1. Introduction

Biosorption as a process of using materials of biological origin to remove metal ions from solution is a promising method for wastewater treatment [1,2]. Biosorption is believed to be the alternative method to conventional techniques of heavy metal removal from aqueous solutions [3]. Yeast can be easily cultivated in substantial quantities using inexpensive growth media and simple fermentation techniques. Moreover, waste yeast collected in large volumes from commercial brewery productions is a readily available, low-price biosorbent with a sufficiently high metal-binding capacity and selectivity for heavy metals [4].

The high capacity of metal sorption by biosorbent as well as the feasibility of metal recovery and the subsequent use of biosorbent are important for its industrial application [5]. Desorption of sorbed metal and consequently re-using of regenerated biomass is desirable for the successful and cost-effective implementation of a biosorption process [1,2,4,6]. The cell surface-bound metal might be removed by the use of eluents, but they have to be carefully selected for the type of biosorbent [7]. They should be capable of desorbing bound metals and should not decrease the metal sorption capacity of the biomass during successive cycles of metal sorption [6]. In contrast to the abundant literature on the sorption ability of various microorganisms, there is not much data available on effective eluents that do not cause the decrease in the sorption efficiency in subsequent cycles of heavy metal removal.

The aim of this work was to screen various eluents and select the most appropriate for lead and cadmium recovery from Saccharomyces biomass.

2. Experimental Procedure

Saccharomyces pastorianus W34/78 (Hefebank Weihenstephan) and Saccharomyces cerevisiae (LOCK 0271) were cultivated from pure culture in wort broth (Merck) for 48 h at a temperature of 25°C. Biomass was then harvested by centrifugation (3000×g, 5 min) and washed twice with deionised distilled water. Waste yeast collected directly after fermentation was provided by a local brewery. Then the yeast slurry was stored at a temperature of 5°C. Metal ion solutions of Cd²⁺ and Pb²⁺ were made by dissolving analytical grade Pb(NO₃)₂, Cd(NO₃)₂·4H₂O in deionised water.

Biosorption experiments were performed with shaking at 150 rpm at a constant temperature of 10°C for 30 min using 100 mL of Cd²⁺ and Pb²⁺ solutions (10 mg L⁻¹) and 2 g of wet biomass, which corresponded to 0.42 g of dry biomass. The pH value of the solution was adjusted to 6.0 with HNO₃ or NaOH (0.1 mol L⁻¹). Following the Cd²⁺ and Pb²⁺ biosorption, biomaterials were separated by
centrifugation (3000×g, 3 min) and the residual Cd²⁺ and Pb²⁺ ion concentrations in the supernatant were determined. The loaded biomass was then suspended in 5 mL or 10 mL of eluent solution. Desorbing agents such as HCl, HNO₃, H₂SO₄, Na₂SO₄, Na₂CO₃, EDTA and NaOH were used at concentrations of 0.05 - 0.5 mol L⁻¹. All chemicals were of analytical grade. Desorbing solutions with added biomass were incubated with shaking at 150 rpm at 10°C for 10 min. After separation of biosorbents by centrifugation (3000×g, 3 min), the concentrations of Cd²⁺ and Pb²⁺ released into eluent solutions were measured. Metals were analyzed by atomic absorption spectrometry (AAS, GBC 932 Plus). Metals were quantified against standard curves prepared on the day of the analysis. The cadmium biosorption process by *S. pastorianus* was performed for the next cycle to assess the capacity of biomaterials for reuse. Resorption experiments were performed with shaking at 150 rpm at a constant temperature of 10°C for 30 min using 100 mL of Cd²⁺ and Pb²⁺ solutions (10 mg L⁻¹) and 2 g of wet biomass, which corresponded to 0.42 g of dry biomass. The pH value of the solution was adjusted to 6.0 with HNO₃ or NaOH (0.1 mol L⁻¹). Following the Cd²⁺ and Pb²⁺ sorption, biomaterials were separated by centrifugation (3000×g, 3 min) and the residual Cd²⁺ and Pb²⁺ ion concentrations in the supernatant were determined.

