Marine Macroalgae as Biosorbents for Cadmium and Nickel in Water

Raize Ofer, Argaman Yerachmiel, Yannai Shmuel

ABSTRACT: Experimental studies showed that brown marine algae, Sargassum vulgaris and Padina pavonia, can be used to develop an efficient biosorbent for heavy metal removal from aqueous solutions. Sargassum vulgaris exhibited high uptake capacities for cadmium (0.9 to 1.1 mmol Cd/gr) and nickel (0.85 to 1 mmol Ni/gr) that are higher than those of other types of biomass and powdered activated carbon, while P. pavonia showed a broader range of nickel and cadmium uptake capacities (0.7 to 1 mmol Ni/gr and 0.8 to 1.1 mmol Cd/gr). The metal adsorption and desorption processes were rapid, with 70% of the sorption and desorption completed within 10 minutes. The equilibrium data for both algae fit well to Langmuir and Freundlich isotherm models. More than 90% desorption of adsorbed metals from the algae was achieved by hydrochloric acid and ethylenediaminetetraacetic acid (1:1 molar ratio). After eight to nine adsorption and desorption cycles, S. vulgaris showed a 15 to 35% decrease in metal uptake capacities; P. pavonia showed a higher decrease of 50 to 60%. Water Environ. Res., 75, 246 (2003).

KEYWORDS: biosorption, brown marine macroalgae, heavy metal removal, aqueous solutions, Padina pavonia, Sargassum vulgaris.

Introduction

The contamination of water by toxic heavy metal ions is a worldwide environmental problem. Precipitation, filtration, ion exchange, membrane separation, and other techniques usually achieve removal of heavy metals. However, in many situations these processes do not work efficiently or fail to lower the metal concentration below the regulatory standards. Heavy metal precipitation produces intractable sludge that must then be treated and disposed, often at a high cost. In addition, many metal-bearing waste streams contain substances such as organic matter, alkaline earth metals, and others that may decrease the removal capability of the metal cations (Brauckmann, 1990; Eilbeck and Mattock, 1987).

Biosorption of heavy metals from aqueous solutions is a relatively new wastewater treatment technology (Volesky, 1990). Adsorbent materials (biosorbents) that are derived from a suitable biomass can be used for the effective removal and recovery of heavy metal ions from wastewater streams. Biosorption of metals involves several mechanisms that differ qualitatively and quantitatively according to the species used and the origin of the biomass and its processing procedure. Metal sequestration during biosorption follows complex mechanisms, primarily ion exchange, chelation, adsorption by physical forces, and ion entrapment in intra intermicroplas and spaces of the structural polysaccharide network. The following chemical groups could attract and sequester the metals in biomass: acetamido, amino, amido, sulfhydryl, sulfate, and carboxyl (Ashkenazy et al., 1997; Crist et al., 1994; Figueira et al., 1999; Holan and Volesky, 1993, 1994, 1995). The biological materials that have been investigated for heavy metal uptake include fungi, bacteria, yeasts, algae, and others (Flemming et al., 1990; Holan and Volesky, 1994, 1995; Kuyucak and Volesky, 1990; Yang and Volesky 1999). In general, uptake capacities of the heavy metal cations varied significantly for different types of biomass. For divalent heavy metal cations, the reported values for bacterial biomass typically ranged from 0.05 to 0.2 mmol/gr; for fungi and yeasts, 0.2 to 0.5 mmol/gr; for freshwater algae, 0.5 to 1 mmol/gr; and for marine algae, 1 to 1.5 mmol/gr. Among these biomass, the metal cation capacities of a few species of marine macroalgae, commonly known as brown algae, were much higher than those of other types of biomass. They were also much higher than those of activated carbon and natural zeolite, and were comparable to those of some synthetic ion-exchange resins. Brown algae contain high concentrations of sulfated polysaccharides and alginic acid. It has been postulated that the function of these polysaccharides, which are absent in terrestrial plants, is to enable marine algae to selectively adsorb metal ions such as potassium and calcium in a saline medium through ion exchange (Figueira et al., 1999; Holan and Volesky, 1994; Lewin, 1962; Percival and McDowell, 1967; Stewart, 1974). These observations imply that metal uptake by nonliving marine algae is essentially an easily reversible physicochemical process because metal ions are deposited on the surface of the marine algae cell wall (Chu et al., 1997). Mineral acids such as hydrochloric acid and chelating agents (e.g., ethylenediaminetetraacetic acid [EDTA]) can be used for recycling the metals adsorbed by the brown algae (Chu et al., 1997; Holan and Volesky, 1993). The metal release is based on ion exchange and competition on the algal cell wall binding sites between metals and hydrogen ions (hydrochloric acid) or a better ligand–metal affinity constant (EDTA) (Crist et al., 1994).

