Effect of a magnetic field on the adsorptive removal of methylene blue onto wheat straw biochar

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ABSTRACT

Biochar pyrolyzed from wheat straw was innovatively used for the adsorptive removal of cationic dye methylene blue through exposure to a magnetic field. The adsorption capability of the biochar pyrolyzed at 200 °C exceeded that of samples pyrolyzed at higher temperatures. The surface acidic functional groups of wheat straw biochar were deduced to be more sensitive to the effects of the external magnetic field. The enhancement of the magnetic field achieved by increases in the initial dye concentration, and a decrease in the biochar dosage and solution pH, were more significant compared with those caused by other conditions. Kinetic experiments indicated that chemisorption occurred during adsorption. The $q_{\max}$ values for dye adsorption without, and with, an external magnetic field were found to be 46.6 and 62.5 mg/g, respectively. These demonstrated that wheat straw biochar could be used for the efficient adsorption of pollutants when assisted by an external magnetic field.

Keywords: Biochar; Adsorption; Magnetic field; Methylene blue

1. Introduction

Large amounts of agricultural wastes including: wheat straw, rice husk, and cornstalk, are generated annually. So, these products are readily available as a low-cost resource for adsorption, as a biomass energy source, and as a precursory material for biochars. Recently attention has been paid to the utilisation and application of biochar, which is derived from the biomass via incomplete combustion operations such as pyrolysis and carbonization (Ahmad et al., 2014; Chen and Chen, 2009; Mohan et al., 2014). As a stable carbon-rich material, the application of biochar for solving environmental problems can span several categories including: carbon sequestration, soil management, pollution remediation, and agricultural by-product/waste recycling. Among these uses, biochar as an adsorbent for the removal of environmental pollutants has emerged as a promising technology (Lee et al., 2010; Lehmann, 2007; Xie et al., 2014; Inyang et al., 2012; Zhou et al., 2014). Currently, low-temperature pyrolysis is usually applied to convert biomass, typically agricultural biomass, into biochars (Keiluweit et al., 2010; Das et al., 2013), which helps to avoid organic leaching and secondary pollution from the raw biomass. Meanwhile, the surface area of the biochars usually increases with an increase in pyrolytic temperature at up to 700 °C (Ahmad et al., 2014). As such, it was deemed both reasonable, and feasible, to promote the application of biochar for practical decontamination purposes.

Concurrently, the magnetic field-exposure method has demonstrated its capability for enhancing the adsorptive removal of pollutants from water as static magnetisation

is convenient, simple, and cost-effective. Basically, the magnetic field is capable of affecting the behaviour and physico-chemical properties of water (Patkowski et al., 2014). Thus, it is not surprising that many studies have focused on the effect of the external magnetic field on the properties of both adsorbent and adsorbate materials. On the one hand, the exposure to the magnetic field can affect the adsorbent significantly. Zhang and his co-workers reported that magnetic treatment is capable of enhancing the ζ potential of Ca-rectorite suspensions in the absence of Cu and of reducing that of the suspension, also in the presence of Cu (Zhang et al., 2004). Bel'chinskaya proved that the surface of materials became less homogeneous under a magnetic field, with increased surface area of sorbent and enhanced adsorption of formaldehyde (Bel'chinskaya et al., 2009). On the other hand, as most of the irradiation from the magnetic field is impinging upon the solution containing adsorbate, the effect of the magnetic field on the adsorbate might be as important as that on the adsorbent. Under a magnetic field, the increased mobility of methylene blue molecules onto magnetic clay has been confirmed, which facilitated the penetration of dye molecules to the adsorption sites (Aline et al., 2014). Similar behaviour of the adsorption of methyl blue onto organo-bentonite was also seen elsewhere (Hao et al., 2012). Furthermore, a static magnetic field was integrated with the conventional adsorption process by activated carbon for the treatment of biologically-treated palm-oil mill effluent and as a result, the decreases in colour, TSS, and COD were considerably enhanced (Rafie et al., 2014). In short, static magnetisation may be an alternative to enhance the adsorption capability of biochar.

