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Removal of remazol brilliant blue dye from aqueous solutions using water hyacinth root powder

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ABSTRACT

Water hyacinth (WH) root powder was successfully utilized as a low cost and efficient adsorbent for the removal of Remazol Brilliant Blue (RBB) dye from aqueous solutions. Batch experiments were conducted for adsorption of Remazol Brilliant Blue dye onto WH root powder. The potential of WH for the dye removal and the effect of several parameters such as initial pH (2.0–9.0), contact time (2–300 min), adsorbent dosage (0.5–20 g L^{-1}), initial dye concentration (50–500 mg L^{-1}) and temperature (303–323 K) were analyzed. The results indicate that an acidic pH of 2.0 supports the adsorption of RBB dye onto WH. The maximum adsorption capacity for this dye was found to be 83.33 mg g^{-1} at 323 K. Freundlich, Langmuir, Dubinin–Radushkevich and Temkin isotherms were utilized for modelling the RBB removal at equilibrium, the results of which revealed that the Langmuir model provided the best fit. The contact time data was found to fit well with the pseudo-second order kinetic model. Kinetic studies proved that the rate of RBB dye uptake was limited by both film diffusion and intra-particle diffusion. Results from thermodynamic studies revealed that the adsorption process was feasible, spontaneous and endothermic in nature ($\Delta G°$ and $\Delta H°$ values at 323 K are –7.33 kJ mol^{-1} and 46.009 kJ mol^{-1}, respectively).

Keywords: Water hyacinth; Dye removal; Remazol brilliant blue; Isotherms; Kinetics

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1. Introduction

Synthetic dyes are primarily used in various industries such as textile, cosmetics, drug, paper, food, etc. These dyes have significant impact in various products used in our daily life and on our health [1]. Textile dyes are classified as reactive dyes, acid dyes, heterocyclic dyes, direct dyes, disperse dyes, basic dyes and vat dyes, based on the dyeing process [2]. Demand for reactive dyes (nearly 45% of all dyes used) is high compared with other textile dyes, due to its intensive use as a colorant for cellulose, cotton and viscose rayon fibres [3]. Typically, reactive dyes consist of anthraquinone-based chromophores, characterized by the presence of isomer, 9,10-anthraquinone (9,10-dioxoanthracene), wherein the keto functional groups are located on the central ring [2]. Remazol Brilliant Blue (RBB) ($C_{22}H_{16}N_2Na_2O_{11}S_3$; Reactive Blue 19; C.I. 61200; molar mass 626.53 g mol^{-1}), which belongs to the family of brilliant blue, is a triphenylmethane dye, is used as a colorant in textile and leather and also is used for biochemical analysis, protein quantification, electrophoresis, etc. [4,5]. It is used as a base material in the production of polymeric dyes. As it is an anthracene derivative, it is a recalcitrant organic contaminant [6].

The main problems associated with RBB dye in textile wastewaters are (i) resistant to biodegradation; (ii) highly visible due to its bright color, even in very low concentration of dye (<1 mg L^{-1}) in the effluent; (iii) toxic to aquatic and vegetative life and (iv) considered undesirable and difficult

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to remove by traditional methods. Textile dye effluents generally have a strong color, extreme pH, high COD, suspended and dissolved solids [7,8]. When discharged into the water bodies, these dye effluents have negative effects on aquatic life, soil quality and ecosystem integrity [9]. Dyes such as RBB and their breakdown products are known for their carcinogenic and mutagenic properties [10]. Potential health effects of this dye include eye and skin irritation, allergies, respiratory and digestive tract irritation, etc. Before its ban, it was used as a common food additive in beverages, dairy products, powders, jellies, confections, icings, syrups, extracts, and condiments. Hyperactivity in children, different types of allergies, asthma, and migraines were observed with the use of this food additive [11].

