Isotherm Models for Predicting the Dye Adsorption Potential of Coon Tail (*Ceratophyllum demersum*) and Water Milfoil (*Myriophyllum spicatum*)

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ABSTRACT: The dye adsorption potential and characteristics of the submerged aquatic plants *Ceratophyllum demersum* and *Myriophyllum spicatum* were investigated using an azo dye (Basic Blue 41 – BB41). Adsorption equilibria were attained after 160 min at various initial BB41 concentrations (in the range 5–80 mg/l). Attempts were made to fit the equilibrium data obtained using the Langmuir, Freundlich, Redlich–Peterson, Temkin and Dubinin–Radushkevich adsorption isotherm models. The data obtained from the *C. demersum* and *M. spicatum* studies were fitted exactly by the Redlich–Peterson and Temkin adsorption isotherms models with correlation coefficient (r) values of 0.999 and 0.981, respectively. The fits of the Langmuir and Freundlich adsorption isotherm models were also acceptable. Evaluation of the experimental data using the Langmuir equation revealed that the maximum adsorption capacities of *C. demersum* and *M. spicatum* were 50.0 mg/g and 64.9 mg/g, respectively.

INTRODUCTION

Dye-containing wastewaters are well-known pollutants for receiving bodies in industrial areas. Much focus and attention has been placed upon the removal of dyes from waste streams due to the adverse effects of dyes on the environment [see Easton *et al*. (1995)]. Dyes used in the textile industry are largely synthetic, typically derived from coal tar and petroleum-based intermediates. Each dyeing process requires a different amount of dye per unit area of fabric to be dyed (Anon. 1997). The ecological and toxicological characteristics of textile dyes are the main issues for environmentalists and have been the subject of growing attention for some years. In certain countries they have become a criterion on which many rulings are based. Dyes are difficult to degrade once discharged into aquatic bodies. Because of the low biodegradability of many textile dyes, biological treatment is not always effective for textile industry wastewater, and decolouration of textile dye effluent cannot be achieved when the latter is treated aerobically in municipal sewerage systems (Willmott *et al*. 1996). Similarly, while organic matter in textile wastewaters can be assimilated, colours are always resistant to biological treatment. Hence, wastewaters containing such dye materials must be removed through proper methods prior to discharge.

BB41 is commonly used for dyeing carpets, cottons and other textile materials. BB41 is a cationic dye and also contains an azo group (Baran *et al*. 2003). Because of their persistence to

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wastewater treatment, certain researchers have focused on azo dyes. BB41 was selected as a model compound for estimating the adsorption capacity of the plants used in the present study.

The conventional methods for treating dye-containing wastewaters are membrane filtration, coagulation and flocculation (Crawford and Gretlyn 1990), reverse osmosis (Asano 1998) and adsorption (Wong *et al*. 2004). Currently, the most widely used and effective physical method for the treatment of coloured wastewater is adsorption. The most convenient method for designing adsorption systems is the use of adsorption isotherms. The theoretical adsorption capacity of the adsorbent for a particular contaminant can be determined by calculating its adsorption isotherm (Tchobanoglous 2003). The performance of a given adsorption system can be demonstrated through the use of adsorption isotherms. The degree to which adsorption will occur and the resulting equilibrium relationships are correlated according to the empirical relationship of Freundlich and the theoretically derived Langmuir relationship (Eckenfelder 1989). The Langmuir isotherm can be linearised to at least four different types. Furthermore, experimental results can be analysed in terms of the Redlich–Peterson, Temkin and Dubinin–Radushkevich adsorption isotherm equations.

Activated carbon is the most popular and widely used adsorbent. In most industries, activated carbon columns are employed for the treatment of toxic, non-biodegradable wastewaters and as a tertiary treatment following biological oxidation (Eckenfelder 1989). However, it is expensive because of the chemicals required for its regeneration after pollutant removal; the higher the quality, the greater the cost. To replace activated carbon with cheaper alternatives and to utilise various waste products, many novel materials have been tested such as micro-organisms (Hu 1992, 1996; Aksu 2001; Aksu and Tezer 2000; Basibuyuk and Forster 2003), algae (Mohan *et al*. 2002), tree barks (Morais *et al*. 1999; Palma *et al*. 2003), tree fern (Ho *et al*. 2005), banana pith (Namasivayam and Kanchana 1992; Namasivayam *et al*. 1998), neem sawdust (Khattri and Singh 2000, peat (Poots *et al*. 1978), agricultural waste residues (Robinson *et al*. 2002), recycled alum sludge (Chu 2001), Fuller's Earth (Atun *et al*. 2003), lignite (Allen and Brown 1995), perlite (Dogan *et al*. 2000), apple pomace and wheat straw (Robinson *et al*. 2002), bottom ash and de-oiled soy (Mittal *et al*. 2005; Gupta *et al*. 2006), carbon slurry waste (Jain *et al*. 2003), bamboo dust, coconut shell, groundnut shell and rice husk (Kannan and Sundaram 2001), coir pith (Namasivayam *et al*. 2001), orange peel (Namasivayam *et al*. 1996), Indian rosewood sawdust (Garg *et al*. 2004), chitosan and chitin (Juang *et al*. 1996), biogas residual slurry (Namasivayam and Yamuna 1992), activated carbon prepared from plum kernels (Wu *et al*. 1999), fly ash (Wang *et al*. 2005), kaolinite (Ghosh and Bhattacharyya 2002), calcinated alumite (Ozacar and Sengil 2002), cement kiln dust (Nassar *et al*. 2002) and aquatic plants including *Spirodela polyrrhiza* (Waranusantigul *et al*. 2003), *Hydrilla verticillata* (Low *et al*. 1993) and *Eichornia crassipes* (Low *et al*. 1995).