Although a number of low-cost adsorbents such as: natural materials, agricultural, and industrial, wastes are capable of removing methylene blue efficiently (Rafatullah et al., 2010), significantly enhanced uptake of methylene blue onto biochar under an external magnetic field has rarely been reported to date. Our previous study has indicated that wheat straw biochar was more sensitive to an external magnetic field than biochars including sugarcane bagasse biochar and cornstalk biochar. In this study, for the first time, wheat straw biochar was prepared and used for the significantly enhanced adsorptive removal of the cationic dye methylene blue under a static magnetic field. The effects of the pyrolytic temperature on biochar adsorption, magnetic pre-treatment time, and initial dye concentration were investigated. The adsorption kinetics and isotherms were also studied as was the mechanism responsible for the effect of the external magnetic field.

2 Materials and methods

2.1 Materials

Methylene blue (mass fraction > 98.5%, chemically pure) was purchased from Tianjin Chemical Reagent Research Institute. The other chemicals used were of analytical grade. Deionised (DI) water was used throughout the study. A pair of permanent magnets (30 mm × 19 mm × 6 mm, Beijing Fengrui Magnetic Material Factory) were used to provide the magnetic field.

2.2 Preparation of biochar from wheat straw

Wheat straw was collected from farmland in Zhengzhou, Henan Province. The

collected biomass was washed, dried, crushed, and sieved through a 40 mesh sieve. The wheat straw biochar was prepared in a furnace by pyrolyzing the biomass at a constant temperature for 3 h. Meanwhile, to maintain an oxygen-limited atmosphere, the pre-treated biomass was put into a ceramic pot, in a compressed state, and covered with a tight-fitting lid. For demineralisation, the resultant wheat straw biochar was placed in a 4 mol/L HCl solution for 12 h and separated by filtration. Then the residues were rinsed with DI water until a neutral solution pH was achieved: the product was then oven-dried overnight at 80 °C. The treated biochars were finally preserved in a desiccator until further use.

2.3 Characterisation

The acidic functional groups, including carboxyl, lactonic, and phenolic groups on the raw wheat straw and the biochars pyrolyzed at 200, 400, and 600 °C, were determined using Boehm's titration method ([Abdulkarim and Abu Al-Rub, 2004](#); [Strelko et al., 2002](#); [Vald'es et al., 2002](#)).

2.4 Batch adsorption experiments assisted by external magnetic field

Adsorption trials of methylene blue (MB) onto the produced wheat straw biochar were conducted in a series of cylindrical flasks. The stock solutions of MB (500 mg/L) were prepared in DI water. All working solutions were prepared by diluting the stock solution with DI water to the desired concentration. A desired amount of wheat straw biochar (200 mg) was added to a conical flask containing 500 mL of MB solution with a concentration of 10 mg/L. Constant and vigorous stirring was maintained by mechanical agitation for 24 h. After adsorption, samples were collected and filtered

through a 0.45 μm pore-size membrane before analysis. For the effect of magnetic pre-treatment, only the MB solution was treated by the magnetic field for a desired period before adding the wheat straw biochar into the pre-treated solutions.

The reaction temperature was held constant at 25 $^{\circ}\text{C}$ except when studying the adsorption isotherm at different temperatures. All solution pHs were maintained at neutral except during the pH effect study itself. Solution pH adjustment was effected by the addition of a dilute HCl, or NaOH, solution.

2.5 Analysis methods

The concentration of MB was analysed using an UVmini-1240 spectrophotometer (Shimadzu) by monitoring emissions at the wavelength of maximum absorption (664 nm). The percentage removal of MB was given by:

$$\text{Removal percentage} = (1 - C_t/C_0) \times 100 \% \quad (1)$$

The adsorption capacities (q_e, q_t) were calculated as follows:

$$q_t = (C_0 - C_e) V/W \quad (2)$$

$$q_t = (C_0 - C_t) V/W \quad (3)$$

where q_e and q_t (mg/g) are the adsorption capacities at equilibrium and time t (minutes); C_0 is the initial concentration of MB in solution, while C_e and C_t (mg/L) are the concentrations of MB at equilibrium and t (minutes), respectively; V (L) is the volume of solution, and W (g) is the mass of adsorbent used.

