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NICKEL BIOSORPTION BY FINELY GROUND WASTE SLUDGE

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Abstract. In this paper, removal of Ni (II) from aqueous solution by finely ground waste sludge (FGWS) was investigated. Waste sludge samples obtained from a varnishes and lacquers industry wastewater treatment plant was dried, ground and pre-treated with 1% H_2O_2 to improve the biosorption capacity. Kinetics of nickel biosorption onto FGWS was investigated by using the FGWS samples with particle size of 62.2 μm. The pseudo-first and -second order rate expressions were used to correlate the experimental data. The kinetic constants were determined for both models and the second order rate expression was found to be more suitable. Three different biosorption isotherms were used to correlate the equilibrium biosorption data and the isotherm constants were determined. The Langmuir isotherm was found to fit the experimental data better than the other tested isotherms. The biosorption capacity (q_m) and saturation constant (K) for the Langmuir isotherm showed that finely ground waste sludge has the largest capacity and affinity for removal of Ni(II) compared to the other Activated sludges.

Keywords: biosorption capacity; finely ground waste sludge (FGWS); second order rate; nickel (II) ions; Langmuir isotherm.

1. Introduction

The indiscriminate use of natural resources has caused serious problems of contamination of aquatic ecosystems, principally due to chemical pollution of organic and inorganic origins, especially by the organochlorinated compounds and heavy metals. The pollution of an aquatic environment can alter its physical, chemical and biological characteristics, jeopardizing the quality of water for human consumption (Marques *et al.* 1996). Of the variety of existing pollutants, heavy metals have received special attention, since some of them are extremely harmful to a large variety of organisms when they exceed the limit permitted by environmental legislation and/or the quantities assimilable by these organisms (Laws 1993).

The conventional methods for treatment of effluents contaminated with heavy metals involve physicochemical processes such as flocculation, precipitation, electrolysis and crystallization. However, these processes are very expensive and generate new product merely resulting in a transfer of the metal from one medium to another, but not providing a definitive solution (Laws 1993; Volesky 1990). For this reason, recent research efforts were concentrated on recovery of heavy metals using different biomaterials, such as waste sludge, digested sludge and waste biomass from commercial bioprocesses (Dean 1977). Because of negative surface charge and membrane compositions, organisms (bacteria, yeast, molds, fungi) are natural adsorbents for metal ions.

Early works on metals in biological treatment processes concentrated on the metal toxicity and the inhibition of organic matter removal (Moulton, Shumate 1963). The two main factors influencing the extent of heavy metal toxicity on biological treatment were reported to be metal speciation and concentration. Other factors such as pH, microorganisms concentration, mean cell residence time, influent strength and type were also reported to affect the extent of toxicity (Sujarittanonta, Sherrard 1981). On the other side, recent investigations have indicated that the tolerance of biological treatment systems to heavy metals can be enhanced greatly by proper acclimation (Chang *et al.* 1986; Stasinakis *et al.* 2002). U. Yetis and C. F. Gokcay (1989) have reported that the substrate removal efficiency of acclimatized activated sludge process was not adversely affected by the presence of Ni^{2+} up to a concentration of 10.0 mg/L, while 5.0 mg/L Ni^{2+} had some stimulatory effects.

Several microbial mechanisms are involved in the removal of metals. Microbial metal uptake generally involves the rapid, metabolism-independent uptake of metals to cell walls and other external surfaces (passive uptake), followed by a slow, metabolism-dependent transport across the cell membrane (active uptake). In most studies, it was shown that passive uptake, especially the complexation by extracellular polymeric substance is the dominant mechanism in metal removal (Brown, Lester 1982; Lawson *et al.* 1984). On the other hand, for some metals, such as nickel, active uptake was indicated to be important at low concentrations (Lester *et al.* 1984).

