This paper discusses the biosorption in a multi-cation system as an example of advances in the method of ions removal/binding to the biomass. 

Biosorption experiments were conducted on *Chlorella kessleri* biomass. The ions used in the experiment were Co(II), Cu(II), Mn(II) and Zn(II) and had the following configurations: binary, ternary and quaternary system. Also, the effect of the following anions Cl\(^{-}\), NO\(_3\)\(^{-}\), SO\(_4\)\(^{2-}\) on the biosorption process in the quaternary system (initial concentration of each ion was 0–300 mg L\(^{-1}\)) was examined.

The affinity order determined in the experiment was as follows: Cu(II)>Zn(II)>Mn(II)>Co(II). At higher concentrations of Cu(II) cations, the strong competition effect between Cu(II) cations with the remaining cations was observed. The modified Langumir competition model was proposed to support the biosorption method in the description of the experimental data of inhibited metal ions biosorption. After the influence of anions was examined, the highest total biosorption capacity was obtained for 1:1:2 system (Cl\(^{-}\): NO\(_3\)\(^{-}\): SO\(_4\)\(^{2-}\)).

**Keywords:** *Chlorella kessleri*, biosorption, multi-cation system, anions

### 1 Introduction

Biosorption is a well-known process thoroughly described in the literature [1] and used as a method for removing organic [2] as well as inorganic [3] pollutants from wastewaters. Recently, it has also been discussed as a process for the enrichment of biomass with microelements. This may make a new generation of products possible: feed additives and fertilizer components with microelements bound by a biological carrier through biosorption. Such products can increase the density of microelements in plant and animal-derived foods, supporting a new generation of functional grocery products biofortified with microelements [4,5].

Biosorption includes a combination of several mechanisms such as electrostatic attraction, complexation, ion-exchange, covalent bonding, Van der Waals forces, adsorption and microprecipitation [6]. The biosorption capacity is strongly related to the type of biosorbent and biosorbate (e.g. metal ions). Metal ions biosorption is associated with the existence of a biosorbent surface of ligands like carboxyl, sulphonate, amine, and hydroxyl groups, which have a different affinity and specificity for metal ions binding. Their presence in the solution can lead to the formation of various types of interactions that may affect the affinity and biosorption capacity. For example, zinc ions can improve the biosorption of chromium by the pairing of their charges and thus decreasing the repulsion between the negative Cr(VI) ions adsorbed on the surface [7].

The current challenge for scientists and investigators is to scale-up the process that until now has been done only at a laboratory scale. The only exception was the Canadian company established by Prof. B. Volesky that constructed installations at a technical scale for the biosorption process [8]. Further investigation is still needed to optimize the maximum efficiency of removal, which is expected to lead to its large scale exploitation. The problem with an elevated scale is to produce a phenomena that would occur in real-life compared to the model scale. Rarely is a single type of ion present in real wastewater. Usually, the systems are more complex. Industrial wastewater contains different kinds of impurities (ions). It is more difficult to predict and describe biosorption behavior in real solutions because of the few kinds of metal cations that have different anions. For this reason, it is necessary to study the simultaneous biosorption of several ion species. The models used to describe metal ions sorption from single-cation solutions cannot be used in binary, ternary or quaternary systems since, the biosorption of one metal ion is influenced by the presence of an other...

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ion [9]. Research on the interactions among biological ligands and both anions and cations in the solution (heavy metal ions, protons, alkaline and alkaline earth metal ions) is a fundamental step in improving the biosorption performances and in optimizing the operating conditions. It is crucial to elaborate valuable mathematical tools to investigate competition mechanisms in the complex media typical for real wastewater [10].

The goal of the present study was to characterize the biosorption of metal cations Co(II), Cu(II), Mn(II) and Zn(II) in binary, ternary and quaternary system, as well as to determine the impact of chloride (Cl\textsuperscript{-}), sulfate (SO\textsubscript{4}\textsuperscript{2-}) and nitrate (NO\textsubscript{3}\textsuperscript{-}) anions on the biosorption process. For this purpose, various configurations of metal ions in the system as well as different anions were investigated using biosorption in the batch mode.

2 Material and Methods

2.1 Biomass

*Chlorella kessleri* Camb. 211−11g was obtained from Culture Collection of Algal Laboratory (CCALA) Institute of Botany, Academy of Sciences of the Czech Republic. Microalga was cultivated in the Bold Basal Medium [11]. Bold Basal culture medium was prepared for *Chlorella kessleri* with analytical grade reagents. The biomass was dried at 60°C for three days.

