

Sorption equilibrium and kinetics of basic dye from aqueous solution using banana stalk waste

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Abstract

The sorption of basic dye from aqueous solutions by banana stalk waste (BSW), an abundant agricultural waste in Malaysia, was studied in a batch system with respect to pH and initial dye concentration. Sorption isotherm of methylene blue (MB) onto the BSW was determined at 30 °C with the initial concentrations of MB in the range of 50–500 mg/L. At pH 2.0, the sorption of dye was not favorable, while the sorption at other pHs (4.0–12.0) was remarkable. Equilibrium data were fitted to the Langmuir, Freundlich and Temkin isotherm models. The equilibrium data were best represented by the Langmuir isotherm model, with maximum monolayer adsorption capacity of 243.90 mg/g. The sorption kinetic data were analyzed using pseudo-first-order, pseudo-second-order and intraparticle diffusion models. It was found that the pseudo-second-order kinetic model was the best applicable model to describe the sorption kinetics. The results showed that BSW sorbent was a promising for the removal of MB from aqueous solutions.

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Keywords: Banana stalk waste; Methylene blue; Sorption isotherm; Equilibrium; Kinetics

1. Introduction

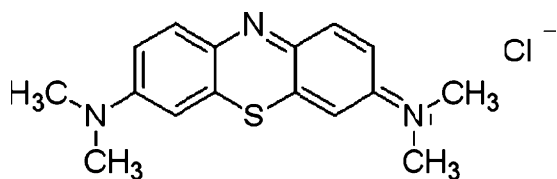
Removal of synthetic dyestuffs from aqueous solution is necessary because of the frequent appearance of these dyestuffs in wastewaters generated from textile and other industries. The presence of dyes in water is undesirable since even a very small amount of these coloring agents is highly visible and may be toxic to the aquatic environment [1–5]. Therefore, removal of dyes is an important aspect of wastewater treatment before discharge.

Activated carbon is the most popular and widely used adsorbent, but there are certain problems with its use. It is expensive and the higher the quality the greater the cost. Furthermore, regeneration using solutions produces a small additional effluent, while regeneration by refractory technique results in a 10–15% loss of adsorbent and its uptake capacity. Therefore, there is a growing interest in using low-cost, easily available materials for the adsorption of dye colors [6].

Because of its low-cost and widespread availability, biomass has often been investigated to remove dyes from aqueous solutions. These include palm ash [7,8], *Posidonia oceanica* (L.) fibers [9], *Luffa cylindrica* fibers [10] and coconut copra meal [11]. In this work, we attempt to use abundantly available lignocellulosic agricultural wastes, banana stalk, as a sorbent to remove methylene blue (MB) from aqueous solution. Banana (*Musa sapientum*) is native to Southeast Asia, where it was one of the first cultivated crops. In Malaysia, banana is grown in most of the states. It remains the second most important fruit crop (after durian). Most of the bananas produced are consumed locally and about 10% are exported. The banana plant (*Musa cavendishii*) produces a residual component named fruit stalk with holocellulose and lignin corresponding to 33 and 8.67% of the dry weight of this component, respectively [12]. The banana fruit stalk which accumulates in the agro-industrial yards, has no significant industrial and commercial uses, but contributes to serious environmental problems [13]. Typically, this banana stalk was casually disposed of into landfills and rivers where it would oxidize and harm the local ecology. Therefore, any attempt to reutilize the banana stalk waste (BSW) will be useful. Recently, the banana stalk was used as a precursor material for the preparation of an adsorbent with carboxylate functionality

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Scheme 1. Chemical structure of methylene blue.

by grafting polyacrylamide onto banana stalk using the Fe^{2+} - H_2O_2 redox initiator system [14]. Shibi and Anirudhan [15] prepared polyacrylamide grafted banana stalk, (PGBS) having $-\text{COOH}$ group (PGBS-COOH) from banana stalk (a waste and an inexpensive precursor), for the removal of $\text{Co}(\text{II})$ from aqueous solutions.

The purpose of this work was to investigate the feasibility of BSW as a sorbent for the removal of methylene blue from aqueous solution. Adsorption isotherms and kinetics of the sorption process were studied. Further, a single-stage batch adsorber has been designed for the removal of methylene blue by BSW based on the equilibrium data obtained.

2. Materials and methods

2.1. Adsorbate

The basic dye used in this study was MB purchased from Sigma-Aldrich. The maximum wavelength of this dye is 668 nm. The structure of MB is shown in Scheme 1.

2.2. Sorbent

The BSW used for the preparation of the adsorbent was collected from the main fruit market of Nibong Tebal, Penang. It was washed with distilled water to remove the surface adhered particles and water-soluble materials. Then it was sliced, spread on trays and oven dried at 60°C for 48 h. The dried slices were ground and sieved to obtain a particle size range of 0.5–1 mm and stored in plastic bottle for further use. No other chemical or physical treatments were used prior to adsorption experiments.

2.3. Equilibrium studies

Adsorption experiments were carried out by adding a fixed amount of sorbent (0.20 g) into 250-ml Erlenmeyer flasks containing 200 ml of different initial concentrations (50–500 mg/L) of dye solution. The temperature was controlled at 30°C . Agitation was provided at 100 rpm for 5 h and 30 min. The initial and equilibrium dye concentrations were determined by absorbance measurement using double beam UV–vis spectrophotometer (Shimadzu, Model UV 1601, Japan) at 668 nm. It was then computed to dye concentration using standard calibration curve. The amount of adsorption at equilibrium, q_e (mg/g), was calculated by

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

where C_0 and C_e (mg/L) are the liquid-phase concentrations of dye at initial and equilibrium, respectively. V (L) is the volume of the solution and W (g) is the mass of dry sorbent used.