Extracellular polymeric substances are reported to have very important roles in complexing and removing heavy metals from solution (Brown, Lester 1982; Jang *et al.* 1984; Rudd *et al.* 1984). They may protect cells against the toxicity of metals. S. Y. Chang *et al.* (1995)

reported that the stimulated production of metal-complexing biopolymers resulted in enhanced removal of heavy metals without drastic reduction in culture viability. Extracellular polymeric substances are also actively involved in the biosorption of metals in the extracellular polymer network, which is thought to involve ion exchange reactions (Chang *et al.* 1996), complexation with negatively charged groups (Brown, Lester 1982; Rudd *et al.* 1984), adsorption (Brown, Lester 1982), and precipitation (Fukushi *et al.* 1996). In addition, the composition of extracellular polymeric substances, when cells are exposed to heavy metals, was reported to change as represented by a change in C/P ratio of the biomass (Brown, Lester 1982).

The term "biosorption" refers solely to technological application of natural systems that have existed for thousands of years. Due to the high polluting capacity of modern society in recent years these processes have been used to the benefit of mankind. "Biosorption" can be defined as the removal of metallic ions by means of passive adsorption or complexation by live biomass or organic waste (Eccles 1995). Some advantages of biosorption for removal of heavy metals over chemical and physical methods can be summarized as follows:

1. Excess sludge from wastewater treatment plants may be used as biosorbent.
2. Low cost, free availability and possible reuse of the biosorbent.
3. High biosorption capacity because of large surface area of sludge organisms.
4. Selective adsorption of metal ions.
5. Operation over a broad range of environmental conditions (pH, ionic strength, temperature).

The inactive or dead microbial biomass can serve as a basis for the development of biosorbent materials capable of the concentration and recuperation of heavy metals. These new biosorbents can be regenerated and reutilized and are selective, efficient, cheap and competitive with artificial products. Therefore they have a potential application in operations of environmental control and recovery of the metal.

Activated sludge is a well-known biomass used for the purification of some industrial effluents and domestic wastes. Excess waste sludge generated in wastewater treatment plants can be separated and utilized for removal of heavy metal ions as an abundant and cheap biosorbent. Waste sludge from wastewater treatment plants contains both bacteria and protozoa. Large numbers of studies were reported in literature on biosorption of heavy metals onto different organisms (Su *et al.* 1995). Most of those studies were done using pure cultures of bacteria, yeasts and molds (Yetis *et al.* 1998). Biosorption of Pb(II) and Cu(II) ions were investigated by Y. Sag *et al.* (2003) using activated sludge as biosorbent in batch and continuous-flow stirred tank reactors.

The Freundlich model described the experimental equilibrium uptake of Pb(II) and Cu(II) ions by the resting activated sludge better than the Langmuir model. R. Gourdon *et al.* (1994) designed an automated bench-scale countercurrent biosorption system (CBS) for the removal of metals from aqueous effluents. The system has been tested with activated sludge microorganisms as a biosorbent for lead and copper as model metals. Nearly 99.9 and 60% removals of lead and copper were obtained, respectively. Biomass from activated sludge reactors operating at different dilution rates (0.09, 0.16 and 0.24 h^{-1}) was used by B. Arican *et al.* (2002) to examine the effect of sludge age on Ni^{2+} removal characteristics by batch adsorption tests. Linear adsorption isotherms were obtained at all dilution rates indicating the presence of equilibrium between biomass and the free nickel species. C. F. Gokcay and U. Yetis (1996) investigated and compared the biosorption capacities of waste activated and waste digested sludge. Surface charge of each was determined in order to relate electronegativity with biosorption capacity.

Activated sludge was found to be more effective than digested sludge for removal of zinc from a metal plating effluent. Sludge biosorption capacity increased with initial zinc concentration. The ability of dried anaerobic activated sludge to adsorb phenol and chromium (VI) ions in a batch system was investigated by Z. Aksu and D. Akpinar (2001). The optimum initial pH for both chromium (VI) ions and phenol biosorption was determined to be 1.0. The cells of dried anaerobic activated sludge bacteria were effective for simultaneous removal and separation of phenol and chromium (VI) ions from aqueous effluents. Utkiger *et al.* (2000) studied the equilibrium biosorption of Zn(II) and Cu(II) by non-viable activated sludge in a packed column adsorber. In binary mixture studies with Cu(II) and Zn(II), equilibrium was reduced by about 30% for each metal ion indicating some competition between the two metals with Cu(II) preferentially adsorbing to achieve a higher equilibrium uptake.

