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Kinetic and Isotherm Modeling of Adsorption of Dyes onto Sawdust

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Abstract

Sawdust has the ability to adsorb the dyestuff from aqueous solution. It may be useful low cost adsorbent for the treatment of effluents, discharged from textile industries. The effectiveness of sawdust has been tested for the removal of color from the wastewater samples containing two dyes namely Direct Blue (DB) and Vat Yellow (VY). Effect of various parameters such as agitation time, adsorbent dose and initial concentration of each dye has been investigated in the present study. The adsorption of dyes has been tested with various adsorption isotherm models. The Langmuir isotherms model is found to be the most suitable one for the dye adsorption using sawdust and the maximum adsorption capacity is 8.706 mg/g and 6.975 mg/g for DB and VY respectively. The adsorption process is best described by second-order kinetics and the corresponding rate constants (K2) are obtained which are found to be 0.2837g/mg.min and 0.1274 g/mg.min for DB and VY respectively at the maximum concentration.

Introduction

The textile industry continually strives to minimize pollution, particularly when dyeing cotton and cotton blend fabrics where large amounts of salts and colour dye pollutants are discharged into water.

There are several methods to remove colour, these include: sedimentation, using flocculants or polyelectrolytes, biological treatment, ultrafiltration, ion exchange, adsorption, chlorination or ozonation [1].

Many dyes used in textile industry are particularly difficult to remove by conventional waste treatment methods, since they are stable to light and oxidizing agents and are resistant to aerobic digestion. The removal of dyes in economic fashion remains an important problem although recently a number of successful systems have been evolved using adsorption techniques. These, commonly, include: adsorption by activated carbon and ion exchange [2].

In this concern adsorption process has been found to be more effective method for the treatment of dye containing wastewater. The most efficient and commonly used adsorbent is commercially activated carbon which is expensive and has regeneration problems. Recent investigations focused on effectiveness of low cost adsorbents like neam leaf powder [3], coconut husk [4], wheat straw [5], maize cobs [6], wood [7], peat [8]; natural adsorbent [9], banana pith [10], chitin [11], agricultural waste [12] in the removal of dyes from wastewater effluent.

Wood has been a source of adsorbent material both in its natural and modified state. The sawdust of a soft spruce wood has been used for the adsorption of a basic and an acidic dye from solution, finding the removal cost using wood to be only 1.5 – 8.2 % that of a commercial carbon. The results shows that spruce wood dose have an affinity for basic dyes rather than acidic dyes, although uptake is much less than for active carbon, peats and lignite [13].

Spruce sawdust was magnetically modified by contact with water-based magnetic fluid stabilised with perchloric acid. The material prepared was used to study the adsorption of selected water-soluble organic dyes. The adsorption isotherms followed Langmuir, generalised Freundlich, generalised Langmuir, and Langmuir-Freundlich adsorption patterns. Maximum adsorption capacities for acridine orange, Bismarck brown, crystal violet, malachite green, methyl green, Nile blue and Saturn blue ranged between 34 and 59 mg g^{-1} dry adsorbent. A change in pH value can increase the dye adsorption [14].

Wood fiber of Phoenix tree is an effective adsorbent for malachite green (MG). Basic condition was favorable for MG adsorption to the adsorbent. The pseudo second order equation well described MG adsorption onto the wood adsorbent. The Freundlich Isotherm could describe the sorption data. [15].

The potential use of mansonia wood sawdust as low-cost adsorbent for the sportive removal of basic dye, methylene blue, from aqueous solution has been studied. The effect of sawdust particle size on the equilibrium methylene blue uptake was examined using batch sorption technique. Adsorption isotherm using various particle sizes (150, 250, 350, 450, and 550 μm) of mansonia sawdust at 26°C. The results revealed that the sawdust particle size has a strong influence on the percentage dye removal. Increasing sawdust particle size from 150 to 550 μm reduced the percentage dye uptake from 93.57% to 29.50% and amount of dye adsorbed per gram of sawdust from 28.7 to 8.85 mg/g. The isotherm data were found to be well described by the Langmuir isotherm model [16].

The objective of the present study is to investigate the possible use of sawdust as an alternate adsorbent material for the removal of two dyes DB and VY from wastewater. Batch experiments are carried out for kinetic studies on the removal of dye from aqueous solution. The influence of various important parameters such as time, adsorbent amount, and initial dye concentration is investigated. The Langmuir, Freundlich, Redlich-Peterson, Koble-Corrigan, Tempkin, Dubinin-Radushkevich and Generalized equation models are used to fit the experimental equation isotherm data obtained in this study. Pseudo first-order, and second-order kinetic models are used to evaluate the mechanism of adsorption.

Material and Method

Adsorbent

Sawdust is collected from the institute workshops; it is washed repeatedly with distilled water to remove the dust and soluble impurities. It is then kept for drying at room temperature in shade for 8 h.

Preparation of dye solutions

The standard solutions for each dye (Direct Blue and Vat Yellow) at different concentration were prepared by dissolving a weighed amount of the powder dye in distilled water.