The dye removal percentage can be calculated as follows:

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

where C_0 and C_e (mg/L) are the liquid-phase concentrations of dye at initial and equilibrium, respectively.

2.4. Effect of solution pH

The effect of initial solution pH was determined by agitating 0.20 g of BSW sorbent and 200 mL of dye solution of initial basic dye concentration of 100 mg/L using water-bath shaker (30°C) at different solution pH ranging from 2 to 12. Agitation was provided for 5.50 h contact time which is sufficient to reach equilibrium with a constant agitation speed of 100 rpm. The pH was adjusted by adding a few drops of diluted NaOH or HCl.

2.5. Batch kinetic studies

Kinetic experiments were identical to those of equilibrium tests. The aqueous samples were taken at preset time intervals and the concentrations of MB were similarly measured. The amount of sorption at time t , q_t (mg/g), was calculated by

$$q_t = \frac{(C_0 - C_t)V}{W} \quad (3)$$

where C_t (mg/L) is the liquid-phase concentrations of dye at any time.

2.6. Scanning electron microscopy and Fourier transform infra red study

Scanning electron microscopy (SEM) analysis was carried out on the BSW to study its surface texture before and after adsorption. Fourier transform infrared (FTIR) analysis was applied on the BSW to determine the surface functional groups, by using FTIR spectroscope (FTIR-2000, PerkinElmer), where the spectra were recorded from 4000 to 400 cm^{-1} .

3. Results and discussion

3.1. Effect of solution pH on dye adsorption

The effect of initial pH on equilibrium uptake capacity of BSW was studied at 100 mg/L initial MB concentration and at 30°C . Fig. 1 shows that the sorption of MB was minimum at the initial pH 2 and increased with pH up to 4.0 and then remained nearly constant over the initial pH ranges of 4–12. Therefore, a pH 7 was chosen for the study of the effect of contact time and initial MB concentration. The fact that the MB sorption rate on the BSW was low at lower pH may be because the surface charge may become positively charged, thus making (H^+) ions compete effectively with dye cations causing a decrease in the amount of dye adsorbed. A similar behavior was observed for

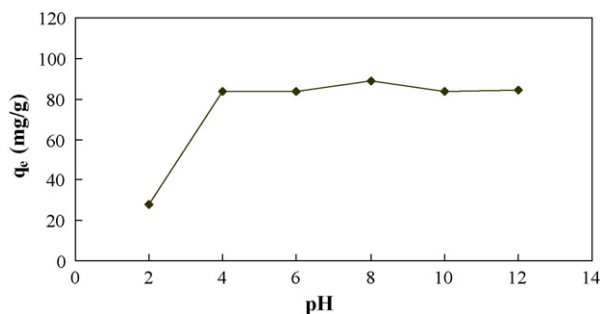


Fig. 1. Effect of the solution pH on the adsorption of methylene blue on BSW ($C_0 = 100$ mg/L, temperature 30°C , stirring rate 100 rpm and $W = 0.2$ g).

biosorption of methylene blue by *P. oceanica* (L.) fibers [9]. At higher pH values (4–12), the dye adsorption was almost constant. At higher pH, the BSW may become negatively charged, which enhances the positively charged dye cations through electrostatic forces of attraction [9]. This finding is similar to that made in previous works on adsorption [6,16,17]. The complex nature of the adsorbent as will be discussed later in Section 3.6 may indicate the possible involvement of some functional groups on the surface of BSW in sorption process.

3.2. Effect of contact time and initial dye concentration on dye adsorption

Fig. 2(a) illustrates the sorption of MB for different initial concentrations of MB between 50 and 500 mg/L at 30°C as a function of contact time. It is evident from Fig. 2(a) that the

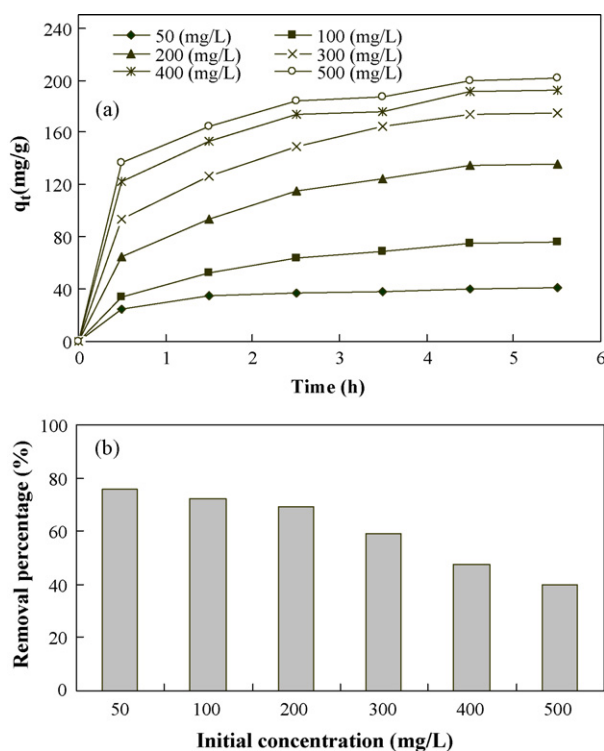


Fig. 2. (a) Effect of agitation time and initial concentration on removal of MB by BSW. Conditions: sorbent dosage, 1.0 g/L; initial pH, 7.0; temperature 30°C . (b) Removal percentage vs. initial concentration.

