Biosorption of Cu (II) on the *Pleurotus Ostreatus*

Ümmühan Danış¹, Yusuf Kaya², Necla Barlık³

(1) Ondokuz May University, Engineering Faculty, Department of Chemical, Samsun/Turkey,

(2) Atatürk University, Science and Letters Faculty, Department of Biology, Erzurum/ Turkey,

(3) Ardahan University, Department of Environmental Engineering, 75000, Ardahan/Turkey,

ummuhanster@gmail.com

Abstract

In this study, batch biosorption experiments were carried out for the removal of Cu (II) from its aqueous solution using P.ostreatus as biosorbent. The biosorption of Cu (II) by P.ostreatus was investigated as a function of contact time, pH, temperature, agitation speed, initial metal ion concentration and biosorbent dosage. In addition, the biosorption mechanism was explained with the study of FTIR spectrum. Electrophoretic studies which were measured at various pHs showed that the presence of the metal affected the zeta potential profiles. According to the BET (N₂) measurements, the specific surface areas of the P. ostreatus were found as 0.835 and 0.384 m²g⁻¹, before and after biosorption, respectively. The efficiencies of Cu (II) removal from aqueous solutions increased with the increase of pH, agitation speed, and temperature. The experimental isotherm data were analysed using the Langmuir and Freundlich equations. It was observed that Langmuir model exhibited the best fit to experimental data. The maximum adsorption capacity for Cu (II) was 27.66 mg g⁻¹ at 298 K.

Keywords: Biosorption, Copper, Mushroom, isotherm, kinetic, equilibrium, FTIR.

Introduction

Heavy metals are continuously released to aquatic environment as a mainly result of urbanization, industrialization and agricultural/mining activities [1]. Heavy metal contamination of industrial water is a significant problem in the modern world. The water pollution with metal cations has dramatically increased in the last fifty years as a consequence of expansion of industrial activities [2].

Copper, a widely used metal in industry, is an essential trace element for human health and play an important role in carbohydrate and lipid metabolism and in the maintenance of heart and blood vessel activity. The adult human body contains 100–150 mg of Cu (II), but excess amounts in the body can be toxic [3]. In aqueous environments, the specification of the metal is dependent both on ligand concentration and pH. While the cupric ion (Cu (II)) is the metallic form most toxic to flora and fauna, it is also a nutrient necessary for algal growth [1].

If allowed to enter the environment excessive amounts of Cu (II) can cause serious potential health issues such as nausea, headache dizziness, respiratory difficulty, hemolytic anemia, massive gastrointestinal bleeding, liver and kidney failure, and death [4–9]. The world health organization (WHO) recommended a maximum acceptable concentration of Cu (II) in drinking water of 1.5 mgL⁻¹[5].

In recent year, increasing concern about the effect of toxic metals in the environment has resulted in more strict environmental regulations for industrial applications that discharge metalbearing effluents [10]. Removal of metal ions from wastewater in an effective manner has become an important issue [2]. Efficient methods for the removal of metals have resulted in the development of new separation technologies. Precipitation, adsorption, ion exchange, flocculation, absorption, electrochemical processes and/membrane processes such as electrodialysis, nanofiltration and reverse osmosis are commonly applied for the treatment of industrial effluents [2, 5, 7, 9, 11–19]. However, these techniques have several disadvantages such as high chemical cost, low removal efficiency, low

selectivity, high-energy requirements, and generation of secondary toxic slurries. Among these various treatment techniques, activated carbon adsorption is one of the most commonly used due to its high efficiency and easy operation. However, it is expensive and may also require complexing agents to improve its ability to remove inorganic matter [11, 20, and 21]. Thus, there is a need to develop a cost effective and an efficient technique for metal removal from wastewaters. That is biosorption. Biosorption is considered as an alternative process for the removal of heavy metals, metalloid species, and compounds from aqueous solution by biological materials. Compared with conventional methods for the removal of toxic metals from wastewater, the biosorption process offers potential advantages such as low operating cost, minimization of the volume of chemical and/or biological sludge to be disposed of, and high efficiency in detoxifying very dilute effluents [13, 19-23, 25-28].Large number of studies were reported in literature on biosorption of [4, 8, 10, 12, 17, 20, 21, 23–38] heavy metals onto different microbial and plant biomass.