In order to eliminate the problems posed to the environment, removal of RBB is the need of the hour. There are several methods for the removal of dyes such as coagulation, ozonation, electrochemical treatment, reverse osmosis and irradiation [12,13]. Amongst all these methods, adsorption is an effective, economical and reliable method for the removal of dyes. Though activated carbon is a highly efficient adsorbent, its high cost and inefficient regeneration promotes the search for more feasible alternatives [14]. Recently, a number of low-cost adsorbents are tested for the dye sorption, such as sugar beet pulp [3], orange peel [15], tamarind seeds [16], *Sargassum wightii* [17], cashew nut shell [18], sawdust [19], corn cob [20], Eucalyptus seeds [9], etc.

The current study deals with the removal of RBB by the mechanism of adsorption on the root of water hyacinth (WH) (*Eichhornia crassipes*), a free-floating perennial plant. WH is considered as the world's worst aquatic plant owing to its rapid and invasive proliferation resulting in choking of water bodies. WH biomass contains 30%–50% cellulose, 20%–40% hemicellulose and 15%–30% lignin. In addition to removal of nutrients, WH also removes heavy metals from sludge and sewage due to their high binding affinity. This suggests that it could be utilized to solve environmental problems [21,22].

Several sorption studies have explored the use of WH as an inexpensive adsorbent for dye removal. WH fixed on alginate beads showed high uptake of methylene blue and crystal violet dyes, indicating good potential for dye removal [23]. An experimental study was conducted for removal of Reactive Orange 16 dye using WH root powder, which showed maximum removal of 93% within 100 min [14]. Another study showed up to 99.338% Malachite Green dye removal using WH root powder [24]. Owing to vegetative reproduction, enormous growth rate, grown in tropical climate, tolerance to pollution and high adsorption capacities qualify WH for use in RBB treatment [22,25]. Thus, utilizing WH roots to decolorize the RBB dye solution is an economic technique which also deals with the problems brought up by these weeds. WH is abundantly available all year long. To date, to the best of our knowledge, study of WH root powder as a natural adsorbent to remove anionic dye RBB is scarce. Hence this research will be the first study of its kind.

2. Materials and methods

2.1. Preparation of adsorbent

The root powder of WH was used as adsorbent in this study. WH plants were collected from Hebbal Lake, Bangalore. The shoot parts were cut out and disposed, the roots were then washed thoroughly to remove all the earthly impurities. They were dried under the sun for 6 d and later placed in a hot air oven for 180 min. The dried roots were crushed in a ball mill for 240 min and the root powder was sieved through 100–120 mesh (average particle size 130 μm) and stored in air-tight containers.

2.2. Preparation of adsorbate

RBB dye was obtained from M/s Merck Chemicals, India. A stock solution of 1,000 mg L^{-1} was prepared and using the stock solution, standards of required concentrations were prepared. The concentration of RBB dye solution was measured at 590 nm using UV–Visible spectrophotometer.

2.3. Batch study

For batch experiments, 100 mL of RBB dye solutions of required concentration were taken in a 250 mL reagent bottles. The solutions were agitated in a wrist action mechanical shaker at 27°C ± 2°C. Different parameters such as effect of initial pH (2.0–9.0), contact time (2–300 min), adsorbent dosage (0.5–20 g L^{-1}), initial dye concentration (50–500 mg L^{-1}) and temperature (303–323 K) were studied on the removal of RBB dye using WH adsorbent. Reusability studies have been carried out for three cycles.

Percentage RBB removal and adsorption capacity were calculated using Eqs. (1) and (2) as follows:

$$\%\ \text{RBB removal} = \frac{C_i - C_f}{C_i} \times 100 \tag{1}$$

$$q = \frac{V}{m} \times (C_i - C_f) \tag{2}$$

where C_i and C_f are the initial and final RBB concentrations (mg L^{-1}); V is the volume of the RBB solution taken in (L); m is the mass of WH adsorbent (g).

2.4. SEM and EDX analysis for WH

Scanning electron microscopy (SEM) coupled with energy dispersive X-ray (EDX) was used to study the morphology and elemental composition of the WH root powder. As shown in Fig. 1, the surface of WH root powder was rough and uneven, easily allowing the RBB dye molecules to attach to the surface. EDX analysis showed the presence of elements Cl, K, Ca, Mn, Fe, Si, Mg, and Al in the WH root powder samples.