Although the contribution of aquatic plants to wastewater treatment in aquatic systems is already known (Moshiri 1993), there is no literature information on the dye adsorption capacities of *C. demersum* and *M. spicatum* in a batch system. The determination of the dye adsorption capability of submerged plants may contribute to system design approaches to aquatic plant systems for dye-containing wastewaters. Data from any dye adsorption studies can also be incorporated into full-scale field applications through the determination of the adsorption characteristics of these plants.

The aim of the present study was to determine the ability of the Langmuir, Freundlich, Redlich–Peterson, Temkin and Dubinin–Radushkevich equations to model the equilibrium adsorption data. An additional aim was to exhibit the adsorption potential of a dye (BB41) towards *C. demersum* and *M. spicatum* at different dye concentrations.

EXPERIMENTAL

Materials and methods

The aquatic plants, *M. spicatum* and *C. demersum,* were collected from agricultural drains near the Seyhan river (Adana, Turkey) (Figure 1). All experiments were undertaken using the specified aquatic plants in a batch system. *C. demersum* (coon tail or hornwort), commonly seen in lakes, ponds, ditches and quiet streams with moderate to high nutrient levels, is entirely submerged with stem lengths of 0.5–3.0 m forming long, branched, large masses (Johnson *et al*. 1995; Wagner *et al*. 1999). *C. demersum* usually grows in hard water lakes and does not produce roots. Instead, it absorbs all the nutrients it requires from the surrounding water. When growing near the lake bottom, it will form modified leaves which are used to anchor it to the sediment (Johnson *et al*. 1995).

M. spicatum (water milfoil) is a perennial submerged aquatic plant. It is a highly invasive and aggressive species that colonizes reservoirs, lakes, ponds, streams, small rivers and the brackish waters of estuaries and bays (Figure 1). Upon collection, both plant specimens were washed with dilute hydrochloric acid (3%, v/v) and rinsed with distilled water before application. The dyestuff, BB41 (C.I. No. 11105), was obtained from a local textile mill. The structure of the dye used is as shown in Figure 2.

A stock solution of BB41 was prepared using de-ionised water. Adsorption tests were conducted at 298 K in conical flasks (250 ml) using an orbital shaker operated at 200 rpm. The initial pH values were maintained between 6 and 7 during the batch experiments and no pH adjustment was made throughout the study. A known amount (2 g wet weight) of *C. demersum* and *M. spicatum* were added to each flask placed on the orbital shaker. The initial dye concentrations for the batch experiments were 5, 10, 20, 40 and 80 mg/l and the contact times were 5, 10, 20, 40, 80, 160 and 320 min. After contacting for the above time lengths, samples of the supernatant aqueous phase were taken and centrifuged at 4000 rpm before being analysed spectrophotometrically (Bausch & Lomb UV–vis spectrophotometer) at a wavelength (λ) of 609 nm to determine the amount of dye remaining in the sample systems. Control experiments were also performed to establish whether



Figure 1. (a) *Ceratophyllum demersum* and (b) *Myriophyllum spicatum* (illustrations provided by Institute of Food and Agricultural Sciences, Center for Aquatic and Invasive Plants, University of Florida, Miami, FL. USA).

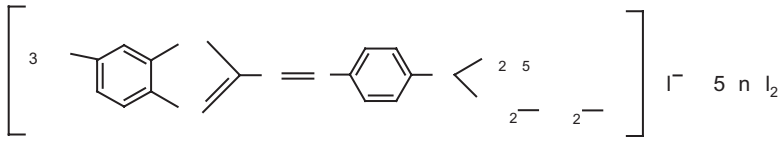


Figure 2. Structure of BB41 (Baran *et al*. 2003).

the dye exhibited any measurable adsorption onto the glassware. Neither precipitation nor adsorption onto the walls of the flasks was observed. The results of the dye analysis were used to calculate the specific adsorption (mg dye adsorbed/g biomass, dry weight). The specific adsorption (q) for *C. demersum* was calculated from the following equation:

$$q = \frac{(C_0 - C_e)V}{W} \quad (1)$$

where C_0 and C_e are the initial and equilibrium concentrations of the dye in the aqueous phase, V is the volume of the aqueous phase and W is the amount of dry adsorbent (g) employed as calculated from the wet weight and water content of *C. demersum* and *M. spicatum*. All experiments were conducted in duplicate and the results are presented as mean values. The difference between the duplicate experiments was within 5%. The equilibrium data were evaluated to obtain the contact time and the corresponding isotherms.