amount adsorbed increased with the increase in the concentration of solution, but the percentage of adsorption decreased (Fig. 2b). When the initial MB concentration was increased from 50 to 500 mg/L, the sorption uptake of BSW increased from 41.04 to 201.61 mg/L. A higher initial concentration provides an important driving force to overcome all resistances of the dye between the aqueous and solid phases, thus increasing the uptake. In addition, increasing the initial dye concentration increases the number of collisions between dye ions and the BSW, which enhances the adsorption process. The percentage removal of MB adsorbed decreased from 75.87 to 40.09% as the initial concentration was increased from 50 to 500 mg/L (see Fig. 2b).

The effect of contact time on the removal of MB by the BSW at initial concentrations 50–500 mg/L and 30°C showed rapid adsorption of dye in the first 30 min. Such short times coupled with high removals indicate a high degree of affinity for the dye groups pointing towards chemisorption. The adsorption rate decreased gradually and the adsorption reached equilibrium in about 3 h and 30 min for initial concentrations of 50–100 mg/L. For MB solutions with initial concentrations of 200–500 mg/L, equilibrium time of 4 h and 30 min was required. The time required to attain this state of equilibrium was termed the equilibrium time and the amount of dye adsorbed at the equilibrium time reflected the maximum dye adsorption capacity of the adsorbent under these particular conditions.

Reported data on the adsorption of MB by various adsorbents have shown a wide range of adsorption rates. Waranusantigul et al. [6] studied methylene blue biosorption by giant duckweed (*Spirodela polyrrhiza*) and reported that the equilibrium states were attained at 60 and 120 min for 300 and 500 mg/L of the dye solutions, respectively. Lata et al. [18] studied methylene blue adsorption using *Parthenium hysterophorus*, an agricultural waste and reported that the equilibrium was established within about 60 and 90 min for sulphuric acid treated *Parthenium* (SWC) and phosphoric acid treated *Parthenium* (PWC), respectively. Senthilkumaar et al. [19] studied the adsorption of MB on jute fiber carbon at various concentrations (50, 100, 150, and 200 mg/L) and reported that the equilibrium was established at 250 min for all the concentrations studied.

3.3. Isotherm studies

The adsorption data were analyzed with three adsorption isotherm models, namely Langmuir, Freundlich and Temkin. The Langmuir adsorption model [20] is based on the assumption that maximum adsorption corresponds to a saturated monolayer of solute molecules on the adsorbent surface. The expression of the Langmuir model is given by the following equation:

$$q_e = \frac{Q_0 b C_e}{1 + b C_e} \quad (4)$$

where q_e (mg/g) and C_e (mg/L) are the amount of adsorbed dye per unit mass of sorbent and unadsorbed dye concentration in solution at equilibrium, respectively. Q_0 is the maximum amount of the adsorbed dye per unit mass of sorbent to form a complete monolayer on the surface bound at high C_e (mg/g), and b (L/mg)

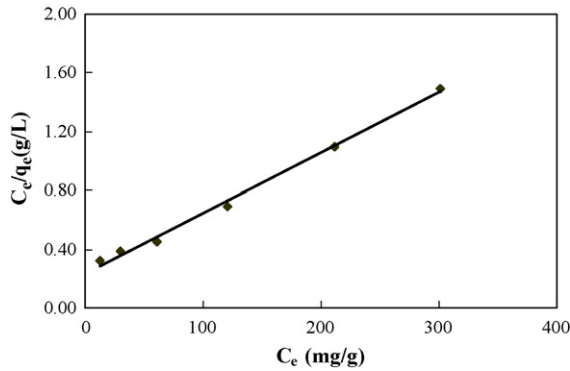


Fig. 3. Langmuir isotherm for MB sorption onto BSW at 30 °C.

is a constant related to the affinity of the binding sites. The linear form of Langmuir model is

$$\frac{C_e}{q_e} = \frac{1}{Q_0 b} + \frac{C_e}{Q_0} \quad (5)$$

The linear plot of specific adsorption (C_e/q_e) against the equilibrium concentration (C_e) (Fig. 3) shows that the adsorption obeys the Langmuir model. The Langmuir constants Q_0 and b were determined from the slope and intercept of the plot and are presented in Table 1.

The essential characteristics of the Langmuir isotherm can be expressed in terms of a dimensionless constant separation factor R_L that is given by the following equation [21]:

$$R_L = \frac{1}{1 + bC_0} \quad (6)$$

where C_0 (mg/L), is the highest initial concentration of adsorbate and b is Langmuir constant. The parameter R_L indicates the nature of the shape of the isotherm accordingly:

$R_L > 1$	unfavorable adsorption
$0 < R_L < 1$	favorable adsorption
$R_L = 0$	irreversible adsorption
$R_L = 1$	linear adsorption

The values of R_L in the present investigation have been found to be 0.103 at 30 °C indicating that the adsorption of MB on BSW is favorable.