Mushrooms serve as delicacies for human consumption and as neutriceuticals "food that also cures". Mushrooms, the fruiting bodies of basidomycetous fungi, contain substances of various kinds that are highly valued as medicines, flavaring and perfumes [37, 38]. It considered healthy food as it is low in calories, fat and cholesterol, while rich in protein, carbohydrate, fibers, vitamins and minerals. Mushrooms are saprophytic, growing on dead organic matter of vegetative origin. Therefore, they can utilize almost all agricultural wastes as substrates. *P. ostreatus* is an edible mushroom [39, 40]. *P. ostreatus* grows on wood on nature, usually on dead standing trees or fallen logs. It has a relatively large size, whitish gills and exceptionally small stem. It fruits in fall and winter and has a brownish cap [39, 41].

In none of the literature studies, the biosorption of Cu (II) ions onto *P. ostreatus* was investigated. In this study, *P. ostreatus* was studied as a biosorbent for the removal of Cu (II) ions from aqueous solutions and the biosorption removal efficiencies were determined as a function of pH, temperature, agitation rate, biosorbent dosage and initial Cu (II) ion concentration. At the end of a 30 min reaction time, the Cu (II) removal efficiency and biosorption capacity were obtained as 83% and 20.6 mgg⁻¹, respectively. Zeta potential measurements have been used experimentally to predict optimum pH levels on *P.ostreatus*.

Context

Collection and preparation of biomass samples

In the present study, *P. ostreatus* was used as a biosorbent for the removal of Cu (II) ions from aqueous solutions. Samples of biomass were collected from dense forests covering area of Erzurum, Atatürk University Campus, Turkey, in April and May of 2008. All samples were washed in distilled water and then dried in the open air. The dried biomass were cut into small pieces, ground in a motor to a very fine powder and sieved to select particles of less than 0.5 mm (mesh size 125-250 μ m) for use as a biosorbent in batch studies. The surface area of biosorbent was measured by the BET method at 77 K using a Quantachrome QS-17 model apparatus. The surface areas of the biosorbent were defined as 0.835 and 0.384 m²g⁻¹, before and after biosorption, respectively.

Zeta potential measurements

In order to understand the biosorption mechanism of the Cu (II) at the solid/solution interface, the zeta potential of *P. ostreatus* was measured before and after the metal ions biosorption using the microelectrophoretic apparatus Zeta Meter (Zeta Meter System 3.0 + 542 USA). *P. ostreatus* biomass was conditioned as follows: 100 mg of the biosorbent was added to an erlenmeyer flask containing 100 ml of distilled water. The pH of the solution was adjusted at defined initial values and the flasks were placed and shaken in a temperature controlled mechanical shaker at 298 K for 30 min. After flasks were removed, the dispersion was transferred to the microelectrophoretic cell. Then, zeta potential was measured. The zeta potentials of *P. ostreatus* biomass were defined as function of suspension pH.

Fourier transforms infrared analysis

Fourier transform infrared (FTIR) study was used to characterize the reaction mechanism of *P.ostreatus*. The FTIR spectra were recorded with a Perkin-Elmer 1720 spectrometer (16 scans; resolution, 2 cm^{-1}) over KBr pellet. The sample (2 mg) was first manually well blended with 100 mg of KBr powder. Then, the mixture was desiccated overnight at 50 °C under a reduced pressure prior to the FTIR measurement.

Synthetic wastewater preparation

Synthetic wastewater solutions were prepared by dissolving analytical grade $CuSO_4.5H_2O$ in distilled water to obtain 1000 mgL⁻¹ of Cu (II) solution. The solution was diluted to the required concentration for experiments. The pH of the solution was measured and observed as 5.4 ± 0.5 and no chemicals were added to change pH.

Methods

Batch biosorption experiments

The biosorption of Cu (II) ions on the *P.ostreatus* biomass was investigated in batch biosorptionequilibrium experiments. The effect of different Cu (II) ions concentration (100-250 mgL⁻¹), amounts of *P. ostreatus* biomass (0.05-0.25 g/50 ml), temperatures (25-55°C), agitation rates (50-200 rpm), and pHs (2-5.4) on removal rate and capacity were studied. Solution pH was adjusted with 0.1 M HCI and NaOH solutions. The mixture was shaken in a mechanical shaker (Thermolyne ROSI 1000). Samples were taken at known time intervals. Preliminary experiments showed that biosorption is fast and the removal rate is negligible after 30 min. Therefore, contact time of 30 min was used for batch test. After each experiment, the mixture was filtered through Whatman filter paper No. 1 and analyzed for Cu (II) ion. The Cu (II) ion concentration in the supernatant solution was determined complexometrically [42]. The metal concentration in the liquid phase was determined at beginning (*Co*) and equilibration (*Ce*) in mgL⁻¹. The following equation was used to compute biosorbent uptake capacity at equilibrium *qe* (mg g⁻¹);

$$q_e = \left(C_o - C_e\right) \frac{V}{M}$$

M is the dry mass of biomass in grams and V is the volume of solution in liters.

