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# Biosorption characteristics of methylene blue dye by two fungal biomasses

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## Abstract

A novel approach has been tried to use both *Aspergillus carbonarius* (AC) and *Penicillium glabrum* (PG) fungi for the first time to remove methylene blue (MB) from aqueous solutions. The biosorption was favoured using a biosorbent concentration of 0.33 g/L at pH 8.2. Biosorption kinetics were evaluated for different dye concentrations (5–25 mg/L). The resulting biosorbent was characterised by scanning electron microscopy (SEM), X-ray diffractometer and Fourier transformer infrared spectroscopy (FTIR) techniques. The maximum biosorption capacities of AC and PG for MB were 21.88 mg/g and 16.67 mg/g, respectively at 30 °C. The results suggested that *A. carbonarius* and *P. glabrum* could be used as biosorbents for the effective removal of methylene blue from dye wastewater in terms of biosorption capacity, availability and low cost.

*Keywords:* Fungal biomass; methylene blue; biosorption; isotherms.

## Introduction

Synthetic dyes, an important group of chemicals, are also pollutants. They are discharged during the production of textiles, cosmetics, paper, pharmaceuticals, volatile organic compounds, and leather, in a spectrum of colours [1]. There are more than 100,000 commercial dyes worldwide, amounting to approximately  $7 \times 10^8$ – $1 \times 10^9$  kg per year [2]. It is estimated that about 10 to 15% of the dyes used in the production processes are lost in the effluent [3], and the average dye concentration detected in the effluents is 300 mg/L [4]. Most of the dyes are considered to be recalcitrant to the natural degradation processes such as heat, photodegradation and biodegradation because of their complex molecular structures [5]. Various physicochemical approaches have been used for the elimination of dyes such as adsorption, precipitation, photo-oxidation, coagulation, flocculation, reduction, and electrochemical treatment [6].

Biosorption is considered an attractive alternative for treating wastewater contaminated with dyes [7]. Current research focuses on microbial biomass, because it is an environment-friendly approach that can be used to remove azo dyes contaminants [8]. Fungal biomass holds distinct advantages over other microorganisms with respect to industrial exploitation. It is available on a large scale, it can grow in a cheap medium, and it can be easily harvested [9]. Besides, the composition of fungal cell walls (chitin, glucan, mannan, proteins, amino and hydroxyl groups), makes their biomasses suitable for biosorption [10]. Fungal species such as *Trichoderma asperellum* [11], *Aspergillus fumigatus* [12], *Trametes versicolor* [13], *Fusarium solani* [14], *Corioloropsis* sp. and *Penicillium simplicissimum* [15, 16] have been reported as efficient dye-decolourizers. Methylene blue (MB) is a thiazine cationic dye. It is considered a common pollutant in textile wastewater and is often used in dye houses and textile industries [17]. Both *Aspergillus carbonarius* (AC) and *Penicillium glabrum* (PG) have been proven to be very efficient in biosorption of Congo red [18].

In the present study these biomaterials were investigated for their capability to remove MB. For this purpose, the main factors affecting decolorisation such as contact time, initial pH, biosorbent concentration, and dye concentration were examined. Biosorption equilibrium data were analysed by Langmuir, Freundlich, Temkin and Dubinin-Radushkevich isotherm models. The biosorption kinetic data of the biomass were tested by the pseudo-first-order, the pseudo-second-order kinetic and intraparticle diffusion models. In order to reveal the adsorption characteristic of AC and PG biomasses, Scanning electron microscopy (SEM) and Fourier Transform Infrared Spectroscopy (FTIR) spectra analyses were carried out.

## **Materials and methods**

### ***Preparation of the biosorbents***

Both micro-fungi *Aspergillus carbonarius* (AC) and *Penicillium glabrum* (PG) were obtained from the fungal collection of the Laboratoire de Génie Chimique, Université de Toulouse (France). They were cultivated on Potato Dextrose Agar (PDA) medium in Petri dishes at room temperature ( $25 \pm 1$  °C). The fungal mycelium was cultured in liquid Sabouraud medium (1L): (10 g sucrose and 7 g peptone) under 25 °C for 19 days of incubation (without shaking). Collected mycelia were washed by distilled water and dried for 24 h at 80 °C. The dried biomass was crushed and sieved to 500 µm particle size using the ASTM standard test sieves (No: 35) to obtain AC and PG biosorbents [19].

### ***Dye solution preparation***

Methylene blue (MB) was chosen as a representative of cationic dye group. MB was supplied by Fluka (chemical formula:  $C_{16}H_{18}ClN_3S$ ; molecular weight 319.86 g/mol; maximum wavelength 663 nm). Figure 1 shows the chemical structure of the dye. A stock solution of 100 mg/L was prepared in ultrapure water. The required concentrations ranging from 10 to 50 mg/L were prepared by diluting the stock solution.

### ***Characterisation of the biosorbents***

The selected biosorbents were characterised using Fourier transform infrared spectrophotometer in the region of 400–4000  $\text{cm}^{-1}$  (FTIR, Perkin-Elmer Spectrum 400). The pattern of X-ray diffraction of the biosorbents; AC and PG was analysed using XRD, Rigaku Dmax-Rapid II. The morphology was visualised using scanning electron microscopy (SEM, Zeiss Supra 55). The images were taken by applying electron beam with an acceleration voltage of 10.0 kV.

### ***Biosorption experimental procedure***

The selected biosorbents underwent a series of batch experiments to study the effect of several parameters such as pH (2–11), initial dye concentration (5–25 mg/L), contact time (0–180 min), and temperature (25, 30 and 35 °C) at pH 8.2. Biosorption experiments were conducted using 10 mg/L dye solutions and 0.33 g/L of biosorbent in 30 mL solution volume. Mixtures were shaken at 30 °C and 250 rpm on a rotary shaker (New Brunswick Scientific Company, New Jersey, USA) to reach equilibrium. After the sorption process, the biosorbent was centrifuged and separated from the dye solution by Microlitre Centrifuges, Heraeus instruments, Biofuge at 16,000 g (12,000 rpm) for 10 min. Then, the remaining dye concentrations in the supernatants were analysed by a UV–vis spectrophotometer (JENWAY UV–vis 6705) at 663 nm. The adsorption equilibrium  $q_e$  (mg/g) at different solute concentrations of MB adsorbed by AC and PG was calculated according to equation (1).