RESULTS AND DISCUSSION

Effects of contact time and dye concentration

Initial pH values between 6 and 7 provided a suitable environment for dye adsorption by *C. demersum* and *M. spicatum*. The adsorption data obtained (Figure 3) clearly show the adsorption of the dye by *C. demersum*. The data further show that the time necessary to achieve equilibrium at 5, 10, 20, 40 and 80 mg/l concentrations of BB41 was 160 min. The amount of dye removed per g of *C. demersum* increased with increasing initial dye concentrations.

A similar trend for the adsorption of BB41 was also observed with *M. spicatum* (Figure 4). In this case also, the equilibrium time observed for 5, 10, 20, 40 and 80 mg/l concentrations of BB41 was 160 min. It was clear in all experiments that the dye concentration was an important factor and that the amount of dye removed per g of *M. spicatum* increased with increasing initial dye concentrations.

Isotherms

Adsorption data for a wide range of adsorbate concentrations are generally examined via the Langmuir and Freundlich isotherms. However, equilibrium relationships between an adsorbent (plant) and an adsorbate (BB41) can also be described by adsorption isotherms such as those of Temkin, Redlich–Peterson and Dubinin–Radushkevich. These various isotherms have all been employed to study the adsorption isotherms for BB41 on *C. demersum* and *M. spicatum*, with the adsorption process being explained in terms of these isotherms.

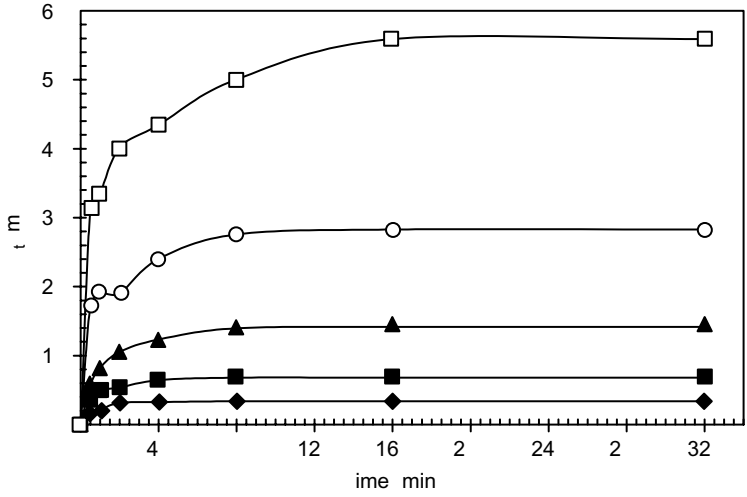


Figure 3. Kinetic results for the adsorption of BB41 at various time intervals (q_t) by *C. demersum* at various initial BB41 concentrations: ◆, 5 mg/l; ■, 10 mg/l; ▲, 20 mg /l; ○, 40 mg/l; □, 80 mg/l.

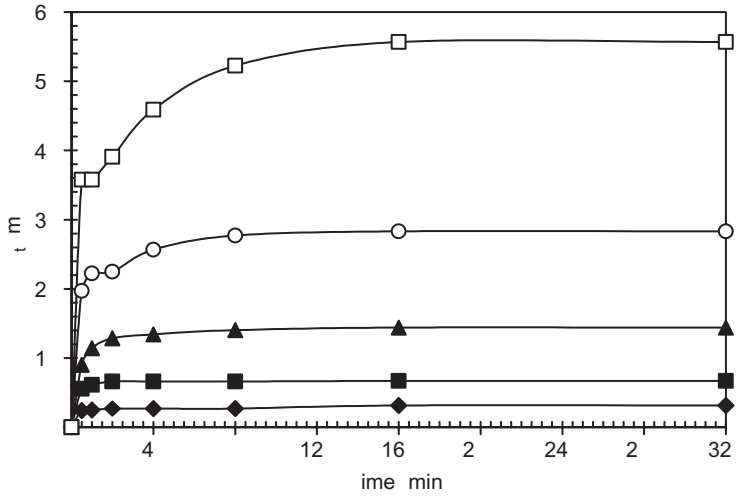


Figure 4. Kinetic results for the adsorption of BB41 at various time intervals (q_t) by *M. spicatum* at various initial BB41 concentrations: ◆, 5 mg/l; ■, 10 mg/l; ▲, 20 mg /l; ○, 40 mg/l; □, 80 mg/l.

