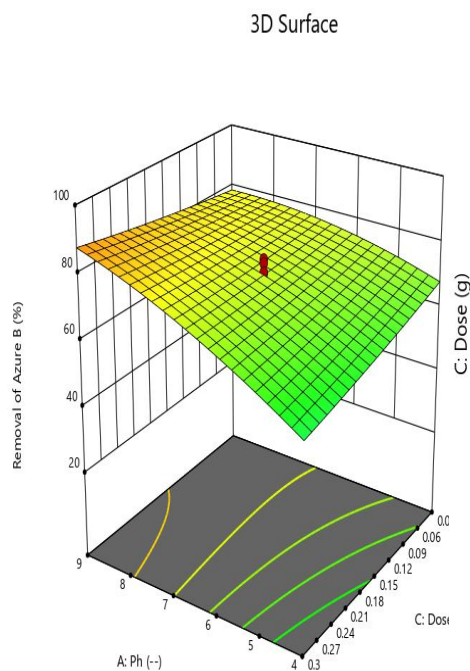
X1 = A

X2 = C

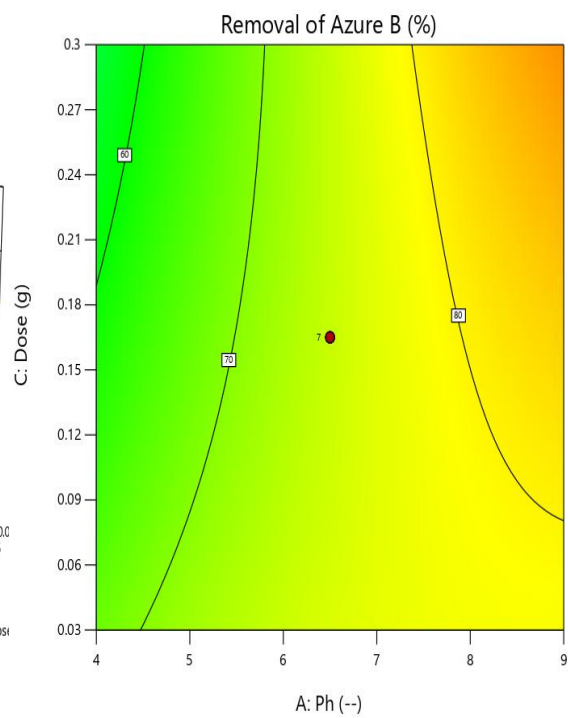
Actual Factors

B = 5.5

D = 75



(c)



(d)

Factor Coding: Actual

Removal of Azure B (%)

Design Points:

● Above Surface

○ Below Surface

20.64 98.66

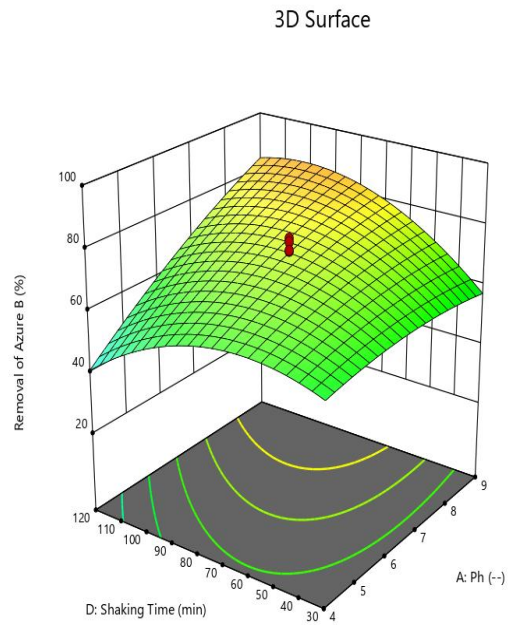
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X2 = D