A. Hammaini and A. Ballester (2002) investigated the adsorption of three metal ions, Cu, Cd and Zn in a bi-component mixture system by activated sludge. The empirical isotherms indicated a competitive uptake with Cu being preferentially adsorbed followed by Cd and Zn. When Cu was present at the highest concentration, a 53% decrease in Cd biosorption was observed. Y. Liu *et al.* (2003) studied the feasibility of aerobic granules as a novel type of biosorbent for cadmium removal from industrial wastewater. A kinetic model was developed to describe Cd2+ biosorption by aerobic granules. Results showed that the Cd2+ biosorption on aerobic granule surface was closely related to both initial Cd2+ and granule concentrations. Z. Aksu *et al.* (2002) also studied biosorption of chromium (VI) and nickel (II) ions, both singly and in combination by dried activated sludge in a batch system as a function of initial pH and metal ion concentrations. The optimal initial pH values for single chromium (VI) and nickel (II) biosorptions were determined to be 1.0 and 4.5, respectively. A multi-component Freundlich model was found to be satisfactory to represent the equilibrium experimental data.

In an earlier study, A. C. Rossin *et al.* (1982) suggested that enhanced metal removal might occur in activated sludge processes, at longer sludge ages, not only due to higher mixed liquor suspended solids (MLSS) concentration, but also due to a change in both the composition of extracellular polymeric substances and the speciation of the metal. However, no further detailed investigations were carried out for a better understanding of sludge age-metal accumulation mechanism interaction, and the subject remained relatively unexplored.

Various types of waste biomass such as bacteria, yeast, molds, marine algae and activated sludge were compared for biosorption of copper, zinc and nickel ions by I. Bakkaloglu *et al.* (1998). Bacteria and molds were found to be more effective biosorbents as compared to the other biomass tested. J. Gabriel and P. Baldrian (2001) investigated biosorption of copper to the pellets of different fungal species in batch and continuous column experiments. Different molds yielded comparable biosorption capacities for copper (5–8 mg Cu g biomass^{-1}).

Since nickel ions are commonly present in metal plating effluents, it was selected as the model metal ion. Activated sludge from a varnishes and lacquers industry wastewater treatment plant was used for biosorption of nickel ions because of its high biosorption capacity.

Waste sludge was dried, finely ground and pretreated with 1% H_2O_2 to improve the biosorption capacity. The pre-treated FGWS was sieved to different particle sizes and used for biosorption of nickel (II) ions from solution. The kinetics and isotherms of the biosorption was investigated using FGWS with an average particle size of 62.2 μm. Biosorption isotherms were established by using the equilibrium data and the isotherm constants were determined.

2. Materials and methods

2.1. Experimental system

Batch shake flask experiments were performed using a gyratory shaker at 150 rpm. Erlenmeyer flasks of 500 ml were charged with 200 ml of tap water. In kinetic studies, nickel ions (in form of $NiCl_2.6H_2O$) and FGWS were added to the flasks to yield 100 mg l^{-1} Ni^{2+} and 1 g l^{-1} FGWS in the solution. In isotherm experiments, the nickel ion concentrations were varied between 50 and 350 mg l^{-1} in each flask while the PWS concentration was 1 g l^{-1}. The pH was adjusted to 5 in all experiments (Gokcay *et al.* 1996). The flasks were incubated in a gyratory shaker at 25 °C for 24 h. Samples were removed from the flaks every hour for analysis. A control flask free of PAS with 100 mg l^{-1} Ni^{2+} ions was used to determine the extent of non-adsorptive nickel removal from the solution.