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

Where  $C_0$  and  $C_e$  are the initial and equilibrium concentrations of methylene blue, respectively (mg/L).  $V$  is the volume of MB solution (L) and  $m$  is the mass of adsorbent used (g). The percent removal of dyes from aqueous solution was calculated using equation (2).

$$R\% = \frac{(C_0 - C_e)}{C_0} \times 100 \quad (2)$$

### ***Nonlinear regression analysis***

All kinetic and isotherm parameters of the models were evaluated by non-linear regression analysis of the experimental data. The correlation coefficients ( $R^2$ ) and the root mean squared error or standard error (RMSE) of the estimate were used as a measure of the goodness-of-fit of the mathematical models. Values of  $R^2$  close to 1.0 and small RMSE values indicate better curve fitting.

$$RMSE = \sqrt{\frac{1}{n-2} \sum_{i=1}^n (q_i - q_{ie})^2} \quad (3)$$

Where,  $q_i$  (mg/g) is the experimental value of uptake,  $q_{ie}$  is the calculated value of uptake using a model (mg/g), and  $n$  is the number of observations in the experiment.

## Results and discussion

### *Characterisation of A. carbonarius and P. glabrum surfaces*

In order to check the structure of AC and PG, an XRD study was performed, as shown in Figure 2(a,b), respectively. The XRD patterns did not show any crystalline phase of the material, only a pronounced wide band at  $2\theta$  in the range of  $10^\circ$  to  $30^\circ$  was observed, indicating an amorphous structure [20]. The SEM images characterising the surface morphology of AC and PG are illustrated in Figure 3(a,b), respectively. Through these images, it can be observed that AC and PG showed an irregular surface structure, with different particle sizes, characterising a rough texture. These characteristics are beneficial for easy and quick mass penetration during adsorption [21]. These properties allow more interaction of the dye with the biosorbent structure [22]. FTIR analysis was performed to characterise the functional groups that were responsible for the biosorption process. Figure 4 (a,b), respectively show the spectrum of FTIR captured before and after MB dye biosorption onto *A. carbonarius* and *P. glabrum*. Table 1 shows the changes in the FTIR functional group bands, along with the band positions, before and after dye loading.

The major bands found in the AC biomass before biosorption were close to 3269, 2924, 2121, 1620, 1023  $\text{cm}^{-1}$ . In the FTIR of AC before biosorption, the broad band with a vibrational elongation around 3269  $\text{cm}^{-1}$  indicates the presence of the hydroxyl (OH) and amino (NH) groups on the surface of AC [23]. The peak at 2926  $\text{cm}^{-1}$  indicates the C–H stretch vibration asymmetric [24]. The band at 1023.18  $\text{cm}^{-1}$  is assigned to the C–O stretching vibration while the large bands at 1620.63  $\text{cm}^{-1}$  could be attributed to C=C bonds. The band at 1620.63  $\text{cm}^{-1}$  is assigned to C=C and C=O stretching in the aromatic ring. Slight horizontal shifts were detected after MB adsorption indicating that –OH, –COOH, and –NH groups on the surface of *A. carbanarius* were responsible for the biosorption process through complexation mechanism.

Figure 4(b) shows the FTIR results of the *P. glabrum* fungal biomass before and after biosorption of methylene blue. The –NH absorption peak is shifted from 3271.0  $\text{cm}^{-1}$  to 3272.0  $\text{cm}^{-1}$  upon adsorption of MB. The peak at 2923 and 2854  $\text{cm}^{-1}$  is indicative of stretching of C–H bond of methyl and methylene groups [25]. The peaks located around 1740  $\text{cm}^{-1}$  are characteristic to carbonyl group stretching vibrations [26]. The amide I band is mainly a C=O stretching mode and is centred at 1643  $\text{cm}^{-1}$ ; the amide II band is a combination of N–H bending and C–N stretching, being centred near 1539  $\text{cm}^{-1}$ ; the C–N stretching of amide III band is located near 1228  $\text{cm}^{-1}$  [27]. The shifting of the band from 1042.9 to 1027.1  $\text{cm}^{-1}$  also suggests the activity of C–O group in MB binding, and the peak observed at 698  $\text{cm}^{-1}$  corresponds to the N–H out-of-plane bending.

### ***Effect of pH***

The pH of the biosorption medium is an important parameter affecting the biosorbent uptake of dye from aqueous solutions. Therefore, MB dye biosorption onto AC and PG was investigated using 0.33 g/L of biosorbent, with initial dye concentration of 10 mg/L, varying the pH from 3 to 11. Figure 5 shows the results, indicating a maximum biosorption capacity



of 21.60 mg/g and 24.53 mg/g for AC and PG at pH 11, respectively. This suggests that MB biosorption onto both fungi is favourable in neutral to alkaline conditions. At these favourable conditions, there is electrostatic force of attraction between the cationic dye and the surface charge of the biosorbents, which became negatively charged at pH >5.76 and 6.40, for AC and PG, respectively. At the low pH values, the dye removal by biosorbent was low because the acidic condition produces more H<sup>+</sup> ions in the aqueous solution. Similar results were reported in the cationic dye adsorption onto *Arundo donax* activated carbon [28].

#### ***Effect of the biosorbent concentration***

Figure 6(a,b), respectively show the effect of the biosorbent concentration on the uptake of methylene blue on *A. carbonarius* and *P. glabrum* fungi. Removal of MB increased from 48.21% to 70.36% and from 41.37% to 71.66% for AC and PG respectively, when the concentration was increased from 0.33 to 0.67 g/L. This can be attributed to the increasing surface area of the adsorbent as well as the availability of more adsorption sites [29]. In contrast, the biosorption capacity decreased from 14.56 to 3.25 mg/g and 17.49 to 3.49 mg/g for AC and PG, respectively. This decrease in biosorption capacity of the dye with increasing biosorbent concentration can be attributed to a greater number of sites that remain unsaturated during the biosorption reaction, as well as the agglomeration of biosorbent particles [30].