Table 1
Langmuir, Freundlich and Temkin isotherm constants and correlation coefficients for adsorption of MB on BSW at 30 °C

Isotherm	Parameters	
Langmuir	Q_0 (mg/g)	243.902
	b (L/mg)	0.0174
	R^2	0.995
Freundlich	K_F	13.258
	n	1.966
	R^2	0.929
Temkin	A (L/g)	0.167
	B	54.163
	R^2	0.978

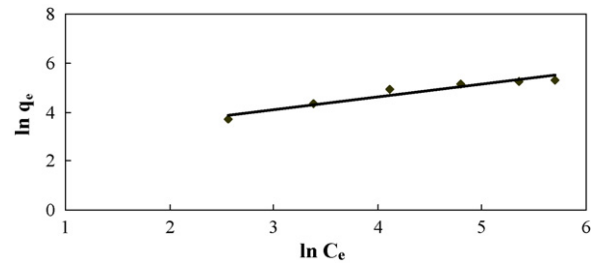


Fig. 4. Freundlich isotherm for MB sorption onto BSW at 30 °C.

The Freundlich model [22] is an empirical equation that assumes heterogeneous adsorption due to the diversity of adsorption sites. The Freundlich equation is expressed as

$$q_e = K_F C_e^{1/n} \quad (7)$$

where K_F (mg/g (L/mg) $^{1/n}$) is roughly an indicator of the adsorption capacity and $1/n$ is the adsorption intensity. The magnitude of the exponent, $1/n$, gives an indication of the favorability of adsorption. Values of $n > 1$ represent favorable adsorption conditions [23,24]. Eq. (7) may also be written in the logarithmic form as

$$\ln q_e = \ln K_F + \left(\frac{1}{n}\right) \ln C_e \quad (8)$$

Values of K_F and n are calculated from the intercept and slope of the plot (Fig. 4) and are listed in Table 1.

Temkin and Pyzhev [25] considered the effects of some indirect adsorbate/adsorbate interactions on adsorption isotherms and suggested that because of these interactions the heat of adsorption of all the molecules in the layer would decrease linearly with coverage. The Temkin isotherm has been used in the following form:

$$q_e = \left(\frac{RT}{b}\right) \ln(AC_e) \quad (9)$$

Eq. (9) can be expressed in its linear form as

$$q_e = \frac{RT}{b} \ln A + \frac{RT}{b} \ln C_e \quad (10)$$

where

$$B = \frac{RT}{b}$$

The adsorption data can be analyzed according to Eq. (10). A plot of q_e versus $\ln C_e$ (Fig. 5) enables the determination of the constants A and B . The constant B is related to the heat of adsorption. The constant A and B together with the R^2 values are shown in Table 1.

The Langmuir, Freundlich and Temkin adsorption constants evaluated from the isotherms at 30 °C with the correlation coefficients are listed in Table 1. As seen from the table, very high regression correlation coefficient (>0.99) was shown by the Langmuir model. This indicates that the Langmuir model was very suitable for describing the sorption equilibrium of MB by the BSW sorbent. Similar results were reported for methylene blue adsorption on wheat shells [16] and methylene blue

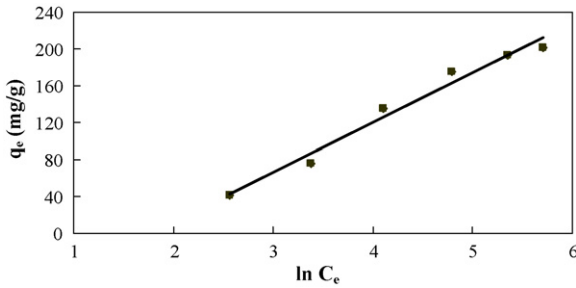


Fig. 5. Temkin isotherm for MB sorption onto BSW at 30°C.

adsorption from aqueous solution by dehydrated peanut hull (123.5 mg/g) [26]. The maximum capacity Q_0 determined from the Langmuir isotherm defines the total capacity of the biosorbent for the dye as 243.90 mg/g. The fact that the Langmuir isotherm fits the experimental data very well may be due to the homogenous distribution of active sites on the BSW surface; since the Langmuir equation assumes that the surface is homogenous. Table 1 also shows that the n value is greater than 1 which indicates favorable adsorption.

The maximum sorption capacity (Q_0) of the BSW sorbent (mg/g) for methylene blue was compared with sorption capacities of different sorbents for methylene blue reported data: palm kernel fiber (223.41 mg/g) [27], dehydrated peanut hull (123.5 mg/g) [26], wheat shells (16.56 mg/g) [16], methylene blue biosorption by pretreated dead *Streptomyces rimosus* (32.98 mg/g) [28] and methylene blue biosorption by giant duckweed (*Spirodela polyrrhiza*) (119.05 mg/g) [6]. The performance of the BSW is seen to be more effective for removal of MB.

3.4. Adsorption kinetics

In order to analyze the sorption kinetics of MB on BSW, the pseudo-first-order and pseudo-second-order kinetic models were applied to the experimental data.

Lagergren proposed a method for adsorption analysis which is the pseudo-first-order kinetic equation of Lagergren [29] in the form:

$$\frac{dq_t}{dt} = k_1(q_e - q_t) \tag{11}$$

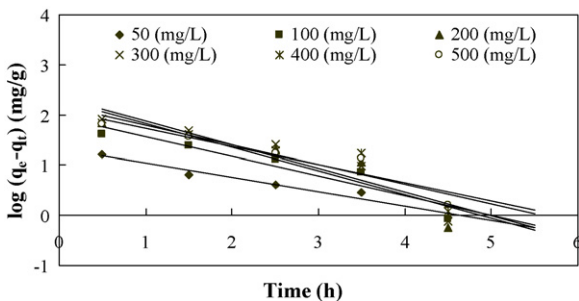


Fig. 6. Pseudo-first-order sorption kinetics of MB onto BSW.