Biomass of brown marine macroalgae is a biological resource that is available in large quantities and can form a good base for the development of biosorbent material. Studies by Chu et al. (1997), Fourest and Volesky (1996), and Holan and Volesky (1993) have focused on the use of this biomass for heavy metal removal from water and wastewater. In the present study, the potential for removing cadmium and nickel from water and wastewater by nonliving brown marine macroalgae, Sargassum vulgaris and Padina pavonia, in their natural form was investigated. Among the relevant heavy metals, cadmium is considered to be one of the more easily removed metals from waste streams, primarily because of its ability to form stable complexes with different ligands. The nickel complexes are much less stable and, hence, nickel is considered to be one of the least removable heavy metals. According to the “hard–soft–acid–base” theory, cadmium is a soft metal that tends to form stable complexes with different ligands by covalent and ionic bonding, while nickel is an “intermediate”
metal that forms less stable complexes, mostly by weaker ionic bonding (Forstner and Wittman, 1981; Schiewer and Volesky, 2000). The difference in stability between cadmium and nickel complexes is also apparent in the Irving–Williams series, where cadmium appears before nickel indicating that cadmium complexes are more stable, according to the crystal field theory (Forstner and Wittman, 1981).

Materials and Methods

**Biomass.** Fresh samples of brown marine macroalgae, *S. vulgaris* and *P. pavonia*, were collected from rocky seashores situated near Haifa, Israel; the first macroalgae is more abundant in the winter season and the second is more abundant in the summer. The macroalgae samples were rinsed with distilled water to remove external salts and sand and then with acetone solution. By doing so, more metal sites become active because of structural changes in the cell wall. In addition, the acetone treatment also removes most of the water originally present in the biomass, which renders it resistant to microbial spoilage. The algal samples after washing were roughly chopped and dried to constant weight. All experiments were performed using duplicate samples.

**Chemicals and Instruments Used.** Analytical grade reagents were used in all experiments. Stock single and multimetal solutions (1000 mg/L) were prepared by dissolving metal salts (cadmium chloride [CdCl2·6H2O], nickel chloride [NiCl2·6H2O], cupric sulfate [CuSO4·5H2O], zinc chloride [ZnCl2], lead chloride [PbCl2], calcium chloride [CaCl2·2H2O], and magnesium chloride [MgCl2·6H2O], Merck, Darmstadt, Germany) in acidic distilled water. All working solutions were prepared by diluting these stock solutions with distilled water, municipal wastewater (after primary settling), or “substitute” wastewater (according to ASTM, 1999), and adjusting the pH value of the solutions between 5 and 7 (if needed). Ethylenediaminetetraacetic acid and hydrochloric acid solutions were used in the desorption stage. Ni2+, Cd2+, Cu2+, Pb2+, Zn2+, and Mg2+ concentrations in the relevant samples were determined simultaneously by an inductively coupled plasma atomic emission spectrophotometer (SpectrAA-300+, Varian ABS, Tempe, Arizona).

**Metal Uptake Calculation.** The algal biomass metal cation uptake capacities after different experiments were calculated from the relevant metal cation concentration in the algal samples after total digestion with boiling concentrated nitric acid, according to the following equation:

\[ q = \frac{C_i - C_e}{V} \]

or, from the relevant metallic cation concentration in the solution as follows:

\[ q = \frac{V(C_i - C_f)}{S} \]

where all variables are defined as in the section on Nomenclature.