#### ***Effect of the contact time***

Figure 7 shows the effect of the contact time (0-180 min) on the biosorption of MB onto the two biosorbents. For both *A. carbonarius* and *P. glabrum* fungal biomass, at an initial dye concentration of 10 mg/L, the biosorption rate was rapid in the first 40 min, then its rate became slow leading to a single, smooth and continuous saturation curve. At equilibrium, MB removal for AC was 20.32 mg/g compared to 12.80 mg/g for PG.

#### ***Effect of the initial dye concentration***

The biosorption process is greatly influenced by the initial concentration of the adsorbate. Figure 8 shows the effect of the initial dye concentration on the biosorption capacity of AC and PG biosorbents. By increasing the initial dye concentration, the biosorption capacity was found to increase from 11.16 to 20.02 mg/g for AC and from 10.76 to 15.91 mg/g for PG; and the removal yield was found to decrease from 74.59 to 26.38% and from 71.33 to 21.82% for AC and PG, respectively. A similar trend was observed with biosorption of methylene blue onto *Carica papaya* wood and *Aspergillus fumigatus* [2, 12]. This trend might be caused by the increase in the necessary driving force to overcome the resistance to the mass transfer of all molecules between the aqueous phase and the biosorbents [31].

### ***Biosorption kinetics***

The pseudo-first-order Lagergen, the pseudo-second-order and the intraparticle diffusion models were tested to describe the biosorption kinetics.

The linear form of the pseudo-first-order rate equation [18] is given as:

$$\ln(q_e - q_t) = \ln q_e - \frac{k_1}{2.303} t \quad (4)$$

Where  $q_e$  and  $q_t$  are the amounts of the MB dye sorbed at equilibrium time (mg/g) and  $t$  (min), respectively, and  $k_1$  is the first-order rate constant ( $\text{min}^{-1}$ ).

The pseudo-second-order rate equation [32] is given as:

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

Where  $k_2$  (mg/g min) is the second-order rate constant,  $q_t$  (mg/g) is the amount of biosorption after time  $t$  (min) and  $q_e$  is the amount of biosorption equilibrium (mg/g). The intraparticle diffusion equation [33] is expressed as:

$$q_t = k_{id} t^{1/2} + C_i \quad (6)$$

Where  $q_t$  (mg/g) is the amount adsorbed at time  $t$  (min),  $k_{id}$  (mg/g min<sup>1/2</sup>) is the rate constant of intraparticle diffusion.  $C_i$  (mg/g) is a constant that gives an idea about the thickness of the boundary layer.

Elovich model [34] is suitable for systems with heterogeneous biosorbing surfaces and can be written as:

$$q_t = \frac{1}{\beta} \ln(\alpha\beta) + \frac{1}{\beta} \ln t \quad (7)$$

The kinetic parameters for methylene blue biosorption onto AC and PG are shown in Table 2. The values of  $R^2$  and RMSE from the table revealed that the pseudo-second-order was better for describing the biosorption process. Thus, the estimated biosorption capacity of biosorbent for MB by the pseudo-second-order model was very close to the experimental values. The straight lines did not go through the origin, indicating that the pore diffusion was not the only rate-controlling step (figure not shown). This indicated that the biosorption process might be of complex mechanism including both surface biosorption and intraparticle diffusion [20].

### ***Biosorption isotherm***

The present results obtained from batch experiment were analysed by using the most common isotherms; Langmuir, Freundlich, Temkin and Dubinin–Radushkevich adsorption isotherm models. The linear form of the Langmuir model [35] is given as:

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

Where  $q_e$  is the amount adsorbed at equilibrium (mg/g) and  $C_e$  is the equilibrium concentration of the adsorbate (mg/L). The Langmuir constants  $q_m$  (mg/g) represent the monolayer biosorption capacity and  $b$  (L/mg) relates to the heat of biosorption. A plot of  $C_e/q_e$  versus  $C_e$  gives a straight line of slope  $1/q_m$  and intercepts  $1/q_m b$  is shown in Figure 9. The

most important characteristics of the Langmuir isotherm can be expressed in terms of a dimensionless separation factor ( $R_L$ ) which is defined according to Dahlan et al. [36].

$$R_L = \frac{1}{1+bC_0} \quad (9)$$

$R_L$  values indicate whether the adsorption process is irreversible ( $R_L = 0$ ), favourable ( $0 < R_L < 1$ ), linear ( $R_L = 1$ ), or unfavourable ( $R_L > 1$ ). As the value of  $R_L$  in our study is less than 1 and greater than 0, this indicates the favourable uptake of methylene blue compounds by both *Aspergillus carbonarius* and *Penicillium glabrum* biomasses.

The Freundlich isotherm assumes a heterogeneous surface with a non-uniform distribution of biosorption heat over the surface, which is expressed in the following equation [37]:

$$\ln q_e = \ln K_f + \left(\frac{1}{n}\right) \ln C_e \quad (10)$$

Where  $K_F$  ( $\text{mg/g (L/mg)}^{1/n}$ ), defined as the adsorption or distribution coefficient, is related to the adsorption capacity;  $n$  is a measure of the adsorption intensity and gives indication on the favourability of the adsorption. Figure 10 shows the linear plot of specific adsorption ( $\ln q_e$ ) against the ( $\ln C_e$ ) for Freundlich model.

The Temkin isotherm assumes that (i) the heat of adsorption of all the molecules in the layer decreases linearly with coverage owing to adsorbent–adsorbate interactions, and (ii) adsorption is characterised by a uniform distribution of binding energies, up to some maximum binding energy, which is expressed in the following equation [38]:

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

Where  $K_T$  (L/g) and  $b_T$  (kJ/mol) are the Temkin constants.  $K_T$  and  $b_T$  constants were determined from the slope and intercepts of the plots obtained by plotting plot of  $q_e$  versus  $\ln C_e$ .