2.5. FTIR analysis

Fourier transform infrared spectrophotometer was employed (in the range of 400–4,000 cm^{-1}) to identify the functional groups present on the WH root powder before and after adsorption (Fig. 2). The peak values from 500 to 1,000 cm^{-1} may be assigned to stretching of C–H alkene and alkyl halide groups. The presence of small peaks at 2,915 and 2,847 cm^{-1}

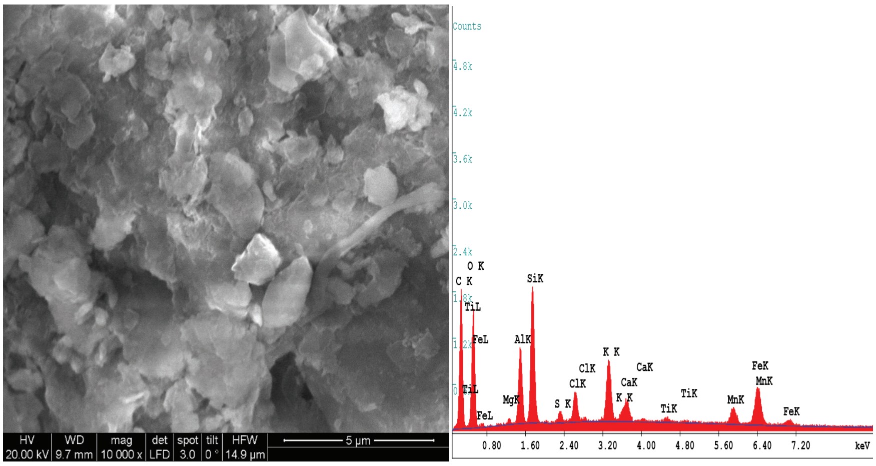

Fig. 1. SEM and EDX images of water hyacinth root powder.

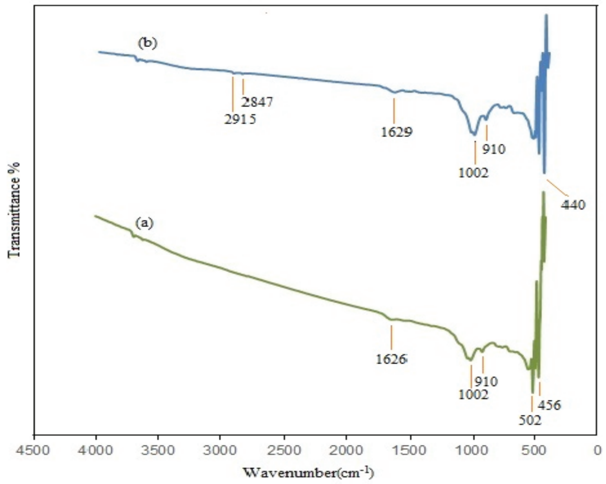

Fig. 2. FT-IR spectra of water hyacinth root powder (a) before and (b) after adsorption.

after adsorption indicate asymmetric and symmetric C–H stretching vibrations. The bands in the region 1,650–590 cm^{-1} are attributed to amine and SO_3 functional groups present in the dye. Additionally, the peak in 1,626 cm^{-1} showed shift mildly to 1,629 cm^{-1}, indicating some unsaturated group was responsible for RBB removal. The band at 1,629 cm^{-1} can be attributed to N–H amine bending vibrations. The adsorption bands at around 1,200–1,000 cm^{-1} can be assigned to C–O single bond in carboxylic acids, alcohols and esters. The band at 1,002 cm^{-1}, which is more prominent after adsorption, can be attributed to C–H alkene bending. Other peaks from FIIR spectra were not changed or shifted significantly.

