Adsorbents for Cr(VI) Uptake from Contaminated Water: Part II Fungal Biomass

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Abstract

This study investigates the potential of Aspergillus niger fungal biomass, cultivated on three different media (Sabouraud Broth, Glucose-Potato Broth, and Malt Broth), for the biosorption of hexavalent chromium (Cr(VI)) from aqueous solutions. A series of batch experiments was conducted to evaluate the influence of operational parameters such as contact time, shaking speed, pH, biomass dosage, and initial Cr(VI) concentration. Optimal removal was observed at pH 2.5, shaking speed of 150 rpm, and a contact time of 60 minutes. Among the tested media, the biomass derived from Malt Broth (MB) exhibited the highest Cr(VI) adsorption capacity and removal efficiency. Adsorption isotherms were modeled using Langmuir and Freundlich equations. The Langmuir model provided a better fit for the experimental data, indicating monolayer adsorption. Results demonstrate that non-living fungal biomass can serve as a low-cost, effective, and sustainable biosorbent for chromium-contaminated water treatment.

Keywords: *Aspergillus niger, fungal biomass, hexavalent chromium*

1. INTRODUCTION

Chromium (Cr), a transition metal, is widely used in various industrial applications, including metallurgy, leather tanning, electroplating, wood preservation, and textile dyeing (Saranraj and Sujitha, 2013; Singh and Verghese, 2016). Due to these activities, significant quantities of chromium are released into the environment, contributing to the contamination of water bodies, soils, and ecosystems. Chromium predominantly exists in two stable oxidation states in natural environments: trivalent chromium [Cr(III)], which is an essential micronutrient in trace amounts, and hexavalent chromium [Cr(VI)], which is highly toxic, mobile, and bioavailable (Gupta & Rastogi, 2009; Qasem et al., 2021).

Cr(VI) is considered a priority pollutant by the U.S. Environmental Protection Agency due to its carcinogenic, mutagenic, teratogenic, and immunotoxic effects on living organisms (Elahi et al., 2020). Its solubility in water and ability to permeate biological membranes make it especially hazardous even at low concentrations. Exposure to Cr(VI) has been associated with various health problems in humans, including liver and kidney damage, respiratory disorders, and increased cancer risk (Majumder et al., 2017; Ayele and Godeto, 2021).

To mitigate chromium pollution, numerous remediation technologies have been developed, such as conventional treatment methods for chromium-contaminated wastewater include chemical precipitation (Qasem et al., 2021), flotation (Saleh et al., 2022; Matis et al., 1991), ion exchange (Bashir et al., 2019; Tiravanti et al., 1997; Rengaraj et al., 2001; Petruzzelli et al., 1995; Gode et al 2007) reverse osmosis (Ozaki et al., 2002; Kapelula and Luis, 2024; Abdullah et al., 2019), membrane filtration (Atès and Uzal, 2018; Kozlowski and Walkowiak, 2002; Shaalan et al., 2001), membrane technologies (Mohammadi et al., 2005), electrochemical reduction (Roundhill and Koch, 2002) and advanced oxidation processes (Singh and Verghese, 2016; Qasem et al., 2021). However, these conventional techniques often suffer from high operational costs, generation of toxic sludge, and limited efficiency at low metal concentrations. Activated carbon is widely studied material for Cr(VI) adsorption due to its high surface area and porosity. Derived from natural precursors including coconut shells, sawdust, and agricultural waste, activated carbon effectively removes chromium ions from wastewater, although performance may vary based on pH, temperature, and competing ions (Mohan and Pittman, 2006; Sarin and Pant, 2006; EPA, 2022).

In recent years, biosorption—the passive uptake of heavy metals by biological materials—has emerged as a promising alternative due to its cost-effectiveness, environmental compatibility, and potential for metal recovery and biosorbent regeneration (Wang and Chen, 2009; Ayele and Godeto, 2021). Biosorbents derived from bacteria, fungi, algae, and agricultural waste possess multiple functional groups (e.g., carboxyl, hydroxyl, amino, phosphate) that facilitate metal binding (Gupta and Rastogi, 2009; Elahi et al., 2020). Moreover, biosorption processes can be applied to both living and non-living biomass, increasing their flexibility in industrial applications (Sudha Bai and Abraham, 2002; Ahluwalia and Goyal, 2010; Elahi et al., 2020).