**Batch Biosorption Tests.** Dry *S. vulgaris* and *P. pavonia* biomass portions of 0.1 gr (dry weight) were thoroughly mixed with 50 mL of metal solutions. The suspensions were stirred with magnetic bars for 1 hour at room temperature using seven 125-mL Erlenmeyer flasks for each biomass. The time intervals for sampling were 10, 20, 30, 40, 50, 60, and 120 minutes. After each time interval, the algal biomass in one of the flasks was taken for Cd2+ and Ni2+ analysis as previously described.

**Kinetic Biosorption Studies.** Dry *S. vulgaris* and *P. pavonia* biomass portions of 0.1 gr (dry weight) were thoroughly mixed with 50 mL of cadmium or nickel solutions. The suspensions were stirred with magnetic bars for 1 hour at room temperature using seven 125-mL Erlenmeyer flasks for each biomass. The time intervals for sampling were 15, and 20 minutes. After each time interval, the algal biomass in one of the flasks was taken for Cd2+ and Ni2+ analysis as previously described.

**Batch Desorption Tests.** Nickel- or cadmium-saturated *S. vulgaris* and *P. pavonia* biomass portions of 0.1 gr (dry weight) were washed repeatedly with deionized water to remove any residual unbounded cadmium and nickel solutions. Each biomass portion was placed in a 125-mL Erlenmeyer flask and thoroughly mixed with 50 mL of hydrochloric acid (0.1 M) or 50 mL of EDTA (0.01 M). At the completion of the test, the algal biomass in each flask was taken for analysis as previously described.

**Kinetic Desorption Studies.** Cadmium- and nickel-saturated *S. vulgaris* and *P. pavonia* biomass portions of 0.1 gr (dry weight) were thoroughly mixed with 50 mL of 0.1 M hydrochloric acid or 0.01 M EDTA. The suspensions were stirred with magnetic bars at room temperature using five 125-mL Erlenmeyer flasks for each alga and each acid. The time intervals for sampling were at 0, 5, 10, 15, and 20 minutes. After each time interval, the algal biomass in one of the flasks was taken for Cd2+ and Ni2+ analysis as previously described.

**Desorption–Remobilization Cycles.** The biosorption and desorption procedures previously described were repeated 8 to 9 times using the same biomass (for assessing the effect of desorption on the ability of the algal biomass to readorb cadmium and nickel). Following each desorption of the biomass with either hydrochloric acid or EDTA, the biomass was washed with distilled deionized water, dried to a constant weight, and reloaded with cadmium or nickel.

**Metal Desorbent Ratio.** The desorption procedures previously described were repeated with different concentrations of desorbers (hydrochloric acid and EDTA). The molar ratios of the adsorbed metals to desorbent agents were approximately 1:4, 1:2, 1:1, and 4:1 for hydrochloric acid and 6:1, 4:1, 2:1, and 1:1 for EDTA solutions. The metal molar quantity was calculated from the biomass weight (grains) and metallic cation uptake capacity (millimoles per grain of biomass). The molar quantities of the desorbents were calculated from their volumes and concentrations.

**Adsorption Isotherms.** Langmuir and Freundlich sorption models were adopted to describe the adsorption isotherms (see Nomenclature section for definition of variables).

Langmuir sorption isotherm equation:

\[ q = q_{max} \frac{bC_f}{1 + bC_f} \]

Freundlich sorption isotherm equation:

\[ q = kC_f^{1/n_f} \]
calculated by nonlinear regression using GraphPad Prism 3 software (GraphPad Software, Inc., San Diego, California); the nonlinear regression was calculated by the Levenberg–Marquardt method.

Results and Discussion

Biosorption Kinetics. The kinetic profiles of nickel and cadmium adsorption by *S. vulgaris* and *P. pavonia* biomass are shown in Figure 1. The uptake capacity of the metal cations was relatively fast. The systems attained the final equilibrium plateau corresponding to 100% of the total uptake capacity of the metal cations within 30 minutes of contact. The system reached more than 70 to 80% of the total biomass metal uptake capacity within 10 minutes of contact. This rapid kinetics has significant practical importance because it may facilitate using smaller reactor volumes, thus ensuring efficiency and economy. The rapid kinetics suggests that the biosorption of metal cations is mostly a surface process in which the metal cation is bound to chemically active groups in the algal cell wall surface (amino, amido, sulfhydryl, sulfate, and carboxyl groups) (Arriff et al., 1999; Waihung et al., 1999; Yang and Volesky, 1999). Similar rapid metal uptake has been reported for lead uptake by *Ecklonia radiata* biomass (Matheickal and Yu, 1996) and cobalt uptake by a dead biomass of *Ascophyllum nodosum* (Kuyucak and Volesky, 1990).