The Langmuir isotherm theory assumes monolayer coverage of the adsorbate over a homogenous adsorbent surface. The Langmuir isotherm may be expressed by the following equation (Langmuir 1918):

$$q_e = \frac{q_{max} K_a C_e}{1 + K_a C_e} \quad (2)$$

where C_e is the equilibrium solute concentration (mg/l), q_e is the amount of dye sorbed at equilibrium (mg/g), q_{max} is the maximum adsorption capacity (mg/g) and K_a is the Langmuir constant (l/mg) which is related to the energy of adsorption. The Langmuir isotherm may be linearised using equations (3)–(6) (Longhinotti *et al*. 1998):

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

$$\frac{1}{q_e} = \left(\frac{1}{K_a q_{max}}\right) \frac{1}{C_e} + \frac{1}{q_{max}} \tag{4}$$

$$q_e = q_{max} - \left(\frac{1}{K_a}\right) \frac{q_e}{C_e} \tag{5}$$

$$\frac{q_e}{C_e} = K_a q_{max} - K_a q_e \tag{6}$$

The performance and capability of equations (3)–(6) were tested by applying them to the experimental data. The Langmuir constants, q_{max}, and the values of K_a could be calculated from plots of C_e/q_e versus C_e, $1/q_e$ versus $1/C_e$, q_e versus q_e/C_e and q_e/C_e versus q_e as obtained via equations (3)–(6), respectively. Plots for the adsorption of BB41 onto *C. demersum* and *M. spicatum* at pH values between 6 and 7 are depicted in Figures 5–8, respectively.

The corresponding equilibrium values for the Langmuir constants are listed in Table 1. The correlation coefficients listed in the table show that the data for the *C. demersum* and *M. spicatum* systems could be fitted by Langmuir equations (4) and (3), respectively (r = 0.998 and 0.800). The values of the Langmuir constants, q_e, calculated from an application of equations (4) and (3) indicate that the maximum dye adsorption capacities of *C. demersum* and *M. spicatum* were 50.0 mg/g and 64.9 mg/g, respectively, without any pH adjustment. Table 2 shows a comparison of the

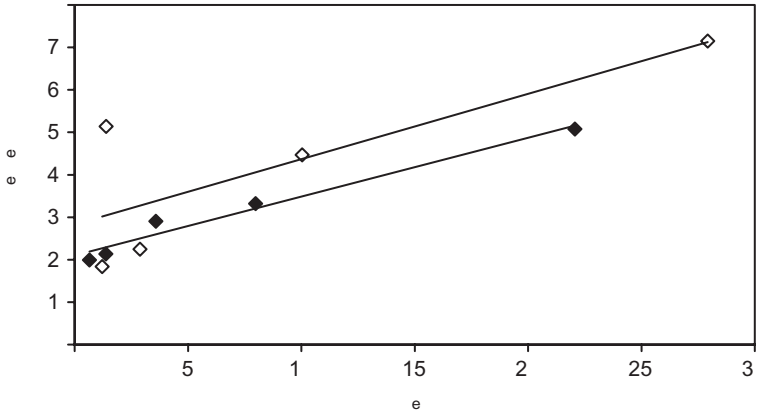


Figure 5. Langmuir isotherm of BB41 adsorbed onto *C. demersum* (◆) and *M. spicatum* (◇) as derived from equation (3).

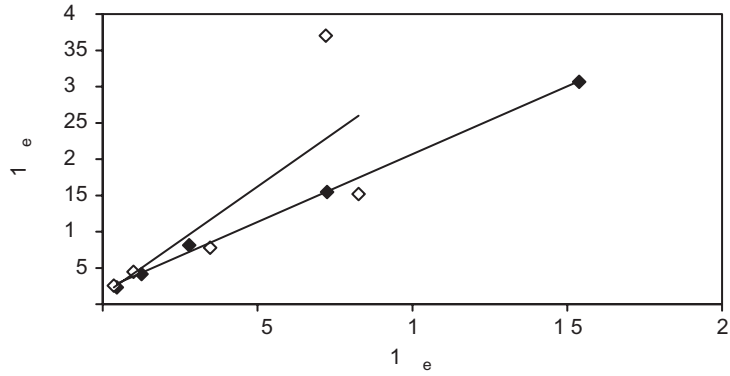


Figure 6. Langmuir isotherm of BB41 adsorbed onto *C. demersum* (◆) and *M. spicatum* (◇) as derived from equation (4).

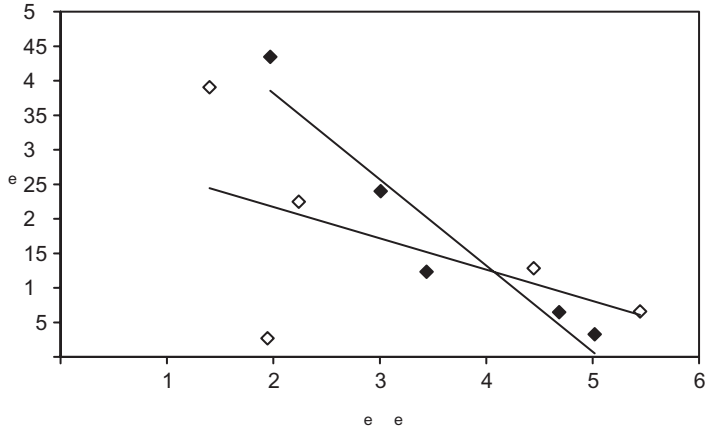


Figure 7. Langmuir isotherm of BB41 adsorbed onto *C. demersum* (◆) and *M. spicatum* (◇) as derived from equation (5).