Batch experiments

The batch experiments are carried out in 500 ml borosil conical flasks. A specific amount of sawdust (adsorbent) is added in 200 ml of aqueous dye solution, and then stirred for period of time at 30°C. Afterwards, the resultant solution is filtered using a filter paper. Adsorption isotherm study is carried out with different adsorbent amount range from 1 to 8 g/l, while maintaining the initial dye concentration at 20 ppm. The influence of time on dye adsorption is studied with an initial dye concentration ranging from 10-30 ppm for DB and VY. The effect of the adsorbent amount is studied by varying it in the range of 10-20 g/l. The concentration of dye in the effluent I determianed spectrophotometrically.

Adsorption isotherm models

Adsorption isotherm are expressed in terms of a relation ship between the concentration of adsorbate in the liquid and the amount of adsorbate adsorbed by the unite mass of adsorbent at a constant temperature. There may not be a simple expression which is capable of describing the equilibrium relation between the adsobate in liquid phase and the adsobate in solid phase, because of the complex nature of liquid-phase adsorption on the microporous substances. It is important to get an accurate equilibrium relationship between the solid and liquid – phase concentrations of dye. In the present study, as the adsorbent developed is new, it is essentially required to test the equilibrium data obtained for dye removal using sawdust with different isotherm models available in the literature so as to know which one is the best suited out of the reported isotherms. Various adsorption isotherm models such as Langmuir [17], Freundlich [18], Redlich-Peterson [19], Koble-Corrigan [20], Tempkin [21], Dubinin-Radushkevich [22] and generalized equation [23] which are available in the literature are described in the following section bringing out the differences among them and the significance of the characteristic parameters of each isotherm model.

Langmuir isotherm

Langmuir isotherm has been extensively used for the adsorption of dyes, heavy metals, organic, etc. [24]. It is applicable for monomolecular layer adsorption. The isotherm is described as a homogeneous one assuming that all adsorption sites have equal adsorption at an adjacent site [17]. The Langmuir isotherm is used to obtain a maximum adsorption capacity produced from the complete monolayer coverage of adsorbent surface, as given by Eq.1:

$$q_e = \frac{Q_m b\, C_e}{1 + b\, C_e} \qquad (1)$$

Freundlich isotherm

Freundlich isotherm describes that the ratio of the amount of solute adsorbed onto a given mass of adsorbent to the concentration of solute in the solution is not constant at different concentrations. For many systems, the heat of adsorption decreases in magnitude with increasing the extent of adsorption [18]. This has been well taken care of by the Freundlich isotherm, previously considered to be an empirical isotherm. For adsorption from solution, the Freundlich isotherm is expressed by Eq. 2:

$$q_e = K_f\, C_e^{nf} \qquad (2)$$

Redlich-Peterson isotherm

Redlich-Peterson isotherm contains three parameters and is an improvement over the Langmuir and Freundlich isotherms [19]. It has a linear dependence in the numerator and an exponential dependence in the dominator on concentration which makes it an overall complex and non-linear dependence on C_e . It can be described by Eq. 3:

$$q_e = \frac{A\, C_e}{1 + B\, C_e^g} \qquad (3)$$

Where A, B and g (0 < g < 1) are the Redlich-Peterson parameters.

Coble-Corrigan isotherm

Koble-Corrigan model is another three-parameter empirical model for representing the equilibrium adsorption data [20]. It is a combination of the Langmuir and Freundlich models and is given by Eq. 4:

$$q_e = \frac{a\, C_e^n}{1 + b\, C_e^n} \qquad (4)$$

Where a, b and n are the Koble-Corrigan parameters, respectively.

Tempkin isotherm

Tempkin isotherm equation [21] contains a factor that takes into account of the adsorbent-adsorbate interactions. It is based on the assumption that the heat of adsorption of all the molecules in the layer decreases linearly with the coverage of molecules due to the adsorbent-adsorbate repulsions and the adsorption of adsorbate is uniformly distributed [25]. In addition, it also assumes that the fall in the heat of adsorption is linear rather than logarithmic, as equation is given by Eq. 5:

$$q_e = \frac{RT}{B_T} \ln(A_T\, C_e) \qquad (5)$$

Dubinin-Radushkevich (D-R) isotherm

Dubinin and Radushkevich have proposed another isotherm which can be used to analyze the equilibrium data [22]. It is not based on the assumption of homogeneous surface or constant adsorption potential, but it is applied to estimate the mean free energy of adsorption (E), if the value of E is between 1 and 16 kJ mol^{-1}, then physical adsorption prevails, and if the value is more than 16 kJ mol^{-1}, then chemisorptions prevails, the non-linear form of D-R equation is given by Eq.6:

$$q_e = Q_m \exp(-K\varepsilon^2) \qquad (6)$$

$$\text{Where } \varepsilon = RT \ln\left(1 + \frac{1}{C_e}\right) \qquad (7)$$

Generalized isotherm

The generalized isotherm is a combination of Langmuir and Freundlich isotherms. It depends on the value of cooperative binding constant (N_b) . A generalized isotherm can also be used to fit the equilibrium data [23]. The linear form of the generalized isotherm is given by Eq.8:

$$\left(\frac{Q_m}{q_e} - 1\right) = K_G\, C_e^{-N_b} \qquad (8)$$

Adsorption kinetics

The dynamics of the adsorption process in terms of the order and the rate can be evaluated using the kinetic adsorption data. The process of dye removal from an aqueous phase by any adsorbent can be explained by using kinetic models and examining the rate-controlling mechanism of the adsorption process such as chemical reaction, diffusion control and mass transfer. The kinetics of removal of dye is explicitly explained in the literature using pseudo first-order and second –order [26].