Despite its advantages, biosorption is not without limitations. Factors such as pH sensitivity, desorption challenges, and competition with co-existing ions can reduce biosorption efficiency in complex effluents. Furthermore, the practical scalability and long-term performance of biosorbents remain critical areas for development (Wang and Chen, 2009; Ayele and Godeto, 2021). Nonetheless, continuous advancements in biomass engineering, pretreatment strategies, and immobilization techniques are addressing these constraints, strengthening biosorption as a viable tool in sustainable wastewater treatment technologies.

Moreover, recent advancements have explored hybrid technologies combining biosorption and activated carbon, as well as genetic engineering of microorganisms to enhance biosorption capacity. These innovations aim to overcome the limitations of each individual approach and provide more robust solutions for chromium remediation (Igiri et al., 2018; WHO, 2020).

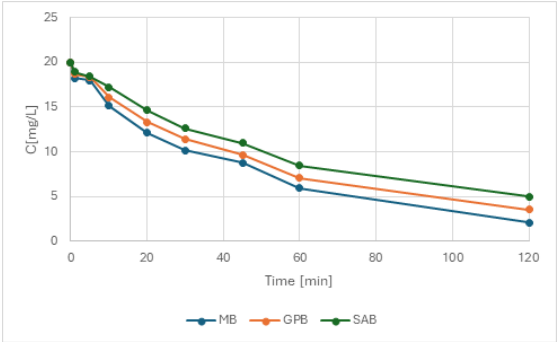

Fig. 1. Effect of contact time on the concentration decay curves for Cr(VI) adsorption on biomass (Co = 20 mg/L, T =25°C, biomass quantity = 1 g, shaking speed = 150 rpm)

Rys. 1. Wpływ czasu kontaktu na krzywe spadku stężenia dla adsorpcji Cr(VI) na biomasie (Co = 20 mg/l, T = 25°C, ilość biomasy = 1 g, prędkość wytrząsania = 150 obr./min)

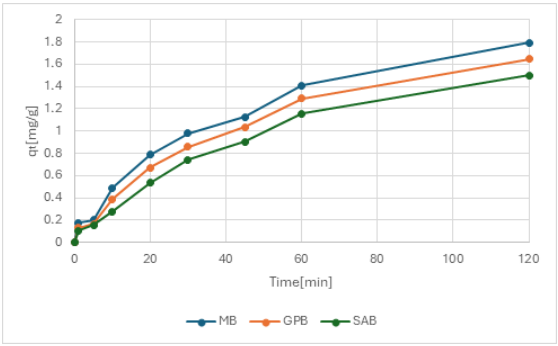

Fig. 2. Effect of contact time value on adsorption capacity of chromium ions for Cr(VI) adsorption on biomass (Co = 20 mg/L, T =25°C, biomass quantity = 1 g, shaking speed = 150 rpm)

Rys. 2. Wpływ czasu kontaktu na pojemność adsorpcyjną jonów chromu w przypadku adsorpcji Cr(VI) na biomasie (Co = 20 mg/l, T = 25°C, ilość biomasy = 1 g, prędkość wytrząsania = 150 obr./min)

The present study describes the influence of several important operational parameters such as shaking speed, biomass dosage, initial pH and contact time on the adsorption of Cr(VI) from aqueous solutions. In addition, the isotherm of Cr(VI) adsorption on 3 different types of biomass was investigated.

2. MATERIALS AND METHODS

2.1. Preparation of biosorbent

The fungal strain (Aspergillus niger) was provided by the Polish Collection of Industrial Microorganisms (KKP). The culture was grown on 3 different media:

- Sabouraud broth SAB (BTL PwP-0133) – peptone 5g/l; peptone K 5g/l; glucose 20g/l
- Glucose-potato broth GPB (BTL P-0427) – potato extract (infusion) 4g/l; glucose 20g/l
- Malt broth MB (BTL P-0197) – malt extract 17g/l; peptone SP 3g/l

The fungus was inoculated into a medium at different pH (5,7 SAB; MB 4,8; GPB 5,6) and 30°C which were optimal conditions for fungal cultivation. After ten days of the incubation period, the biomass of the fungus was harvested, washed, and treated with distilled water and a 1% formaldehyde solution, respectively. Then the biomass dried at 60°C for 24 h., pulverized and stored in polythene bags for further experiments.

