

REMOVAL OF BORON USING CLAY-EFFECT OF PROCESS PARAMETERS, KINETIC AND ISOTHERM STUDIES

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Abstract

In this study, a low-cost eco-friendly adsorbent was prepared from naturally available sarooj clay and is proposed for the removal of boron from aqueous phase. The effect of process parameters, namely initial pH, sorbent quantity, initial boron concentration, shaking speed and temperature were studied on the metal uptake under batch conditions. The process efficiency was observed to be strongly parameter dependent and the optimal pH was found to be 10.0. The uptake capacity decreased with increase in sorbent dose and increased with boron concentration. Temperature was found to have a positive influence confirming the endothermic nature of the process. Equilibrium sorption data were analysed using Langmuir, Freundlich, Temkin and Dubinin-Radushkevich isotherm and represented well by Freundlich isotherm. The Freundlich constant was evaluated as 14.791 L g^{-1} at $35 \text{ }^\circ\text{C}$. The mechanism of sorption was investigated using kinetic models, namely, pseudo-second order and intra-particle diffusion models. The batch experimental fitted well to pseudo-second order model and the rate constant was found to be $0.0017 \text{ g mg}^{-1}\text{min}^{-1}$ with an initial boron concentration of 100 mg L^{-1} . The sorbent characteristics were studied using X-ray diffraction, scanning electron microscope with energy dispersive X-ray detector and X-ray fluorescence methods.

Keywords: Boron, Clay mineral, Kinetics, Equilibrium.

1. Introduction

Metal pollution is more serious than organic wastes because metals are non-biodegradable and have the tendency to bio accumulate in living tissues leading to serious disorders [1]. Boron is present in the natural environment in the form of borate salts and boric acid. The major sources of boron pollution are industrial waste waters, urban waste waters containing surfactants and detergents and different

Nomenclatures

$1/n$	Adsorption intensity
C_o	Initial concentration of the dye, mg L ⁻¹
C_e	Concentration of the dye at equilibrium, mg L ⁻¹
H	Heat of adsorption, J mol ⁻¹
I	Constant that is related to boundary layer thickness, mg g ⁻¹ .
k_2	Equilibrium rate constant for pseudo-second order adsorption, g mg ⁻¹ min ⁻¹
K_f	Freundlich constant, mg g ⁻¹
K_L	Langmuir constant, L mg ⁻¹
K_T	Equilibrium binding constant
k_i	Intra particle diffusion rate constant, mg/(g min ^{1/2}).
M	Adsorbent dosage, g L ⁻¹ .
q_1	Maximum adsorption capacity, mg g ⁻¹
q_e	Amount of dye adsorbed on the adsorbent, mg g ⁻¹
q_{max}	Maximum adsorption capacity, mg g ⁻¹
q_t	Amount of dye adsorbed at time, t, mg g ⁻¹
R	Gas constant, J mol ⁻¹ K ⁻¹
T	Solution temperature, K
V	Volume of the solution, L

Greek Symbols

θ	Activity coefficient related to sorption mean energy, mol ² kJ ⁻²
ε	Polanyi potential

chemicals used in agriculture [2]. Higher concentrations of boron in the range of 20-30 mg L⁻¹ were reported to be found in geothermal waste water [3]. Even though boron is an essential element for the growth of certain plants, excess boron levels lead to boron toxicity which causes necrosis of leaves [3]. Conventional methods for removal of metals from aqueous solutions like chemical oxidation or reduction, reverse osmosis, chemical precipitation and evaporation are ineffective and extremely expensive to treat metal concentration in the range of 1-100 mg L⁻¹ [4]. Even though ion exchange resins and activated carbon are recognized adsorbents, they suffer from disadvantages like high cost and low efficiency. Due to the inherent ability of all solids to adsorb pollutants to a certain limit, natural inorganic materials like clay, synthetic materials like zeolite and several industrial inorganic wastes like ash have gained tremendous attention for their use for metal pollution control [5].

Sorption is a process in which ions of the solute are transferred from the solution to the solid surface. It is basically a mass transfer process involving physical and chemical interactions [6]. The suitability of the adsorption process depends on the ability of the metals to interact in the solid-solution interface. Among natural materials, clays occupy a prominent position, mainly due its low being low material cost, availability in abundance with good sorption properties [7]. Clays are hydrous alumino silicates broadly defined as those minerals that make up the colloidal fraction of soils, sediments and rocks. They play an important role in the depollution of impure water by taking up the anions and cations either by adsorption or ion exchange or both as the removal mechanism [7]. There are various types of clay such as bentonite, ball clay, common clay,

sepiolite and kaolin. Montmorillonite type of clay accounts for 68% of the clay used as adsorbents followed by bentonite and kaolin [8].