Table 2

Comparison of the pseudo-first-order, pseudo-second-order adsorption rate constants and calculated and experimental q_e values obtained at different initial MB concentrations

Initial conc.	$q_{e,exp}$ (mg/g)	Pseudo-first-order kinetic model			Pseudo-second-order kinetic model		
		k_1 (L/h)	$q_{e,cal}$ (mg/g)	R^2	k_2 (g/mg h)	$q_{e,cal}$ (mg/g)	R^2
50	41.04	0.658	20.82	0.958	0.056	43.67	0.999
100	76.22	0.896	90.16	0.895	0.012	89.29	0.997
200	135.72	1.091	201.50	0.839	0.007	156.25	0.996
300	174.92	1.097	230.30	0.878	0.007	196.08	0.997
400	192.67	0.900	152.67	0.831	0.010	208.33	0.997
500	201.61	0.841	127.31	0.878	0.012	212.77	0.998

Integrating this for the boundary conditions $t=0$ to $t=t$ and $q_t=0$ to $q_t=q_t$, gives

$$\log(q_e - q_t) = \log q_e - \frac{k_1}{2.303}t \tag{12}$$

where k_1 is the rate constant (1/h), q_e the amount of solute adsorbed on the surface at equilibrium (mg/g), q_t the amount of solute adsorbed at any time (mg/g). The value of the adsorption rate constant (k_1) for MB sorption by BSW was determined from the plot of $\log(q_e - q_t)$ against t (Fig. 6). The parameters of pseudo-first-order model are summarized in Table 2. In many cases the first-order equation of Lagergren does not fit well to the whole range of contact time and is generally applicable over the initial stage of the adsorption processes [30]. Although the correlation coefficients, R^2 , for the application of the pseudo-first-order model are reasonably high in some cases, the calculated q_e is not equal to experimental q_e , suggesting the adsorption of MB on BSW is not likely to be a pseudo-first-order for the initial concentrations examined.

The pseudo-second-order equation based on equilibrium adsorption [24] is expressed as

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{1}{q_e}t \tag{13}$$

where k_2 (g/mg h) is the pseudo-second-order rate constant determined from the plot of t/q_t versus t , as shown in Fig. 7. The q_e and k_2 can be calculated from the slopes and intercepts

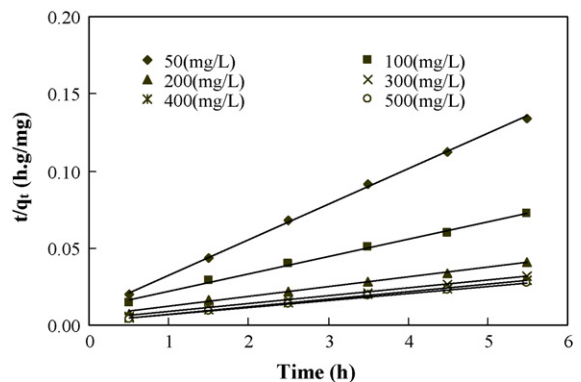


Fig. 7. Pseudo-second-order sorption kinetics of MB on BSW.

Table 3
Intraparticle diffusion constants for different initial MB concentrations

Initial conc. (mg/L)	$q_{e,cal}$ (mg/g)	k_i (mg/g h ^{1/2})	C	R^2
50	42.434	9.122	21.04	0.907
100	80.208	26.315	18.50	0.969
200	143.071	44.821	37.97	0.965
300	183.844	51.781	62.42	0.966
400	198.614	43.363	96.93	0.957
500	207.271	39.962	113.56	0.961

of the plots t/q_t versus t . The second-order rate constants values are shown in Table 2.

It can be seen from Table 2 that the coefficients for the pseudo-first-order kinetic model obtained at all the studied concentrations were low. Also the theoretical q_e values found from the pseudo-first-order kinetic model did not give reasonable values. This suggests that this sorption system is not a first-order. The calculated q_e values agree very well with the experimental values for the case of pseudo-second-order kinetics, and a regression coefficient of above 0.99 shows that the model can be applied for the entire adsorption process and confirms the chemisorption of MB onto BSW. Similar results were reported for methylene blue adsorption on wheat shells [16], methylene blue adsorption from aqueous solution by dehydrated peanut hull (123.5 mg/g) [26] and methylene blue adsorption on wheat shells [16]. From Table 2, it was observed that the pseudo-second-order rate constant (k_2) decreased with increased initial concentration.