2.2. Determination of Cr concentration in aqueous solution

Analytical grade potassium dichromate ($K_2Cr_2O_7$) was used as the source of Cr(VI). All aqueous solutions were prepared with deionized water, which was produced by WG-HLP demineralizer. HLP systems can produce water that meets the requirements of the following standards: PN-EN ISO 3696:1999, ASTM, CLSI, FP VIII. Cr (VI) in aqueous solutions was determined by UV–vis spectrophotometry using a Dr. Lange Cadas 200 spectrophotometer at the absorption wavelength of 540 nm. 1, 5-difenil carbazide was used as an indicator.

2.3. Adsorption experiments

Each sample was prepared in triplicate to minimize measurement error. After the adsorption process the chromium(VI) content in the solutions was measured using a UV-VIS spectrophotometer. The Cr (VI) adsorption capacity (qt) and percentage removal (R) were calculated by Eq. (1) and Eq. (2) (Wang et al., 2020):

$$q_t = \frac{(C_o - C_t)V}{m}\left[\frac{mg}{g}\right] \quad (1)$$

$$R = \frac{C_o - C_t}{C_o} \cdot 100[\%] \quad (2)$$

where V is the volume of the solution (dm^3), C_0 and C_t (mg/dm^3) are the concentrations of Cr(VI) at initial and equilibrium in the solution, respectively, and m is the weight of activated carbon used (g).

2.3.1 Effect of contact time

100 mL aqueous solution with a 20mg/l Cr (VI) concentration was contacted with 1 g of biomass in 250 mL Erlenmeyer flasks, which were shaken in an orbital shaker at a constant

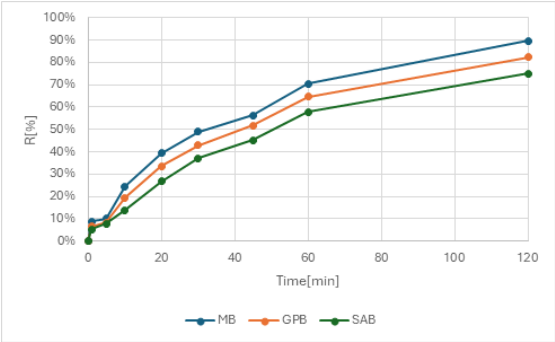

Fig. 3. Effect of contact time value on percentage removal of chromium ions for Cr(VI) adsorption on biomass. (Co = 20 mg/L, T =25°C, biomass quantity = 1 g, shaking speed = 150 rpm)

Rys. 3. Wpływ czasu kontaktu na procentowe usunięcie jonów chromu w przypadku adsorpcji Cr(VI) na biomasie. (Co = 20 mg/l, T = 25°C, ilość biomasy = 1 g, prędkość wytrząsania = 150 obr./min)

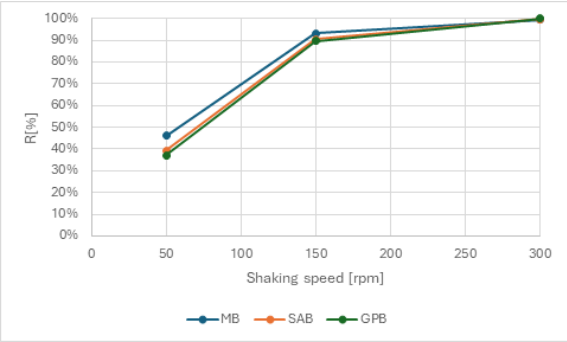

Fig. 4. Effect of shaking speed on percentage removal of chromium ions for Cr(VI) adsorption on biomass. (Co = 20 mg/L, pH=2,5, biomass quantity = 1 g, T=25°C; t=1h)

Rys. 4. Wpływ prędkości potrząsania na procentowe usunięcie jonów chromu w celu adsorpcji Cr(VI) na biomasie. (Co = 20 mg/l, pH=2,5, ilość biomasy = 1 g, T=25°C; t=1h)

speed of 150 rpm, temperature 25°C and at a certain time (1, 5, 10, 20, 30, 45, 60 and 120min).

2.3.2 Effect of shaking speed

To evaluate the effect of shaking speed on adsorption process 1g of biomass was added to a 250 ml Erlenmayer flask containing 100 mL of aqueous solution with a 20mg/l Cr (VI) concentration. The flasks were placed for 1 hour in an incubator with a shaker at different shaking speed (50, 150, 300rpm) at 25°C.