All experiments were conducted in triplicate and the mean values were used in data analysis. Statistical significance of the data was determined by Student’s t-test. A p-value below 0.05 was considered statistically significant.

The amount of Cd²⁺ and Pb²⁺ adsorbed by biomass (q) was calculated using the following equation:

\[
q = (C_0 - C) \times V (mg),
\]

where:

- \(C_0\) is the initial metal concentration (mg L⁻¹),
- \(C\) is the final metal concentration (mg L⁻¹),
- \(V\) is the volume of metal solution (L).

The desorption efficiency of various eluents (\(E_d\)) was calculated using the following equation:

\[
E_d = \frac{100 \times C_d \times V_d}{q} (\%)
\]

3. Results and Discussion

There were significant differences in metal removal by different yeast species (Table 1). The highest cadmium and lead uptake was obtained with *S. cerevisiae*. The lead biosorption capacity of all kinds of biomass was higher than cadmium.

The cadmium and lead desorption efficiency of various eluent solutions was investigated. The efficiency of particular eluents in metal desorption from the different types of biomass employed varied significantly, although all the yeast types tested belonged to the same genus (Tables 2-5). This confirms the fact that the eluent has to be selected for a particular biosorbent.

The application of EDTA and mineral acids resulted in the maximum elution of cadmium. Approximately 85% of biomass-bound cadmium was desorbed with 10 mL EDTA, HCl and H₂SO₄ (Table 2). It has been hypothesized that the efficiency of mineral acids in metal recovery results from the increased metal mobility in acidic condition and the replacement of bound metal by H⁺ ions. The effectiveness of desorption could depend on the binding strength of eluent cations to the biosorbent. It has been suggested that the high concentration of hydrogen ions is responsible for the displacement of adsorbed metals through the ion exchange mechanism [8]. Moreover, desorption of the adsorbed cadmium by mineral acids may be attributed to the acid’s ability to dissolve certain groups of polysaccharides found on the surface of biomass. The dissolution of these polysaccharides forming cadmium binding sites would release cadmium back into solution. However, HNO₃ was not as effective in remobilizing cadmium from biomass cultivated from pure yeast culture as EDTA and other mineral acids (Tables 2, 3). The extent of biomass-bound cadmium desorption from waste yeast was much lower, and there were not large differences among various eluents in the efficiency of metal recovery. Na₂CO₃ and NaOH were the least effective cadmium eluents, which is likely associated with the rise in pH upon their contact with the biosorbent. Complexes formed between bicarbonate and cadmium are not strong enough to rupture biosorbent-metal complexes. However, bicarbonates and sulfates were reported by Tobin et al. [9] to be efficient eluents from *Rhizopus arrhizus* biomass. Bicarbonates were also effective in stripping uranium from fungal biomass.
The distilled water control demonstrated negligible cadmium desorption. Despite a higher affinity of lead towards yeast biomass, not in all cases was it more difficult to desorb lead than cadmium. EDTA, HNO₃ and HCl were the most effective in remobilizing the biomass-bound lead. EDTA was able to elute more than 85% of the sorbed lead from S. pastorianus (Table 4). In this case H₂SO₄ was a much worse eluent. Na₂CO₃, NaOH as well as Na₂SO₄ were the least effective lead eluents.

Total or nearly total elution of metals from biosorbents using mainly mineral acids or EDTA were reported by some authors. Most bibliographic data on cadmium and lead recovery relate to desorption from algal biomass. Aldor et al. [5] completely desorbed cadmium from Sargassum fluitans with 0.1 mol L⁻¹ H₂SO₄, HCl and HNO₃. Chu et al. [8] achieved almost a complete recovery of cadmium from Sargassum baccularia with 3.24 mmol L⁻¹ EDTA and 80% with HCl at pH = 2. Elution of cadmium from Saccharomyces cerevisiae