2.2 Biosorption experiments

The equilibrium experiments of the biosorption process of cations in the two-cation system, three-cation system and four-cation system were performed in Erlenmeyer flasks containing 200 mL of metal ions (Co(II), Cu(II), Mn(II) and Zn(II)) solution in a thermostated water bath shaker at 150 rpm under ambient temperature. The solutions of metal ions were prepared in deionized water (by dissolving appropriate amounts of inorganic salt Co(NO\textsubscript{3})\textsubscript{2} × 6H\textsubscript{2}O, CoSO\textsubscript{4} × 7H\textsubscript{2}O, CoCl\textsubscript{2} × 6H\textsubscript{2}O, CuCl\textsubscript{2} × 2H\textsubscript{2}O, CuSO\textsubscript{4} × 5H\textsubscript{2}O, MnSO\textsubscript{4} × H\textsubscript{2}O, MnCl\textsubscript{2} × 4H\textsubscript{2}O, ZnCl\textsubscript{2}, ZnSO\textsubscript{4} × 7H\textsubscript{2}O (from POCh S.A. Gliwice) which depended on the initial concentration of ions ranging from 10 to 100 mg L\textsuperscript{-1} (1, 5, 10, 20, 30, 40, 60, 80, 100 mg L\textsuperscript{-1}) for the equilibrium experiments of the biosorption process of cations in a two-cation system, a three-cation system and a four-cation system. Three biosorption experiments were performed that focused on the influence of the anions of inorganic salt on the biosorption capacity of Co(II). Each experiment was conducted, with a different salt: CoCl\textsubscript{2} × 6H\textsubscript{2}O, Co(NO\textsubscript{3})\textsubscript{2} × 6H\textsubscript{2}O and CoSO\textsubscript{4} × 7H\textsubscript{2}O. The initial concentration of ion (Co(II)) was ranged from 25 to 300 mg L\textsuperscript{-1} (25, 50, 75, 100, 125, 150, 200, 250, 300 mg L\textsuperscript{-1}) and obtained by dissolving appropriate amounts of inorganic salt. The pH of the solutions was adjusted with 0.1 mol L\textsuperscript{-1} solution NaOH/HCl (from POCh S.A. Gliwice). pH measurements were conducted using a pH-meter Mettler-Toledo (Seven Multi) equipped with an electrode InLab413 with compensation of temperature and was set at 5.00 ± 0.05. The process was carried out at the concentration of the biomass C\textsubscript{s} 1 g L\textsuperscript{-1}. After shaking the flasks for a predetermined time interval (1 hour as determined previously in kinetic experiments [12]), the reaction mixture was filtered through paper filter, the filtrate was used to analyze metal ions concentration by inductively coupled plasma-optical emission spectrometry (Varian VISTA-MPX ICP-OES) according to the method described by Zielińska and Chojnacka [12]. The metal ions binding capacity of the biomass was calculated using Eq. 1:

$$q_t = \frac{C_0 - C_t}{C_s}$$  \hspace{1cm} (1)

The scheme of the experiments was presented on Fig. 1.

2.3 Calculations

Model parameters of equations describing kinetics of the process in biosorption experiments were determined using nonlinear estimation and multiple regression modules of Statistica software ver. 8.0. The significance of differences was examined with a t test. The correlation was considered statistically significant at α < 0.05.

A Chi-square test (χ\textsuperscript{2} test) was also used, which was calculated from Eq. 2, which more accurately described the fit of the model to experimental data compared to the determination coefficient R\textsuperscript{2}.

$$\chi^2 = \frac{(\text{experimental value} - \text{model value})^2}{\text{model value}}$$  \hspace{1cm} (2)

3 Results and Discussion

3.1 Biosorption in a multi-cation system

The goal of this research study was to study the biosorption process in a multi-cation system in the presence of different
anions. The experiment was carried out on the biomass of *Chlorella kessleri* using the binary, ternary and quaternary systems.