2.3.3 Effect of pH

To evaluate the effect of different pH on adsorption process 1g of biomass was added to a 250 ml Erlenmayer flask containing 100 mL of aqueous solution with a 20mg/l Cr (VI) concentration. The assumed pH level (2,5-12) was obtained with 0.1M/1M NaOH solution or 0.1M HCl solution. The flasks were placed in an incubator with a shaker at 25°C and 150rpm for 1 hour.

In this study pH 2,5 was chosen, considering the higher removal efficiency compared with that at other pH values.

2.3.4 Effect of Cr(VI) concentration

100 mL aqueous solution with a different Cr(VI) concentration (20 mg/L, 50 mg/L, 100 mg/L, 200 mg/L and 500 mg/L) was contacted with 1 g of biomass in 250 mL Erlenmeyer flasks, which were shaken in an orbital shaker at a constant speed of 150 rpm, temperature 25°C and at a certain time 60min.

2.3.5 Effect of adsorbent dosage

The test was conducted for biomass samples weighing 1, 2, 3, 5, and 10 g. The samples were tested in solutions with a Cr(VI) concentration of 20 mg/L. The appropriate amount of biomass was weighed into 250ml Erlenmeyer flasks and then 100 ml of Cr(VI) solution was added. The prepared samples were placed on a shaker for 15 minutes. The time was shortened to obtain comparable and representative results that did not fall below the determination range.

3. RESULTS AND DISCUSSION

3.1 Effect of contact time

Figure 1-3 shows the change in Cr (VI) concentration and adsorption capacity in aqueous solution as a function of adsorption time at 25°C.

An analysis of the charts indicates that adsorption occurred rapidly during the initial phase (up to 30 minutes), then plateaued, indicating equilibrium was reached within 60–120 minutes. This aligns with biosorption being a surface phenomenon driven by mass transfer to active sites.

Biosorption is a mechanism independent of metabolism that can occur both in living cells and in dead biomass of microorganisms (Bilal et al., 2018; Chojnacka, 2010; GracePavithra et al., 2019; Javanbakht et al., 2014; Majumder et al., 2017; Srivastava & Thakur, 2006). In biosorption mechanisms, toxic heavy metal ions, such as Cr(VI), bind to various functional groups of the cell wall of microorganisms and are then removed by surface precipitation, ion exchange, or complexation/chelation (Rezaei, H., 2016; Ayele and Godeto, 2021). The composi-

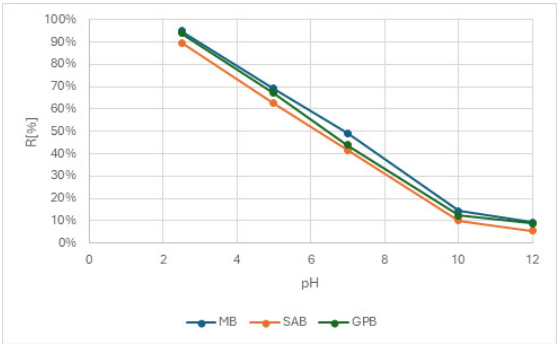

Fig. 5. Effect of pH on percentage removal of chromium ions for Cr(VI) adsorption on biomass. (Co = 20 mg/L, T=25°C, biomass = 1 g, shaking speed = 150 rpm)

Rys. 5. Wpływ pH na procentowe usunięcie jonów chromu w celu adsorpcji Cr(VI) na biomasie. (Co = 20 mg/l, T=25°C, biomasa = 1 g, prędkość wytrząsania = 150 obr./min)

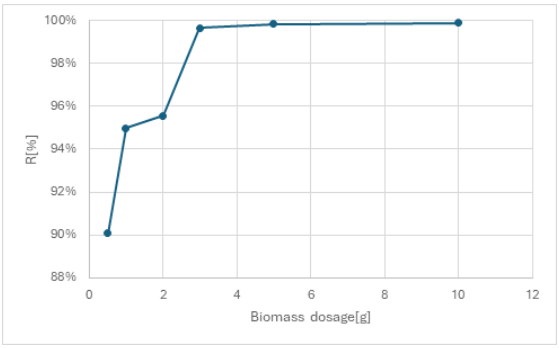

Fig. 6. Effect of quantity of MB biomass on the removal of Cr(VI). (Co = 20 mg/L, pH=2,5, shaking speed = 150 rpm; T=25oC; t=1h)