The above two equations cannot identify the diffusion mechanism; the intraparticle diffusion model which refers to the theory proposed by Weber and Morris is thus tested [31] to identify the diffusion mechanism. According to this theory:

$$q_t = k_i t^{1/2} + C \tag{14}$$

where k_i is the intraparticle diffusion rate constant (mg/g h^{1/2}) and C (mg/g) is a constant that gives an idea about the thickness of the boundary layer, i.e., the larger the value of C the greater is the boundary layer effect. If the Weber–Morris [32] plot of q_t versus $t^{0.5}$ gives a straight line, then the sorption process is controlled by intraparticle diffusion only. The k_i and C can be calculated from slope and intercept of the plots q_t versus $t^{0.5}$. The intraparticle diffusion rate constants values are shown in Table 3. It can be seen from Fig. 8 that the regression was lin-

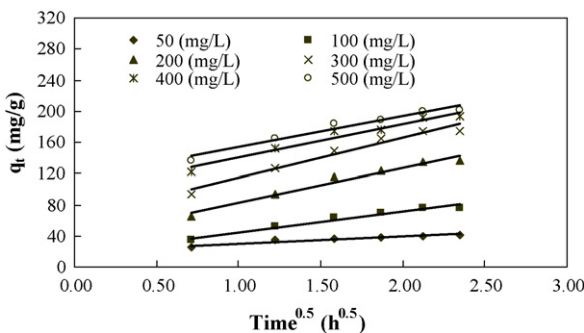


Fig. 8. Plots for evaluating intraparticle diffusion rate constant for sorption of MB onto BSW.

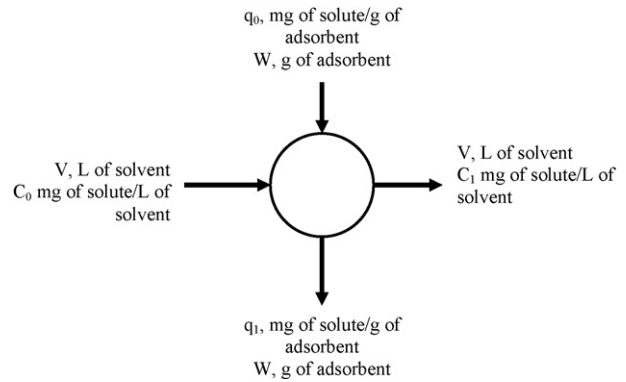


Fig. 9. A single-stage batch adsorber.

ear, but the plot did not pass through the origin, suggesting that adsorption involved intraparticle diffusion, but that was not the only rate-controlling step. Other kinetic models may control the adsorption rate. This finding is similar to that made in previous work on methylene blue adsorption [33].

3.5. Design of batch sorption from isotherm data

Fig. 9 shows a schematic diagram for the batch sorption process where the effluent contains V (L) of water and an initial MB concentration C_0 , which is to be reduced to C_1 in the adsorption process. In the treatment stage, a mass of W (g) fresh BSW is added to solution and the dye concentration on the solid changes from $q_0 = 0$ to q_1 . The mass balance for the dye in the single stage is given by

$$V(C_0 - C_1) = W(q_0 - q_1) \tag{15}$$

Under equilibrium conditions,

$$C_1 \rightarrow C_e \quad \text{and} \quad q_1 \rightarrow q_e$$

$$VC_0 + Wq_0 = VC_e + Wq_e \tag{16}$$

For the adsorption of MB on BSW, the Langmuir isotherm gives the best fit to experimental data. Consequently equation can be best substituted for q_1 in the rearranged form of Eq. (16) giving

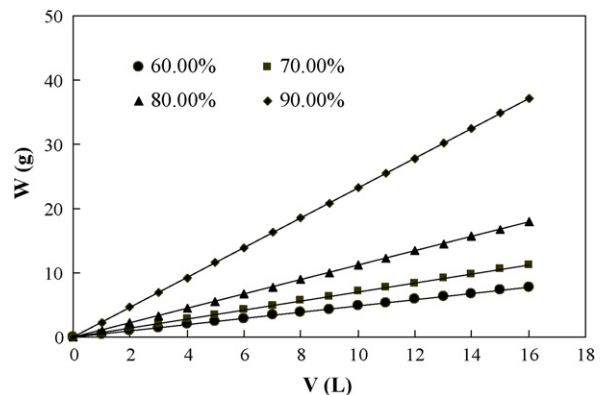


Fig. 10. Adsorbent mass (W) against volume of effluent (V) treated for different percentages of MB removal.

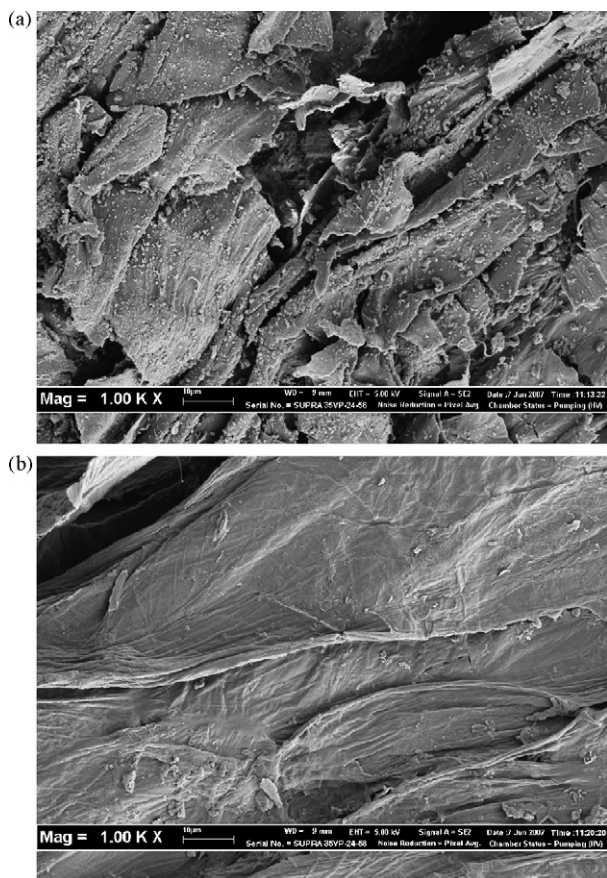


Fig. 11. Scanning electron microscope of fresh BSW (a) and dye adsorbed with MB (b) (magnification: 1000 \times).

adsorbent/solution ratios for this particular system,

$$\frac{W}{V} = \frac{C_0 - C_1}{q_e} = \frac{C_0 - C_e}{Q_0 b C_e / 1 + b C_e} \quad (17)$$

Fig. 10 shows a series of plots (60, 70, 80 and 90% dye removal at different solution volumes) derived from Eq. (17) at initial dye concentration of 50 mg/L and 30 °C.