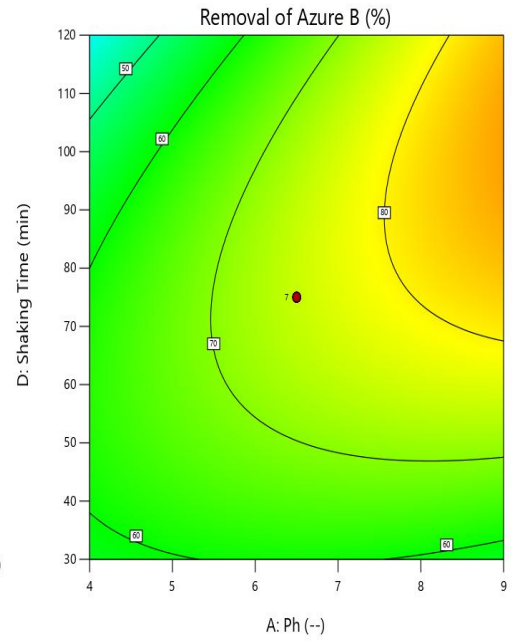
Actual Factors

B = 5.5

C = 0.165



(e)



(f)

Factor Coding: Actual

Removal of Azure B (%)

Design Points:

● Above Surface

○ Below Surface

20.64 98.66

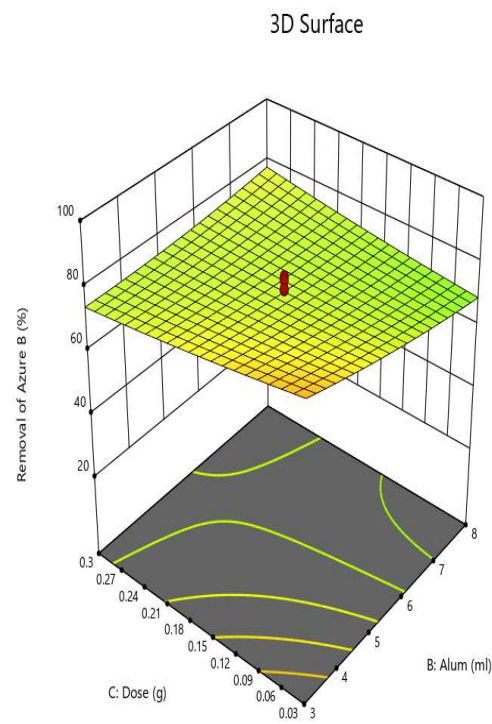
X1 = B

X2 = C

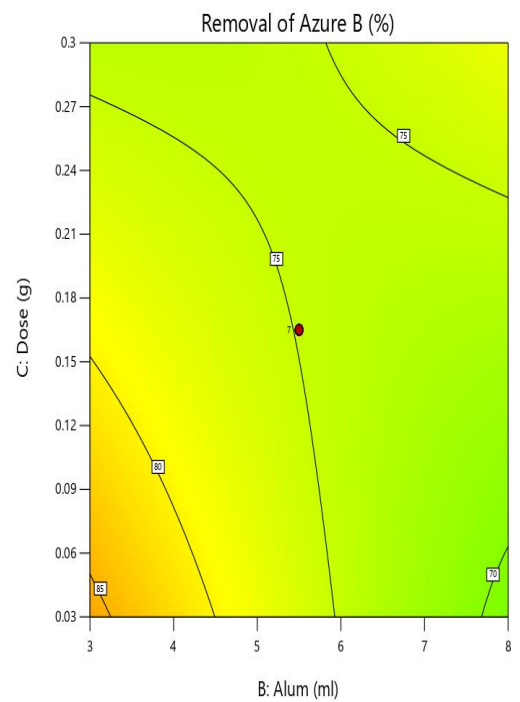
Actual Factors

A = 6.5

D = 75



(g)



(h)

Factor Coding: Actual

Removal of Azure B (%)

Design Points:

● Above Surface

○ Below Surface

20.64 98.66

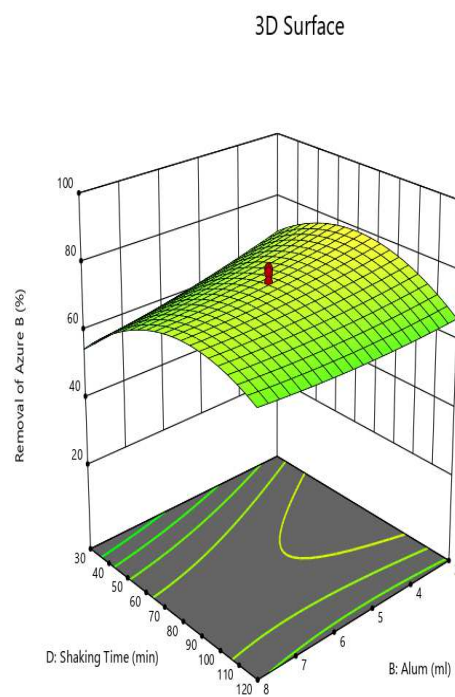
X1 = B

X2 = D

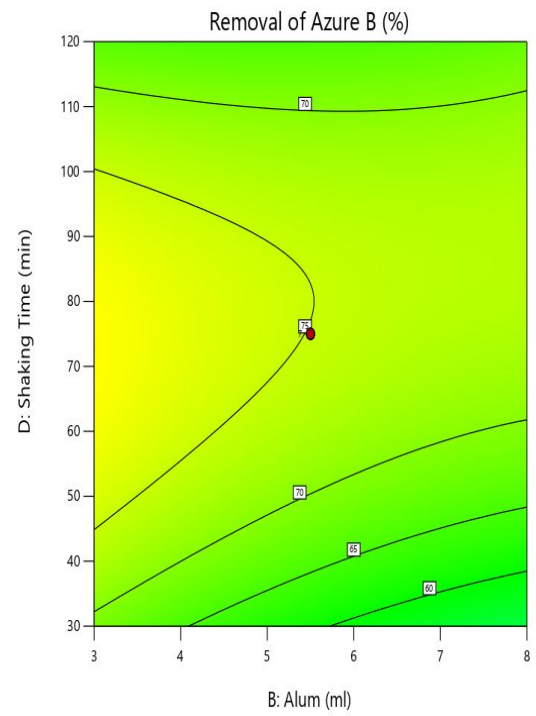
Actual Factors

A = 6.5

C = 0.165



(i)



(j)

Factor Coding: Actual

Removal of Azure B (%)

Design Points:

● Above Surface

○ Below Surface

20.64 98.66

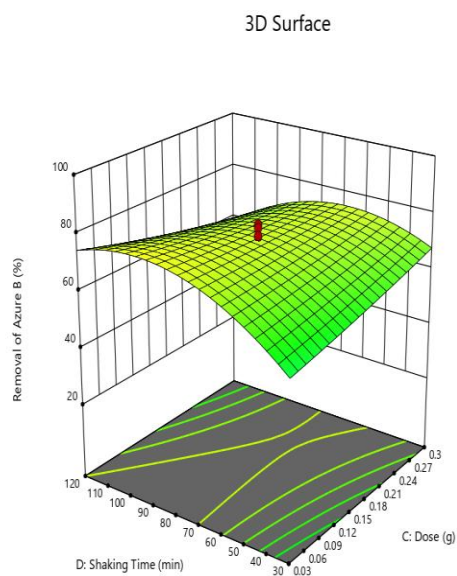
X1 = C

X2 = D

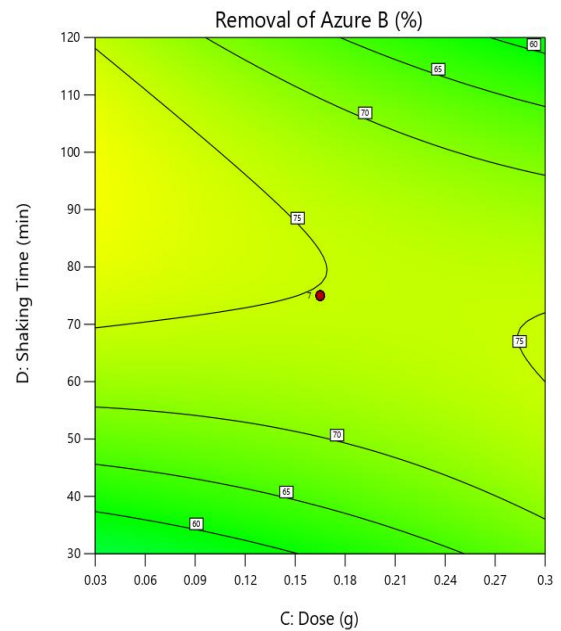
Actual Factors

A = 6.5

B = 5.5



(k)



(l)

Figure 10-3D and Contour plots showing interactive influence of (a, b) pH and Alum (c, d) pH and dose (e, f) pH and shaking time (g, h) alum and dose (i, j) alum and shaking time (k, l) dose and shaking time for azure B Removal

Adsorptive Removal Mechanism of Potassium Ions and Azure B

The removal of potassium ions (K^+) and Azure B dye by the SA/AA-Fe-MSP nanocomposite occurred through multiple adsorption mechanisms provided by the crosslinked hydrogel network as shown in fig-12. The sodium alginate and acrylic acid matrix contained abundant $-OH$ and $-COO^-$ functional groups, which served as active binding sites for pollutant uptake. Potassium ion removal mainly occurred through electrostatic attraction and ion-exchange interactions between K^+ ions and negatively charged carboxylate groups within the polymer matrix [24]. The embedded $\alpha-Fe_2O_3$ nanoparticles further enhanced adsorption by increasing the surface area and providing additional active sites. In the case of Azure B dye, adsorption was primarily governed by electrostatic attraction, hydrogen bonding, and $\pi-\pi$ interactions between the cationic dye molecules and the functional groups of the composite [25]. Moreover, moringa seed powder contributed additional oxygen-containing functional groups that improved the adsorption efficiency and stability of the nanocomposite, resulting in effective removal of both pollutants from wastewater [26].