Rys. 6. Wpływ ilości biomasy MB na usuwanie Cr(VI). (Co = 20 mg/l, pH=2,5, prędkość wytrząsania = 150 obr./min; T=25oC; t=1h)

tion and structure of the cell wall vary depending on the microorganisms and culture conditions. The binding of hexavalent chromium to the fungal cell is due to the presence of chemical components, mainly proteins, lipids, and polysaccharides such as galactosamine, chitin, and glycan, as well as various functional groups such as carboxyl (–COOH), phosphate (PO_4^{3-}), amino ($–NH_2$) ,thiol (–SH), and hydroxyl (–OH) (García-Hernández et al., 2017). It can be seen that all biomasses adsorb significant amounts of Cr(VI) ions, and the amount adsorbed at a given concentration varies between them. All tested biomasses (MB, SAB, GPB) exhibited the ability to adsorb Cr(VI); however, biomass cultivated in Malt Broth (MB) demonstrated the highest adsorption efficiency, as confirmed by both numerical data and removal efficiency graphs over time (Figs. 1–3).

MB biomass showed the most significant Cr(VI) concentration decrease and highest removal percentage, suggesting favorable surface properties and a rich presence of functional groups involved in metal binding.

3.2 Effect of shaking speed

Figure 4 shows the change in Cr (VI) concentration in aqueous solution as a function of shaking speed at 25°C.

An increased shaking speed enhances the diffusion of Cr(VI) ions toward the active adsorption sites, thereby improving the overall efficiency of the biosorption process. Among the tested biomasses, MB consistently exhibited the highest adsorption efficiency. A slight improvement in adsorption was observed at 300 rpm, but this was not substantial enough to justify the increased agitation. Consequently, a shaking speed of 150 rpm was selected for subsequent experiments. Similar observations were reported by Yang et al. (2015), who found that the adsorption rate increased with shaking speeds between 70 and 170 rpm, but remained stable beyond that range, suggesting that external mass transfer resistance becomes negligible at higher agitation rates.

3.3 Effect of pH

Fig. 5 shows the effect of pH on the adsorption process of Cr(VI) ions by activated carbons.

As can be seen from Fig. 5, the removal of Cr(VI) from aqueous solution is highly dependent on the pH value, with maximum adsorption occurring when the pH value is 2.5. This impact is due to the fact that in aqueous solutions, Cr(VI) can exist in several forms, including dichromate ($Cr_2O_7^{2-}$), chromate (CrO_4^{2-}), chromic acid (H_2CrO_4), and hydrogen chromate ($HCrO_4^-$). The speciation of Cr(VI) depends on several factors such as the pH of the solution, total chromium concentration, the presence of oxidizing or reducing agents, redox potential, and the kinetics of redox reactions (Jobby et al, 2018). At pH values above 7, CrO_4^{2-} is the predominant species, regardless of the total Cr(VI) concentration. In contrast, within the acidic pH range of 1 to 6, $HCrO_4^-$ is the dominant form (Barrera-Díaz et al., 2012; Dhal et al., 2013). The following equilibrium reactions illustrate the transformations between Cr(VI) species:

$$H_2CrO_4 \rightleftharpoons H^+ + HCrO_4^- \quad (pH \approx 1–6) \quad (1)$$

$$HCrO_4^- \rightleftharpoons H^+ + CrO_4^{2-} \quad (pH > 7) \quad (2)$$

$$2\ HCrO_4^- \rightleftharpoons Cr_2O_7^{2-} + H_2O \quad (3)$$

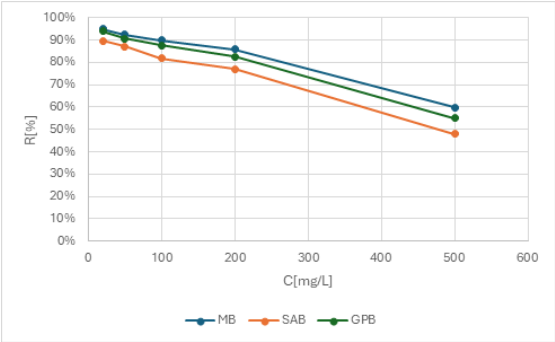

Fig. 7. Effect of concentration on percentage removal of chromium ions for Cr(VI) adsorption on biomass. (pH=2,5, biomass = 1 g, shaking speed = 150 rpm; t=1h; T=25°C)