During the first stage, the study was conducted in a binary system (Co-Cu and Mn-Zn). In the experiment (results shown in Table 1), where the solution contained Co(II) and Cu(II), a decrease in biosorption capacity of Co ions was observed at the equilibrium concentration greater than 50 mg L$^{-1}$. This decrease was not observed for the capacity of the Cu(II) cations (Fig. 2a). Similar observations were made for another binary system Mn-Zn (Fig. 2b) in which Cu(II) ions were absent. This may indicate a competition of Cu(II) ions in binding Co(II) to the biomass. Attempts to describe the experimental results for Co(II) biosorption capacity resulted in a degenerate distribution data when the traditional Langmuir model, a widely accepted and easily linearized adsorption model, was used.

$$q_{eq} = q_{max} \frac{K_1 \cdot C_{eq}}{1 + K_2 \cdot C_{eq}}$$

Consequently an additional parameter was introduced to the Langmuir equation: a competition constant $K_c$. The modified model was described by Eq. 3. Table 1 shows the parameters of the modified Langmuir competition model and the parameters of the standard model, which describe the experimental points obtained for Cu(II) biosorption and the other ions in the system where the competition factor (Cu(II) ions) was not present.

$$q_{eq} = q_{max} \frac{K_1 \cdot C_{eq} - C_{eq}^2}{1 + K_2 \cdot C_{eq}^2}$$

Experiments in the ternary system without Cu(II) yielded the following series of affinity: Zn(II) > Mn(II) > Co(II) (Fig. 2c). Additionally, experiments were performed in the quaternary system of Cu(II) ions, but their maximum initial concentrations were 5 mg L$^{-1}$. The biomass bound almost all Cu(II) ions present in the solution. By lowering the initial concentration of Cu(II), there was no reduction in the biosorption capacity of the other ions (Fig. 2d). The affinity order was as follows: Cu(II) > Zn(II) > Mn(II) >

**Figure 1:** The scheme of biosorption experiments in multi-cation system. Different anion are marked with the different colors presented in the legend.

**Table 1:** The parameters of the Langmuir modified model that describe the biosorption of microelements in a multi-cation system with the competition as well as parameters of the traditional Langmuir model.

| System       | Langmuir modified | Langmuir       |
|--------------|-------------------|----------------|
|              | $q_{max}$ mg g$^{-1}$ | $K_1$ mg$^{-1}$ | $K_2$ mg L$^{-1}$ | $R^2$ | $\chi^2$ | $q_{max}$ mg g$^{-1}$ | $K_1$ L mg$^{-1}$ | $R^2$ | $\chi^2$ |
| Co-Cu        | 10.5***            | 0.245**        | 231.5**         | 0.975 | 1.374 | 34.3***           | 0.122***       | 0.990 | 2.00 |
| Cu           | 16.1***            | 0.0767**       | 0.965           | 1.17  |
| Zn           | 21.6***            | 0.114**        | 0.967           | 3.81  |
| Co-Mn-Zn     | 9.97***            | 0.0787**       | 0.952           | 2.06  |
| Mn           | 11.8***            | 0.123**        | 0.953           | 1.50  |
| Zn           | 22.0***            | 0.0812**       | 0.983           | 1.74  |
| Co-Cu-Mn-Zn  | 14.4***            | 0.151***       | 0.993           | 0.601 |
| Cu           | 14.8***            | 0.79**         | 0.982           | 0.574 |
| Mn           | 21.6***            | 0.0430***      | 0.991           | 0.741 |
| Zn           | 26.3***            | 0.0589**       | 0.991           | 1.30  |

ns – no statistical differences; * - $p < 0.1$; ** - $p < 0.05$*** - $p < 0.001$
Co(II). Similar findings were observed by Albadarina et al. in the biosorption of Cr(III) in the binary and ternary system. When Cu(II) was present, the biosorption capacity decreased [7].

3.2 Effect of anion from inorganic salts on biosorption process

This experiment was carried out in quaternary systems, to which salts delivered different anions, and the same cations were introduced. All the salts are presented in the first column of Table 2. The ratio of anions: Cl⁻:NO₃⁻:SO₄²⁻ in the following systems was as follows: 4:0:0, 3:0:1, 0:0:4 and 1:1:2, respectively. Since the experiment was conducted in the presence of Cu(II) ions, the effect which was discussed in the previous section was also observed. The modified competition Langmuir model with \( K_c \) constant (Eq. 3) was used to describe the experimental results. The determined parameters for various variants of competition are presented in Table 2. The results were described by both, traditional Langmuir and the modified competition Langmuir models. Additionally, p-value and error \( \chi^2 \) (Eq. 2) were reported. Isotherms for micronutrient ions biosorption are shown in Fig. 3.

Experiments on the effect of the anion on the biosorption in a multicomponent system confirmed the affinity that was determined in the previous experiments and was as follows: Cu(II) > Zn(II) > Co(II) > Mn(II) (Table 2). Additionally, it is consistent with the affinity to several divalent metal ions for nitrogen and oxygen reported in the literature (Mn < Fe < Co < Cu > Zn) [13,14].