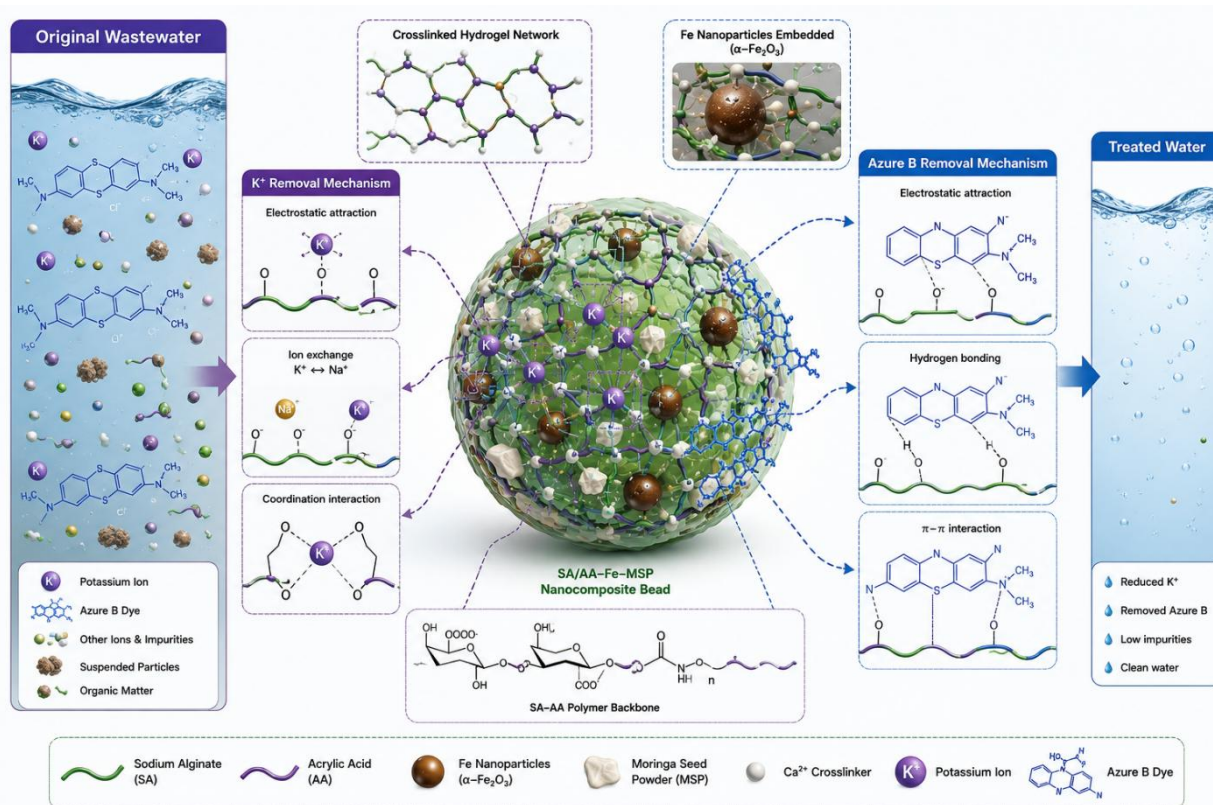


Figure 11- Schematic Illustration of Potassium Ion and Azure B Adsorption Mechanism

The removal efficiencies of SA/AA-Fe-MSP nanocomposite, which are around 98% for Azure B dye and 85% for K^+ , are comparable to the recent findings that SA-based hydrogels containing Fe_3O_4 -NPs can remove cationic dyes up to 99% due to strong surface interactions [22]. Incorporation of Moringa oleifera seed powder into the polymeric matrix is justified, as recent RSM-optimized study has shown Moringa oleifera seed powder effectively removes

turbidity of synthetic wastewater by electrostatic interactions and hydrogen bonding up to 98.5% and removes dye from synthetic wastewater up to 92.2% [27, 28]. This adsorption mechanism, based on electrostatic attraction, ion exchange and hydrogen bonding, is supported by recent studies using sodium alginate-acrylic acid hydrogels, in which the adsorption efficiencies of the ionic complexes formed between the functional groups of the hydrogels and the cationic pollutants were reported to be higher than 99% [29]. The use of Response Surface Methodology-Central Composite Design for optimizing interactive parameters such as pH, adsorbent dose and contact time is consistent with the application of other statistical methodologies that have demonstrated a high level of predictability in predicting coagulation-adsorption performance with high R^2 values [30]. The slight difference in removal efficiency between K^+ and Azure B dye could be due to the synergy required for alum-assisted coagulation for ionic species since Moringa coagulants alone were found to be less effective in removing dissolved ions such as ammonia with removal efficiencies of only 30% without the addition of other treatment agents [31].

Conclusion

In the present study, a sustainable SA/AA-Fe-MSP nanocomposite was successfully synthesized through a simple polymerization and crosslinking approach for the efficient removal of potassium ions and Azure B dye from wastewater. The incorporation of sodium alginate, acrylic acid, $\alpha\text{-Fe}_2\text{O}_3$ nanoparticles, and moringa seed powder provided a multifunctional adsorbent with abundant active sites, enhanced surface area, and improved adsorption capability. The adsorption process was systematically optimized using Response Surface Methodology based on Central Composite Design (CCD), which effectively evaluated the interaction of operational parameters and identified the optimum removal conditions. The developed nanocomposite exhibited remarkable adsorption performance toward both ionic and dye pollutants due to the synergistic effects of electrostatic attraction, ion exchange, hydrogen bonding, and surface complexation mechanisms. Furthermore, the environmentally friendly nature, facile synthesis route, and promising adsorption efficiency demonstrate the potential applicability of the synthesized material for advanced wastewater treatment systems. The findings of this study highlight the significance of bio-based nanocomposites as cost-effective and sustainable adsorbents for the remediation of contaminated aquatic environments.