Rys. 7. Wpływ stężenia na procentowe usunięcie jonów chromu w przypadku adsorpcji Cr(VI) na biomasie. (pH=2,5, biomasa = 1 g, prędkość wytrząsania = 150 obr./min; t=1h; T=25°C)

Fig. 6. Effect of quantity of MB biomass on the removal of Cr(VI). (Co = 20 mg/L, pH=2,5, shaking speed = 150 rpm; T=25oC; t=1h)

Rys. 6. Wpływ ilości biomasy MB na usuwanie Cr(VI). (Co = 20 mg/l, pH=2,5, prędkość wytrząsania = 150 obr./min; T=25oC; t=1h)

Biomass	Langmuir			Freundlich		
	Q_m	K_a	RMSE	K_F	n	RMSE
MB	34.03	0.0369	0,336	3.68	2.50	1,87
GPB	30.99	0.0344	0,403	2.67	2.49	1,70
SAB	27.59	0.0262	0,363	3.42	2.56	1,78

The chromate ion (CrO_4^{2-}), due to its double negative charge, typically requires two active adsorption sites, whereas species such as hydrogen chromate ($HCrO_4^-$) and dichromate ($Cr_2O_7^{2-}$) generally occupy only one. As a result, the adsorption capacity for Cr(VI) increases under acidic conditions, primarily due to the greater prevalence of $HCrO_4^-$ at lower pH values, which forms at the expense of CrO_4^{2-}. In contrast, at higher pH levels, a decrease in adsorption efficiency is often attributed to competition between chromate and hydroxide ions for available binding sites (Yang et al., 2020). Based on these findings, an initial pH of 2.5 was selected as the optimal condition for Cr(VI) adsorption in all subsequent experiments.

3.4 Effect of adsorbent dosage

Figure 7 shows the change in Cr (VI) concentration in aqueous solution as a effect of biomass dosage at 25°C.

Analysis of the data reveals that the efficiency of Cr(VI) adsorption by the MB biomass is highly influenced by the applied dosage. Increasing the sorbent dose enhances the number of available adsorption sites, resulting in a greater surface area for interaction and improved removal of Cr(VI) ions. Notably, MB demonstrates high adsorption efficiency even at relatively low dosages, indicating its substantial adsorption capacity and effectiveness in Cr(VI) removal from aqueous solutions.

3.5 Effect of Cr(VI) concentration

Figure 8 shows the change in Cr (VI) concentration in aqueous solution as a effect of initial Cr(VI) concentration at 25°C.

The study demonstrated that increasing the initial concentration of Cr(VI) led to more pronounced differences in adsorption efficiency among the tested sorbents, likely due to variations in their adsorption capacities and surface characteristics. At higher metal concentrations, the availability of binding sites becomes a limiting factor, which can accentuate the performance differences between biosorbents. Moreover, elevated concentrations of toxic metals may saturate active sites more rapidly and impose greater stress on the sorbent material, potentially affecting its binding affinity and overall biosorption performance. These findings highlight the importance of optimizing sorbent selection based on both the concentration of the contaminant and the physicochemical properties of the biosorbent.

3.6 Adsorption isotherm

The adsorption isotherm is characterized by certain constants whose value expresses the surface properties and affinity of the sorbent and is used to compare the biosorption capacity of biomass. The Langmuir and Freundlich isotherms representing this equilibrium are most applicable to water treatment (Şenol et al, 2021; Atsu and Kutsal, 1990; Donmez et al, 1990; El-Sikaily et al., 2007). The Langmuir equation, which is important for the sorption of a monolayer on a surface, has a finite number of identical sites and is defined by the following equation:

$$q_e = \frac{Q_m K_a C_e}{1+K_a C_e} \quad (3)$$

where Q_m is the maximum amount of metal ion per unit mass of biomass to form a complete monolayer on a surface bound at high C_e (mg/g), and K_a is a constant related to affinity of binding sites (mg/L). Q_m and K_a can be determined from a line plot of C_e/q_t as a function of C_e.