Percent removal of Cu (II) is $\frac{(C_o - C_e)}{C} 100$

Adsorption isotherm models

The Langmuir isotherm was used to describe observed sorption phenomena and suggests that uptake occurs on a homogeneous surface by monolayer sorption without interaction between adsorbed molecules. In addition, the model assumes uniform energies of adsorption onto the surface and no transmigration of the adsorbate. The lineer form of the equation can be written as

$$\frac{Ce}{qe} = \frac{1}{b \times q_{\max}} + \frac{Ce}{q_{\max}}$$
(1)

where Ce is the equilibrium concentration of Cu(II), q_e is the amount of adsorption at equilibrium,

 $q_{\rm max}$ is the maximum monolayer capacity, and *b* is an equilibrium constant of Langmuir. The shape of the Langmuir isotherm can be used to predict whether a sorption system is favorable or unfavorable in a batch adsorption process. The essential features of the isotherm can be expressed in terms of a dimensionless constant separation factor (R_{t}) that can be defined by the following relationship [8].

$$R_L = \frac{1}{(1+bC_o)} \tag{2}$$

where C_o is the initial concentration(mgL⁻¹) and b is the Langmuir equilibrium constant (Lmg⁻¹). It is reported that, when $0 < R_L < 1$, the sorption system is a favorable isotherm. It can be explained apparently that when b > 0, sorption system is favorable [9].

The Freundlich isotherm is a nonlinear sorption model. This model proposes a monolayer sorption with a heterogeneous energetic distribution of active sites, accompanied by interactions between adsorbed molecules. The linear form of the equation can be written as

$$\ln q_e = \log K_F + \frac{1}{n} \log C_e$$
(3)
where, $K_F (\text{mgg}^{-1})$ is the adsorption capacity and n is related to the adsorption intensity of the

adsorbent. K_F and $\frac{1}{n}$ can be determined from the linear plot of log (q_e) versus log (C_e).

Results

Effect of biosorbent dose

Effects of biosorbent dose on percentage of Cu (II) ion removal and the amount of Cu (II) adsorbent (q_e) at equilibrium conditions are shown in Fig. 1. The amount of copper adsorbed was decreased with an increase in adsorbent dosage.

The copper biosorption capacities for different biosorbent dosages from 0.05 - 0.25 g were 31.74, 25.4, 20.65 and 20 mg g⁻¹, respectively, as seen in Fig.1. The percentage copper removal was increased from 68.28 % - 80 % for an increase in biomass concentration from 0.05 - 0.25 g.



Figure 1: Effect of biosorbent dose on percent Cu(II) ion removals and biosorbed Cu(II) ion concentrations with the amount of the biosorbent (*qe*) (C_o =100 mg L⁻¹, pH = 5.4, T = 298 K, agitation speed = 150 rpm).

Effect of initial metal ion concentration

The effects of initial metal concentration on the biosorption capacity and percentage of Cu (II) ion removal at equilibrium conditions are shown in Fig.2.

Biosorption experiments were carried out at different Cu (II) concentrations ranging from 100 to 250 mg L^{-1} . Ion removal percentage increases from 42.8% to 82.6 %, when the initial ion concentration decreases from 250 to 100 mg L^{-1} .



Figure 2: Effect of Cu (II) ion concentration (C_o) on percent removals and biosorbed Cu (II) concentrations with the amount of the biosorbent (*qe*) (pH 5.4, biosorbent dose = 0.2 g per 50 mL, T = 298 K, agitation speed = 150 rpm).

Effect of agitation speed

From Fig. 3, it is observed that as the agitation speed increased from 50 to 150 rpm, the biosorption capacity of the *P. ostreatus* increased. It was found that the agitation speed in 150-200 rpm was sufficient to ensure the availability of all surface binding sites for metal ions uptake by *P. ostreatus*.