The D–R (Dubinin–Radushkevich) isotherm equation used to distinguish physical and chemical adsorption is described by equation [39]:

$$\ln q_e = K\varepsilon^2 + \ln q_{DR} \quad (12)$$

Polanyi potential ( $\varepsilon$ ) is given as equation:

$$\varepsilon = RT \ln(1 + 1/C_e) \quad (13)$$

Where  $q_{DR}$  is the Dubinin–Radushkevich maximum adsorption capacity of dye (mg/g),  $K$  is the Dubinin–Radushkevich constant ( $\text{mol}^2/\text{kJ}^2$ ),  $R$  is the universal gas constant (8.314 J/mol.K) and  $T$  is the absolute temperature (K). The plot of  $\ln q_e$  versus  $\varepsilon^2$  gives a straight line with a slope of  $K$  and an intercept of  $\ln q_{DR}$ . The Dubinin–Radushkevich constant can give valuable information regarding the mean energy of adsorption by the following equation:

$$E = (-2K)^{-1/2} \quad (14)$$

The adsorption isotherm parameters calculated for biosorption of MB by both *Aspergillus carbonarius* and *Penicillium glabrum* are presented in Table 3. The Langmuir isotherm model gave the most accurate description of MB sorption by the considered fungal strains. According to the Langmuir isotherm model, the maximum sorption capacities were 21.88 and 16.67 mg/g for *A. carbonarius* and *P. glabrum*, respectively. The equilibrium parameter or separation factor ( $R_L$ ) obtained from Langmuir model indicated favourable dye biosorption of MB onto AC and PG. From Freundlich isotherm, the value of  $n_F$  constant, falling in the range of 1-10 also showed a suitable biosorption process [40]; whereas the values of  $K_T$  and  $b_T$  determined from Temkin for AC and PG model were 0.018, 0.163 L/g and 0.722 and 0.331 kJ/mole, respectively. The (D–R) isotherm parameter; mean free energy ( $E$ ) provides information about the biosorption mechanism as chemical ion exchange or physical adsorption. The values of the calculated mean energy ( $E$ ) for both fungi AC and PG were less

than 8 kJ/mol, indicating that the biosorption process of the dye was probably physically controlled [41]. Table 4 shows a comparison of the maximum adsorption capacity with those of some other adsorbents reported in literature. Both AC and PG biomasses showed relatively better biosorption potential of MB dye. The availability and cost effectiveness of *Aspergillus carbonarius* and *Penicillium glabrum* might provide a cheap source of biosorbents for the sequestration of toxic dyes from industrial effluents.

## Conclusions

Both *Aspergillus carbonarius* and *Penicillium glabrum* biomasses were used for the removal of methylene blue (MB) from aqueous solutions. The adsorption equilibrium is consistent with Langmuir's model, and the adsorption kinetics fit the pseudo-second-order equation, indicating that the adsorption is controlled by interaction rather than diffusion. The maximum biosorption capacities of methylene blue onto *A. carbonarius* and *P. glabrum* were 21.88 mg/g and 16.67 mg/g, respectively, at optimum conditions of pH (8.2) and temperature equals 30°C. The biosorption equilibrium was reached in 120 min. These results suggested that the biomaterials *A. carbonarius* and *P. glabrum* can be used as environmentally feasible and low cost biosorbents for the removal of methylene blue from aqueous solutions.

## Disclosure Statement

No potential conflict of interest was reported by the authors.