Pseudo first-order kinetics

Lagergren showed that the rate of adsorption of solute on the adsorbent is based on the adsorption capacity and followed a pseudo first-order equation. The non-linear form of the pseudo first-order equation is given by Eq.9:

$$\frac{dq_t}{dt} = k_{ad}(q_e - q_t) \qquad (9)$$

The integrated rate law after application of the initial condition of $q_t = 0$ at $t = 0$, becomes a linear equation as given by Eq.10:

$$log(q_e - q_t) = \log q_e - \left(\frac{k_{ad}t}{2.303}\right) \qquad (10)$$

Second-order kinetics

As pseudo first-order kinetic model gives only k_{ad} and as q_e cannot be estimated using this model [27], applicability of second-order kinetics has to be tested for the estimation of q_e with the rate equation given by Eq.11:

$$\frac{dq_t}{dt} = k_2(q_e - q_t)^2 \qquad (11)$$

From the boundary conditions, $t = 0$ to t and $q_t = 0$ to q_t, the integrated form of the equation becomes Eq.12:

$$\frac{1}{(q_e - q_t)} = \frac{1}{q_e} + k_2 t \qquad (12)$$

Results and Discussion

In the present study, wood sawdust is used as an adsorbent for dye removal from wastewater. It is found that, using the sawdust as an adsorbent, the maximum capacity obtained for DB and VY dye adsorption is 8.706 mg/g , 6.975 mg/g respectively. The comparison of the adsorbent capacity of different low cost adsorbent is shown in Table 1. When compared with other low cost adsorbents, the results of the present study indicates that sawdust as an adsorbent has best adsorption capacity, so sawdust proves to be cost effective adsorbent that can be used for the removal of dye from wastewater. The uptake on sawdust mainly depends on the dye concentration, and adsorption and reduction phenomena that simultaneously take place on the adsorbent surface [23].

Table 1 Comparison of maximum adsorbent capacity of various low-cost sorbents for textile dye removal

Sorbents	Textile dyes	T °C	Langmuir $q°$ (mg/g)	Ref.
Posidonia oceanica	Reactive red	30	5.74	29
Orange peel	Procion orange	29	1.33	10
Apple pomace	Reactive dyes	20	2.79	28
Pichia carsonii	Reactive blue	28	5	28
Kluyveromyces marxianus	Cibacron orange	25	8.5	30
Chitosan	Basic violet	25	2.4	31
Chitosan + fly ashes	Basic violet	25	4.9	31
Chitosan + sawdust	Basic violet	25	8.1	31
Commercial activated carbon	Malachite green	30	8.27	32
Arundo donax root carbon	Malachite green	30	8.69	33
Wood sawdust	Methylene blue	25	8.85	16
Wood sawdust	Direct blue	25	8.706	This study
Wood sawdust	Vat yellow	25	6.975	This study

Another key factor which dominates the adsorption of dye on sawdust is the available surface area. In general, naturally occurring adsorbents have less surface area which results in a lower adsorption capacity of dye. The specific surface area of sawdust is obtained as 0.84 m^2/g, which is much higher as compared to other low-cost adsorbent such as apple pomace which has a specific area of 0.39 m^2/g [28]. Large specific surface area is one of the important reason for the higher uptake of dye on sawdust. Sawdust has a lesser bulk density (0.123 g/cm^3) because of which almost all the surface is available for adsorption. This is also the one of the reason for the higher adsorption capacity of dye on sawdust.

Effect of agitation time

The effect of contact time on dye adsorption on sawdust is investigated to study the rate of dye removal. Fig.1and Fig. 2 show the percentage removal of dye for different values of initial DB and VY dye concentration ranging from 10 to 30 ppm at pH 6.8. It is evident from Fig.1 that time is an important parameter for adsorption of dye on sawdust. While increasing the dye concentration from 10 to 30 ppm, the percentage removal decreases from 67% to 47% for 200 min of contact time. After that, the percentage removal of dye reaches slowly to 85% and 80% for the initial DB dye concentration of 10 and 30 ppm respectively till 900 min (Fig.1). Hence the equilibrium time obtained is 900 min for dye adsorption on sawdust. The nature of adsorbent and the available adsorption sites affect the rate of adsorption of dye. The mechanism of solute transfer to the solid includes diffusion through the fluid film around the adsorbent particle and diffusion through the pores to the internal adsorption sites. In the initial stage of adsorption of dye, the concentration gradient between the film and the available pore sties is large, and hence the rate of adsorption of dye is faster. The rate of adsorption decreases in the later stage of the dye adsorption probably due to the slow pore diffusion of the solute dye into the bulk of the adsorbent [28].