3. Results and discussion

3.1. Effect of initial pH on removal of RBB

pH of the medium is a key factor controlling the rate of adsorption. This parameter is associated with the competition between hydrogen and dye anions for binding to the active site [26]. The influence of initial pH was studied in the pH range of 2.0–9.0 by adding 0.1 g of WH adsorbent to 100 mL of 100 mg L^{-1} RBB dye solutions at 27°C ± 2°C and a contact time of 120 min. The pH was adjusted using 0.1 N HCl and NaOH. Maximum dye removal of 87% was found to be at pH 2.0 (Fig. 3). Adsorption was observed to decrease from pH 2.0 to 4.0 indicating that dissociation rate of the dye is more in highly acidic medium. No dye removal was observed from pH 4.0 to 6.0 and beyond pH 6.0 precipitation of the dye was observed. The WH surface is protonated at lower pH, thereby enabling the adsorption of negatively charged RBB dye. The more positively charged sites on WH facilitated the binding of anionic RBB dye molecules. The optimum pH was thus considered to be 2.0. Higher RBB dye removal observed at lower pH can be attributed to electrostatic attraction between RBB dye molecules and WH surface [27]. Al-Degs et al. [28] and Soni et al. [14] reported a similar trend observed for reactive dyes.

3.2. Effect of contact time

Results of contact time studies provide a good estimation of time taken to achieve equilibrium [29]. In this study, the effect of contact time (2–300 min) was investigated at a temperature of 27°C ± 2°C with initial dye concentrations of 100 mg L^{-1} maintained at a pH of 2.0 with 2 g L^{-1} of WH adsorbent. The WH root powder actively adsorbed over 80% of the dye within 15 min of contact time. After 15 min, a gradual increase was observed in percentage dye removal with attainment of equilibrium at 120 min. Beyond 120 min, adsorption remained almost constant due to decrease in surface area for binding and the saturation of WH active sites [30].

3.3. Effect of adsorbent dosage

This parameter was evaluated by varying the WH adsorbent dosage from 0.5 to 20 g L^{-1}. The experiment was conducted using 100 mg L^{-1} dye solution maintained at pH 2.0, at a contact time of 120 min and temperature of 27°C ± 2°C. As observed in Fig. 4, RBB dye removal favoured increase in weight of WH adsorbent. When the dosage was increased from 0.5 to 5 g L^{-1}, percentage dye removal was found to increase from 47.07% to 94.82%. This enhancement in adsorption with WH adsorbent dosage can be ascribed

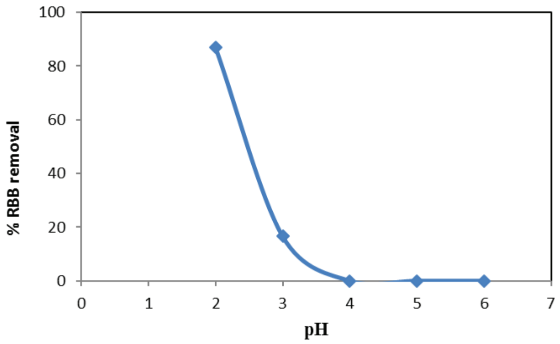

Fig. 3. Variation of % removal of RBB dye onto WH with pH at a contact time of 120 min, 1 g L^{-1} of WH dosage, initial dye concentration of 100 mg L^{-1} and temperature of 27°C ± 2°C.

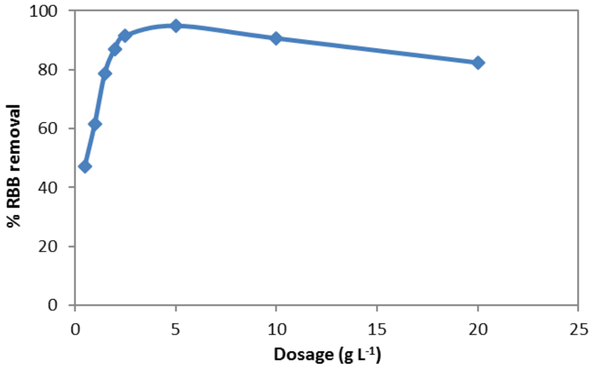

Fig. 4. Variation of % removal of RBB dye with WH adsorbent dosage at an optimum pH of 2.0, contact time of 120 min, initial dye concentration of 100 mg L^{-1} and at temperature 27°C ± 2°C.

to increased adsorbent surface area and availability of more vacant sites [31]. But when the adsorbent dosage was further increased from 5 to 20 g L^{-1}, percentage removal reduced from 94.82% to 82.35%. These experimental results reveal that higher adsorbent dose causes aggregation of adsorbent and accordingly, the available adsorption sites and adsorption intensity reduces [32].