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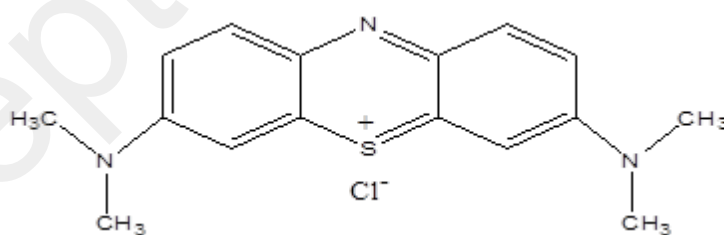
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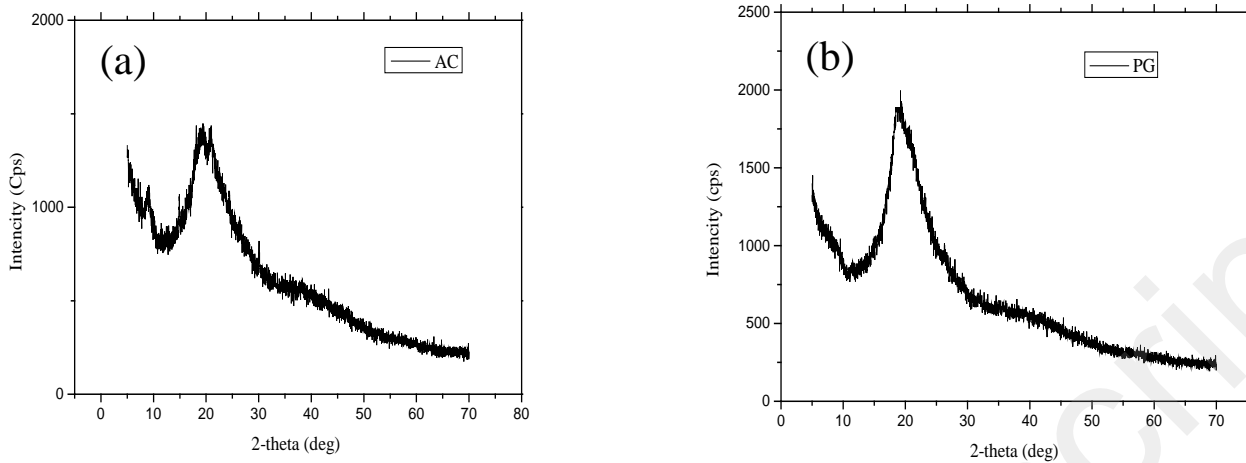
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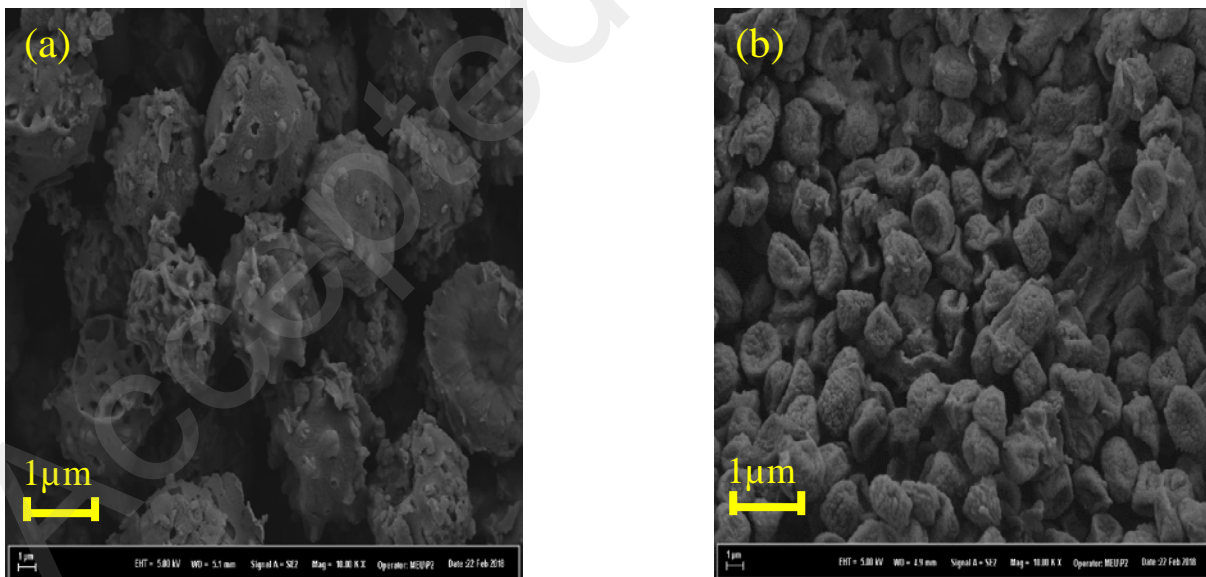
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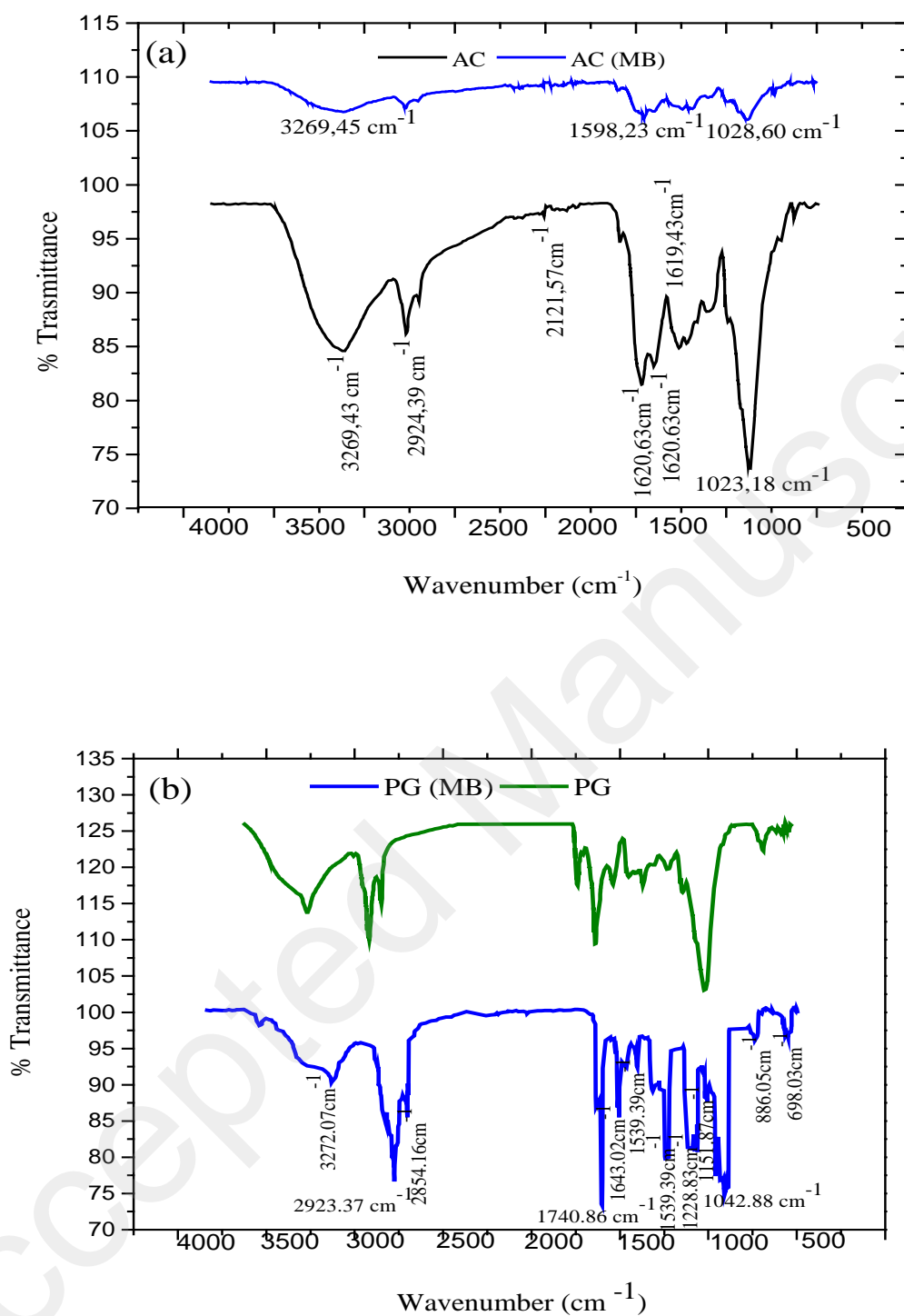
**Figure 1.** Chemical structure of methylene blue.