Figure 3: Effect of agitation speed on percent Cu (II) ion removals and biosorbed Cu (II) concentrations with the amount of the biosorbent (*qe*) (pH = 5.4, biosorbent dose = 0.2 g per 50 mL, T = 298 K, C_a =100 mg L⁻¹)

Effect of pH

Accordingly, Cu (II) adsorption principally depended on the type and ion state of the functional groups (ligands) in fungi. Fig. 4 shows the effect of pH on the biosorption of Cu (II) onto *P. ostreatus*. Cu (II) removal increased from 33.3 % at pH 2.0 to 82.6 % at pH 5.4. It can be seen from Fig.4 that the biosorption capacity of Cu (II) onto *P. ostreatus* increases significantly with increasing pH and reaches maximum 8.32-20.65 mg g⁻¹.



Figure 4: Effect of pH on percent Cu(II) ion removals and biosorbed Cu(II) ion concentrations with the amount of the biosorbent (*qe*) (C_o =100 mg L⁻¹, biosorbent dose = 0.2 g per 50 mL, agitation speed = 150 rpm, T = 298 K).

Characterization of the biosorbent

Changes in the functional groups and surface properties of the biosorbent were confirmed by FTIR spectra before and after Cu (II) adsorption. Fig. 5 shows the FTIR spectra of *P. ostreatus* owning different functional groups before and after the bisorption. After biosorption of Cu (II) ions on *P. ostreatus*, a considerable shifting of peaks were observed from 500 to 4000 wavenumbers.



Figure 5: FTIR spectra of *P. ostreatus* with Cu (II) and without (C_o =100 mg L⁻¹; T= 298 K; biosorbent dosage = 0.2/50 ml; pH = 5.4; agitation speed = 150 rpm; *t* = 30 min).

Effect of temperature

The effect of temperature on the biosorption capacity and percentage of Cu(II) ion removal at equilibrium conditions is shown in Fig. 6 and it was determined that there was very little increase in biosorption capacity with rise in temperature.



Figure 6: Effect of temperature on percent Cu(II) ion removals and biosorbed Cu(II) ion concentrations with the amount of the biosorbent (*qe*) (C_o =100 mg L⁻¹, biosorbent dose = 0.2 g per 50 mL, agitation speed =150 rpm).

From the Figure 6, it can be observed that when the temperature of the solution is changed from 303 to 328 K, biosorption capacity increases from 20.65 to 21.25 mg g^{-1} . It can be also observed from Fig.6 that the percentage Cu (II) removal is increased from 82.6 % to 85 % for an increase in temperature from 298 to 328 K.

Adsorption isotherm models

The equilibrium data were analysed using two isotherm equations namely, Langmuir and Freundlich isotherm models. Fig. 7 shows the sorption isotherms of Cu (II) ions on the fungi.



Figure 7: Equilibrium curves for Cu (II) on to *P.ostreatus* (pH 5.4, Co =100 mg L^{-1} , adsorbent concentration = 0.2 g per 50 mL, agitation speed = 150 rpm).

The best fit equilibrium model was determined based on the linear regression correlation coefficient R^2 (Fig.8 (a and b)).



Figure 8 (a, b): Langmuir and Freundlich isotherm of Cu (II) on *P. ostreatus* (Co =100 mgL⁻¹, pH=5.4, agitation speed = 150 rpm, T= 298 K).

Discussion

Effect of biosorbent dose

Biosorbent dose is a significant factor to be considered for effective metal removal as it determines sorbent-sorbate equilibrium of the system [40]. It was observed that the amount of copper adsorbed varied with varying of *P. ostreatus* biomass concentration. Dose of biomass added into the solution determine the number of binding sites available for adsorption. The number of adsorption sites or surface area increases with the weight of adsorbent and hence results in a higher percent of metal removal at a high dose. However, as shown in Fig.1, the amount of metal ions adsorbed per unit weight of adsorbent (*qe*) decreases with the adsorbent dose. This is due to the fact that at higher adsorbent dose, in the solution ion concentration drops to a lower value and the system reaches equilibrium at lower values of "*qe*" indicating the adsorption sites remain unsaturated.