2.2. Experimental procedure

Waste activated sludge samples obtained from different wastewater treatment plants were tested for their nickel ion biosorption abilities and the sludge obtained from ASTRAL varnishes and lacquers industry in Tunis, Tunisia was found to be superior to the other sludges tested. The selected sludge was dried, finely ground and sieved to desired particle size before use in biosorption experiments. Due to low biosorption capacity of the untreated powdered waste sludge, the FGWS samples were pre-treated using three different pre-treatment solutions: 1% HNO_3, 1% NaOH and 1% H_2O_2. Two hundred millilitre pre-treatment solution was mixed with 2 g of FGWS in a 500 ml Erlenmeyer flask and placed on a gyratory shaker at 150 rpm and 25 °C for 6 h for pre-treatment. Pre-treated FGWS was washed with deionized water on a filter paper until the filtrate pH was neutral. Pre-treatment with 1% H_2O_2 was found to be superior to the other methods yielding the highest biosorption capacity (80 mg g FGWS^{-1}). For this reason the varnishes and lacquers industry sludge was used after pre-treatment in all kinetic and isotherm studies. Pre-treated and washed FGWS samples were dried at 80 °C, reground and sieved to different mesh sizes. Only the size fraction between 200 and 260 meshes with an average particle size of 62.2 μm was used in kinetic and isotherm studies reported in this article.

2.3. Analytical methods

The samples (5 ml) withdrawn from the Erlenmeyers every hour were centrifuged at 8000 rpm (7000 g) to remove solids. The clear supernatants were analyzed for copper ion contents using an Atomic Absorption Spectrometer (ATI Coleman 395D spectrophotometer,) at 218.6 nm wavelength.

3. Results and discussion

3.1. Kinetic studies

The kinetics of biosorption of nickel ions onto pre-treated FGWS samples were investigated for the particle size of 62.2 μm with initial nickel and FGWS concentrations of 100 mg l^{-1} and 1 g l^{-1}, respectively. Fig. 1 depicts variation of aqueous and solid phase (biosorbed) nickel concentrations with time. Solid phase Ni^{2+} concentration increased and the aqueous phase concentration decreased with time and reached equilibrium after 6 h of incubation. The equilibrium biosorption capacity of FGWS was 63 mg Ni g FGWS^{-1}. Two different kinetic models were used for correlation of biosorption data. The pseudo-first order kinetic model (Padmavathy *et al.* 2003; Ho and McKay 1999) has the following form:

$$\ln\left(1-\frac{q}{q_e}\right) = -k_1 t \quad \text{or} \quad q = q_e(1-\exp(-k_1 t)), \qquad (1)$$

where q and q_e are the solid phase nickel ion concentrations at any time (t) and at the equilibrium (mg g^{-1}), respectively and k the first order rate constant (h^{-1}). q_e is 63 mg g^{-1} as obtained from Fig. 1.

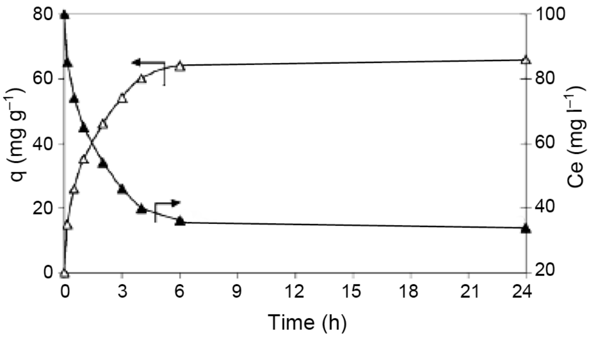

Fig. 1. Variation of solid phase (biosorbed) and aqueous phase nickel ion concentrations with time

When the experimental data was plotted in form of $\ln\left(1-\frac{q}{q_e}\right)$ versus time, a straight line was obtained as shown in Fig. 2. From the slope and the intercept of the line, the first order rate constant was found as $k_1 = 0.65\ \mathrm{h}^{-1}$ ($R^2 = 0.95$).