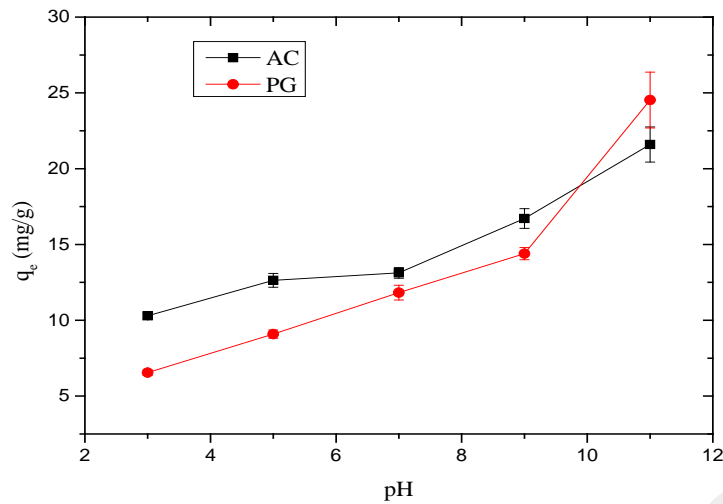
**Figure 2.** The X-ray diffraction (XRD) pattern of (a) *Aspergillus carbonarius* (AC) and (b) *Penicillium glabrum* (PG).



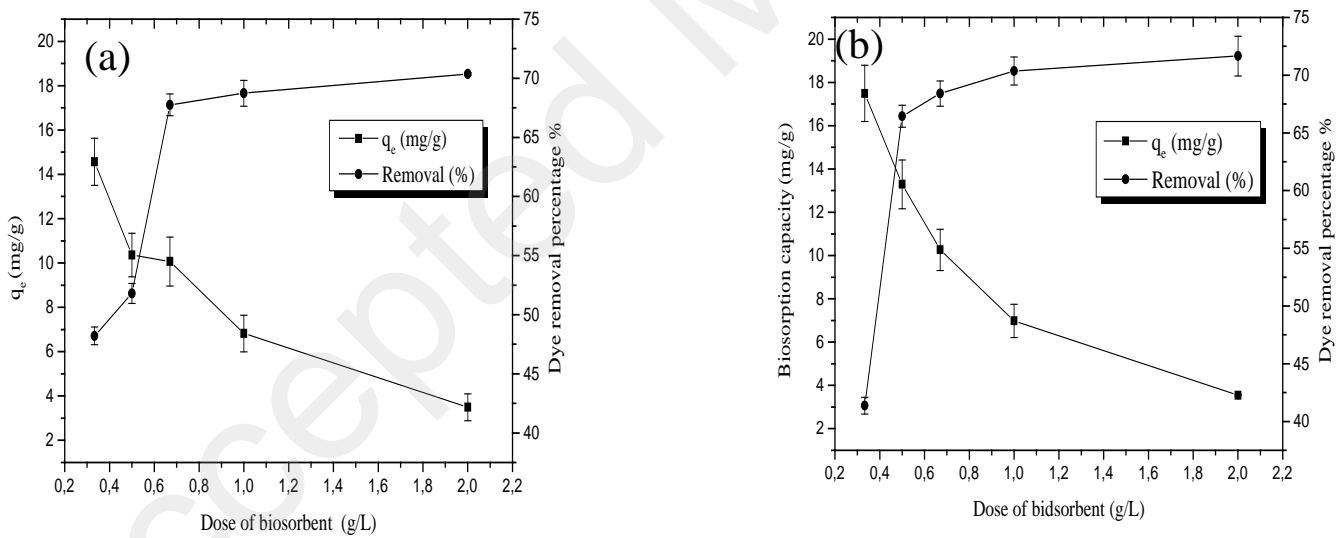
**Figure 3.** Scanning electron microscopy (SEM) micrographs of (a) *Aspergillus carbonarius* (AC) and (b) *Penicillium glabrum* (PG).



**Figure 4.** (a) FTIR spectra of *Aspergillus carbonarius* (AC) before and after biosorption of methylene blue. (b) FTIR spectra of *Penicillium glabrum* (PG) before and after biosorption of methylene blue.

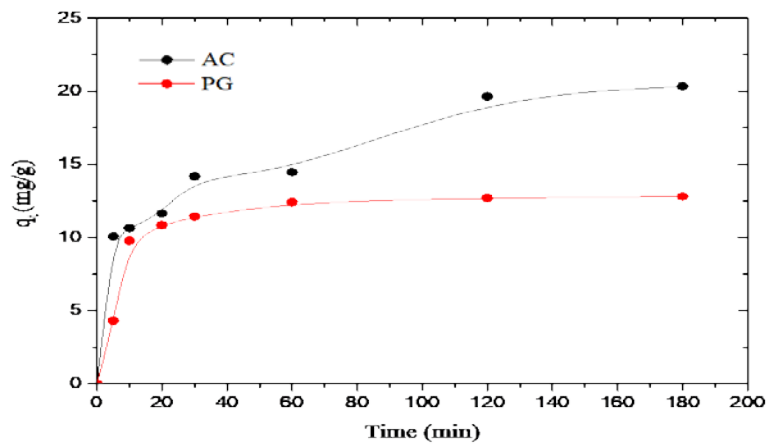


**Figure 5.** Effect of pH on the equilibrium uptake capacity of *Aspergillus carbonarius* (AC) and *Penicillium glabrum* (PG) for methylene blue. Conditions:  $C_i = 10$  mg/L, concentration of 0.33 g/L,  $T = 303$  K.

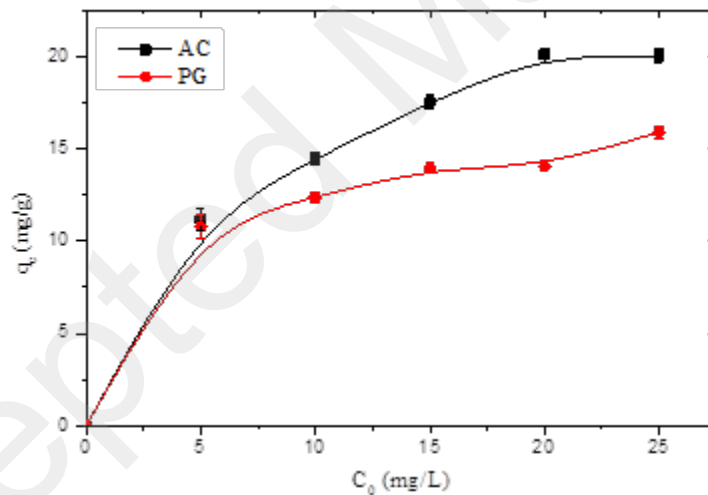


**Figure 6.** Effect of biosorbent concentration on the biosorption of methylene blue onto (a) *Aspergillus carbonarius* (AC) and (b) *Penicillium glabrum* (PG) [(% removal of methylene blue and biosorption capacity (mg/g)]. Experimental conditions: initial concentrations = 10 mg/L, biosorbent concentration = 0.33–2 g, contact time 2 h, pH 8.2.