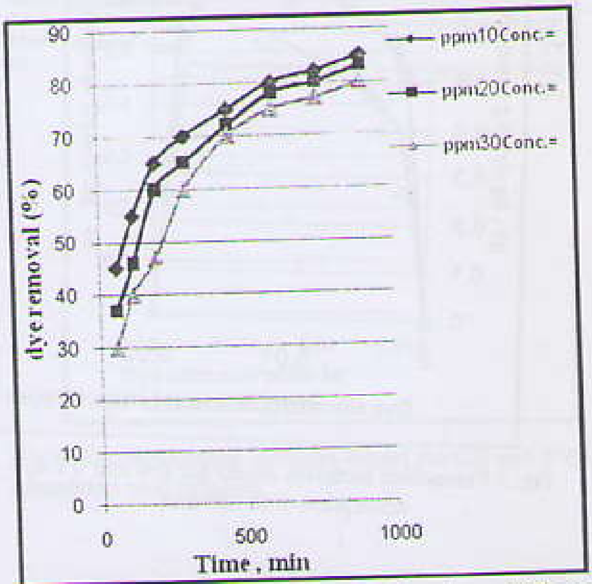

Fig.1 Effect of contact time on the adsorption of DB dye using sawdust at 25°C and pH 6.8 for different initial dye concentrations.

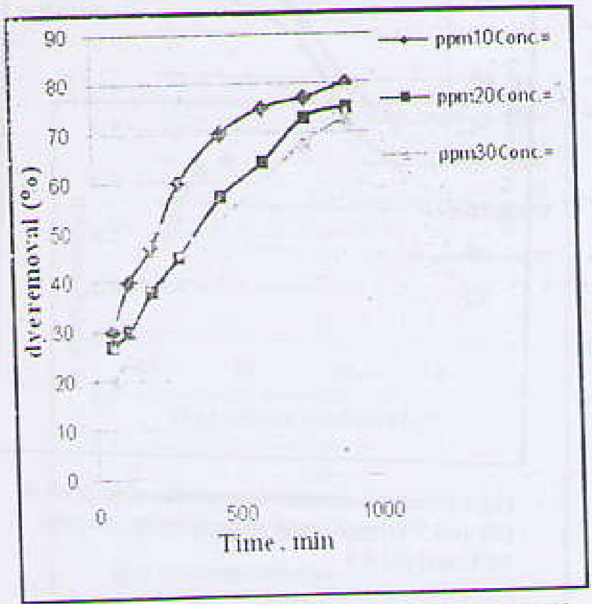

Fig.2 Effect of contact time on the adsorption of VY dye using sawdust at 25°C and pH 6.8 for different initial dye concentrations

Effect of adsorbent dose

Study on the effect of sawdust amount for dye removal is important to get the trade-off between the adsorbent capacity and the percentage removal of dye resulting in an optimum sawdust amount. The influence of sawdust amount, varying from 5 to 25 g/l onto the DB and VY dye adsorption is shown in Fig.3. The percentage of dye removal increases from 50% to 85% with an increase in the sawdust dose from 5 to 25 g/l respectively. The increase in dye removal with an increase in the sawdust amount is due to the increase in surface area and adsorption sites available for adsorption. The drop in adsorption capacity is basically due to the sites remaining unsaturated during the adsorption process [16].

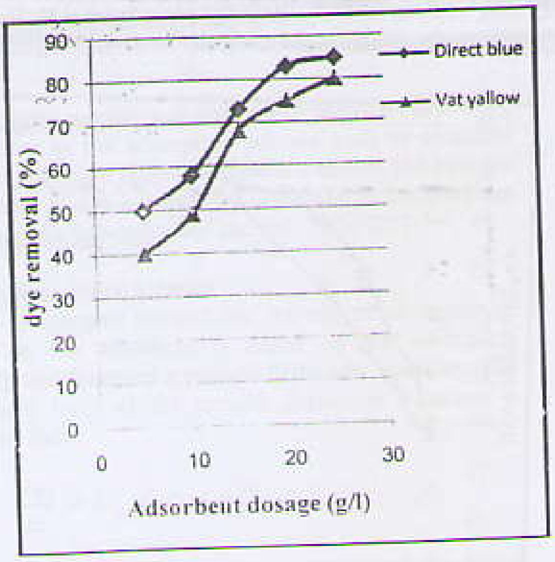

Fig.3 Effect of sawdust dose on the adsorption of DB and VYdye at intial concentration, 10 ppm, 25°C and pH 6.8

Effect of initial concentration

Dye adsorption is significantly influenced by the initial concentration of DB and VY dye in aqueous solutions. In the present study, the adsorption experiments are performed to study the effect of initial dye concentration by varying it from 10 to 30 ppm at an initial pH value of 6.8 while maintaining the sawdust amount of 10 g/l and obtained the results are presented in Fig.1and Fig.2. The results show that with an increase in the DB dye concentration from 10 to 30 ppm, the percentage removal decreases from 85% to 80%. The decrease in the percentage removal of dye can be explained with the fact that all the adsorbents had a limited number of active sites, which have become saturated above a certain concentration [30].