### Table 2. The cadmium desorption efficiency of 10 mL of various eluents (liquid to solid ratio of 0.02 L g⁻¹).

| Eluent | Eluent concentration [mol L⁻¹] | Cadmium recovery [%] | Waste yeast |
|--------|-------------------------------|---------------------|-------------|
|        | S. pastorianus | S. cerevisiae | |
| Water  | 0 | 2 | 2 | 2 |
| EDTA   | 0.05 | 79 | 56 | 19 |
|        | 0.125 | 87 | 60 | 19 |
|        | 0.25 | 73 | 53 | 18 |
| HCl    | 0.05 | 83 | 58 | 29 |
|        | 0.1 | 81 | 54 | 27 |
|        | 0.5 | 74 | 53 | 21 |
| H₂SO₄ | 0.05 | 69 | 56 | 21 |
|        | 0.1 | 85 | 56 | 22 |
|        | 0.5 | 66 | 55 | 21 |
| HNO₃  | 0.05 | 49 | 44 | 25 |
|        | 0.1 | 68 | 52 | 32 |
|        | 0.5 | 50 | 46 | 27 |
| Na₂SO₄| 0.05 | 33 | 24 | 21 |
|        | 0.1 | 37 | 32 | 22 |
|        | 0.5 | 63 | 39 | 28 |
| Na₂CO₃| 0.05 | 5 | 5 | 6 |
|        | 0.1 | 7 | 9 | 7 |
|        | 0.5 | 10 | 15 | 7 |
| NaOH  | 0.05 | 15 | 6 | 3 |
|        | 0.1 | 28 | 15 | 9 |
|        | 0.5 | 15 | 10 | 9 |

### Table 3. The cadmium desorption efficiency of 5 mL of various eluents (liquid to solid ratio of 0.01 L g⁻¹).

| Eluent | Eluent concentration [mol L⁻¹] | Cadmium recovery [%] | Waste yeast |
|--------|-------------------------------|---------------------|-------------|
|        | S. pastorianus | S. cerevisiae | |
| Water  | 0 | 2 | 2 | 2 |
| EDTA   | 0.05 | 45 | 44 | 15 |
|        | 0.125 | 59 | 44 | 17 |
|        | 0.25 | 56 | 43 | 14 |
| HCl    | 0.05 | 56 | 41 | 19 |
|        | 0.1 | 55 | 40 | 18 |
|        | 0.5 | 53 | 38 | 16 |
| H₂SO₄ | 0.05 | 51 | 41 | 12 |
|        | 0.1 | 59 | 44 | 16 |
|        | 0.5 | 50 | 33 | 17 |
| HNO₃  | 0.05 | 41 | 19 | 22 |
|        | 0.1 | 50 | 36 | 23 |
|        | 0.5 | 44 | 24 | 20 |
| Na₂SO₄| 0.05 | 20 | 20 | 13 |
|        | 0.1 | 23 | 35 | 13 |
|        | 0.5 | 51 | 43 | 15 |
| Na₂CO₃| 0.05 | 5 | 4 | 5 |
|        | 0.1 | 6 | 5 | 6 |
|        | 0.5 | 8 | 21 | 7 |
| NaOH  | 0.05 | 14 | 11 | 5 |
|        | 0.1 | 26 | 15 | 9 |
|        | 0.5 | 22 | 13 | 9 |
was studied by Wilhelmi and Duncan [11]. The metal was totally eluted with 0.1 mol L\(^{-1}\) and 1 mol L\(^{-1}\) HCl from immobilised yeast slurry in a packed column. Gong et al. [12] compared different eluents used for lead desorption from *Spirulina maxima* biomass. In their study the best desorption efficiency was achieved with HNO\(_3\) and EDTA. More than 90% of lead was recovered with these agents. However, there were not statistically significant differences in the desorption efficiency of HNO\(_3\), EDTA and HCl. EDTA and HNO\(_3\) were also the most efficient lead desorbents from *Cladophora fascicularis* [13]. The recovery with 0.1 mol L\(^{-1}\) HNO\(_3\) was 85% and with 0.01 mol L\(^{-1}\) EDTA 82%.