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Declarations

The authors declare that all procedures performed in this study complied with relevant research and publication standards.

Ethical Approval

This article does not contain any studies with human participants or animals performed by any of the authors.

Consent to Participate

Not applicable.

Consent to Publish

Not applicable.

Competing Interests

The authors declare that they have no competing interests.

Data Availability

The datasets generated during and analysed during the current study are available from the corresponding author on reasonable request.

References

1. Maloofi, F. and A. Dadvand Koochi, *Impregnation of ZnO over a new hydrogel bead based conducting polymer and alginate for textile dye treatment: Interface charge transfer assessment, real wastewater treatment, and dye selectivity*. Int J Biol Macromol, 2025. **286**: p. 138226.
2. Tabish, M., et al., *Physical, chemical and biological treatment of textile wastewater for removal of dyes and heavy metals*. Desalination and Water Treatment, 2024. **320**: p. 100842.
3. Lee, S.Y., et al., *A state-of-the-art review of metal oxide nanoflowers for wastewater treatment: Dye removal*. Environ Res, 2024. **259**: p. 119448.
4. Zhao, H., et al., *Development of a Novel Nanoclay-Doped Hydrogel Adsorbent for Efficient Removal of Heavy Metal Ions and Organic Dyes from Wastewater*. Gels, 2025. **11**(4): p. 287.
5. Tripathi, M., et al., *Recent Strategies for the Remediation of Textile Dyes from Wastewater: A Systematic Review*. Toxics, 2023. **11**(11): p. 940.
6. Kulal, P. and V. Badalamoole, *Modified gum ghatti based hybrid hydrogel nanocomposite as adsorbent material for dye removal from wastewater*. Int J Biol Macromol, 2024. **283**(Pt 1): p. 137409.
7. Mahmoud, A.S., M.K. Mostafa, and R.W. Peters, *A prototype of textile wastewater treatment using coagulation and adsorption by Fe/Cu nanoparticles: Techno-economic and scaling-up studies*. Nanomaterials and Nanotechnology, 2021. **11**: p. 18479804211041181.
8. Zhou, R., et al., *Research progress on the application of hydrogel adsorbent materials in wastewater treatment: A review*. Chemical Engineering Research and Design, 2025. **216**.
9. Elnagar, E.R., et al., *Enhanced performance of polyvinylidene fluoride with triethanolamine and polyethylene glycol ultrafiltration membrane for textile wastewater treatment*. International Journal of Environmental Science and Technology, 2025. **22**(7): p. 5529-5542.
10. Tsoutsas, E.K., et al., *An Update on Agricultural Wastes Used as Natural Adsorbents or Coagulants in Single or Combined Systems for the Removal of Dyes from Wastewater*. Water, Air, & Soil Pollution, 2024. **235**(3): p. 178.
11. Kalra, A. and A. Gupta, *Recent advances in decolourization of dyes using iron nanoparticles: A mini review*. Materials Today: Proceedings, 2021. **36**: p. 689-696.
12. KK, K. and A. Kalaicelvi, *Bioremediation of colour removal in dye effluent by Moringa oleifera seed powder*. International Journal of Agricultural and Life Sciences, 2016. **2**(4).
13. Shruthi Keerthi, D. and M. Mukunda Vani, *Optimization studies on decolorization of textile wastewater using natural coagulants*. Materials Today: Proceedings, 2022. **57**: p. 1546-1552.
14. Ahmed, S., S. Inayat, and I. Javed, *Synthesis methods and characterization of iron oxide nanoparticles: A biomedical perspective*. Synthesis and Sintering, 2025.
15. Orisawayi, A.O., et al., *Development of hybrid electrospun alginate-pulverized moringa composites*. RSC Advances, 2024. **14**: p. 8502-8512.
16. Afolabi, A., S. Oluyamo, and I. Fuwape, *Synthetic characterization and Structural Properties of Nanocellulose from Moringa oleifera seeds*. Journal of the Nigerian Society of Physical Sciences, 2021.
17. Kashyap, S., R. Sankannavar, and G. Madhu, *Iron oxide (Fe₂O₃) synthesized via solution-combustion technique with varying fuel-to-oxidizer ratio: FT-IR, XRD, optical and dielectric characterization*. Materials Chemistry and Physics, 2022.
18. Manatunga, D., et al., *Metal and polymer-mediated synthesis of porous crystalline hydroxyapatite nanocomposites for environmental remediation*. Royal Society Open Science, 2018. **5**.