Adsorption isotherm study

Adsorption isotherms are important to describe the adsorption mechanism for the interaction of dye on the adsorbent surface. The equilibrium studies are useful to obtain the adsorption capacity of sawdust for DB and VY dye removal. An adsorption isotherm is characterized by certain constants that express the surface properties and the affinity of the adsorbent towards dye. The equilibrium data for the adsorption of dye using sawdust fits into various isotherm models which results in a suitable model that can be used for the design of an adsorption process. In the present study, seven equilibrium models (The Langmuir, Freundlich, Redlich-Peterson, Koble-Corrigan, Tempkin, Dubinin-Radushkevich and Generalized equation models) are analyzed to investigate the suitable adsorption isotherm, as the adsorbent developed is new, see Fig. 4-10.

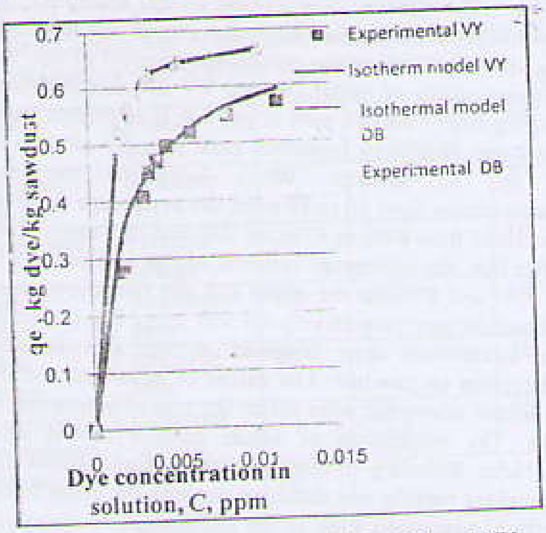

Fig. 4 Langmuir isotherm model for DB and VY dye adsorption onto sawdust

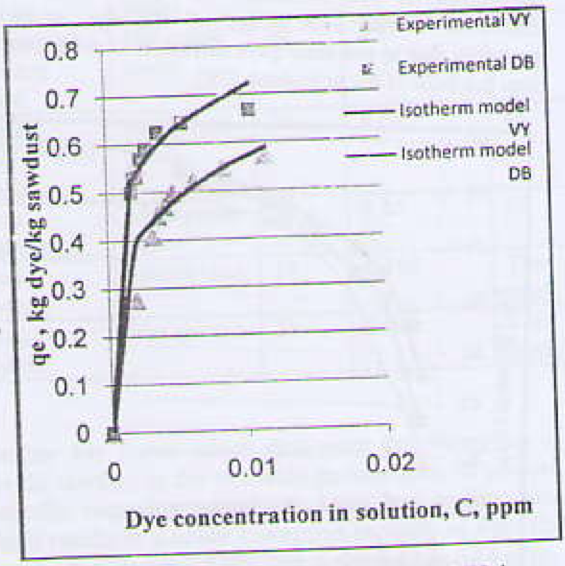

Fig. 5 Freundlich isotherm model for DB and VY dye adsorption onto sawdust.

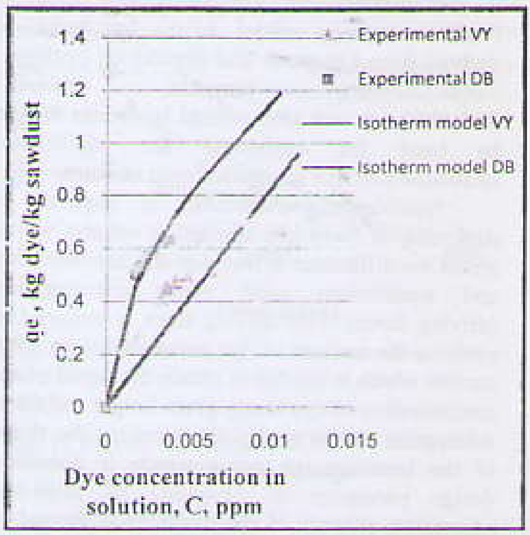

Fig. 6 Redlich-Peterson isotherm model for DB and VY dye adsorption onto sawdust.

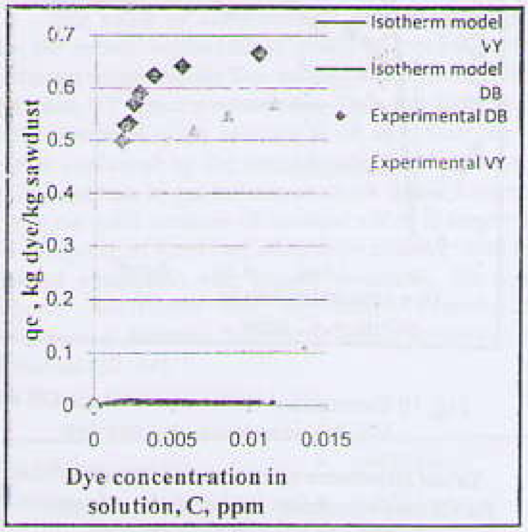

Fig. 8 Tempkin isotherm model for DB and VY dye adsorption onto sawdust.