3 Results and discussion

3.1 Effect of the pyrolytic temperature of biochars on the adsorption of MB

The surface chemistry of the biochars pyrolyzed at different temperatures differs

gradually from low temperature to high temperature due to the loss of O- and H-containing functional groups. The resulting surface polarity and aromaticity are important characteristics affecting the sorption of organic contaminants (Chen et al., 2008). Considering the significant loss of organic matter from the raw wheat straw (WS) during pyrolysis, the adsorption performance of the raw WS and of the biochars pyrolyzed at 200, 400, and 600 °C was compared and the results are presented in Fig. 1. The biochars pyrolyzed at 200, 400, and 600 °C were referred to as BC200, BC400, and BC600, respectively. Typically, the adsorptive removal percentages of the raw WS, BC200, BC400, and BC600, at 24 h were 81.5%, 81.6%, 76.8%, and 80.5%, respectively in the absence of an external magnetic field. Once the external magnetic field was applied, the removal percentages by the raw WS, BC200, BC400, and BC600, at 24 h reached 83.1%, 91.4%, 88.8%, and 86.7%, respectively. The removal percentages by raw WS, BC200, BC400, and BC600 were enhanced by 2.0%, 9.8%, 12.0%, and 6.2%, respectively. The pyrolytic temperature could be as low as 200 °C, at which the adsorption capability for MB removal outperformed other WS biochars involved. The lower the pyrolytic temperature, the less energy was used in biochar preparation. The BC200 was selected for the following tests as it yielded the highest uptake of MB. Meanwhile, as the surface chemistry changed from the raw WS to the prepared biochars with increasing pyrolytic temperature, it demonstrated that the surface chemistry of biochars can significantly affect the adsorption of MB.

Fig. 1

3.2 Effect of biochar dose on the adsorption of MB

The effect of biochar dose on the adsorptive removal of MB onto wheat straw biochar was investigated with, and without, the assistance of an external magnetic field (Fig. 2). The biochar BC200 doses selected were: 50, 100, and 200 mg in 500 mL of dye solution. At biochar doses of 50, 100, and 200 mg, the removal percentages of MB after 24 h were 47.9%, 66.1%, and 80.4%, respectively. Considering the low expenditure on the production of wheat straw biochar, it can be expected that the increased dose of biochar could be an optimal choice for the efficient removal of pollutants. Once the external magnetic field was applied across the reaction solutions, the counterpart removal percentages achieved were 62.7%, 76.2%, and 91.4%, respectively. Thus, with the help of the external magnetic field, the dye removal percentages at biochar doses of 50, 100, and 200 mg were enhanced by as much as 30.9%, 15.3%, and 13.7%, respectively. This indicated that a significant improvement can be achieved by using the external magnetic field. The increased biochar dose actually reduced the irradiation density of the magnetic field per unit mass of biochar. Accordingly, it can be noted that the enhancement of the external magnetic field declined with increasing dose of biochar BC200. Therefore, the effect of the magnetic field was thought to be highly dependent on the reaction conditions. As the comparatively higher adsorptive removal efficiency was achieved at a dose of 200 mg, the BC200 dose was fixed at 200 mg for the following tests.