predicted maximum adsorption capacities for the BB41 molecule per g plant species with those obtained by other workers for the same dye molecule on other materials. Even though the adsorption capacities for the materials studied in the present work were lower than those for materials in previous studies, the use of our materials for the tertiary treatment of wastewater containing BB41 could have the following advantages:

- *C. demersum* and *M. spicatum* are invasive plants and are found abundantly in lakes, ponds, streams and small rivers throughout the year.
- *C. demersum* and *M. spicatum* do not need any processing whereas the materials used in the various studies listed in Table 2 required processing before their use as adsorbents.
- The performances of the materials studied previously depended on various external factors such as the pH, particle size and temperature.

Hence, the materials studied in the present work are likely to have lower associated costs relative to the various other materials listed in Table 2.

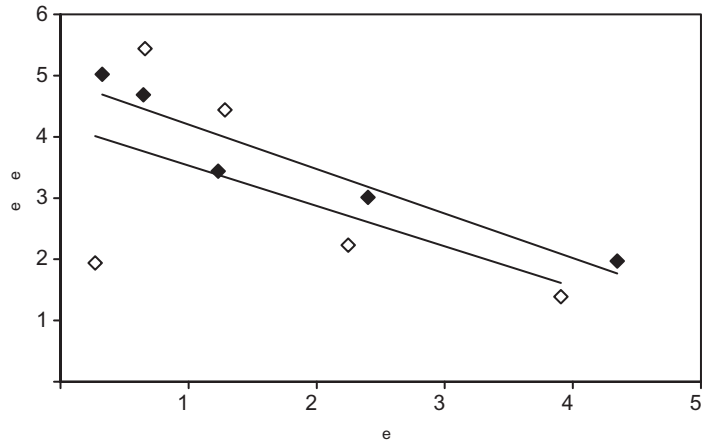


Figure 8. Langmuir isotherm of BB41 adsorbed onto *C. demersum* (◆) and *M. spicatum* (◇) as derived from equation (6).

TABLE 1. Summary of Correlation Coefficients (r) and Isotherm Parameters

Isotherms	Parameters	Plants	
		M. spicatum	*C. demersum*
Langmuir [equation (3)]	q_{max}	64.9	71.9
	K_a	0.054	0.066
	r	0.800	0.989
Langmuir [equation (4)]	q_{max}	79.3	50.0
	K_a	0.042	0.107
	r	0.760	0.998
Langmuir [equation (5)]	q_{max}	38.7	63.0
	K_a	0.220	0.080
	r	0.546	0.952
Langmuir [equation (6)]	q_{max}	63.5	67.7
	K_a	0.066	0.072
	r	0.547	0.952
Freundlich	K_F	4.125	4.809
	1/n	0.710	0.735
	r	0.915	0.997
Redlich–Peterson	A	6.148	5.090
	B	0.328	0.144
	g	0.703	0.775
	r	0.659	0.999
Temkin	K_T	1.146	1.811
	b_T	0.234	2.774
	r	0.981	0.958
Dubinin–Raduskevich	K_{DR}	0.035	0.160
	X_m	19.96	251.18
	r	0.297	0.979

TABLE 2. Comparison of the Maximum Adsorption Capacity, q_{max} (mg/g), for BB41 on Various Adsorbents

Adsorbent	q_{max} (mg/g)	References
C. demersum	50.00	This study
M. spicatum	64.90	This study
Hard wood	88.70	Asfour *et al*. (1985)
Linseed cake	407.70–573.00	Liversidge *et al*. (1997)
Peat	363.10	Liversidge *et al*. (1997)
Biodegradable wastes	77.00–164.00	Elizalde-González and Peláez-Cid (2003)

Non-linear and linear forms of the Langmuir equation have also used by Kumar and Sivanesan (2005) and by Ho *et al*. (2005a,b) for evaluating experimental data. According to Kumar and Sivanesan, the non-linear method provides a better route for obtained equilibrium isotherm parameters. However, Ho *et al*. used the linear Langmuir isotherm equations to describe their experimental data. Linear forms of the Langmuir equation have been employed in the current study, from which it was found that the correlation coefficient for the *C. demersum* data was higher than that for the *M. spicatum* data.