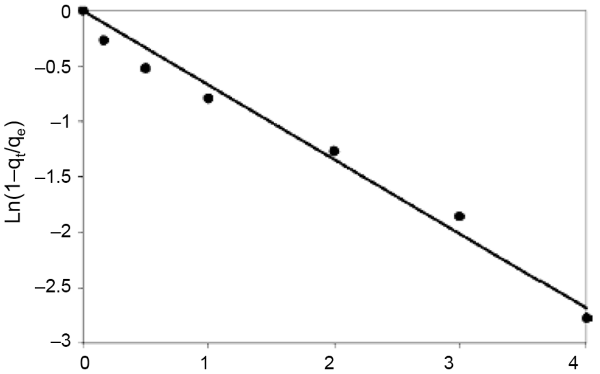

Fig. 2. A plot of ln (1–*q*/*q*e) vs. time according to the pseudo-first order adsorption kinetics

The pseudo-second order kinetic model as developed by Ho and McKay (1999) has the following form:

$$\frac{t}{q} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e}. \tag{2}$$

When the data presented in Fig. 1 was plotted in form of $\frac{t}{q}$ versus time, a straight line was obtained as shown in Fig. 3. From the slope and the intercept of the line in Fig. 3, the following constants were determined.

$k_2 = 0.0179\ (\mathrm{mg\ g^{-1}})^{-1}\ \mathrm{h}^{-1}$, $q_e = 70.2\ \mathrm{mg\ g^{-1}}$ ($R^2 = 0.97$).

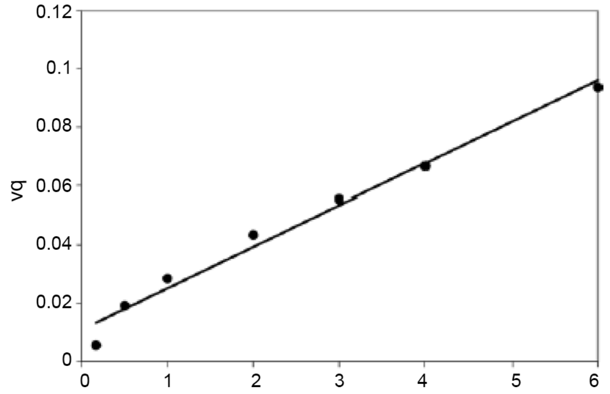

Fig. 3. A plot of *t*/*q* vs. time according to the pseudo-second order adsorption kinetics

Apparently, the pseudo-second order model represented the kinetics of biosorption of nickel ions onto FGWS particles slightly better than the pseudo-first order model, although the first order model also represented the data reasonably well.

3.2. Isotherm studies

Three different biosorption isotherms were used to correlate the equilibrium data. The biosorption isotherms used were the Langmuir, Freundlich and the generalized biosorption isotherms. Langmuir isotherm has the following form:

$$q_e = \frac{X}{M} = \frac{q_m C_e}{\left(K + C_e\right)}, \tag{3}$$

which may be written in a linearized form as follows:

$$\frac{1}{q_e} = \frac{1}{q_m} + \frac{K}{q_m C_e}, \tag{4}$$

where X is the amount of nickel removed from solution by biosorption ($V\left(C_0 - C\right)$ mg); M – the amount of biosorbent used (g); q_e – the equilibrium nickel ion concentration on the biosorbent (mg g^{-1}); q_m – the maximum biosorption capacity of the adsorbent for nickel ions (mg g^{-1}); C_e – the liquid phase equilibrium concentration of the nickel ions (mg l^{-1}) and K is the saturation constant (mg l^{-1}). The plots of equilibrium concentrations of nickel ions in the solid and aqueous phases, that is q_e versus C_e and also $\frac{1}{q_e}$ versus $\frac{1}{C_e}$ are presented in Fig. 4 a and b, respectively.

From the slope and intercept of the line in Fig. 4b, the Langmuir constants were found as:

$q_m = 81.3\ \mathrm{mg\ g^{-1}}$, $K = 2.1\ \mathrm{mg}\ l^{-1}$ ($R^2 = 0.95$).