Extensive studies have been undertaken on the application of clay for the removal of metals like cadmium, cobalt, copper, iron, lead and nickel [7]. Beidellite has been used for the removal of lead and cadmium and their respective metal uptake capacities were in the range of 83.3 - 86.9 and 42 - 45.6 mg g⁻¹, respectively [9]. Bentonite, on the other hand, has been investigated for its potential to remove metals like lead, zinc and iron [10, 11]. Boron removal was investigated using resins like Amberlite IRA 743 [12], Purolite S 108 and Diaion CRB 02 [13]. Adsorption of boron has been studied using coal and fly ash [14] or activated sludge [15] as adsorbents. The abundant availability of the natural Sarooj clay in Oman and its cheap cost are likely to favour the choice of it as a potential sorbent material in pollution control applications. In this research work, Raw sarooj clay, is investigated for its potential to remove boron from the aqueous solution. In Oman, Sarooj has been used in buildings, forts and for making water distribution systems. Longer durability and low permeability are found to be some unique properties with Sarooj clay [16].

To the best of our knowledge, no published literature is available on the removal of boron using raw Sarooj clay. The effects of operating variables like initial pH, sorbent dose, initial metal concentration, temperature and agitation speed were investigated under batch experimental conditions. The chemical analyses of the clay were performed using X-ray diffraction and X-ray fluorescence studies. The equilibrium studies were performed to verify the nature of sorption. Kinetic studies were conducted to analyse the rates of boron adsorption.

2. Experimental

2.1. Adsorbent preparation

The raw Sarooj clay used in this study was obtained from Northern Oman. The clay received was in the form of bigger flocs and was ground and sieved to obtain particle size range of 0.85-1.70 mm. The clay was washed twice with water and used after drying without any processing. The adsorbent produced is called Raw Sarooj Clay (RSC).

2.2. Characteristics of the adsorbent

The chemical analyses of the RSC were carried out using X-Ray Diffraction (XRD) method. The X-ray Diffraction patterns of RSC were prepared using a X-ray diffractometer (Xpert Pro XRD, PANalytical). The powdered sample was ground and packed on the sample holder by back pressure technique followed by air drying, glycol treatment and heat treatment at 550 °C for 40 minutes. The elemental composition of the clay was estimated using X-ray Fluorescence (XRF) method. The surface morphology of RSC was observed using a Field Emission Scanning Electron Microscope with an Energy Dispersive X-ray detector (Jeol-7600 F, Japan) with an accelerating voltage of 20 kV.

2.3. Adsorbate

Boron solutions of desired concentrations have been prepared by dissolving calculated quantity of boric acid, supplied by Merck, Germany. All other chemicals used in this study were analytical Grade supplied by Sigma Aldrich, USA.

2.4. Batch experiments

Different sets of adsorption experiments were carried out to investigate the effect of experimental conditions on the metal removal efficiency. To optimize the boron removal process, the effect of operating variables namely initial pH, initial boron concentration, sorbent quantity, shaking speed and temperature are studied [17]. In the first set of experiments, the pH was varied in the range of 2.0 - 12.0 at a fixed metal concentration of 50 mg L⁻¹. The optimal pH identified from the first set of experiments was used for all the other studies. The influence of boron concentration on the removal efficiency was studied in the range of 0- 100 mg L⁻¹.

The effect of sorbent quantity was studied by mixing various amounts of raw Sarooj clay (1.0 - 6.0 g L⁻¹) in conical flasks containing 50 mg L⁻¹ metal concentration. The effect of temperature was studied in the range of 30-40 °C by shaking the flasks in a thermostatic water bath shaker operating at 400 rpm for 90 min (fixed after preliminary experiments) to ensure the attainment of equilibrium. The effect of agitation speed was studied in the range of 0-600 rpm at optimal conditions of pH and sorbent dosage at a fixed boron concentration of 50 mg L⁻¹. All the experiments were conducted at room temperature of 35 °C unless otherwise specified. The results of these equilibrium studies were verified with isotherms.

2.5. Isotherm studies

The adsorption capacity (expressed as mg of COD removed per g of adsorbent) of the Sarooj clay was estimated using the following Eq. (1).

$$q_e = \frac{V(C_0 - C_e)}{M} \quad (1)$$

The boron removal efficiency was estimated using the following Eq. (2).

$$\% \text{ boron removal efficiency} = \frac{(C_0 - C_e)}{C_0} \times 100 \quad (2)$$

Four equilibrium models representing different sorption mechanisms namely, Langmuir, Freundlich, Temkin and Dubinin –Radushkevich (D-R) models [Eqs. (3), (4), (5) and (6) respectively] were employed to fit the batch experimental data [17, 18].