The basic features of the Langmuir isotherm can be expressed in terms of a dimensionless constant separation factor or equilibrium parameter, R_L (Hall *et al*. 1966), which may be expressed by the relationship:

$$R_L = \frac{1}{1 + K_a C_0} \tag{7}$$

where K_a is the Langmuir constant and C_0 the initial dye concentration. The value of R_L may be related to the shape of isotherms as follows:

Value of R_L	Type of isotherm
$R_L > 1$	Unfavourable
$R_L = 1$	Linear
$0 < R_L < 1$	Favourable
$R_L = 0$	Irreversible

Using the form of the Langmuir equation expressed in equations (4) and (3) for the data for the adsorption of *C. demersum* and *M. spicatum*, respectively, the R_L values determined for 5, 10, 20, 40 and 80 mg/l BB41 solutions were determined as 0.651, 0.483, 0.467, 0.233, 0.116 and 0.786, 0.647, 0.478, 0.314, 0.186, respectively. Since all these R_L values lie between 0 and 1, the adsorption of BB41 onto *C. demersum* and *M. spicatum* may be described as favourable.

The Freundlich equation includes a heterogeneity factor, 1/n; the lower the value of this factor, the higher the heterogeneity of the adsorbent surface. The linearised form of the Freundlich isotherm expressed in equation (8) was used to assess whether the experimental data fitted the Freundlich isotherm:

$$\log q_e = \log K_F + 1/n \log C_e \tag{8}$$

where q_e is the solid-phase adsorbate concentration at equilibrium (mg/g), C_e is the liquid-phase adsorbate concentration at equilibrium (mg/l), the constant K_F, i.e. the Freundlich constant, is an indicator of the adsorption capacity while 1/n is the heterogeneity factor. The constants K_F and n incorporate all the various factors capable of affecting the adsorption process (Freundlich 1926). To examine the application of the Freundlich isotherm as expressed by equation (8) to the adsorption data obtained, plots were undertaken of log q_e versus log C_e as depicted in Figure 9. The values of the corresponding constants K_F and n obtained at various initial dye concentrations are also listed in Table 1.

The Redlich–Peterson isotherm may be expressed by the following equation (Redlich and Peterson 1959):

$$q_e = \frac{AC_e}{1 + BC_e^g} \tag{9}$$

where A, B and g all representing isotherm constants. The linearised form of the Redlich–Peterson isotherm equation may be written as:

$$\ln\left(A\frac{C_e}{q_e} - 1\right) = g \ln C_e + \ln B \tag{10}$$

Since the Redlich–Peterson isotherm equation includes three unknown parameters (A, B and g), the MS Excel® Solver package was applied to determine those values of A, B and g which corresponded to the maximum correlation coefficient, r. Using equation (9), the values of A, B and g ascertained for *C. demersum* and *M. spicatum* were 5.090, 0.144, 0.775 and 6.148, 0.328, 0.703, respectively. Based on the correlation coefficients for the Redlich–Peterson isotherm listed in Table 1, it can be seen that this equation could not adequately explain the adsorption process for *M. spicatum* (r = 0.659) although that for *C. demersum* could be well expressed (r = 0.999). The Redlich–Peterson isotherms for both plants obtained through the application of equation (9) are plotted in Figure 10.

As seen in the figure, the values obtained from the *C. demersum* isotherm correlated well with the linearised regression line, whereas the corresponding *M. spicatum* isotherm values were skewed from the regression line at lower BB41 concentrations.

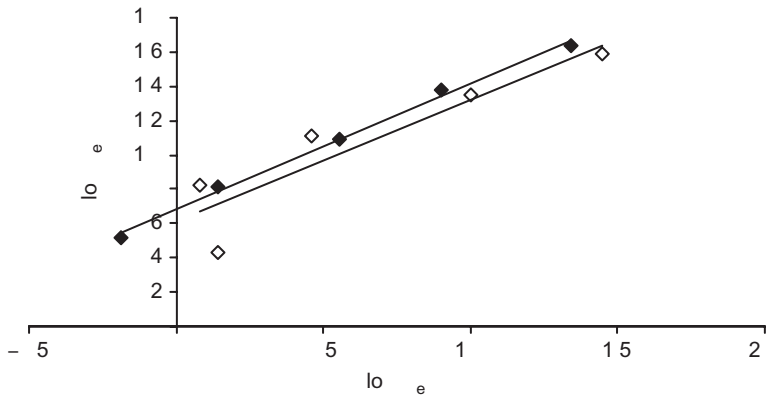


Figure 9. Freundlich isotherm of BB41 adsorbed onto *C. demersum* (◆) and *M. spicatum* (◇) as derived from equation (8).

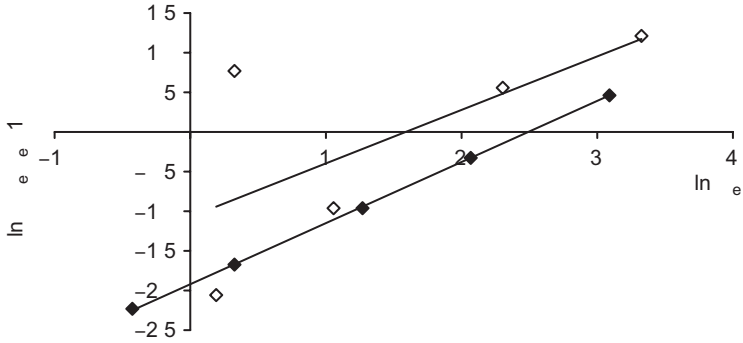


Figure 10. Redlich–Peterson isotherm of BB41 adsorbed onto *C. demersum* (◆) and *M. spicatum* (◇) as derived from equation (9).