Fig. 2

3. 3 Effect of the initial concentrations of MB and the pre-treatment time by magnetic field on the adsorption

The effects of the initial concentrations of MB on the adsorption process with, and without, the external magnetic field were also investigated within 24 h (Fig. 3a). In the absence of the magnetic field, the adsorption capacities at initial dye concentrations of 5, 10, 20, 40, and 80 mg/L were 10.2, 20.0, 32.1, 42.6, and 45.6 mg/g, respectively. The increased initial dye concentration significantly enhanced the uptake of MB onto the wheat straw biochar. In contrast, once the external magnetic field was applied, the adsorption capacities with initial dye concentrations of 5, 10, 20, 40, and 80 mg/L were 10.6, 22.5, 36.0, 56.8, and 61.6 mg/g, respectively. Due to the effect of the external magnetic field, the adsorption capacities with initial dye concentrations of 5, 10, 20, 40, and 80 mg/L were increased by 3.8%, 11.9%, 15.0%, 33.3%, and 35.0%, respectively. As the aforementioned result (Fig. 2), the increased biochar BC200 dose decreased the enhancement effect arising from the application of the external magnetic field; however, in this case, the enhancement of the external magnetic field increased with an increase in the initial dye concentration from 5 to 80 mg/L. It was deduced that both the surface chemistry of the biochar BC200 and the positively-charged molecules of MB were sensitive to the presence of the external magnetic field.

Fig. 3

The magnetic treatment has been reported to be capable of reducing the viscosity and surface tension of solutions as a result of resonance (Duan et al., 2012). This resonance could impart energy to the system, changing the structure and nature of the materials involved. Batch adsorption experiments were also conducted to investigate the effect of the pre-treatment time by the magnetic field on the adsorption of MB. The pre-treatment time varied from 0 min to 120 min while the adsorption duration was maintained at 24 h. The experimental results are shown in Fig. 3b. It was observed that the removal percentages of MB at magnetic pre-treatment times of 0, 30, 60, and 120 min were 91.4%, 97.5%, 97.8%, and 98.0%, respectively. These removal percentages were much higher than those observed without the magnetic field (80.4%); however, the removal percentages at a magnetic pre-treatment time of 30, 60, and 120 min were much closer to each other, while slightly higher than that at 0 min pre-treatment time, indicating that prolonged magnetic pre-treatment was unnecessary. Considering the weak effect of the magnetic pre-treatment, the dye solution was not pre-treated by the magnetic field in the other tests.

3.5 Effect of solution pH on adsorption kinetics

The effect of solution pH on the adsorption kinetics of MB onto the biochar BC200 was investigated at pH 3.0, 5.0, 7.0, 9.0, and 11.0, respectively. The kinetic data at pH 3.0, 7.0, and 11.0 are plotted in Fig. 4. Kinetic models, including

pseudo-first-order, pseudo-second-order, Elovich, and double-constant models, were used to fit the experimental data. The mathematical representations of the non-linear models of pseudo-first-order and pseudo-second-order kinetics are those available in the literature (Lagergren, 1898; Ho and McKay, 1999):

$$q_t = q_e (1 - e^{-k_1 t}) \quad (4)$$

$$q_t = \frac{k_2 q_e^2 t}{(1 + k_2 q_e t)} \quad (5)$$

where q_e and q_t are the adsorption capacities (mg/g) at equilibrium and at time t (minutes), respectively; and k_1 (min^{-1}) and k_2 ($\text{g min}^{-1} \text{mg}^{-1}$) are the related adsorption rate constants for pseudo-first-order and pseudo-second-order model, respectively.

The Elovich model, used to describe chemisorption occurring on a solid-liquid interface, can be written as (Kithome et al., 1988; Cheung et al., 2000):

$$q_t = k \ln(t) + a \quad (6)$$

where a ($\text{g} \cdot \text{mg min}^{-1}$) and b (mg g^{-1}) are constants.

The double-constant kinetic model is an empirical equation derived from the classical Freundlich isotherm and is mainly suitable for more complex reaction kinetics. It is expressed as Eq. (7) (Zheng et al., 2015):

$$\ln q_t = k_0 \ln(t) + a \quad (7)$$

where k_0 is the double-constant kinetic constant, and a is an adsorption rate constant associated with activation energy of adsorption.