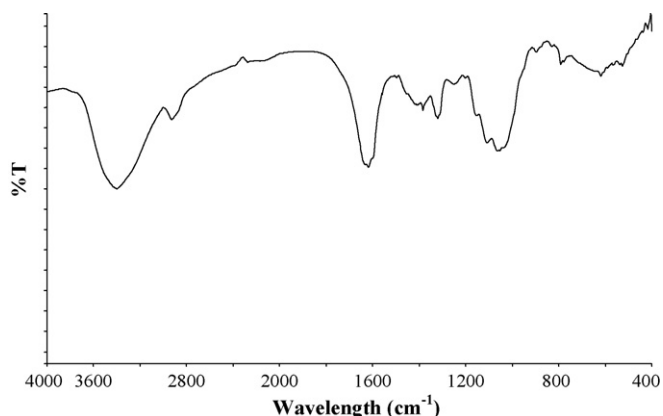


Fig. 12. FTIR spectrum of BSW.

3.6. SEM and FTIR of BSW

The surface structure of BSW was analyzed by SEM before and after MB adsorption (Fig. 11a and b). The textural structure examination of BSW particles can be observed from the SEM photographs (Fig. 11a). This figure reveals that the pores within the BSW particles are highly heterogeneous. After dye adsorption, a significant change is observed in structure of the BSW (Fig. 11b). It can be seen that the BSW surface became rough because it is covered by dye molecules.

The FTIR spectrum obtained (Fig. 12) for the BSW displayed the following bands:

- 3400.8 cm⁻¹: O–H stretch
- 2928.73 cm⁻¹: C–H stretch
- 1618.22 cm⁻¹: C=C stretch
- 1497.47 cm⁻¹ and 1407.86 cm⁻¹: phenyl
- 1384.64 cm⁻¹ and 1320.75 cm⁻¹: C–(CH₃)₂
- 1108.21 cm⁻¹: C–O stretch
- 1054.66 cm⁻¹: C–O–C stretch
- 620.28 cm⁻¹: C–OH twist

It is clear from Fig. 12 that the adsorbent displays a number of absorption peaks, reflecting the complex nature of the adsorbent.

4. Conclusions

The present work shows that banana stalk waste, abundantly available in Malaysia, is an efficient sorbent for the removal of MB from aqueous solution and it may be an alternative to more costly adsorbents such as activated carbon. The equilibrium data have been analyzed using Langmuir, Freundlich and Temkin isotherms. The Langmuir isotherm was demonstrated to provide the best correlation for the sorption of MB onto BSW sorbent. The maximum monolayer adsorption capacity of BSW was found to be 243.90 mg/g at 30 °C. The sorption kinetics of the MB onto the BSW is well described by the pseudo-second-order model.

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References

- [1] G. Crini, Non-conventional low-cost adsorbents for dye removal: a review, *Bioresour. Technol.* 97 (2006) 1061–1085.
- [2] J.J.M. Orfao, A.I.M. Silva, J.C.V. Pereira, S.A. Barata, I.M. Fonseca, P.C.C. Faria, M.F.R. Pereira, Adsorption of a reactive dye on chemically modified activated carbons—influence of pH, *J. Colloid Interface Sci.* 296 (2006) 480–489.
- [3] S.B. Hartono, S. Ismadji, Y. Sudaryanto, W. Irawaty, Utilization of teak sawdust from the timber industry as a precursor of activated carbon for the removal of dyes from synthetic effluents, *J. Ind. Eng. Chem.* 11 (2005) 864–869.
- [4] A. Jumariah, T.G. Chuah, J. Gimbon, T.S.Y. Choong, I. Azni, Adsorption of basic dye onto palm kernel shell activated carbon: sorption equilibrium and kinetics studies, *Desalination* 186 (2005) 57–64.