Effect of initial metal ion concentration

Ion removal percentage increases from 42.8% to 82.6 %, when the initial ion concentration decreases from 250 to 100 mg L⁻¹. At low ion concentrations, the ratio of surface active sites to the total metal ions in the solution is high and hence metal ions may interact with the adsorbent and be removed from the solution. Also, at high concentration levels of metal ions, more Cu (II) ions are left unadsorbed in solution due to the saturation of binding sites on the biomass surface. However, amount of metal adsorbed per unit weight of adsorbent, *qe*, is higher at high concentrations as shown in Fig.2 and with increase in initial concentration the amount of Cu (II) adsorbed increases from 20.65 to 26.75 mg g⁻¹.

Effect of agitation speed

When the agitation speed was further increase beyond 150 rpm, it was seen from Fig. 3 that the biosorption capacity slight increased. Lower speeds probably caused inefficient dispersion of biomass particles in water that led to agglomeration of particles. Since adsorption is a surface phenomenon, under buried layers do not play their role in metal uptake. The highest Cu (II) ions removal percentage and biosorption capacity was recorded at 150 rpm (82.6 % /20.65), with slight increaction at 200 rpm (86 % / 21.5 mgg⁻¹) and lowest at 50 rpm (71 % / 17.75) mg g⁻¹).

Effect of pH

An important factor controlling the process of adsorption is pH, as it affects the surface charge of the adsorbents and the degree of ionization. It was found from speciation diagram for the Cu(II)-H₂O system that almost all copper ions were present in the ionic form of Cu(II) at pH<6.0[43]. Thus, the variation in Cu (II) removal from pH 2 to 5.4 could not be explained by the change in Cu (II) speciation in the solution.

The increase in adsorption levels with an increase in pH can be explained by the surface charge of the adsorbent and the H^+ ions present in the solution. At low pH values, the surface of biosorbent would also be surrounded by hydronium ions, which decrease the Cu (II) interaction with binding sites of

P.ostreatus by greater repulsive force and therefore lower biosorption. As the pH was increased, the competing effect of hydrogen ions decreased and the biosorbent surface became more and more negatively charged, and therefore the biosorption of positively charged Cu^{++} and $Cu(OH)^{+}$ species were more favourable (Fig.9).

At higher pH values, it was thought that precipitation of Cu (II) hydroxide occured and precipitated on the surface of biosorbent. The three species of copper complex in the Cu (II) solution at pH 2-5.4 are dominant species as shown in Fig.9.



Figure 9: Specifications of Cu (II) as a function of pH [44].

The zeta potential values of the *P. ostreatus* biomass at pH 2-5.4 in the distilled water were bigger than those of Cu (II) solution (Fig.10). The dominant species in the Cu (II) solution were physically and chemically affected by sites on the surface of biomass and then adsorbed on the surface of *P. ostreatus* biomass. Biosorption of Cu (II) on *P. ostreatus* biomass caused a decrease of zeta potential values of biomass. The decrease in the zeta potential values of biomass was a sign of biosorption of Cu (II) on the surface of the biomass.



Figure 10: Relation between zeta potentials and pH (C_o =100 mg L⁻¹; agitation speed 150 rpm; T = 298 K; *t* = 30 min; adsorbent/solution = 100 mg/100 ml).

Characterization of the biosorbent

Fig. 5 shows that the Cu (II) ions adsorbed on *P. ostreatus* modified the transmittance values of functional groups. According to the FTIR spectra, it was thought that there was a physical and chemical attraction between the Cu (II) ions and the functional sites on the *P. ostreatus* biomass. This interaction between the Cu (II) ions and the sites on *P. ostreatus* biomass modified the values of transmittance versus the wavenumbers. Thus, the biosorption spectra of functional groups on *P. ostreatus* changed as seen Fig. 5.

The functional groups on *P. ostreatus* having specific value of absorbance at different wavenumbers are summarized in Tablo 1. The bonds at different wavenumbers (3232.25, 2134.45, 1488.11, and 1188.81 cm⁻¹) on *P. ostreatus* before biosorption were detected as O - H, C=C, C=N, and C - N, respectively. After Cu (II) ions were adsorbed on *P. ostreatus*, the values of transmittance and wavenumbers of bonds on the *P. ostreatus* changed and formed new bonds. The new bonds formed at different wavenumbers of 2918.76, 2857.14, 2134.45, 1574.82, 1485.31, 1376.22, 1311.88, 1188.81, 1075.68, 895.10, 855.94 cm⁻¹ were C - H, C - H, C=C, C=N, C - H, NO₂, C - N, C - O, C - H, and C - H, respectively (Table 1). Those changes at bonds show biosorption of Cu (II) ions on the *P. ostreatus*.