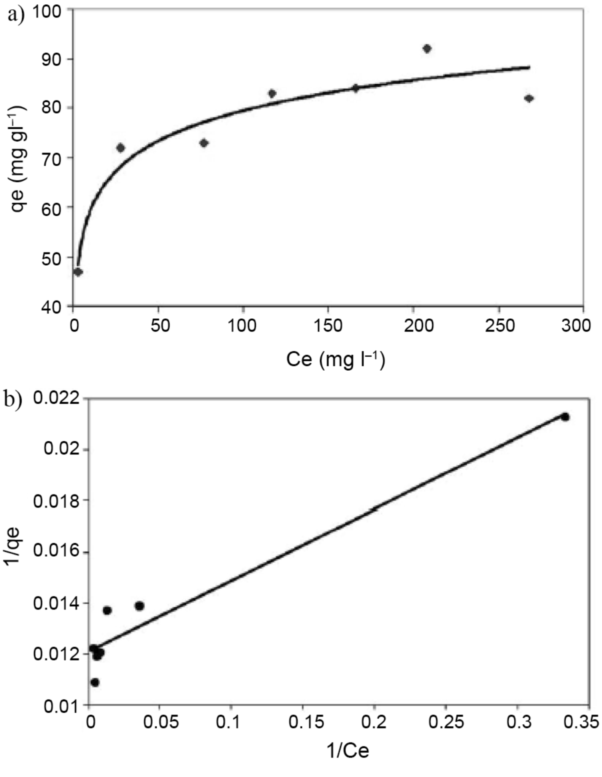

Fig. 4. A plot of q_e vs. C_e, (a); Langmuir isotherm plot of $1/q_e$ vs. $1/C_e$ (b) for biosorption of nickel ions onto pre-treated FGWS. *D*p = 62.2 µm

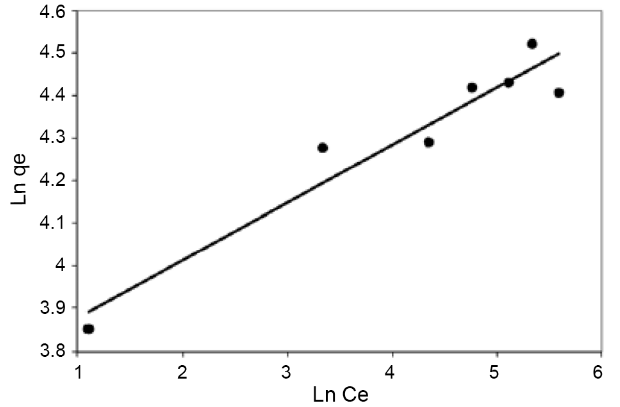

Fig. 5. Freundlich isotherm plot of ln q_e vs. lnC_e for biosorption of nickel ions onto pre-treated FGWS. Dp = 62.2 μm

Apparently, equilibrium biosorption data of nickel ions fit to the Langmuir isotherm reasonably well (R^2 = 0.95). As compared to the literature studies (Betul *et al.* 2003), low value of the saturation constant (K) indicates more effective biosorption of nickel ions onto the FGWS used. Freundlich isotherm has the following form:

$$q_e = KC_e^{\frac{1}{n}} \tag{5}$$

or in linearized form Eq. (5) can be written as:

$$\ln q_e = \ln K + \left(\frac{1}{n}\right)\ln C_e , \tag{6}$$

where K is the Freundlich capacity constant (mg g^{-1}); n – the affinity constant; q_e – the equilibrium nickel ion concentration in solid phase (mg g^{-1}) and C_e is the equilibrium nickel ion concentration in aqueous phase (mg l^{-1}).