3.4. Effect of initial RBB dye concentration and effect of temperature on adsorption

Initial dye concentration ranges of 50–500 mg L^{-1} were taken in this study. This study was conducted employing 2 g L^{-1} WH adsorbent and a contact time of 120 min, at a pH of 2.0 and temperature of 303, 313 and 323 K. The experimental results have been displayed on a plot of percentage RBB removal vs. initial dye concentration at different temperatures (Fig. 5). The adsorption yield was observed to decrease as the initial dye concentrations were increased. At higher concentrations of the dye, removal efficiency was lesser because of the reduced surface area and vacant sites available in WH adsorbent [33]. The increase in percentage RBB dye removal with increased temperature reflects the endothermic nature of the process. Furthermore, at higher temperatures the RBB dye molecules have sufficient kinetic energy to interact with the adsorbent active sites facilitating an increased surface activity [10]. In general, the increase in temperature will increase the binding sites and increase the diffusion rate of dye molecules across the external boundary layer and into the pores of biomass particles.

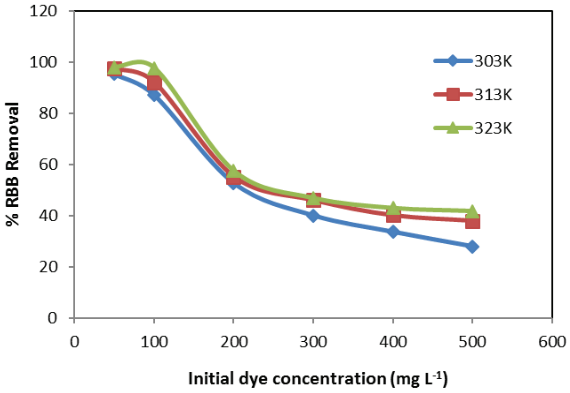

Fig. 5. Variation of % RBB dye removal with initial dye concentration at different temperatures.

3.5. Adsorption isotherms

The data obtained from the effect of initial dye concentration studies at different temperatures were fit into Langmuir, Freundlich, Dubinin–Radushkevich and Temkin isotherm models (Table 1). The frequent use of Langmuir and Freundlich isotherms can be attributed to its simplicity, physical meaning and ease of interpretation. The Freundlich isotherm model involves reversible, non-ideal and multilayer adsorption on a heterogeneous surface whereas Langmuir isotherm assumes localized, monolayer adsorption [34,35]. Dubinin–Radushkevich isotherm relates the adsorption mechanism with Gaussian energy distributions on heterogeneous surfaces [36]. Temkin isotherm accounts for heat of interactions between adsorbent-adsorbate molecules affecting the adsorption process [37].

The linear form of the Langmuir, Freundlich, Dubinin–Radushkevich and Temkin equations are given by Eq. (3) as follows:

$$\frac{1}{q_e} = \frac{1}{q_{\max} b}\frac{1}{C_e} + \frac{1}{q_{\max}} \tag{3}$$

$$\ln q_e = \ln K + \frac{\ln C_e}{n} \tag{4}$$

$$\ln q_e = \ln q_{mD} - B(RT\ln(1+1/C_e))^2 \tag{5}$$

$$q_e = \frac{RT}{bT}\ln K_T + \frac{RT}{bT}\ln C_e \tag{6}$$

where q_e is the amount of RBB dye adsorbed per gram of WH root powder at equilibrium (mg g^{-1}), $q_{\max}$ is the maximum monolayer uptake of RBB dye (mg g^{-1}), b is the Langmuir biosorption constant (L mg^{-1}) related to affinity of RBB