	Bond	Type of compound	Frequency, cm ⁻¹	Reference frequency range, cm ⁻¹
Before biosorption	0 – H	Hydrojen-bonded alcohols, phenols	3232.25	3200 – 3600
	C = C	Alkynes	2134.45	2100 – 2260
	C = N	Schiff bases	1488.11	1710 – 1470
	C – N	Amines, amides	1188.81	1180 – 1360
	C – H	Alkanes	2918.76	2850 – 2970
After biosorption	C – H	Alkanes	2857.14	2850 – 2970
	C ≡ C	Alkynes	2134.45	2134 – 2146
	C = C	Aromatic rings	1574.82	1500 – 1600
	C = N	Schiff bases	1485.31	1710 – 1470
	C – H	Alkanes	1376.22	1340 – 1470
	NO ₂	Nitro compounds	1311.88	1300 – 1370
	C – N	Amines, amides	1188.81	1180 – 1360
	C – O	Alcohols,ethers,carboxylic acids, esters	1075.68	1050 – 1300
	C – H	Aromatic rings	895.10	690 – 900
	C – H	Aromatic rings	855.94	690 – 900

Table1: The FTIR spectral characteristics of *P.ostreatus* before and after adsorption

Effect of temperature

From the Figure 8, it can be observed that when the temperature of the solution is changed from 303 to 328 K, biosorption capacity increases from 20.65 to 21.25 mg g^{-1} . Since adsorption is an energy-independed phenomenon, it is less likely to be affected.

Anirudhan and Radhakrishman (2008) reported that this case may be a result of increase in the mobility of Cu (II) ions with temperature [44]. Igbal and Edyvean (2004) also reported that increase in metal uptake at increased temperature is due to either higher affinity of sites for metal or an increase in binding sites on relevant biomass [45]. Meena et al., (2005) reported that the increase in adsorption with temperature may be attributed to either an increase in the number of active surface sites available for adsorption on the adsorbent or the decrease in the thickness of the boundary layer surrounding the adsorbent with temperature, so that the mass transfer resistance of adsorbate in the boundary layer decreases [46].

Adsorption isotherm models

The isotherm constants and correlation coefficient (R^2) are summarized in Table 2. As shown in Table 2 and Fig. 9, it was observed that the Langmuir was better fits the experimental equilibrium adsorption data than the Freundlich isotherm equation for Cu (II) adsorption according to the values of R^2 . In

Langmuir isotherm, the highest value of R^2 was 0.99 for Cu (II) (see Table 2). It was also seen from Table 2 that the Langmuir maximum adsorption capacity q_{max} (mg g⁻¹) is 27.66 and the equilibrium constant *b* (L mg⁻¹) is 0.275. The Freundlich constant K_F is 15.5 mg g⁻¹. Furthermore, the value of "*n*" at equilibrium is 8.34. The correlation coefficient of Freundlich isotherm (R^2) was 0.71.

Langmuir model		Freundlic	h model
q _{max} (mg g ⁻¹)	27.66	$K_{F}(mg g^{-1})$	15.5
b(L m g⁻¹)	0.275	n	8.34
R ²	0.99	R ²	0.71

Table 2: Langmuir and Freundlich parameters for Cu (II) sorption on P.ostreatus

The values of R_L for Cu (II) adsorption onto *P. ostreatus* biomass were found to be 0.0350, 0.0236, 0.017 and 0.014 at 298 K. As can be observed, the value of R_L decreased with increasing initial Cu (II) concentration, indicating that the Cu (II) adsorption on *P. ostreatus* is more favorable at 298 K. In addition, for $0 < R_L < 1$ the adsorption process is favorable.

Conclusion

In the present study, the ability of *P.ostreatus* to bind Cu (II) ion from aqueous solutions was investigated. The biosorption process has been shown to be affected by biosorbent concentration, initial Cu (II) concentration, pH, agitation speed and contact time. At the end of a reaction time of 30 min. The efficiency of Cu (II) removal and biosorption capacity were obtained as 83 % and 20.65 mg g⁻¹, respectively and maximum sorption was found to occur at initial pH 5.4. The result shows that the adsorption equilibrium data fitted the Langmuir adsorption model very well. The maximum adsorption capacity was found to be 27.66 mgg⁻¹ at 298 K.

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