A \( t \) test was performed for dependent variables to determine whether the difference between microelement biosorption capacities were statistically significant. The following p-values were obtained: the \( p \) test parameter: for Co(II)-Cu(II) \( p = 0.0188 \), for Cu(II)-Mn(II) \( p = 0.0114 \).

Some anions react with the metal cations and form soluble or insoluble complexes. Anions stabilize the cationic form of metal ions to form complexes with them which can affect their reduced availability and, consequently, the affinity in the biosorption process.
### Table 2: The parameters of the Langmuir modified model that describe the biosorption of microelements in a multi-cation system with the competition as well as parameters of the traditional Langmuir model

| System            | Ion          | $q_{max}$ (mg g$^{-1}$) | $K_L$ (mg L$^{-1}$) | $K_R$ (L mg$^{-1}$) | $R^2$ | $\chi^2$ | $q_{max}$ (mg g$^{-1}$) | $K_L$ (mg L$^{-1}$) | $R^2$ | $\chi^2$ |
|-------------------|--------------|-------------------------|---------------------|---------------------|-------|----------|-------------------------|---------------------|-------|----------|
| Co(NO$_3$)$_2$·6H$_2$O | Co           | 14.0$^a$                | 0.101$^m$           | 220$^a$             | 0.865 | 3.29     | -                       | -                   | -     | -        |
| CuCl$_2$·2H$_2$O  | Cu           | 57.4$^m$                | 0.030$^m$           | 6715$^m$            | 0.982 | 4.75     | 41.0$^{***}$            | 0.0487$^{***}$      | 0.980 | 5.46     |
| MnSO$_4$·H$_2$O   | Mn           | 13.4$^m$                | 0.0237$^m$          | 186$^m$             | 0.816 | 1.66     | -                       | -                   | -     | -        |
| ZnSO$_4$·7H$_2$O  | Zn           | 10.6$^m$                | 0.0044$^m$          | 727$^{**}$          | 0.934 | 0.105    | -                       | -                   | -     | -        |
| CoCl$_2$·6H$_2$O  | Co           | 7.41$^m$                | 0.193$^m$           | 403$^m$             | 0.695 | 1.03     | -                       | -                   | -     | -        |
| CuCl$_2$·2H$_2$O  | Cu           | 27.7                    | 0.227               | 2.68·10$^13$        | 0.882 | 1.17     | 27.7$^{***}$            | 0.227$^{**}$        | 0.882 | 1.17     |
| MnCl$_2$·4H$_2$O  | Mn           | 7.95$^m$                | 0.159$^m$           | 517$^{**}$          | 0.651 | 1.17     | -                       | -                   | -     | -        |
| ZnCl$_2$          | Zn           | 14.86$^m$               | 0.138$^m$           | 429$^m$             | 0.768 | 2.07     | -                       | -                   | -     | -        |
| CoCl$_2$·6H$_2$O  | Co           | 8.03$^m$                | 0.110$^m$           | 543$^m$             | 0.682 | 1.03     | -                       | -                   | -     | -        |
| CuCl$_2$·2H$_2$O  | Cu           | 29.8                    | 0.143               | 2.04·10$^2$         | 0.934 | 0.105    | 29.8$^{***}$            | 0.143$^{***}$       | 0.935 | 0.922    |
| MnSO$_4$·H$_2$O   | Mn           | 5.45$^m$                | 0.259$^m$           | 286$^m$             | 0.747 | 0.536    | -                       | -                   | -     | -        |
| ZnCl$_2$          | Zn           | 20.9$^m$                | 0.044$^m$           | 904$^m$             | 0.803 | 1.37     | -                       | -                   | -     | -        |
| CoSO$_4$·7H$_2$O  | Co           | 18.3$^*$                | 0.0398$^m$          | 171$^{***}$         | 0.878 | 72.7     | -                       | -                   | -     | -        |
| CuSO$_4$·5H$_2$O  | Cu           | 38.1$^*$                | 0.043$^m$           | 4789$^m$            | 0.985 | 3.68     | 27.2$^{***}$            | 0.0732$^{**}$       | 0.80  | 4.57     |
| MnSO$_4$·H$_2$O   | Mn           | 8.89$^*$                | 0.0802$^m$          | 299$^{***}$         | 0.975 | 0.433    | -                       | -                   | -     | -        |
| ZnSO$_4$·7H$_2$O  | Zn           | 25.7$^m$                | 0.0543$^m$          | 199$^{**}$          | 0.959 | 1.32     | -                       | -                   | -     | -        |