The experimental data were also examined using the linearised form of the Temkin isotherm model given below in equation (11) and plotted in Figure 10 as q_e versus ln C_e (Temkin and Pyzhev 1940):

$$q_e = \frac{RT}{b_T} \ln K_T + \frac{RT}{b_T} \ln C_e \qquad (11)$$

where $1/b_T$ corresponds to the adsorption potential of the adsorbent and K_T is the Temkin isotherm constant (l/g). Using equation (11) it was possible to calculate the Temkin adsorption potential, K_T, of *C. demersum* biomass for BB41 and the Temkin constant, b_T, related to the adsorption heat of the BB41 molecules. These values are also listed in Table 1.

Since the Temkin isotherm assumes that the adsorption enthalpy changes linearly with adsorbate concentration, it can be inferred from the results plotted in Figure 11 that the adsorption enthalpy increased linearly for both *C. demersum* and *M. spicatum*.

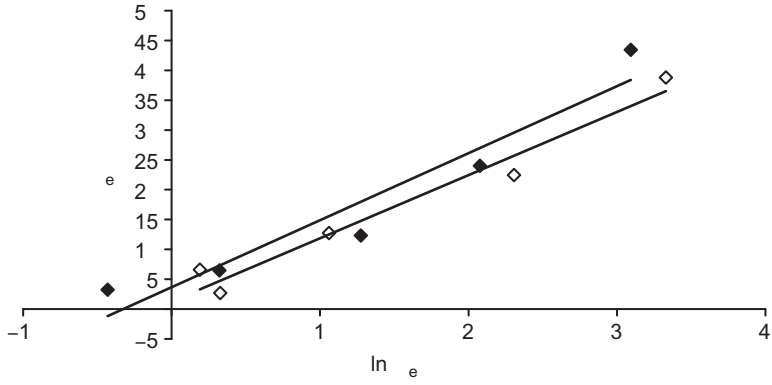


Figure 11. Temkin isotherm of BB41 adsorbed onto *C. demersum* (◆) and *M. spicatum* (◇) as derived from equation (11).

Another model employed for estimating the characteristic porosity and apparent free energy of adsorption was that of Dubinin and Radushkevich. The linearised form of the Dubinin–Radushkevich equation is given in equation (12) (Horsfall and Spiff 2005):

$$\ln q_e = \ln X_m - K_{DR}\varepsilon^2 \tag{12}$$

where K_{DR} is related to the free energy of adsorption and X_m is the Dubinin–Radushkevich isotherm constant related to the degree of sorbate adsorption by the biomass surface. The initial value of ε was found using equation (13) as expressed below and this value was then incorporated into equation (12) to determine the values of K_{DR} and X_m. These are also tabulated in Table 1.

$$\varepsilon = RT \ln\left(\frac{C_0}{C_e}\right) \tag{13}$$

For *C. demersum*, the porosity factor, K_{DR}, for the plant biomass towards BB41 was found to be 0.1607. A value of K_{DR} less than unity implies that the use of *C. demersum* biomass for the removal of BB41 may require several cycles to reduce the dye concentration below the desired level. Confirmation of the isotherm model was obtained by plotting ln q_e versus ε^2 when the data points yielded a straight regression line (Figure 12). The corresponding listed values of K_{DR} and X_m for the *M. spicatum* data indicate that the correlation coefficient (r) for the Dubinin–Radushkevich isotherm was low (0.297).

Figures 13 and 14 show the experimental data and the predicted equilibrium curves for the equilibrium isotherms of *C. demersum* and *M. spicatum* at 298 K, respectively. It will be seen from the data recorded in Table 1 for *C. demersum* that the value of the correlation coefficient for the Langmuir equation [equation (4)] was higher than those for the Freundlich, Temkin and Dubinin–Radushkevich isotherms, but lower than that for the Redlich–Peterson equation. Hence the Langmuir equation as expressed in equation (4) represents a better fit for the experimental data than the other isotherm equations, other than the Redlich–Peterson isotherm (Figure 13). This figure shows that the isotherm values obtained for q_e from an application of the Redlich–Peterson

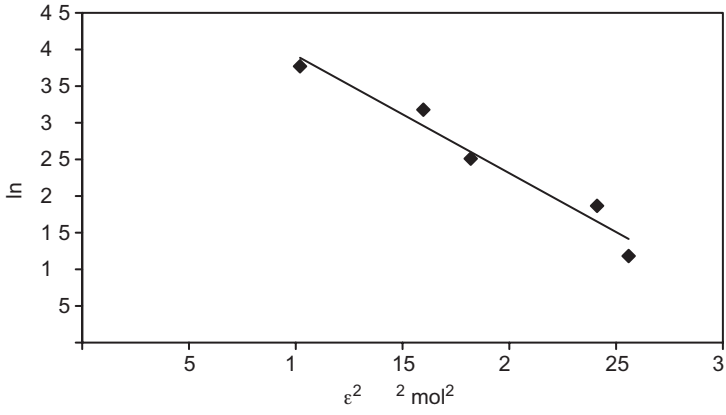


Figure 12. Dubinin–Radushkevich isotherm of BB41 adsorbed onto *C. demersum* as derived from equation (12).