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

$$\ln q_e = \ln K_f + \frac{1}{n} \ln c_e \quad (4)$$

$$q_e = H \ln K_T + H \ln c_e \quad (5)$$

$$\ln q_e = \ln q_{max} - \beta \varepsilon^2 \quad (6)$$

2.6. Kinetic experiments

The design of adsorption process required details on rate of adsorption and mechanism of adsorption. Adsorption kinetics provides essential details for identifying the above said phenomena. The kinetic studies were conducted to estimate the contact time required for the attainment of equilibrium between the dissolved and solid bound adsorbate. The kinetic experiments were carried out by using boron concentrations such as 25, 50, 75 and 100 mg L⁻¹ at the optimum conditions as given above. Samples were taken at specific intervals of time and analysed for residual boron concentration. In this study, the pseudo-second-order equation [Eq. (7)] and intraparticle diffusion model [Eq. (8)] have been applied to the experimental data to analyze the kinetics of removal of boron ions [19, 20]:

$$\frac{t}{q_t} = \frac{1}{k_2 q_1^2} + \frac{1}{q_1} t \quad (7)$$

The intraparticle diffusion model is represented as

$$q_t = k_t t^{1/2} + I \quad (8)$$

2.7. Analysis of the metal

Samples of solutions were filtered through 0.45 µm membrane filter and then the filtrates were analyzed for boron concentration by curcumine method using spectrophotometer (Biochrom, UK) at an absorption wavelength of 555 nm [13]. All experiments were conducted in duplicate and the mean values were reported.

3. Results and discussion

3.1. Characterization of the adsorbent

The chemical composition of major elements of the raw Sarooj clay was presented in Table 1. From the Table 1, it was found that SiO₂ (66.381%) and Al₂O₃ (16.428%) were the two main components present in the clay sample. The presence of trace elements was found out and Table 2 shows the trace elements whose concentrations are greater than 15 ppm in the sample. The SEM-EDX analysis were carried out for the raw Sarooj clay and the images are shown Fig. 1. The clay mineral identification was done based on XRD analysis and the minerals Kaolinite (Al₂Si₂O₅(OH)₄) and Illite (KyAl₄(Si_{3-y}Al_y)O₂₀(OH)₄) with reflection at 7.1 and 10.0 Å respectively, are reported to be the major impurities. Figure 1 shows clustered pattern of molecules within the clay microstructure in its raw form.

3.2. Effect of pH

The solution pH plays a vital role in any separation process involving surface attraction or exchange of sorbate ions. Presence of hydronium ions initiates a competition between the sorbate metal ions and hydronium ions for sorption at surface active sites. The effect of pH on the uptake of boron by the clay was studied by varying the initial pH in the range of 2.0-12.0 under constant experimental conditions.

From Fig. 2, it was observed that the metal uptake increased with pH in the range of 2.0 - 10.0 with a maximum uptake capacity of 31.4 mg g⁻¹ reached at pH 11.0.

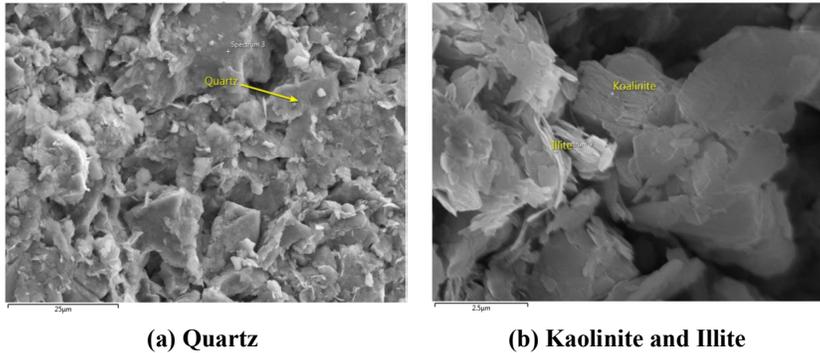


Fig. 1. SEM imaging of clay sample.

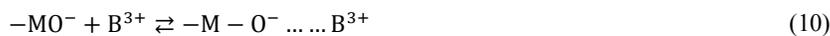
Table 1. Major elements in clay.

Compound	% concentration
SiO ₂	66.381
TiO ₂	0.362
Al ₂ O ₃	16.428
Fe ₂ O ₃	0.501
MnO	0.005
MgO	0.24
CaO	2.415
Na ₂ O	0.472
K ₂ O	1.604
P ₂ O ₅	0.055

Table 2. Trace elemental composition of clay.