ns - no statistical differences; * - $p<0.1$; ** - $p<0.05$ *** - $p<0.001$

**Figure 3:** The equilibrium of biosorption of microelement ions in four-cation system: a) Cl$^-$:NO$_3^-$:SO$_4^{2-}$ = 4:0:0, b) Cl$^-$:NO$_3^-$:SO$_4^{2-}$ = 3:0:1, c) Cl$^-$:NO$_3^-$:SO$_4^{2-}$ = 0:0:4 and d) Cl$^-$:NO$_3^-$:SO$_4^{2-}$ = 1:1:2.
The correlation between biosorption capacity and the absolute value of the constant for the first stage of hydrolysis \( |\log K_{w,1}| \).

Benaiss and Benguell [15] observed that the presence of sulfate and carbonate anions affected the biosorption capacity of chitin for Cd(II). The greater the value of the logarithm of the complex stability constant (\( \log K \)) for Cd(II) anions, the higher the competition. There was no effect of Cl (\( \log K = 1.98 \)), on the biosorption capacity, while the presence of carbonate ions (\( \log K = 4.02 \)) reduced the capacity by 50% [15]. Kapoor and Viraraghavan [16] demonstrated that the biosorption capacity decreased in the presence of EDTA, sulfates, chlorides, phosphates and carbonates. Das et al. [17] observed no effect of Cl, NO\(_3\), SO\(_4^{2-}\) on the biosorption performance. Taking into consideration the constant of the first stage of hydrolysis \( |\log K_{w,1}| \), which is also a measure of the stability of metal ions in aqueous solution, it can be seen that the smaller the value, the higher the biosorption capacity. Plots \( f(\log K_{w,1}) = q_{\text{max}} \) are shown in Fig. 4. The correlation coefficient for each of the discussed four-cation biosorption systems in the different environment, increased as follows: -15.8 for 1:1:2 (Cl\_NO\(_3\):SO\(_4^{2-}\)), -11.2 for 0:0:4 (Cl\_NO\(_3\):SO\(_4^{2-}\)), -3.0 for 4:0:0 (Cl\_NO\(_3\):SO\(_4^{2-}\)) and -79.0 for 4:0:0 (Cl\_NO\(_3\):SO\(_4^{2-}\)). It can be concluded that the lowest decrease of biosorption capacity was found in the four-cation biosorption experiment where only chlorides were used as a source of metal ions.

The effect of anions is an issue often neglected in biosorption experiments. More often, the effects of cations on biosorption performance are discussed in the literature. The effect of the presence of different salts such as: NH\(_4\)Cl, NH\(_4\)NO\(_3\), KNO\(_3\), MgSO\(_4\), NaHCO\(_3\), and K\(_2\)P\(_2\)O\(_7\), on the removal of Cr(VI) onto lignin was studied by Albadarin et al. [7]. Cr(VI) removal percentage decreased dramatically in the presence of NaHCO\(_3\), and K\(_2\)P\(_2\)O\(_7\), salts, which can be due to the high competition of CO\(_3^{2-}\) and P\(_2\)O\(_7^{4-}\) with Cr(VI) for the binding sites, while the presence of SO\(_4^{2-}\) enhanced the percentage of removal [7].

Table 3 shows the correlation matrix between the parameters of the modified Langmuir model. The presence of Cu(II) in the studied systems, which in the affinity order takes first place, is a factor that causes the loss of biosorption capacity of other metal ions. The confirmation of that statement is a negative correlation between the coefficients of the modified Langmuir model and \( q_{\text{max, Cu}} \), even though they are not statistically significant (with the exception of \( b_{\text{Mn}} \)) there is a clear tendency. The higher the biosorption capacity for Cu(II), the lower the affinity constant \( b \) and lower competition constant \( K_a \) for other micronutrient ions. The lower the value of the competition constant \( K_a \), the greater the degree of competition.