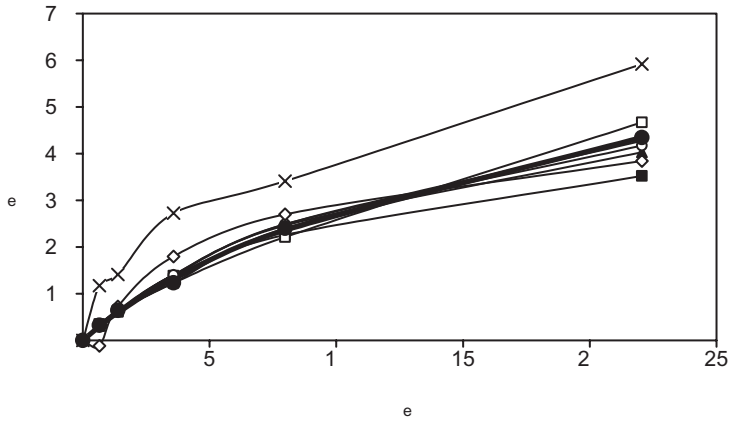


Figure 13. Comparison of an application of different isotherms for describing the adsorption of BB41 onto *C. demersum*. The data points correspond to the following: ●, experimental data; ◆, Langmuir [equation (3)]; ■, Langmuir [equation (4)]; ▲, Langmuir [equation (5)]; ○, Langmuir [equation (6)]; □, Freundlich; ◇, Temkin; ×, Dubinin–Radushkevich; ——, Redlich–Peterson.

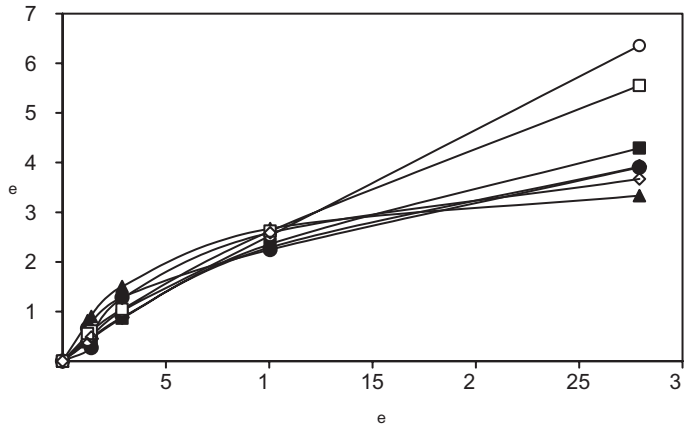


Figure 14. Comparison of an application of different isotherms for describing the adsorption of BB41 onto *M. spicatum*. The data points correspond to the following: ●, experimental data; ◆, Langmuir [equation (3)]; ■, Langmuir [equation (4)]; ▲, Langmuir [equation (5)]; ○, Langmuir [equation (6)]; □, Freundlich; ◇, Temkin.

and Langmuir equations [equation (4)] to the experimental data overlap perfectly with the experimental q_e line. On the other hand, the value of the correlation coefficients for the Freundlich and Langmuir equations [equation (3)] were higher than the ones calculated from the Redlich–Peterson and Dubinin–Radushkevich isotherms, but not from the Temkin equation for *M. spicatum* [Figure (14)]. Thus, the Temkin equation provides a better fit for the experimental data for this species than all the other isotherms studied. Plots for the Redlich–Peterson and Dubinin–Radushkevich isotherms are not depicted in Figure 14 since their correlation (r) values were much lower than those obtained for other isotherms.

CONCLUSIONS

The present study has shown that the textile dye BB41 can be removed by adsorption onto the submerged aquatic plants *C. demersum* and *M. spicatum*. The Langmuir, Freundlich, Redlich–Peterson, Temkin and Dubinin–Radushkevich adsorption isotherms were used in an attempt to obtain a mathematical description of the adsorption of BB41 onto *C. demersum* and *M. spicatum* biomass. Characteristic parameters for each isotherm and related correlation coefficients were determined from the linear plots of these equations. The correlation coefficients for the Langmuir and Freundlich isotherms were in the range ca. 0.800–0.998. However, the Redlich–Peterson and Temkin isotherms were shown to provide the best correlation for the adsorption data of BB41 dye onto *C. demersum* and *M. spicatum*, respectively (r = 0.999 and 0.981). On the basis of the Langmuir constants, maximum adsorption capacities (q_m) of 50.0 and 64.9 mg/g were obtained for BB41 onto *C. demersum* and *M. spicatum*, respectively.

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