Element	Concentration (ppm)
Zn	643.6
Ba	269.5
Sr	190.4
Rb	119.6
Zr	75.9
Ce	44.5
Mn	37
V	33.4
Cr	29.1
La	25.3
Ga	23.5
Nd	19
Pb	18

There was no significant increase in boron uptake in the pH range of 10.0 – 12.0. The concept of aqua complex formation of oxides on the clay surface could be utilized to explain the effect of pH [21]. The surface charges in acidic environment were highly positive and thus reduce the affinity for the metal ions. In a basic medium, the clay surface becomes negatively charged and thus favour boron uptake as explained below in Eqs. (9) and (10) [21].



Reduced uptake at acidic pH range is attributed to the presence of excess hydrogen ions which compete with the metal cations for the same adsorption sites [22]. Also, at lower pH values of (2.0 - 5.0) the adsorbent surface is covered with relatively more number of positively charged sites which does not favor the sorption of metal cations (B^{3+}). Studies on removal of methylene blue on mesoporous clay reported better results in the pH range of 11.0 -12.0 [23].

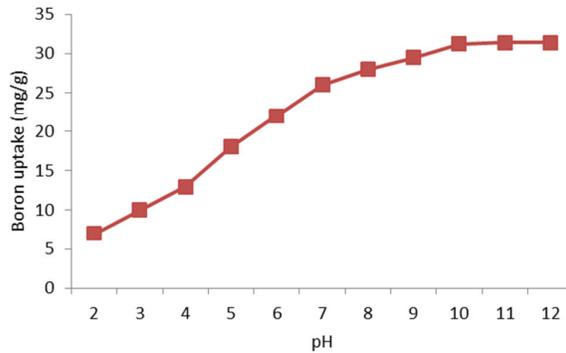


Fig. 2. Effect of initial pH on the uptake of Boron by RSC (metal concentration= 50 mg L⁻¹; sorbent dose = 4.0 g L⁻¹; contact time = 90 min; shaking speed= 400 rpm; T=35 °C).

3.3. Effect of RSC concentration

The effect of different quantities of clay on the uptake of boron was studied in the range of 1.0 - 6.0 g L⁻¹ at an optimal pH of 1.0 for an equilibrium time of 90 min. Figure 3 presents the boron uptake and removal efficiencies obtained at different doses of clay. The removal efficiency of boron increased linearly with increase in sorbent dose in the range of 1.0 – 4.0 g L⁻¹ and the curve flattened in the higher dosage range of 5.0 – 6.0 g L⁻¹.

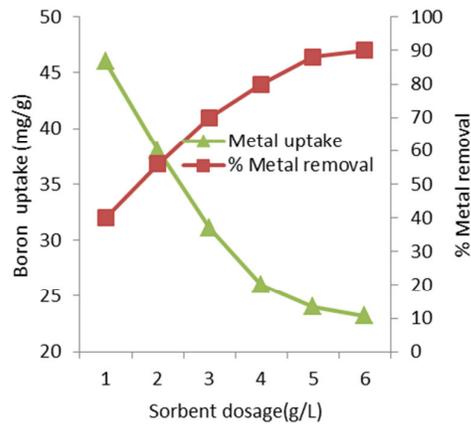


Fig. 3. Effect of sorbent dosage on the % removal and uptake of Boron by RSC (metal concentration= 50 mg L⁻¹; pH = 10.0; contact time = 90 min; shaking speed= 400 rpm; T=35 °C).

The boron uptake, expressed as mass of metal removed per unit mass of sorbent, decreased with increase in the sorbent dose. Improved removal percentages with increase in sorbent dose is attributed to increase in the ratio of adsorbent to adsorbate which provided more surface area and active sites for sorption of boron. This result was in agreement with other studies on metal removal using adsorption as the technique [24, 25]. The maximum removal efficiency obtained was 90% at a sorbent dosage of 6.0 g L^{-1} . The boron uptake decreased from 46 to 23.2 mg g^{-1} when the clay dose increased from 1.0 to 6.0 g L^{-1} . The relationship between the amount of boron adsorbed at equilibrium (q_e) and the adsorbent dosage [M] is given by Eq. (11),