- [5] A. Gürses, Ç. Doğar, S. Karaca, M. Açıkyıldız, R. Bayrak, Production of granular activated carbon from waste *Rosa canina* sp. Seeds and its adsorption characteristics for dye, *J. Hazard. Mater.* 131 (2006) 254–259.
- [6] P. Waranusantigul, P. Pokethitayook, M. Kruatrachue, E.S. Upatham, Kinetics of basic dye (methylene blue) biosorption by giant duckweed (*Spirodela polyrrhiza*), *Environ. Pollut.* 125 (2003) 385–392.
- [7] A.A. Ahmad, B.H. Hameed, N. Aziz, Adsorption of direct dye on palm ash: kinetic and equilibrium modeling, *J. Hazard. Mater.* 141 (2007) 70–76.
- [8] B.H. Hameed, A.A. Ahmad, N. Aziz, Isotherms, kinetics and thermodynamics of acid dye adsorption on activated palm ash, *Chem. Eng. J.* 133 (2007) 195–203.
- [9] M.C. Ncibi, B. Mahjoub, M. Seffen, Kinetic and equilibrium studies of methylene blue biosorption by *Posidonia oceanica* (L.) fibres, *J. Hazard. Mater.* B139 (2007) 280–285.
- [10] H. Demir, A. Top, D. Balköse, S. Ülkü, Dye adsorption behavior of *Luffa cylindrica* fibers, *J. Hazard. Mater.* 153 (2008) 389–494.
- [11] Y.S. Ho, A.E. Ofomaja, Biosorption thermodynamics of cadmium on coconut copra meal as biosorbent, *Biochem. Eng. J.* 30 (2006) 117–123.
- [12] R.G. Medeiros, M.L.A. Soffner, J.A. Thomé, A.O.G. Cacaís, R.S. Estelles, B.C. Salles, H.M. Ferreira, S.A. Lucena Neto, F.G. Silva Jr., E.X.F. Filho, The production of hemicellulases by aerobic fungi on medium containing residues of banana plant as substrate, *Biotechnol. Progr.* 16 (2000) 522–524.
- [13] C. Krishna, Production of bacterial cellulases by solid state bioprocessing of banana wastes, *Bioresour. Technol.* 69 (1999) 231–239.
- [14] I.G. Shibi, T.S. Anirudhan, Synthesis, characterization and application as a mercury(II) sorbent of banana stalk (*Musa paradisiaca*)-polyacrylamide grafted copolymer bearing carboxyl groups, *Ind. Eng. Chem. Res.* 41 (2002) 5341–5342.
- [15] I.G. Shibi, T.S. Anirudhan, Adsorption of Co(II) by a carboxylate-functionalized polyacrylamide grafted lignocellulosics, *Chemosphere* 58 (2005) 1117–1126.
- [16] Y. Bulut, H. Aydın, A kinetics and thermodynamics study of methylene blue adsorption on wheat shells, *Desalination* 194 (2006) 259–267.
- [17] R. Han, Y. Wang, P. Han, J. Shi, J. Yang, Y. Lu, Removal of methylene blue from aqueous solution by chaff in batch mode, *J. Hazard. Mater.* B137 (2006) 550–557.
- [18] H. Lata, V.K. Garg, R.K. Gupta, Removal of a basic dye from aqueous solution by adsorption using *Parthenium hysterophorus*: an agricultural waste, *Dyes Pigments* 74 (2007) 653–658.
- [19] S. Senthilkumar, P.R. Varadarajan, K. Porkodi, C.V. Subbhuraam, Adsorption of methylene blue onto jute fiber carbon: kinetics and equilibrium studies, *J. Colloid Interface Sci.* 284 (2005) 78–82.
- [20] I. Langmuir, The adsorption of gases on plane surfaces of glass, mica and platinum, *J. Am. Chem. Soc.* 40 (1918) 1361–1403.
- [21] K.R. Hall, L.C. Eagleton, A. Acrivos, T. Vermeulen, Pore- and solid-diffusion kinetics in fixed-bed adsorption under constant-pattern conditions, *IEC Fundam.* 5 (1966) 212–223.
- [22] H. Freundlich, Über die adsorption in lösungen (Adsorption in solution), *Z. Phys. Chem.* 57 (1906) 384–470.
- [23] R.E. Treybal, *Mass Transfer Operations*, 2nd ed., McGraw Hill, New York, 1968.
- [24] Y.S. Ho, G. McKay, Sorption of dye from aqueous solution by peat, *Chem. Eng. J.* 70 (1978) 115–124.
- [25] M.J. Tempkin, V. Pyzhev, Recent modifications to Langmuir isotherms, *Acta Physiochim. URSS* 12 (1940) 217–222.
- [26] D. Özer, G. Dursun, A. Özer, Methylene blue adsorption from aqueous solution by dehydrated peanut hull, *J. Hazard. Mater.* 144 (2007) 171–179.
- [27] A.E. Ofomaja, Sorption dynamics and isotherm studies of methylene blue uptake on to palm kernel fibre, *Chem. Eng. J.* 126 (2007) 35–43.
- [28] Y. Nacèra, B. Aicha, Equilibrium and kinetic modelling of methylene blue biosorption by pretreated dead *Streptomyces rimosus*: effect of temperature, *Chem. Eng. J.* 119 (2006) 121–125.
- [29] S. Lagergren, About the theory of so-called adsorption of soluble substances, *Kungliga Svenska Vetenskapsakademiens Handlingar* 24 (4) (1898) 1–39.
- [30] G. McKay, Y.S. Ho, The sorption of lead(II) on peat, *Water Res.* 33 (1999) 578–584.
- [31] W.J. Weber, J.C. Morris, *Proceedings of the International Conference on Water Pollution Symposium 2*, Pergamon, Oxford, 1962, pp. 231–266.
- [32] W.J. Weber Jr., J.C. Morris, Kinetics of adsorption on carbon from solution, *J. Sanitary Eng. Div. Proceed. Am. Soc. Civil Eng.* 89 (1963) 31–59.
- [33] I.A.W. Tan, B.H. Hameed, A.L. Ahmad, Equilibrium and kinetic studies on basic dye adsorption by oil palm fibre activated carbon, *Chem. Eng. J.* 127 (2007), 111–111.