Fig. 4

The experimental kinetic data at pH 3.0, 7.0, and 11.0 were fitted by the four non-linear kinetic models, and the simulated curves are also presented in Fig. 4. Apparently, it was noted that the Elovich and double-constant models better described the experimental data than the pseudo-first-order and pseudo-second-order kinetic models under the three pH conditions tested here. Furthermore, the calculated kinetic parameters are also shown in Table 1. The correlation coefficients (R^2) of the Elovich and double-constant models were all greater than 0.952 and most of them were around 0.990. In contrast, the R^2 values of pseudo-first-order model were less than 0.919 and most were less than 0.900. The R^2 values were higher for the pseudo-second-order model than for the pseudo-first-order model, indicating that the overall adsorption process was controlled by chemisorption. Nevertheless, the R^2 values of the pseudo-second-order model were still a little less than those of the Elovich and double-constant models. It has been suggested that diffusion accounted for the Elovich kinetic pattern and the rate-determining step might be diffusive in nature (Aharoni et al., 1991; Pavlatou and Polyzopouls, 1988). The well-fitted double-constant model also indicated the more complex reaction kinetics. It can be inferred that chemisorption occurred between MB molecules and wheat straw biochar.

Table 1

Additionally, as presented in Table 1, in the absence of a magnetic field, the q_e values (pseudo-second-order model) at pH 3.0, 7.0, and 11.0 were 13.3, 17.9, and

21.8 mg/g, respectively. Once the external magnetic field was applied, the q_e values at pH 3.0, 7.0, and 11.0 were 17.9, 20.9, and 21.9 mg/g, respectively. This result suggested that, both the magnetic field, and the increasing solution pH values, benefitted the adsorption of MB. MB is a cationic dye throughout the pH range examined while the normally negatively-charged wheat straw biochar BC200 is expected to be more negatively-charged with increasing solution pH (Ahmad et al., 2014). As a result, the electrostatic attractive force could be enhanced and more dye molecules can be adsorbed onto the biochar. Concurrently, considering the effect of the external magnetic field, the adsorption capacities at pH 3.0, 7.0, and 11.0 were increased by 34.6%, 16.8%, and 0.5%, respectively. As indicated above, the effect of the external magnetic field was highly dependent upon the reaction conditions including the dose of biochar and the initial dye concentration. In this case, the lower the solution pH values, the more powerful the external magnetic field. As the aqueous chemistry of MB molecules is comparatively simpler than the surface chemistry of the wheat straw biochar, it may demonstrate that the effect of the external magnetic field on the surface chemistry of the biochar was essential to the adsorption process.

3.6 Adsorption isotherms

The adsorption isotherm can provide information about the surface properties of adsorbent and the adsorption behaviour. Isotherm studies were compared considering the presence and absence of the external magnetic field (Fig. 5). Both the Langmuir and Freundlich models were selected to fit experimental data and the parameters for both models are listed in Table 2.

Fig. 5

The Langmuir adsorption isotherm has, to date, been the adsorption isotherm most widely used to express the adsorption of a solute from a liquid solution. The saturated monolayer isotherm can be represented as (Freundlich, 1906):

$$q_e = \frac{q_m k_L C_e}{1 + k_L C_e} \quad (8)$$

where, q_m (mg g^{-1}) is q_e for a complete monolayer, a constant related to sorption capacity; and K_L (L mg^{-1}) is a constant related to the affinity of the binding sites and energy of adsorption.

The Freundlich isotherm, an empirical equation describing the adsorption onto a heterogeneous surface, is commonly presented as (Yang et al., 2013):

$$q_e = k_F C_e^{\frac{1}{n}} \quad (9)$$

where, K_F and n are the Freundlich constants related to the adsorption capacity and the adsorption intensity of the adsorbent, respectively.