Table 1
Isotherm parameters for adsorption of RBB onto WH

Temperature (K)	Langmuir isotherm				
	$q_{\max}$ (mg g^{-1})	b (L mg^{-1})	R^2	ND	NSD
303	58.824	0.288	0.966	8.2379	9.920
313	71.428	0.424	0.932	14.241	17.575
323	83.334	0.429	0.924	16.629	20.991
Temperature (K)	Freundlich isotherm				
	K mg g^{-1} (L mg^{-1})$^{1/n}$	n	R^2	ND	NSD
303	22.198	5.076	0.950	5.635	7.792
313	25.003	4.739	0.934	9.744	11.251
323	30.205	5.348	0.827	16.279	18.322
Temperature (K)	Dubinin–Radushkevich isotherm				
	q_{mD} (mg g^{-1})	B	R^2	ND	NSD
303	58.492	0.392	0.839	11.577	12.983
313	67.572	0.157	0.742	20.356	22.242
323	75.452	0.118	0.830	23.399	28.607
Temperature (K)	Temkin isotherm				
	K_T (L g^{-1})	b_T (J mol^{-1})	R^2	ND	NSD
303	8.013	294.423	0.970	5.086	5.622
313	7.026	244.828	0.865	10.173	12.467
323	17.969	267.233	0.787	17.379	19.151

dye molecules onto WH root powder, C_e is the equilibrium concentration of RBB in solutions (mg L^{-1}), K is Freundlich adsorption constant (mg g^{-1} (L mg^{-1})$^{1/n}$), n is Freundlich biosorption intensity, which is a measure of extent of deviations from linearity of the biosorption, q_{mD} is the Dubinin–Radushkevich monolayer uptake of RBB dye (mg g^{-1}), B is the Dubinin–Radushkevich adsorption energy constant, R is universal gas constant (J mol^{-1} K^{-1}), T is the temperature (K), K_T is the Temkin adsorption constant (L g^{-1}), b_T heat of adsorption (J mol^{-1}).

The linearized forms of these models were used to fit the experimental data. In addition to values of determination coefficient, best fit was also evaluated based on error analysis. Normalized deviations and standard deviations for all isotherms were estimated using Eqs. (7) and (8), respectively, as follows:

$$\text{Normal deviation} = \frac{100}{N}\sum\left|\frac{q_{e(\exp)} - q_{e(\text{pred})}}{q_{e(\exp)}}\right| \tag{7}$$

$$\text{Normalized standard deviation} = 100\sqrt{\frac{\sum\left(\frac{q_{e(\exp)} - q_{e(\text{pred})}}{q_{e(\exp)}}\right)^2}{N}} \tag{8}$$

where N is the number of observations and $q_{e(\text{pre})}$ and $q_{e(\exp)}$ are the predicted and experimental RBB dye uptake. As per the determination coefficients ($0.95 < R^2 < 1$) and the deviations, Langmuir isotherm was found to provide the best fit for the experimental data. This indicates that uniform, monolayer RBB dye adsorption onto WH root powder is preferred, indicating adsorption to sites with equal affinities [21].

Maximum dye uptake $q_{\max}$ at 323 K was determined to be 83.33 mg of dye/g of adsorbent with Langmuir constant b as 0.429 L mg^{-1}. Table 2 illustrates the maximum dye uptake of several other adsorbents used for the removal of RBB dye including the results of this study. It is apparent from the comparison that the current study provides a better adsorption strategy owing to its relatively higher value of $q_{\max}$. Thus, it can be deduced that there exist stronger interactive forces between WH adsorbent and RBB dye molecules. WH is also a viable adsorbent for RBB contaminated water treatment because it is cheap and largely available.