$$q_e = 0.9929 M^2 - 11.553 M + 56.76 \quad (11)$$

3.4. Effect of contact time and initial metal concentration

In order to determine the optimal equilibrium time for different initial metal concentrations, experiments were conducted in the boron concentration range of 25-100 mg L^{-1} at fixed conditions of pH 10.0, dosage 4 g L^{-1} , agitation speed, 400 rpm and temperature, $35 \text{ }^\circ\text{C}$. From Fig. 4, it was observed that the boron uptake increased with increase in metal concentration while the uptake rate was fast during the initial phase of 15 min after which a dynamic steady state adsorption was achieved. The equilibrium contact time required increased from 50 to 80 min when the boron concentration increased from 25 to 100 mg L^{-1} . The increased concentration gradient available during the initial stages of the adsorption process was responsible for better uptakes during the earlier phase of experimental period. Also, the resistance to mass transfer will be less at this condition. The boron uptake capacities varied from 20.2 to 47.4 mg g^{-1} when the concentration was increased from 25 to 100 mg L^{-1} . The increase in metal concentration resulted in decrease in metal removal efficiency which was attributed to the saturation of active sites on the clay at high metal ions/sorbent sites ratio. Similar observations on mercury removal were reported using eucalyptus bark as the adsorbent [26].

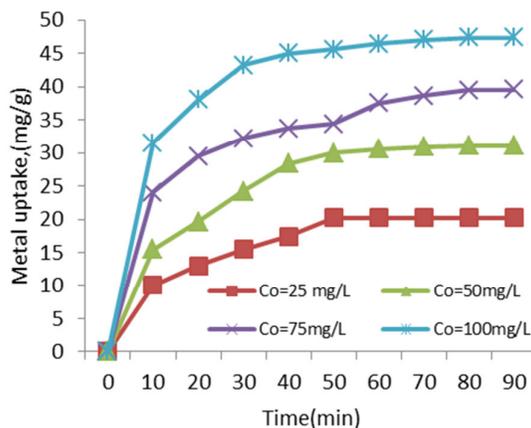


Fig. 4. Effect of contact time and initial metal concentration on the uptake of Boron by RSC (pH = 10.0; contact time = 90 min; shaking speed= 400 rpm; T=35 °C).

3.5. Effect of shaking speed

In this set of experiments performed to study the effect of agitation speed, predetermined conditions of pH 10.0 and sorbent dose of 4.0 g L^{-1} were used at an initial boron concentration of 50 mg L^{-1} . Figure 5 presents the variation in the uptake of boron by raw Sarooj clay at different shaking speed in the range 0-600 rpm. The metal uptake increased from 8.2 to 31.1 mg g^{-1} when the shaking speed increased from 0 (static condition) to 400 rpm and the uptake exhibited a decreasing trend when the speeds were greater than 400 rpm. Better external mass transfer through the film was reported to occur at higher mixing speeds by reducing the boundary layer thickness at the film. More collisions between the sorption sites and metal ions are also reported to be a reason for this behaviour. Reduced uptakes at very high speeds could be due to loss of suspension homogeneity [17, 22].

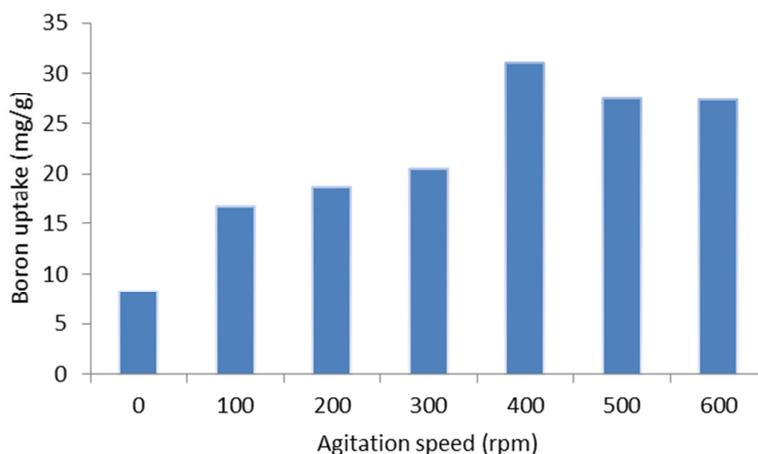


Fig. 5. Effect of shaking speed on the uptake of Boron by RSC (pH = 10.0; contact time = 90 min; boron concentration = 50 mg L^{-1} ; $T=35 \text{ }^\circ\text{C}$).