From the curves simulated in Fig. 5, both the Langmuir and Freundlich models fitted the experimental data well. As shown in Table 2, the correlation coefficients (R^2) with the Freundlich model were only slightly greater than those found when using the Langmuir model. Using the Langmuir model, the calculated maximum adsorption capacities for MB in the absence, and presence, of the external magnetic field were 46.6 and 62.5 mg/g, respectively. The $q_{\max}$ value was enhanced by 34.1% with the help of the external magnetic field. The results also indicated the significant

enhancement of the external magnetic field on the uptake of MB.

Table 2

3.6 Adsorption mechanism

3.6.1 Enhanced adsorption mechanism by the external magnetic field

As stated above, the wheat straw biochar alone was capable of removing MB efficiently. Usually, three adsorption mechanisms are involved in the adsorption process. Firstly, MB is a cationic dye throughout the pH range examined while the biochar surfaces are normally negatively-charged. The electrostatic interaction between dye molecules and biochar was thought to be dominant in the adsorption process, as indicated by the aforementioned results. Secondly, the biochar with the graphitized surface has a higher π -electron density, indicating that the biochar is accepted as a π -electron donor. MB can be regarded as a π -electron acceptor. A mechanism of π - π electron-donor-acceptor (EDA) interaction might contribute to the adsorption of MB onto the biochar (Teixidó et al., 2011; Zheng et al., 2013; Jing et al., 2014; Zhang et al., 2014). Finally, the H-bond interaction between the MB molecules and the biochar might also be responsible for the adsorption.

The effect of the external magnetic field on the adsorption of MB is even more complicated. On the one hand, the magnetization of water changes the bond angle of water molecules, which increases their dipole moment and decreases the cluster structures of water molecules (Zhang et al., 2014). The smaller hydration molecule of MB increases the mobility of the dye under a magnetic field, and more dye molecules

could be adsorbed onto the biochar surface. On the other hand, the biochar surface becomes more heterogeneous with a consequent increase in surface area and adsorption capacity (Aline et al., 2014; Hao et al., 2012), which might have been indicated by the higher regression coefficients of the Freundlich model compared to those found when using the Langmuir model (Table 2). From this point of view, the external magnetic field can be used to replace the magnetic sorbents with normal sorbents since its effect was significant enough to improve the adsorption.

3.6.2 Effect of the surface acidic functional groups of the biochars

The effect of total surface acidic functional groups including carboxyl, lactonic, and phenolic groups on the adsorption of MB was investigated (Fig. 6). The surface functional groups of the raw WS, BC200, BC400, and BC600 were quantified by Boehm's titration. The total content of the three groups in the raw WS, BC200, BC400, and BC600 were 0.8658, 1.5785, 0.764, and 0.6774 mmol/g, respectively. Meanwhile, the removal percentages for MB using the raw WS, BC200, BC400, and BC600 were 81.5%, 81.6%, 76.8%, and 80.5%, respectively. Under the magnetic field, the removal percentages for MB using the raw WS, BC200, BC400, and BC600 were 83.1%, 91.4%, 88.8%, and 86.7%, respectively. The above confirmed that the surface acidic functional groups were particularly sensitive to the magnetic field, which actually enhanced the adsorption capability for the removal of MB to some extent. Considering the increase in the surface area with increasing pyrolytic temperature (Ahmad et al., 2014), the enhancement in MB removal seemed reasonable as the

removal percentages by BC400 and BC600 were too high if only the effect of the surface functional groups were considered. Even though, it was difficult to exclude the effect of other moieties and functional groups of the biochar such as amino groups. On the whole, the surface properties of the different biochars might determine variations in their performance under the magnetic field.

Fig. 6

3. Conclusion

The adsorptive removal of MB on wheat straw biochar was innovatively enhanced by an external magnetic field. Under the magnetic field, the adsorption capability of the biochar pyrolyzed at 200 °C outperformed that of the other biochars examined here, which might be attributed to the highest content of the total surface acidic functional groups. The effect of pre-treatment by magnetic field was insignificant. An increased biochar dose decreased the uptake of MB significantly, while its enhancement effect increased significantly with an increase in the initial dye concentration and decreasing solution pH. Kinetic experiments indicated a chemisorption process.