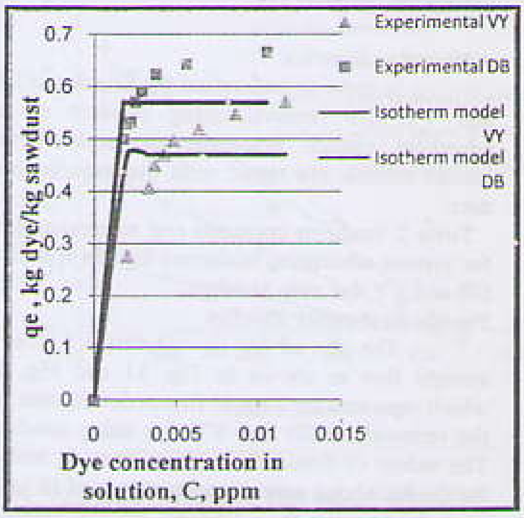

Fig. 7 Koble-Corrigan isotherm model for DB and VY dye adsorption onto sawdust.

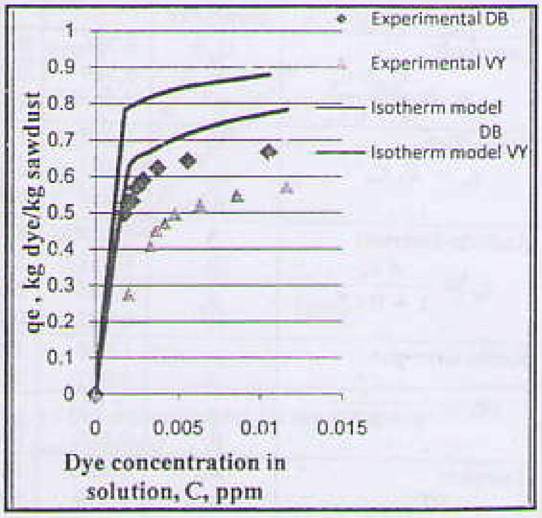

Fig. 9 Dubinin-Radushkevich isotherm model for DB and VY dye adsorption onto sawdust.

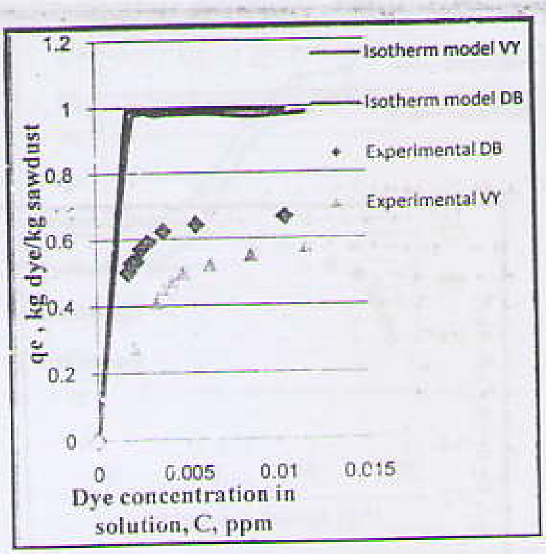

Fig. 10 Generalized isotherm model for DB and VY dye adsorption onto sawdust

Table(2)Isotherm constants and regression data for various adsorption isotherms for adsorption of DB and VY dye onto sawdust

Adsorption isotherm	Isotherm parameter	DB dye	VY dye
Langmuir $q_e = \frac{Q_m b\, C_e}{1 + b\, C_e}$	Q_m b R^2	8.706 0.549 0.991	6.975 0.496 0.974
Freundlich $q_e = K_f\, C_e^{\,n_f}$	K_f n_f R^2	1.678 0.185 0.951	1.691 0.237 0.948
Redlich-Peterson $q_e = \frac{A\, C_e}{1 + B\, C_e^g}$	A B g R^2	142.93 10.512 0.465 0.922	82.54 2.670 2.587 0.922
Koble-Corrigan $q_e = \frac{a\ C_e^n}{1 + b\ C_e^n}$	a b n R^2	1.686 2.957 -2.931 0.886	1.560 3.320 -1.768 0.834
Tempkin $q_e = \frac{RT}{B_T}\ln(A_T\, C_e)$	A_T B_T R^2	1609.5 9.379 0.702	888.62 9.997 0.698
Dubinin-Radushkevich $q_e = Q_m \exp(-K\varepsilon^2)$	Q_m $K\times10^8$ R^2	0.989 1.12 0.918	1.023 1.987 0.914
Generalized $\left(\frac{Q_m}{q_e} - 1\right) = K_G\, C_e^{\,-N_b}$	K_G N_b R^2	28.469 6.171 0.659	21.047 3.776 0.747

Final remarks on isotherm study

From Table 2, the experimental equilibrium data are found to be fitted well with the Langmuir isotherm model which indicates the monomolecular adsorption of dye onto sawdust. It is also fitting with Freundlich and Redlich-Peterson isotherm model, as the last model is derived from Langmuir and Freundlich isotherm. Koble-Corrigan, Tempkin, Dubinin-Radushkevich and Generalized isotherms cannot be used for explaining the equilibrium relationship of dye adsorption onto sawdust.