19. Farea, M., A. Abdelghany, and A. Oraby, *Optical and dielectric characteristics of polyethylene oxide/sodium alginate-modified gold nanocomposites*. RSC Advances, 2020. **10**: p. 37621-37630.
20. Flores, A.V.E., et al., *Synthesis of biocompatible hydrogel of alginate-chitosan enriched with iron sulfide nanocrystals*. SLAS technology, 2024: p. 100158.
21. Fernandes, R., et al., *Thermal, microstructural, and spectroscopic analysis of Ca²⁺ alginate/clay nanocomposite hydrogel beads*. Journal of Molecular Liquids, 2018.
22. Umar, M., et al., *Adsorptive removal of cationic dyes from wastewater using a novel sodium alginate-based iron oxide nanocomposite hydrogel: DFT and advanced statistical physics modelling*. Process Safety and Environmental Protection, 2024.
23. Hurtado-Alonso, N., et al., *Optimization of cementitious mixes through response surface method: a systematic review*. Archives of Civil and Mechanical Engineering, 2024. **25**.
24. Ismail, O. and Ö.G. Kocabay, *Absorption and adsorption studies of polyacrylamide/sodium alginate hydrogels*. Colloid and Polymer Science, 2021. **299**: p. 783-796.
25. Aljeboree, A. and A. Alkaim, *Studying removal of anionic dye by prepared highly adsorbent surface hydrogel nanocomposite as an applicable for aqueous solution*. Scientific Reports, 2024. **14**.
26. Thakur, S. and O. Arotiba, *Synthesis, swelling and adsorption studies of a pH-responsive sodium alginate–poly(acrylic acid) superabsorbent hydrogel*. Polymer Bulletin, 2018. **75**: p. 4587-4606.
27. Hui, Y., et al., *Sodium alginate based adsorbent: Facile fabrication, extraordinary removal efficacy of anionic dyes and adsorption mechanism*. International journal of biological macromolecules, 2024: p. 132842.
28. Thakur, S. and O. Arotiba, *Synthesis, characterization and adsorption studies of an acrylic acid-grafted sodium alginate-based TiO₂ hydrogel nanocomposite*. Adsorption Science & Technology, 2018. **36**: p. 458-477.
29. Gaayda, J.E., et al., *Optimization of turbidity and dye removal from synthetic wastewater using response surface methodology: Effectiveness of Moringa oleifera seed powder as a green coagulant*. Journal of Environmental Chemical Engineering, 2021.
30. Adesina, O., et al., *Response surface methodology approach to optimization of process parameter for coagulation process of surface water using Moringa oleifera seed*. South African Journal of Chemical Engineering, 2019.
31. Tong, C., F. Yusuf, and C. Derek. *Fish Farm Wastewater Treatment using Moringa oleifera Seed Powder as Natural Coagulant*. 2021.