In summary, the best results for each of the cationic systems were as follows: Co(II): 0:0:4 > 1:1:2 > 3:0:1 > 4:0:0 (Cl\_NO\(_3\):SO\(_4^{2-}\)); Cu(II): 1:1:2 > 0:0:4 > 3:0:1 > 4:0:0 (Cl\_NO\(_3\):SO\(_4^{2-}\)); Mn(II): 1:1:2 > 0:0:4 > 4:0:0 > 3:0:1 (Cl\_NO\(_3\):SO\(_4^{2-}\)); Zn: 0:0:4 > 3:0:1 > 4:0:0 > 1:1:2 (Cl\_NO\(_3\):SO\(_4^{2-}\)) (Table 2). The results allowed to choose the best system. For the system 1:1:2 (Cl\_NO\(_3\):SO\(_4^{2-}\)) the highest biosorption capacity were determined. To compare the biosorption capacity of biosorption process, in each of discussed systems, the amount of bound metal ions Co(II), Cu(II), Mn(II) and Zn(II) expressed in the molar unit (meq g\(^{-1}\)), which considers the valency of an ion, was added. Totally (the sum of biosorption capacity of all metal ions), the biomass bound 3.09 meq g\(^{-1}\) in the system 1:1:2 (Cl\_NO\(_3\):SO\(_4^{2-}\)), 2.92 meq g\(^{-1}\) in 0:0:4 (Cl\_NO\(_3\):SO\(_4^{2-}\)), 2.05 meq g\(^{-1}\) in 3:0:1 (Cl\_NO\(_3\):SO\(_4^{2-}\)) and 1.87 meq g\(^{-1}\) in 4:0:0 (Cl\_NO\(_3\):SO\(_4^{2-}\)).

### 3.3 The influence of anions on biosorption of Co(II)

Also, experiments on the effect of the anion in a single-cation system were conducted. The study was carried out on Chlorella kessleri biomass, which was enriched in Co(II) ions. Three experiments were conducted by using salts with various anions: nitrate, sulfate and chloride. The experimental results were described by the Langmuir model. Isotherms are shown in Fig. 5 and the estimated parameters in Table 4.

A statistical \( t \) test for a single variable was performed to determine whether the differences in biosorption capacity calculated for various anions were statistically significant. The resulting test values were as follows: for \( q_{\text{max}} \), \( p = 1 \) and \( t = 3.7\times10^{-4} \), \( b, p = 1 \) and \( t = 6.7\times10^{-4} \) and indicated no statistically significant effect of the anion of an inorganic salt on the biosorption capacity.
Conclusions

The conducted experiments regarding the biosorption process in a multi-cation system in the presence of different anions the Cu(II) ions were found to have a higher biosorption capacity when compared with Co(II), Mn(II) and Zn(II); if present in higher concentrations an inhibited binding of other metal ions were present in the solution. For that reason the modified Langmuir model was proposed to describe the experimental results of ions that was influenced by the presence of Cu(II). The affinity order in this experiment was as follows: Cu(II) > Zn(II) > Mn(II) > Co(II).

Additionally, an examination was conducted to determine the effect of different anions of inorganic salts used to prepare the solution for biosorption experiments. The highest total biosorption capacity was obtained for 1:1:2 system (Cl⁻: NO₃⁻: SO₄²⁻). At the same time no influence of anions was observed in the single-metal system.

Results that were obtained can be useful for scaling up biosorption by pointing out the influence of the presence of other ions, as well as the anions in the solution designed for biosorption. Understanding the interactions between the ions is essential in process optimization. Performing the biosorption in a multi-cation system is technologically easier and cheaper. At the same time, several ions are

![Figure 5: The influence of anion of inorganic salt on biosorption capacity of Co(II) by Chlorella kessleri (C₅ 1.0 g L⁻¹, C₆ – 25-300 mg L⁻¹, 25°C, pH 5).](image-url)
The results reported in the present study may be important in the elaboration of technologies based on biosorptoin.

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**Abbreviations**

- $C_0$ – initial solute concentration (mg L$^{-1}$)
- $C_{eq}$ – equilibrium solute concentration (mg L$^{-1}$)
- $C_s$ – biomass concentration (g L$^{-1}$)
- $C_t$ – solute concentration in specific time (mg L$^{-1}$)
- $K_K$ – competition constant of modified Langumuir competition model (L mg$^{-1}$)
- $K_L$ – constant of Langumuir model (L mg$^{-1}$)
- $q$ – the adsorbed metal capacity (mg g$^{-1}$ or meq g$^{-1}$)
- $q_{eq}$ – equilibrium biosorption capacity (mg g$^{-1}$)
- $q_{max}$ – maximum biosorption capacity (mg g$^{-1}$ or meq g$^{-1}$)
- $q_t$ – biosorption capacity in the specific time (mg g$^{-1}$)
- $R^2$ – coefficient of determination
- $t$ – time
- $\chi^2$ – chi-square test ($\chi^2$ test)

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