Equilibrium relationship is required in designing of fixed-bed adsorption column which yields the difference in liquid-phase concentration and equilibrium solid phase concentration (driving force). This driving force is required to evaluate the amount of dye accumulated on solid surface which is needed to obtain the liquid-phase concentration of dye at any given height and time. Adsorption isotherm also characterizes the shape of the breakthrough curve which is dominant design parameter in designing of fixed-bed adsorption column. If the isotherm is favorable, the breakthrough curve becomes steeper which results decrease in the length of unused bed and higher percentage removal of dye of fixed-bed adsorption column [31].

Adsorption kinetics

In order to understand the kinetics of DB and VY dye removal using sawdust as an adsorbent, pseudo first-order and second-order kinetic models are tested with the experimental data.

Table 2 Isotherm constants and regression data for various adsorption isotherms for adsorption of DB and VY dye onto sawdust.

Pseudo first-order kinetics

The plot of *log* $(q_e - q_t)$ versus *t* gives a straight line as shown in Fig. 11 and Fig. 12 which represent the pseudo first-order kinetics for the removal of DB and VY dye using sawdust. The values of first-order rate constant, k_1 and q_e for the initial dye concentration ranges of 10 to 30 ppm, by keeping the adsorbent amount constant (10 g/l), are calculated and listed in Table 3.

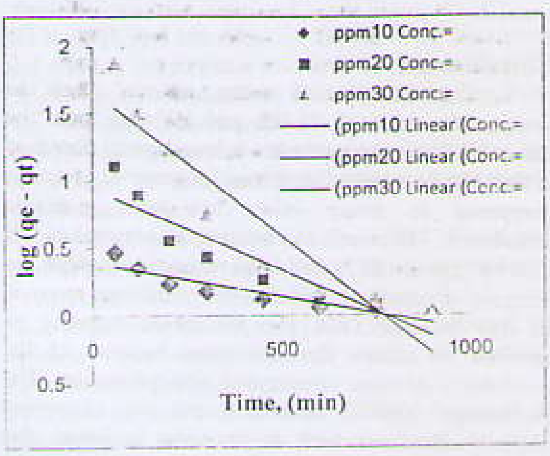

Fig. 11 Pseudo first-order plot for the adsorption of DB dye onto sawdust.

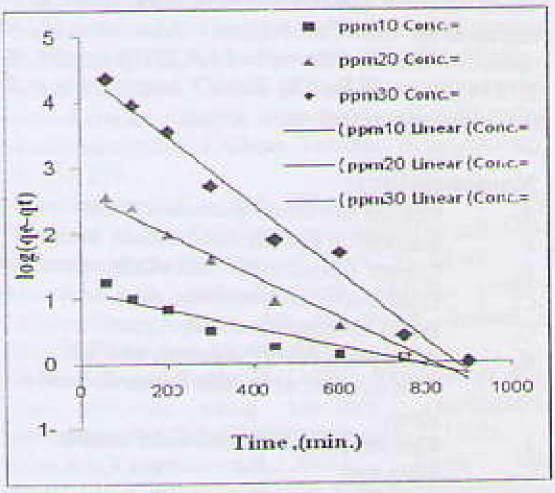

Fig. 12 Pseudo first-order plot for the adsorption

Second-order kinetics

The plot of t / q_t versus t gives a straight line as shown in Fig. 13 and Fig. 14 which represent the second-order kinetics for the removal of DB and VY dye using sawdust. The values of second-order rate constant, k_2 and estimated equilibrium capacity, q_e for the initial dye concentration ranges of 10 to 30 ppm, by keeping the adsorbent amount constant (10 g/l), are calculated and listed in Table 3.

Final remarks on kinetics studies

The value of coefficient of determination (R^2) for the second-order kinetic model is more than that obtained using pseudo first-order models for all initial DB and VY dye concentration. Thus the kinetics of dye adsorption using sawdust as an adsorbent can be better explained by the second-order kinetics model. It is important to get the rate at which dye is adsorbed on to the solid surfaces of sawdust which is important in designing of fixed-bed adsorption column. With the use of adsorption rate kinetic constants, the mass transfer coefficient and equilibrium capacity of adsorbent at different fluid phase concentration can be obtained [32, 34].