3.6. Effect of operating temperature

The rate of removal of a sorbate ion depends on the operating temperature which in turn influences the surface energies of the active sites. The effect of temperature on the uptake of boron was studied in the range of $30 - 40 \text{ }^\circ\text{C}$ with an initial boron concentration of 50 mg L^{-1} , pH of 10, sorbent dose of 4.0 g L^{-1} and shaking speed of 400 rpm and was shown in Fig.6. The result observed proved that the uptake capacity increases with increase in temperature confirming the endothermic nature of the process. The enhancement in uptake is attributed to better interaction between metal ions and sorbent, creation of new sorption sites and increased intraparticle diffusion at higher temperatures [26]. The entropy of the system was reported to increase at higher temperatures which led to more successful collisions between the sorbate and sorbent molecules [23]. Even though the boron uptake increased with temperature, the rate of increase was comparatively higher in the temperature range of $30-35 \text{ }^\circ\text{C}$ compared to $35-40 \text{ }^\circ\text{C}$.

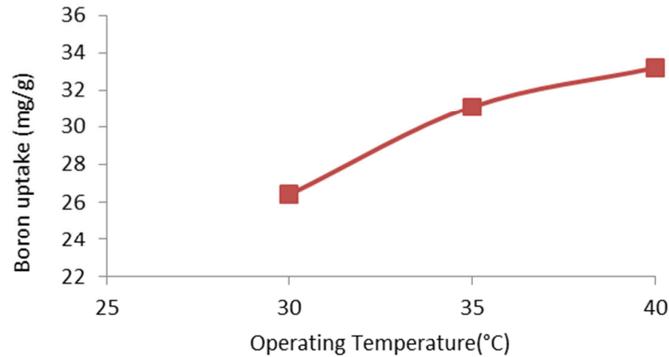


Fig. 6. Effect of operating temperature on the uptake of Boron by RSC (metal concentration= 50 mg L⁻¹; pH = 10.0; contact time = 90 min; shaking speed= 400 rpm).

3.7. Isotherm studies

The adsorption isotherms of boron removal were studied by conducting experiments in the concentration of 25 -100 mg L⁻¹ at predetermined optimal conditions of pH, sorbent dose, speed and temperature. The equilibrium data were fitted to four different isotherms namely, Langmuir, Freundlich, Temkin and D-R isotherms. Langmuir isotherm is based on the assumption that the sorption takes place as mono-layer process with finite number of identical sites on the adsorbent. Freundlich isotherm is based on the assumption of exponential distribution of active centers. Temkin isotherm represents the adsorbate- adsorbent interactions and related with adsorption heat [27]. Langmuir model was verified by making a plot of (C_e/q_e) vs. q_e , as shown in Fig.7. The Langmuir isotherm constants, K_L and q_{max} , were determined from the slopes and intercepts of the respective linear plots.

Figure 8, which is a plot of $\ln q_e$ vs. $\ln C_e$ represents the Freundlich isotherm and the Freundlich isotherm constants, K_f and n , were determined from Fig. 8. Temkin isotherm was represented by q_e vs. $\ln C_e$ and was shown in Fig. 9. Temkin isotherm constants, B and K_T were estimated. The Dubinin-Radushkevich equation has a semi-empirical origin and is based on the assumptions of a change in the potential energy between the adsorbed phases and a characteristic energy of a given solid. This equation yields a macroscopic behaviour of adsorption loading for a given pressure. The suitability of the Dubinin-Radushkevich isotherm was verified by making a linear plot between $\ln q_e$ and ϵ^2 and the isotherm constants, β and q_{max} were estimated from the slope and intercept of Fig. 10. From Table 3, it was observed that Freundlich isotherm represented the equilibrium sorption of boron confirming the occurrence of adsorption on heterogeneous surfaces at different energies and the value of regression coefficient (R^2) was comparatively higher for Freundlich isotherm. The nature of the values of Freundlich isotherm constant ($n > 1$) showed that the adsorption process was favourable. The heterogeneity of the clay surface with different energies was attributed to its irregular shape of pore, size of the pore, presence of different surface functional groups and impurities [23]. Langmuir constants also increased with increase in temperature confirming the endothermic nature of the boron removal.

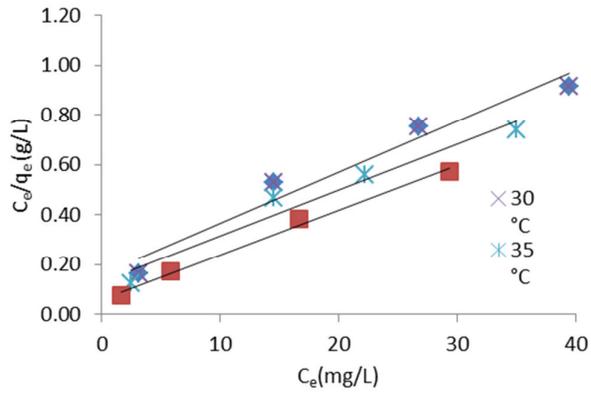


Fig. 7. Langmuir plot for the removal of Boron by RSC.