3.6. Adsorption kinetics

For analysis of adsorption kinetics of RBB dye on WH root powder, different mathematical correlations between adsorbed quantities and contact time were considered, namely pseudo-first order, pseudo-second order and intra-particle diffusion models [47–49].

$$\ln(q_e - q) = \ln q_e - k_1 t \tag{9}$$

$$\frac{t}{q} = \frac{1}{k_2 q_e^{\,2}} + \frac{t}{q_e} \tag{10}$$

$$q = k_3 \times \sqrt{t} + C \quad (11)$$

where q and q_e are RBB dye uptake (mg g^{-1}) at time t and at equilibrium time, k_1 is pseudo-first order rate constant (min^{-1}), t is the contact time (min), k_2 is pseudo-second order rate constant (g mg^{-1} min^{-1}), k_3 is intra-particle diffusion constant (mg g^{-1} $min^{-1/2}$).

Pseudo-first and pseudo-second order kinetic equations (Eqs. (9) and (10)) were used to fit the data obtained from contact time studies. Table 3 gives the comparison of pseudo-first and pseudo-second order models. Based on coefficient of determination values, pseudo-second order kinetic model (R^2 = 0.99) fits the adsorption kinetic data better than the pseudo-first order kinetic model (R^2 = 0.74). More ever on comparison of RBB dye uptake obtained by experiment with values calculated from the models, the adsorption of RBB on WH was deduced to follow pseudo-second order kinetic model.

To test the possibility of intra-particle diffusion as proposed by Weber and Morris (Eq. (11)), a plot of q vs. $t^{1/2}$ was made (Fig. 6). The multi-linearity of the intra-particle diffusion plot indicates that two steps primarily influence the adsorption process: The first sharper portion in the initial period of contact indicates that instantaneous attachment of RBB dye on the external surface of WH. This may be due to strong electrostatic interaction and bonding between RBB dye and WH root powder (film diffusion or external diffusion). Adsorption is distinctly influenced by solute transfer from surface to internal active sites or intra-particle diffusion. The second portion represents the intra-particle diffusion of RBB dye within the particles till equilibrium is achieved [50]. Moreover, both stages having non-zero intercepts, the deviation from the origin reveals that intra-particle diffusion is not the only rate-controlling step. In RBB dye adsorption, other steps might be contributing simultaneously.

3.7. Thermodynamic analysis

Thermodynamic parameters indicate the inherent energetic changes and feasibility of the adsorption process. The thermodynamic parameters of Gibbs free energy change ($\Delta G°$), standard enthalpy ($\Delta H°$) and entropy changes ($\Delta S°$) are estimated using Eqs. (12) and (14).

$$\Delta G° = -RT \ln K_c \quad (12)$$

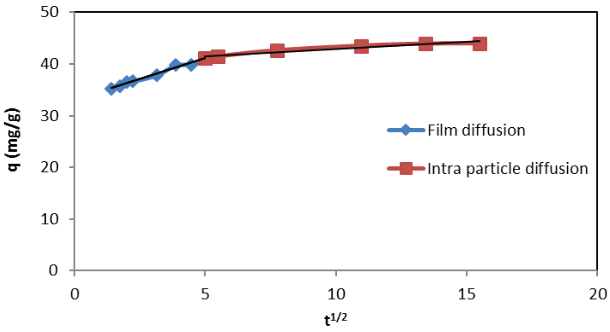

Fig. 6. Plot for intra-particle diffusion of RBB dye onto WH adsorbent.

Table 2
Dye uptake for RBB obtained with different studies

S. No	Adsorbent	Maximum adsorption capacity (mg g^{-1})	Reference
1	Orange peel	10.7	[15]
2	Red mud	27.8	[38]
3	*Scenedesmus quadricauda* (green algae)	68	[39]
4	*Salvinia natans* (aquatic fern)	50.2	[40]
5	Pineapple leaf powder and lime leaf powder	9.58	[41]
6	Watermelon rind activated carbon (low-cost adsorbent)	243.74	[42]
7	Pirina pretreated with nitric acid	23.63	[43]
8	Commercial activated carbon	199.45	[43]
9	Activated carbon prepared from a pine cone	60.97	[44]
10	Surfactant-modified zeolite	13.9	[45]
11	Bone char prepared by CO_2 atmosphere	20.6	[46]
12	Water hyacinth root powder	83.33	Present study