Fig. 5 depicts a plot of $\ln q_e$ versus $\ln C_e$ for nickel ion biosorption. From the slope and intercept of the line, the following Freundlich isotherm constants were found:

$$K = 41.9 \text{ mg g}^{-1} (\text{mg } l^{-1})^{1/n},$$

$$\frac{1}{n} = 0.133, \quad (n = 7.5), \ R^2 = 0.92.$$

Apparently Freundlich isotherm represents the equilibrium data reasonably well. However, the fit is not as good as the Langmuir isotherm. The third isotherm tested for correlation of the equilibrium data was the generalized biosorption isotherm equation which has the following form:

$$q_e = \frac{q_m C_e^n}{K + C_e^n} . \tag{7}$$

Eq. (7) can be written as follows in linearized form:

$$\ln\left(\left(\frac{q_m}{q_e}\right) - 1\right) = \ln K - n\ln C_e , \tag{8}$$

where K is the saturation constant (mg l^{-1}); n – the cooperative binding constant; q_m – the maximum biosorption capacity of the adsorbent (mg g^{-1}); q_e (mg g^{-1}) and C_e (mg l^{-1}) are the equilibrium nickel ion concentrations in the solid and liquid phases, respectively. A plot of the equilibrium data in form of $\ln\left(\frac{q_m}{q_e}\right)$ versus $\ln C_e$ is depicted in Fig. 6.

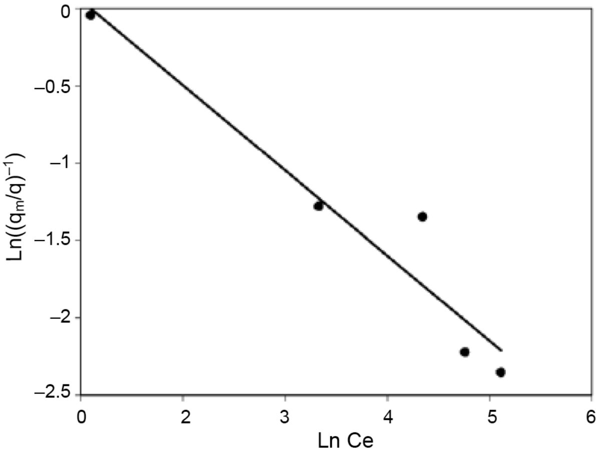

Fig. 6. Generalized biosorption isotherm plot of ln $((q_m/q)^{-1})$ vs. lnC_e

The q_m value was taken as q_m = 81.3 mg g^{-1} as determined from the Langmuir isotherm.

From the slope and intercept of the line presented in Fig. 6, the following values were found for the constants of the generalized biosorption isotherm.

$$K = 1.82 \ (\text{mg } l^{-1})^n, \quad n = 0.54 \quad (R^2 = 0.93).$$

Apparently, the generalized adsorption isotherm represents the equilibrium data reasonably well, but the fit is not as good as the Langmuir isotherm.

Table 1 summarizes the results of the isotherm constants for the three different equilibrium isotherms tested. On the basis of the correlation coefficients (R^2), Langmuir isotherm seemed to represent the equilibrium adsorption data with a slightly better fit as compared to the other isotherms.

Table 1. Summary of the isotherm constants and the correlation coefficients for different isotherms

Parameter	Langmuir isotherm	Freundlich isotherm	Generalized isotherm
q_m (mg g^{-1})	81.3	–	81.3
K (mg l^{-1})	2.1	41.9	1.82
N	–	7.5	0.54
R^2	0.95	0.92	0.93

As compared to the literature studies on biosorption of nickel ions onto waste activated sludge (Utkiger *et al.* 2000) the maximum biosorption capacity (q_m) obtained in this study (82 mg g^{-1}) is superior to the literature values which vary between 55 and 68 mg g^{-1}. The saturation constant for the Langmuir isotherm (K = 2.1 mg l^{-1}) is also considerably lower than those reported in literature on nickel biosorption (Betul *et al.* 2003) indicating high affinity of the waste sludge used for nickel biosorption. This may be because of the selection of better waste sludge and pre-treatment with 1% H_2O_2.