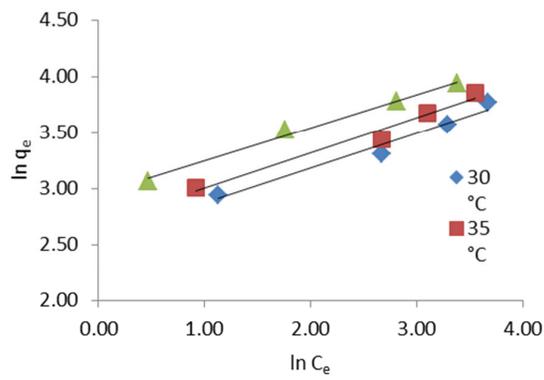


Fig. 8. Freundlich plot for the removal of Boron by RSC.

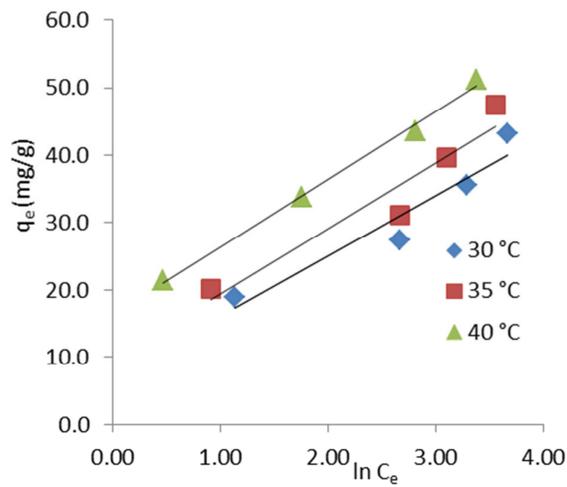


Fig. 9. Temkin plot for the removal of Boron by RSC.

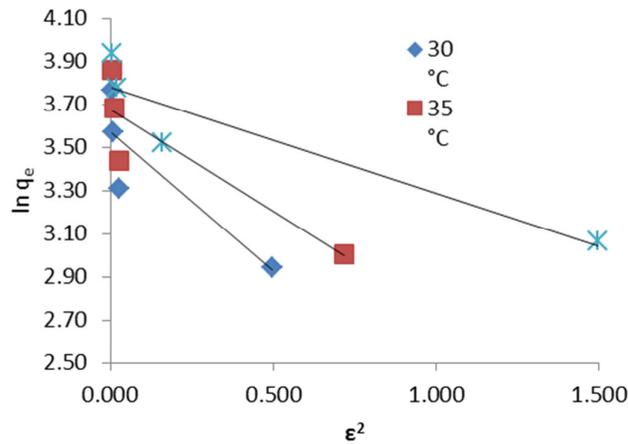


Fig. 10. D-R plot for the removal of Boron by RSC.

Table 3. Comparison of constants in the isotherms at different temperatures.

Isotherm constants	Temperature, °C		
	30	35	40
Langmuir isotherm			
q_{max} (mg g ⁻¹)	49.26	54.05	55.87
K_L (L mg ⁻¹)	0.123	0.143	0.290
R^2	0.956	0.953	0.991
Freundlich isotherm			
n	3.20	3.29	3.38
K_f (L g ⁻¹)	12.897	14.791	19.114
R^2	0.973	0.969	0.992
Temkin isotherm			
H (J/mol)	8.904	9.684	10.032
K_T (L g ⁻¹)	2.27	2.74	5.11
R^2	0.915	0.918	0.996
D-R isotherm			
q_{max} (mg g ⁻¹)	35.51	39.44	43.86
β (mol ² kJ ⁻²)	1.2811	0.9396	0.4917
R^2	0.761	0.803	0.866

3.8. Kinetic studies

The kinetics of boron sorption onto the raw Sarooj clay was tested using two models namely pseudo-second order and intra-particle diffusion models. Figure 11, a linear plot of t/q vs. t , was representing pseudo-second order model and the rate constant (k_2) and maximum adsorption capacity (q_1) were determined from the slope and intercept. The possibility of intra-particle diffusion as the rate determining step was verified using the intra-particle diffusion model. Figure 12 presents the intra-particle diffusion model as a plot of q vs. $t^{1/2}$. The values of the correlation