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Figure Captions

Fig.1 Effect of the pyrolytic temperature (200, 400 and 600 °C) used for biochar preparation on the adsorption of MB in the presence and absence of [the](#) external magnetic field. The MB concentration was 10 mg/L. Biochar dosages 200 mg were added to 500 mL of MB solution.

Fig.2 Effect of the external magnetic field on the adsorption of MB onto wheat straw biochar with the assistance of [the](#) external magnetic field. MB concentration 10 mg/L. BC200 dosages were of 50, 100 and 200 mg in 500 mL of dye solution.

Fig.3 Effect of the initial concentrations of MB (a) and the pretreatment time by magnetic field (b) on the adsorption by BC200.

Fig.4 Effect of solution pH on the adsorption kinetics of MB onto BC200.

Fig.5 Langmuir and Freundlich isotherms for the adsorption of MB onto BC200.

Fig.6 Effect of total surface acidic functional groups on the adsorption of MB.

Fig.1

Fig.2

Fig.3

Fig.4

Fig.5

Fig.6

Table 1 Kinetic parameters for the adsorption of MB on BC200.

Model	condition	parameters	pH=3	pH=5	pH=7	pH=9	pH=11
Pseudo-first order	no magnetic field	R^2	0.897	0.914	0.856	0.850	0.904
		q_e (mg g ⁻¹)	11.6	16.5	16.3	18.7	20.3
		k_1 (min ⁻¹)	0.005	0.00733	0.0174	0.0155	0.0347
	magnetic field	R^2	0.919	0.91	0.838	0.878	0.889
		q_e (mg g ⁻¹)	15.6	18.8	19.4	19.7	20.5
		k_1 (min ⁻¹)	0.00455	0.00633	0.0311	0.0246	0.0442
Pseudo-second order	no magnetic field	R^2	0.944	0.959	0.930	0.923	0.968
		q_e (mg g ⁻¹)	13.3	18.9	17.9	20.7	21.8
		k_2 (g mg ⁻¹ min ⁻¹)	4.78×10 ⁻⁴	5.02×10 ⁻⁴	0.00131	0.00102	0.00216
	magnetic field	R^2	0.955	0.956	0.924	0.947	0.962
		q_e (mg g ⁻¹)	17.9	21.5	20.9	21.6	21.9
		k_2 (g mg ⁻¹ min ⁻¹)	3.34×10 ⁻⁴	3.87×10 ⁻⁴	0.00203	0.00147	0.00282
Elovich	no magnetic field	R^2	0.956	0.974	0.989	0.978	0.992
		a	-3.427	-4.313	-1.535	-1.84	1.105
		k	2.09	3.08	2.86	3.25	3.21
	magnetic field	R^2	0.952	0.969	0.988	0.987	0.988
		a	-4.448	-5.07	0.929	-0.978	2.925
		k	2.75	3.46	3.07	3.40	2.98
Double-constant	no magnetic field	R^2	0.993	0.987	0.993	0.987	0.961
		a	-0.119	0.585	1.16	1.265	1.788
		k_0	0.377	0.335	0.259	0.263	0.199
	magnetic field	R^2	0.993	0.991	0.979	0.97	0.962
		a	0.184	0.617	1.686	1.522	1.954
		k_0	0.374	0.347	0.209	0.235	0.177

Table 2 Langmuir and Freundlich isotherm parameters for the adsorption of MB onto BC200.

	Langmuir isotherm			Freundlich isotherm		
	$q_{max} (mg\ g^{-1})$	$k_L (L\ mg^{-1})$	R^2	$k_F (mg\ g^{-1})$	n	R^2
no magnetic field	46.6	0.458	0.918	19.7	4.553	0.926
under magnetic field	62.5	0.394	0.867	23.4	3.912	0.931