4. Conclusions

From the foregoing discussions, the following conclusions were drawn:

1. Pseudo-first order and -second order kinetic models were used to correlate the pre-equilibrium biosorption data and the kinetic constants were determined for both models. Pseudo second order kinetic model represented the data slightly better than the first order model for biosorption of nickel ions onto FGWS.
2. The langmuir isotherm was found to fit the experimental data slightly better than the other isotherms tested although the other isotherms also represented the data reasonably well. The maximum biosorption capacity of pre-treated FGWS for the nickel ions was found to be nearly 82 mg Ni g $FGWS^{-1}$.
3. The varnishes and lacquers industry waste sludge used for nickel ion biosorption was found to be superior to the waste sludges used by other investigators yielding higher biosorption capacity (q_m) and lower saturation constant (K) for the Langmuir isotherm

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NIKELIO BIOSORBAVIMAS SMULKIAI SUMALTU NUOTEKŲ DUMBLU

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Santrauka

Nagrinėjami Ni(II) šalinimo iš vandeninių tirpalų smulkiai sumaltu nuotekų dumblu (SSND) tyrimų rezultatai. Nuotekų dumblo pavyzdžiai imti iš glazūravimo ir lakavimo pramonės nuotekų valymo įrenginių, išdžiovinti, susmulkinti ir apdoroti 1 % H_2O_2, kad padidėtų biosorbcijos tūris. Nikelio sorbcijos SSND kinetika tirta naudojant SSND bandinius, kurių dalelių dydis 62,2 μm. Pseudo pirmojo ir antrojo laipsnio greičio išraiškos buvo taikomos eksperimentinių duomenų koreliacijai apibrėžti. Kinetinė konstanta nustatyta abiejų modelių, tačiau antrojo laipsnio greičio išraiška buvo tinkamesnė. Pagal tris skirtingas biosorbcijos izotermes nustatyta biosorbcijos pusiausvyros duomenų koreliacija, rastos izotermių konstantos. Langmiuro (Langmuir) izotermė geriau atitiko eksperimentinius duomenis nei kitos tirtosios izotermės. Pagal Langmiuro izotermę biosorbcijos geba (q_m) ir prisotinimo konstanta (K) rodė, kad smulkiai sumalto nuotekų dumblo geba šalinti Ni(II) yra didžiausia, palyginti su kitos rūšies aktyvintojo dumblo.

Reikšminiai žodžiai: biosorbcijos geba, smulkiai sumaltas nuotekų dumblas, antrojo laipsnio greitis, nikelio(II) jonai, Langmiuro (Langmuir) izotermė.

БИОСОРБЦИЯ НИКЕЛЯ МЕЛКО ИЗМЕЛЬЧЕННЫМ ИЛОМ СТОКОВ

Я. Ганнах

Резюме

Исследуется удаление Ni(II) из водных растворов мелко измельченным илом стоков (МИИС). Образцы ила стоков были взяты из оборудования по очистке стоков в промышленности по глазурованию и лакованию. Затем образцы были высушены, измельчены и обработаны 1-процентным H_2O_2 с целью увеличить объем биосорбции. Кинетика сорбции никеля МИИС исследовалась с применением образцов МИИС, величина частиц которых составляла 62,2 μм. Выражения скорости псевдо-первой и псевдо-второй степени использовались для определения корреляции экспериментальных данных. Кинетическая константа была установлена для обеих моделей. Однако выражение скорости второй степени оказалось более приемлемым. Три разные изотермы биосорбции применялись для определения корреляции данных по равновесию биосорбции и констант изотерм. Изотерма Langmuir лучше совпала с экспериментальными данными, чем другие испытуемые изотермы. Способность биосорбции (q_m) изотермы Langmuir и константа насыщения (K) показали, что мелко измельченный ил стоков обладает наибольшей способностью удалять Ni(II) по сравнению с другими видами активированного ила.

Ключевые слова: способность биосорбции, мелко измельченный ил стоков, скорость второй степени, ионы никеля (II), изотерма Langmuir.

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