coefficients ($R^2 > 0.99$) indicated a better fit of pseudo-second order model compared to the intra-particle diffusion model. Many other sorption studies reported the suitability of this model for their metal removal kinetics [28, 29]. The applicability of pseudo-second order model implies that the adsorption is likely to be controlled by chemisorption which involves sharing of electrons between metal ions and clay [24]. The evaluated kinetic constants were presented in Table 4. The values of the pseudo-second order rate constant (k_2) decreased from 2.8×10^{-3} to $1.7 \times 10^{-3} \text{ g mg}^{-1} \text{ min}^{-1}$ with an increase in boron concentration from 25 to 100 mg L^{-1} . This observation emphasizes the enhancement of rate due to mass transfer occurring with an increase in concentration gradient [30]. It was usually a two sectioned plot with intraparticle diffusion model, the first linear portion followed by a plateau region. In this studies also, the similar pattern was observed. The value of the intraparticle diffusion constant (I) was measured from the intercept of the lines shown in Fig. 12 and are found to be lower at lower boron concentrations which indicate significance of chemisorption effects at higher metal concentrations. Similar observations were reported on studies on chromium removal [24].

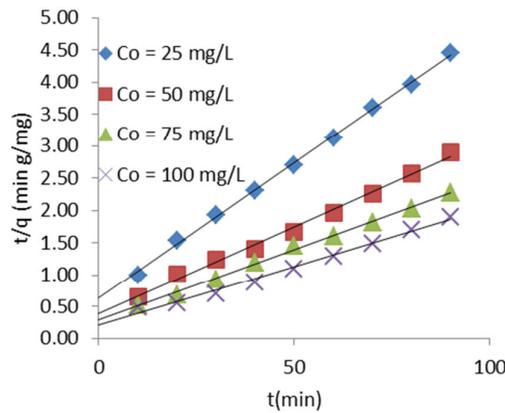


Fig. 11. Pseudo-second-order kinetic plots for the sorption of Boron at 35 °C.

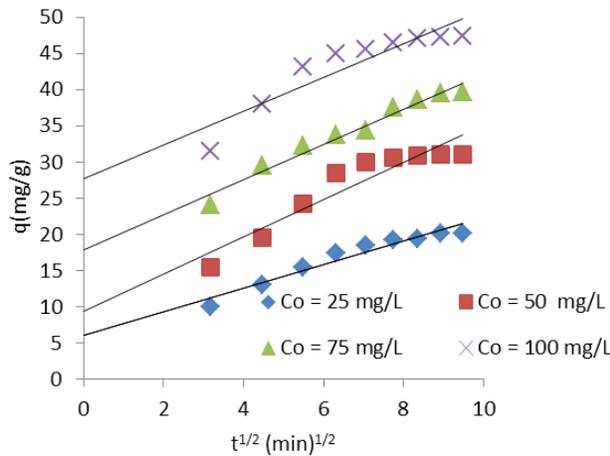


Fig. 12. Intra-particle diffusion kinetic plot for the removal of boron at 35 °C.

Table 4. Pseudo-second order and intraparticle diffusion model parameters.

Initial Boron Concentration(mg.L ⁻¹)	Temperature:35 °C			
	25	50	75	100
Pseudo second order model				
k_2 (g mg ⁻¹ min ⁻¹)×10 ³	2.80	1.89	1.80	1.70
q_1 (mg g ⁻¹)	23.75	36.90	45.45	54.35
R^2	0.999	0.994	0.996	0.999
Intraparticle diffusion model				
k_p (mg(g ⁻¹ min ^{1/2}))	1.63	2.57	2.42	2.32
I	6.02	9.38	17.9	27.7
R^2	0.940	0.887	0.967	0.840

Various studies on removal of different metals like lead and cadmium using beidellite reported an uptake of 42 – 45.6 mg g⁻¹, tungsten using montmorillonite coated with chitosan reported an uptake of 23.9 mg g⁻¹, and copper, nickel, cobalt and manganese using kaolinite and montmorillonite reported an uptake of 11.0 mg g⁻¹ [7]. These values are comparable with the uptake value for boron, 55.87 mg g⁻¹, reported in this study.

4. Conclusions

This study explained the potential application of raw sarooj clay as a suitable inexpensive adsorbent for the removal of boron. The adsorption process was found to be pH dependent and the metal uptake capacity varied with respect sorbent dose, initial metal concentration, shaking speed and temperature. Higher temperature was favoured confirming the endothermic nature of sorption process. The elemental composition and clay mineral analyses were determined using XRD and SEM-EDS. Freundlich, Langmuir, Temkin and D-R isotherm models in downward manner, was the order of best fit for the equilibrium data. The maximum adsorption capacity attained was 55.87 mg g⁻¹ and was found to be better than many other adsorbents tried earlier. The kinetic experiments were represented well using pseudo-second order model.

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