The use of EDTA at a concentration of 0.125 mol L\(^{-1}\) allowed the recovery of more cadmium and lead than at a concentration of 0.05 mol L\(^{-1}\) and 0.25 mol L\(^{-1}\). The effectiveness of desorption did not increase with increasing concentration of mineral acids from 0.1 mol L\(^{-1}\) to 0.5 mol L\(^{-1}\). However, the use of H\(_2\)SO\(_4\) and HNO\(_3\) at a concentration of 0.1 mol L\(^{-1}\) led to a higher efficiency in remobilizing cadmium than at a concentration of 0.05 mol L\(^{-1}\). An increase in metal recovery efficiency with increasing acid concentration indicated an ion exchange process. It is likely that saturation for proton exchange was achieved and the increase of proton concentration did not cause higher metal recovery. A similar phenomenon was described by Ferraz et al. [7] in studies of chromium desorption from *S. cerevisiae*. More effective cadmium desorption was observed with higher concentrations of Na\(_2\)SO\(_4\).

The effect of the liquid to solid ratio was assessed using 5 mL and 10 mL of eluting agent. The ratios of the volume of eluting agent to the dry biomass were 0.01 and 0.02 L g\(^{-1}\), respectively. The desorption effectiveness of 10 mL of eluent in metal desorption was higher. The recovered metals were concentrated in small volumes. However, a high concentration of metal released into solution can decrease desorption efficiency as it results in some remaining residual metal. For efficient metal recovery, the optimization of the eluate volume to the mass of loaded biomass is required to attain a high degree of metal extraction and a highly concentrated eluate. In previous studies, different liquid to solid ratios were applied to desorb heavy metals from biosorbents. Gong et al. [12] desorbed lead from *S. pastorianus* at a ratio of 0.015 L g\(^{-1}\). Chu et al. [8] recovered cadmium from *Cladophora fascicularis* at a ratio of 0.01 L g\(^{-1}\) and Aldor et al. [5] from *Sargassum fluitans* at a ratio of 0.5 L g\(^{-1}\). Deng et al. [13] eluted lead from *Sargassum polycystum* at a ratio of 0.5 L g\(^{-1}\) but Diniz and Volesky [14] eluted lanthanum, europium and ytterbium from *Sargassum polycystum* at a solid to liquid ratio ranging from 0.5 to 8 L g\(^{-1}\). Small volumes of eluting agents would enable high metal concentrations and economic metal recovery.

In this study the use of H\(_2\)SO\(_4\), HNO\(_3\) and EDTA as desorbing agents caused a dramatic loss in the ability of *S. pastorianus* to remove cadmium from the solution in the next sorption cycle (Fig. 1). The biosorption effectiveness of this biomass after the earlier use of HCl

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**Table 4.** The lead desorption efficiency of 10 mL of various eluents (liquid to solid ratio of 0.02 L g\(^{-1}\)).

| Eluent | Eluent concentration [mol L\(^{-1}\)] | S. pastorianus Lead recovery [%] | S. cerevisiae | Waste yeast |
|--------|-------------------------------------|---------------------------------|--------------|------------|
|        |                                     |                                |              |            |
| Water  | 0                                   | 2                              | 1            | 1          |
| EDTA   | 0.05                                | 81                             | 62           | 46         |
|        | 0.125                               | 87                             | 67           | 54         |
|        | 0.25                                | 85                             | 65           | 47         |
| HCl    | 0.05                                | 51                             | 48           | 50         |
|        | 0.1                                 | 50                             | 43           | 50         |
|        | 0.5                                 | 37                             | 34           | 43         |
| H\(_2\)SO\(_4\) | 0.05 | 9                              | 6            | 8          |
|        | 0.1                                 | 10                             | 4            | 5          |
|        | 0.5                                 | 4                              | 3            | 3          |
| HNO\(_3\) | 0.05 | 42                             | 55           | 44         |
|        | 0.1                                 | 58                             | 76           | 45         |
|        | 0.5                                 | 49                             | 72           | 41         |
| Na\(_2\)SO\(_4\) | 0.05 | 18                             | 14           | 2          |
|        | 0.1                                 | 18                             | 14           | 2          |
|        | 0.5                                 | 15                             | 14           | 2          |
| Na\(_2\)CO\(_3\) | 0.05 | 9                              | 12           | 21         |
|        | 0.1                                 | 8                              | 17           | 21         |
|        | 0.5                                 | 17                             | 36           | 28         |
| NaOH   | 0.05                                | 10                             | 2            | 13         |
|        | 0.1                                 | 18                             | 11           | 18         |
|        | 0.5                                 | 15                             | 8            | 15         |
for metal recovery also decreased. These desorbents were destructive to biomass and did not allow the effective application of yeast in the next biosorption process. Therefore neither mineral acids nor EDTA seem to be appropriate desorbents, despite exhibiting good desorption efficiency. In turn, NaOH was inefficient as a desorbing agent, but significantly increased the yeast sorption capacity in subsequent biosorption.