Table 3
Kinetic parameters for adsorption of RBB onto WH

Experimental	Pseudo-first order model			Pseudo-second order model			Intra-particle diffusion model		
q_e (mg g^{-1})	k_1 (min^{-1})	q_e (mg g^{-1})	R_1^2	k_2 (g mg^{-1} min^{-1})	q_e (mg g^{-1})	R_2^2	C	k_3 (mg g^{-1} $min^{-1/2}$)	R_3^2
43.525	0.048	10.66	0.74	0.242	45.45	0.99	33.01	1.615	0.981

Table 4
Thermodynamic parameters for adsorption of RBB onto WH

Adsorbent	$\Delta G°$ (kJ mol^{-1}) = $-RT\ln K_c$			$\ln K_c = \frac{\Delta S°}{R} - \frac{\Delta H°}{RT}$	
	303 K	313 K	323 K	$\Delta H°$ (kJ mol^{-1})	$\Delta S°$ (J K^{-1} mol^{-1})
Water hyacinth root powder	–4.034	–5.745	–7.337	46.009	165.19

$$K_c = \frac{C_{\text{Ae}}}{C_e} \tag{13}$$

$$\ln K_C = \frac{\Delta S°}{R} - \frac{\Delta H°}{RT} \tag{14}$$

where K_c is the equilibrium constant, C_e is the equilibrium concentration of RBB in solution (mg L^{-1}), C_{Ae} is the amount of RBB adsorbed on WH root powder per litre of solution at equilibrium (mg L^{-1}), R (8.314 J mol^{-1} K^{-1}) is the universal gas constant and T (K) is the solution temperature. Table 4 reports the values of thermodynamic parameters for adsorption of RBB on WH root powder at different temperatures.

Negative $\Delta G°$ values reaffirm the spontaneous nature of RBB dye adsorption process and the increasing trend observed with rise in temperature indicates that adsorption is more energetically favourable [50,51]. The positive value of enthalpy ($\Delta H°$) shows that RBB adsorption is endothermic which is in agreement with the results of experimental study [26]. The magnitude of $\Delta H°$ (46.009 kJ mol^{-1}) reveals that physisorption is the dominant mechanism of RBB dye removal from the solution. Physical adsorption of RBB dye onto WH root powder involves intermolecular forces (Van der Waals forces), which do not involve a significant change in the electronic orbital patterns of the species [52]. The negative value of $\Delta S°$ is indicative of the random aggregation of RBB dye on the surface of WH root powder [10,53].

3.8. Reusability study

The reusability of RBB dye loaded adsorbent was assessed by carrying out three cycles of sorption–desorption and regeneration in a batch system. 0.1 N hydrochloric acid solution was used as an elutant for desorbing RBB dye from the dye loaded adsorbent. After desorption, the adsorbent was washed with distilled water and reused for RBB removal. More than 85% of dye was desorbed and 16% decrease in sorption of dye on adsorbent was observed in three cycles.

4. Conclusions

The present work shows that WH, the worst aquatic plant in the world has proved to be an efficient and cost-effective adsorbent for the removal of RBB dye from waste water. Effect of different parameters such as pH (2.0–9.0), contact time (2–300 min), adsorbent dosage (0.5–20 g L^{-1}), initial dye concentration (50–500 mg L^{-1}) and temperature (303, 313, 323 K) on removal of RBB dye were studied. Thermodynamic analysis indicated RBB adsorption to be a spontaneous and endothermic process. The results show that the adsorption rate conformed to pseudo-second order kinetics. The Langmuir isotherm model gave the best fit to the equilibrium data, confirming that RBB dye removal is a homogeneous adsorption process. Maximum dye uptake of 83.33 mg of RBB dye/g of WH was achieved at 323 K with pH of 2.0.

As per our knowledge of the reports on adsorption of RBB dye, no previous reports have examined RBB dye removal by utilizing WH root powder as adsorbent. Consequently, it can be concluded that WH root powder can be used as a cost effective and eco-friendly alternative for the removal of RBB dye during wastewater treatment.

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