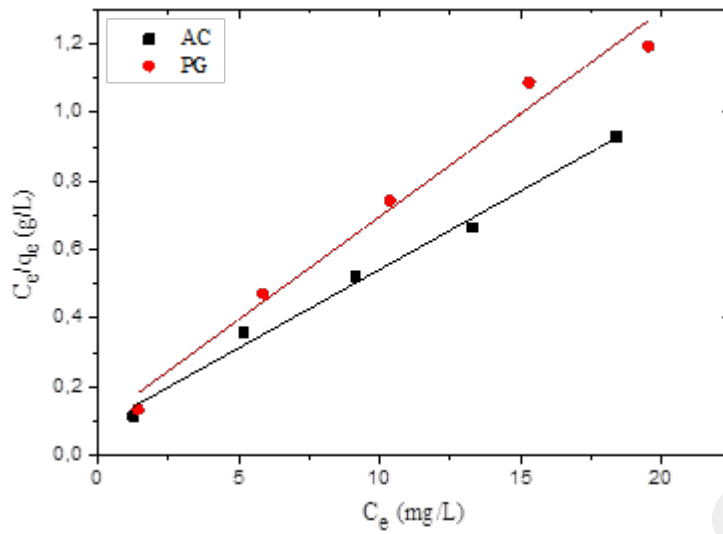




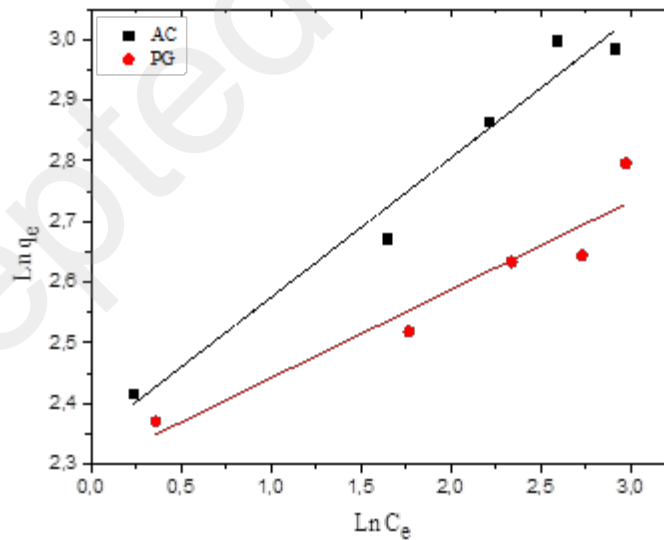
**Figure 7.** Effect of contact time on the biosorption capacity of methylene blue on *Aspergillus carbonarius* (AC) and *Penicillium glabrum* (PG). Conditions:  $C_i = 10$  mg/L, concentration of 0.33 g/L,  $T = 303$  K, pH 8.2.



**Figure 8.** Effect of initial dye concentration ( $C_0$ ) on biosorption capacity of *Aspergillus carbonarius* (AC) and *Penicillium glabrum* (PG) biosorbents for methylene blue (contact time: 2 h, biosorbent concentration: 0.33 g/L, pH 8.2).



**Figure 9.** The Langmuir isotherm plot for the biosorption of methylene blue onto *Aspergillus carbonarius* (AC) and *Penicillium glabrum* (PG). Conditions:  $C_i = 10$  mg/L, biosorbent concentration of 0.33 g/L,  $T = 303$  K, pH 8.2.



**Figure 10.** The Freundlich isotherm plot for the biosorption of methylene blue onto *Aspergillus carbonarius* (AC) and *Penicillium glabrum* (PG) Conditions:  $C_i = 10$  mg/L, biosorbent concentration of 0.33 g/L,  $T = 303$  K, pH 8.2.

**Table 1.** FTIR spectral characteristics of *Aspergillus carbonarius* and *Penicillium glabrum*

before and after methylene blue sorption

| <i>Aspergillus carbonarius</i>    |                   | <i>Penicillium glabrum</i>        |                   | Suggested assignments   |
|-----------------------------------|-------------------|-----------------------------------|-------------------|---|
| Band position (Cm <sup>-1</sup> ) |                   | Band position (Cm <sup>-1</sup> ) |                   |   |
| Before biosorption                | After biosorption | Before biosorption                | After biosorption |   |
| 3269.43                           | 3269.45           | –                                 | –                 | –OH and/or–NH stretching vibration                                      |
| –                                 | –                 | 3271.05                           | 3272.07           | –N–H stretching vibration   |
| 1620.63                           | 1619.43           | –                                 | –                 | N–H deformation vibration of amide I groups                             |
| 1023.18                           | 1028.60           | –                                 | –                 | C–N stretch of amide or amine   |
| –                                 | –                 | 2923.80                           | 2923.37           | –CH stretch aliphatic   |
| –                                 | –                 | 1742.74                           | 1740.86           | C=O stretching vibration of carboxylate (–COO–) / (–COOR–)              |
| –                                 | –                 | 1642.76                           | 1643.02           | C=O stretching vibration of N–H deformation vibration of amide I groups |
| –                                 | –                 | 1542.59                           | 1539.39           | N–H deformation vibration of amide II groups                            |
| –                                 | –                 | 1027.11                           | 1042.88           | C–O stretching of carboxylic groups                                     |

**Table 2.** Kinetic parameters for the biosorption of methylene blue onto *Aspergillus carbonarius* and *Penicillium glabrum* at various initial dye concentrations.