The reduction of cadmium uptake in the second cycle of adsorption can result from the destruction of binding sites on the surface of biomass or the alteration of the configuration of binding sites by mineral acids or EDTA. It can be hypothesized that EDTA could form highly stable complexes with binding site elements. Substantial inhibition of cadmium uptake by biomass after desorption with EDTA or mineral acids has been noted earlier by Chu et al. [8]. In contrast, in the study conducted by Aldor et al. [5] HCl (0.1 mol L⁻¹ and 1 mol L⁻¹) was found to be the most effective eluent of cadmium from Sargassum fluitans, which did not cause the deterioration of biosorbent.

4. Conclusions

The efficiency of particular eluents in cadmium and lead desorption from different biomass varied significantly. This confirms that the eluent has to be selected for the

| Table 5. The lead desorption efficiency of 5 mL of various eluents (liquid to solid ratio of 0.01 L g⁻¹). |
|---------------------------------------------------------------|
| **Eluent** | **Eluent concentration** | **Lead recovery [%]** | **S. pastorianus** | **S. cerevisiae** | **Waste yeast** |
|-----------|--------------------------|------------------------|------------------|----------------|----------------|
| Water     | 0                        | 1                      | 1                | 1              |
| EDTA      | 0.05                     | 42                     | 50               | 32             |
|           | 0.125                    | 70                     | 58               | 41             |
|           | 0.25                     | 49                     | 52               | 38             |
| HCl       | 0.05                     | 46                     | 42               | 24             |
|           | 0.1                      | 47                     | 43               | 41             |
|           | 0.5                      | 36                     | 44               | 48             |
| H₂SO₄     | 0.05                     | 9                      | 3                | 5              |
|           | 0.1                      | 5                      | 2                | 3              |
|           | 0.5                      | 2                      | 2                | 2              |
| HNO₃      | 0.05                     | 34                     | 44               | 29             |
|           | 0.1                      | 47                     | 61               | 34             |
|           | 0.5                      | 38                     | 59               | 32             |
| Na₂SO₄    | 0.05                     | 13                     | 1                | 1              |
|           | 0.1                      | 18                     | 1                | 1              |
|           | 0.5                      | 15                     | 1                | 2              |
| Na₂CO₃    | 0.05                     | 10                     | 2                | 12             |
|           | 0.1                      | 5                      | 4                | 13             |
|           | 0.5                      | 13                     | 10               | 15             |
| NaOH      | 0.05                     | 9                      | 2                | 17             |
|           | 0.1                      | 21                     | 4                | 23             |
|           | 0.5                      | 9                      | 4                | 17             |

Figure 1. The efficiency of cadmium removal by *S. pastorianus* in the second biosorption process after previous desorption with 10 mL of various eluents (presented values are the mean of three replicates with standard deviation).
particular biosorbent. EDTA, HNO₃, and HCl were the most effective in remobilizing the biomass-bound lead. EDTA was able to elute more than 85% of the sorbed lead from *S. pastorianus*. The application of EDTA and mineral acids accomplish the highest cadmium recovery from *Saccharomyces* biomass. However, these desorbents damaged the binding sites of *S. pastorianus* enough to seriously impair cadmium uptake in the subsequent biosorption cycle. Therefore neither mineral acids nor EDTA seem to be appropriate desorbents.

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