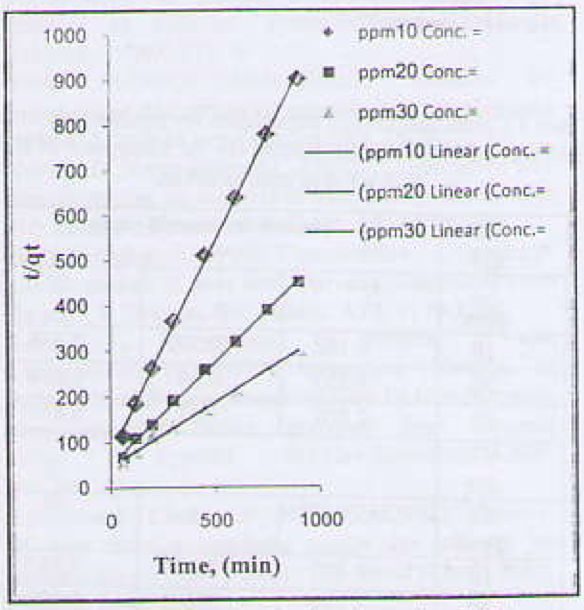

Fig. 13 Second-order plot for the adsorption of DB dye onto sawdust

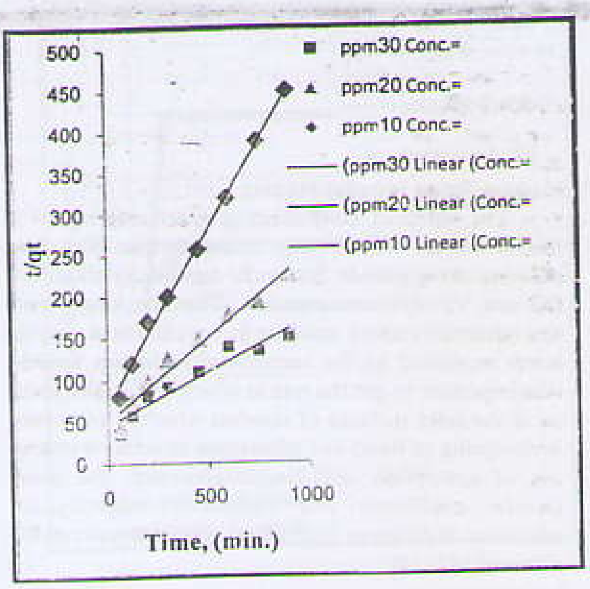

Fig. 14 Second-order plot for the adsorption of VY dye onto sawdust

Table 3 Calculated kinetic parameters for pseudo first-order and second-order kinetic models for the adsorption of DB and VY dye onto sawdust.

DB dye	First-order kinetic model		
C_o ppm	$k_1 \times 10^3$	q_e	R^2
10	0.152	0.392	0.858
20	1.253	0.947	0.859
30	2.207	1.671	0.882
VY dye			
C_o ppm	$k_1 \times 10^3$	q_e	R^2
10	1.405	1.114	0.882
20	3.234	2.643	0.973
30	5.219	4.514	0.982
DB dye	Second-order kinetic model		
C_o ppm	k_2	q_e	R^2
10	0.934	74.226	0.9985
20	0.450	50.271	0.9982
30	0.284	45.376	0.9957
VY dye			
C_o ppm	k_2	q_e	R^2
10	0.4[illegible]6	68.603	0.9957
20	0.159	50.891	0.967
30	0.127	46.364	0.9193

Conclusions

Utilization of waste material such as sawdust for removal of DB and VY dye from the industrial wastewater streams is investigated. Sawdust is found to be a better adsorbent for removal of dye as compared to many other low cost available adsorbents. The maximum percentage removal of DB and VY dye are 85% and 80% respectively. With the increase of adsorbent amount, the percentage removal of dye increases and the adsorption capacity of sawdust to adsorb dye decreases because of the availability of more unsaturated adsorption sites. The percentage removal decreases and the adsorption capacity increases with an increase in initial dye concentration. The equilibrium adsorption data are tested with various isotherm models. The equilibrium data are best fitted with Langmuir isotherm model which confirms the monolayer adsorption of dye onto the sawdust. The maximum adsorption capacity is 8.706 mg/g and 6.975 mg/g for DB and VY respectively. The kinetics of DB and VY dye adsorption using sawdust as an adsorbent for different values of initial dye concentration is explained by the second-order kinetic model, and rate constants (k_2) are obtained which are found to be 0.2837g/mg.min and 0.1274 g/mg.min for DB and VY respectively at the maximum concentration.

Nomenclature:

A_T	Equilibrium binding constant, l/min
b	Adsorption equilibrium constant, l/min
B_T	Costant related to the heat of adsorpton
C_e	Equilibrium concentration, mg/l
C_o	Initial concentration of dye, ppm
K	Adsorption energy constant, mol^2/kJ^2
k_1	Rate constant of pseudo first-order model, l/min
k_2	Rate constant of second-order model, g/mg.min
K_f	Freundlich constant, mg.l/g
K_G	Saturation constant, mg/l
N_b	Cooperative binding constant
n_f	Freundlich coefficient
q_e	Equilibrium adsorption capacity, mg/g
Q_m	Maximum adsorption capacity, mg/g
q_t	Amount of adsorbent at any time, mg/g
R	Universal gas constant (8.314 J/mol.K)
T	Absolute temperature, K
t	Time, min

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