The empirical Freundlich equation based on sorption on a heterogeneous surface is defined by:

$$q_e = K_F {C_e}^{1/n} \quad (4)$$

qe and Ce have the same meaning as in the Langmuir isotherm, and K_F and n are Freundlich constants depending on several environmental factors. K_F and n are the indicators of adsorption capacity and adsorption intensity, respectively.

Equation (2) can be linearized to logarithmic form and Freundlich constants can be determined:

$$logq_e = logK_F + \frac{1}{n} logC_e \quad (5)$$

The Freundlich isotherm is also widely used, but does not provide information on adsorption capacity.

Langmuir Isotherm:

- The highest adsorption capacity was observed for MB, while the lowest was for SAB.
- MB also exhibited the highest Ka, which indicates a stronger affinity between the adsorbate and the adsorbent.
- The low RMSE values (0.34–0.40) suggest that the Langmuir model fits the experimental data well.

Freundlich Isotherm Conclusions:

- All samples showed n > 1, indicating favorable adsorption conditions on heterogeneous surfaces.
- MB and GPB had higher KF values than SAB, implying a greater adsorption capacity.
- The RMSE values for the Freundlich model (1.7–1.9) were higher than those for the Langmuir model, indicating that Langmuir provides a better overall fit to the experimental data.

Considering the fit quality (based on RMSE) and adsorption parameters, the Langmuir model more accurately describes the adsorption behavior suggesting monolayer adsorption on a homogeneous surface. Across both isotherms, MB consistently demonstrates the highest efficiency as an adsorptive medium.

4. CONCLUSIONS

The biosorption process has many advantages over other mechanisms for removing toxic metals from contaminated environments: the presence of multifunctional groups and uniform distribution of binding sites on the cell surface, no need for additional nutrients (chemicals), minimal preparation, low costs, high efficiency, biosorbent regeneration and possibility of metal recovery. Studies have shown that non-living dried fungal biomass of Aspergillus niger has great potential for removing metals. In fungi, Cr(VI) is adsorbed on the cell surface by forming a chemical bond with functional groups present on the cell surface proteins.

The research presented in this article showed that:

- Fungal biomass from Aspergillus niger shows strong potential for Cr(VI) removal through biosorption, with adsorption efficiencies influenced by biomass origin and operational parameters.
- The highest adsorption capacity and affinity were observed for MB-derived biomass, which outperformed SAB and GPB media in all experimental conditions.
- Biosorption was most effective at low pH (2.5), where $HCrO_4^-$ is the dominant chromium species favorable for surface binding.
- Increasing biomass dosage improved Cr(VI) removal due to a greater number of available active sites, while the effect of shaking speed plateaued beyond 150 rpm.
- Isotherm modeling revealed that the Langmuir model better described the adsorption process compared to the Freundlich model, suggesting monolayer adsorption on a homogeneous surface.

The results support the application of fungal biomass as an environmentally friendly and efficient alternative for removing hexavalent chromium from contaminated water.

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Adsorbenty do wychwytywania Cr(VI) z zanieczyszczonej wody: Część II Biomasa grzybów

W niniejszym badaniu zbadano potencjał biomasy grzyba Aspergillus niger, hodowanego na trzech różnych podłożach (Sabouraud Broth, Glucose-Potato Broth i Malt Broth), do biosorpcji sześciowartościowego chromu (Cr(VI)) z roztworów wodnych. Przeprowadzono serię eksperymentów wsadowych w celu oceny wpływu parametrów operacyjnych, takich jak czas kontaktu, prędkość wytrząsania, pH, dawka biomasy i początkowe stężenie Cr(VI). Optymalne usuwanie zaobserwowano przy pH 2,5, prędkości wytrząsania 150 obr./min i czasie kontaktu 60 minut. Spośród testowanych podłoży biomasa pochodząca z Malt Broth (MB) wykazała najwyższą pojemność adsorpcji Cr(VI) i wydajność usuwania. Izotermy adsorpcji modelowano przy użyciu równań Langmuira i Freundlicha. Model Langmuira zapewnił lepsze dopasowanie do danych eksperymentalnych, wskazując na adsorpcję monowarstwową. Wyniki badań dowodzą, że nieożywiona biomasa grzybów może być stosowana jako niedrogi, skuteczny i zrównoważony biosorbent w oczyszczaniu wody zanieczyszczonej chromem.

Słowa kluczowe: *Aspergillus niger, biomasa grzybów, chrom sześciowartościowy*