| Samples                                    | <i>Aspergillus carbonarius</i> |                       |                       | <i>Penicillium glabrum</i> |                       |                       |
|--|--------------------------------|-----------------------|-----------------------|----------------------------|-----------------------|-----------------------|
|  | 5                              | 10                    | 20                    | 5                          | 10                    | 20                    |
| C <sub>0</sub> of MB (mg/L)                | 5                              | 10                    | 20                    | 5                          | 10                    | 20                    |
| q <sub>eq</sub> (exp) (mg/g)               | 12.26                          | 20.30                 | 24.63                 | 11.38                      | 12.80                 | 15.83                 |
| Pseudo-first order                         |                                |                       |                       |                            |                       |                       |
| K <sub>1</sub> (min <sup>-1</sup> )        | 3.91×10 <sup>-2</sup>          | 3.93×10 <sup>-2</sup> | 5.22×10 <sup>-2</sup> | 4.81×10 <sup>-2</sup>      | 8.07×10 <sup>-2</sup> | 3.01×10 <sup>-2</sup> |
| q <sub>1</sub> (cal) (mg/g)                | 05.54                          | 07.69                 | 13.33                 | 02.31                      | 04.92                 | 04.96                 |
| R <sup>2</sup>                             | 0.821                          | 0.888                 | 0.925                 | 0.976                      | 0.927                 | 0.592                 |
| RMSE                                       | 0.89                           | 10.77                 | 17.68                 | 0.064                      | 4.93                  | 6.93                  |
| Pseudo-second order                        |                                |                       |                       |                            |                       |                       |
| K <sub>2</sub> (g/mg.min)                  | 1.1×10 <sup>-2</sup>           | 0.39×10 <sup>-2</sup> | 0.90×10 <sup>-2</sup> | 3.77×10 <sup>-2</sup>      | 1.22×10 <sup>-2</sup> | 1.58×10 <sup>-2</sup> |
| q <sub>2</sub> (cal) (mg/g)                | 12.05                          | 20.58                 | 24.04                 | 11.34                      | 13.46                 | 15.04                 |
| R <sup>2</sup>                             | 0.996                          | 0.971                 | 0.991                 | 0.999                      | 0.997                 | 0.999                 |
| RMSE                                       | 1.11                           | 2.02                  | 1.05                  | 0.40                       | 1.37                  | 1.10                  |
| Intraparticle diffusion model              |                                |                       |                       |                            |                       |                       |
| K <sub>id</sub> (mg/g min <sup>1/2</sup> ) | 0.64                           | 1.07                  | 0.58                  | 0.25                       | 0.74                  | 0.74                  |
| C  | 5.14                           | 7.35                  | 16.78                 | 8.68                       | 6.06                  | 7.90                  |
| R <sup>2</sup>                             | 0.867                          | 0.952                 | 0.887                 | 0.904                      | 0.584                 | 0.578                 |
| RMSE                                       | 0.82                           | 0.75                  | 0.56                  | 0.09                       | 4.99                  | 5.16                  |
| Elovich                                    |                                |                       |                       |                            |                       |                       |
| α (mg/g.min)                               | 2.86                           | 4.35                  | 15.21                 | 7.78                       | 2.72                  | 4.46                  |
| β (g/mg)                                   | 1.85                           | 2.84                  | 1.52                  | 0.72                       | 2.35                  | 2.38                  |
| R <sup>2</sup>                             | 0.930                          | 0.871                 | 0.788                 | 0.986                      | 0.774                 | 0.785                 |
| RMSE                                       | 6.67                           | 17.86                 | 5.65                  | 0.012                      | 2.71                  | 2.63                  |

**Table 3.**

Isotherm parameters for the biosorption of methylene blue from aqueous solutions onto *Aspergillus carbonarius* and *Penicillium glabrum*.

| Samples  | <i>Aspergillus carbonarius</i> | <i>Penicillium glabrum</i> |
|--|--------------------------------|----------------------------|
| Langmuir                                       |                                |                            |
| $q_m$ (mg/g)                                   | 21.88                          | 16.67                      |
| $b$ (L/mg)                                     | 0.538                          | 0.621                      |
| $R_L$  | 0.157                          | 0.139                      |
| $R^2$  | 0.991                          | 0.984                      |
| RMSE   | 15.72                          | 03.60                      |
| Freundlich                                     |                                |                            |
| $K_F$ (mg/g) (mg/L) <sup>1/n</sup>             | 10.43                          | 9.94                       |
| $n_F$  | 4.34                           | 6.87                       |
| $R^2$  | 0.927                          | 0.915                      |
| RMSE   | 0.74                           | 0.62                       |
| Temkin   |                                |                            |
| $K_T$ (L/g)                                    | 0.018                          | 0.163                      |
| $b_T$ (kJ/mole)                                | 0.722                          | 1.331                      |
| $R^2$  | 0.949                          | 0.873                      |
| RMSE   | 0.96                           | 0.75                       |
| Dubinin-Radushkevich                           |                                |                            |
| $q_{DR}$ (mg/g)                                | 18                             | 14                         |
| $K_{DR}$ (mole <sup>2</sup> /kJ <sup>2</sup> ) | 2E-07                          | 2E-07                      |
| $E$ (kJ/mole)                                  | 1.581                          | 1.581                      |
| $R^2$  | 0.781                          | 0.673                      |
| RMSE   | 5.46                           | 2.36                       |

**Table 4.** Comparison of biosorption capacities of various biosorbents for removal of methylene blue.

| Biosorbents                    | pH   | q <sub>m</sub> (mg/g) | References   |
|--------------------------------|------|-----------------------|--------------|
| <i>Aspergillus fumigatus</i>   | 7.0  | 125                   | [5]          |
| <i>Aspergillus wentii</i>      | 6.33 | 3.30                  | [42]         |
| <i>Aspergillus niger</i>       | 6.0  | 18.54                 | [43]         |
| Activated carbon               | 10   | 294.12                | [44]         |
| Orange peel                    | 7.2  | 13.90                 | [45]         |
| <i>Carica papaya</i> wood      | 7.35 | 32.25                 | [2]          |
| <i>Casuarina</i> seed-biocha   | 7.93 | 4.69                  | [1]          |
| USM–chitin                     | 10   | 26.69                 | [46]         |
| <i>Posidonia oceanica</i>      | 6.0  | 5.56                  | [47]         |
| Cereal chaff                   | 7.0  | 20.30                 | [48]         |
| Sugarcane dust                 | 7.5  | 04.88                 | [49]         |
| <i>Aspergillus carbonarius</i> | 8.2  | 21.88                 | Present work |
| <i>Penicillium glabrum</i>     | 8.2  | 16.67                 | Present work |