Metal Uptake Capacities. The cadmium and nickel uptake capacities of *S. vulgaris* and *P. pavonia* after a series of tests are shown in Table 1. Both algae showed similar ranges for cadmium and nickel uptake capacities after adsorption tests from different solutions (municipal wastewater and aqueous solutions). The fact that the algal biosorbents exhibit similar uptake capacities from different solutions may indicate that they are less affected by the presence of organic matter and suspended solids in the solution (wastewater and “substitute wastewater”) than ion-exchange resins or membrane processes (DeSilva and Gottlieb, 1996; Kratochvil and Volesky, 1998). The tests were carried out with winter and summer algal samples. The *Sargassum* cadmium and nickel uptake capacities ranged from 100 to 130 and from 40 to 60 mg/gr dry algal biomass, respectively. The *Padina* cadmium and nickel uptake capacities ranged from 80 to 125 mg/gr and 35 to 60 mg/gr, respectively. In the case of *Sargassum*, there was no significant change in the metal cation uptake capacities in different seasons. In the case of *Padina*, the metal cation uptake capacities of the summer algal samples were 10 to 20% higher than those of the winter samples. A possible explanation for this observation is seasonal changes in the chemical composition of the algal cells (Lewin, 1962; Stewart, 1974), which may increase the number of metal cation binding sites on the cell wall. In metal biosorption, one of the basic conditions for finding a good and competitive biosorbent (to conventional metal removal process) is metal uptake capacity of approximately 1 mmol metal/gr dry biomass or 100 mg/gr dry biomass (Schiewer and Volesky, 2000). The cadmium and nickel uptake capacities of *S. vulgaris* and *P. pavonia* (Table 1) are similar to this value (although *P. pavonia* showed somewhat smaller cadmium and nickel uptake capacities than those of *S. vulgaris*). Matheickal et al. (1999) reported on cadmium uptake capacities of different adsorbents like fungi, yeast, bacteria, brown algae, ion-exchange resin, and granular activated carbon. The reported values were lower than *S. vulgaris* and *P. pavonia* cadmium uptake capacities except for *Durvillaea potatorum*, which showed similar values (*D. potatorum*, *S. vulgaris*, and *P. pavonia* are brown algae).

Desorption Kinetics. Desorption kinetics of nickel and cadmium from laden *S. vulgaris* and *P. pavonia* biomass by 0.03 M hydrochloric acid and 0.01 M EDTA are shown in Figure 2. Metal desorption was relatively fast. The systems reached approximately 80 to 90% of the total metal release within 5 minutes of contact and total release after 20 minutes of contact. The rapid and efficient desorption has significant practical importance as it will shorten the regeneration stage in continuous-flow systems, ensuring high efficiency and economy. No significant differences in desorption efficiency between hydrochloric acid and EDTA for any of the metals were observed with the two algal biomasses used.

Metal Desorbent Ratio. The desorption efficiency of nickel and cadmium from laden *S. vulgaris* and *P. pavonia* biomasses by hydrochloric acid and EDTA are shown in Figure 3. Metal desorption is presented as a function of the metal–biosorbent molar ratio. For an economically feasible biosorption process, this ratio must be as low as possible because, in this case, the desorbent volumes and concentrations for biomass regeneration should be minimal and the treated/regenerated volumes ratio should be maximal. Figure 3 shows that for a 1:1 metal/desorbent molar ratio, the nickel and cadmium desorption efficiencies were 95 to 100%

![Figure 1—Cadmium and nickel biosorption kinetics by *S. vulgaris* and *P. pavonia.*](image)

<table>
<thead>
<tr>
<th>Solutions</th>
<th>Sargassum vulgaris Cadmium uptake (mg/gr dry alga)</th>
<th>Sargassum vulgaris Nickel uptake (mg/gr dry alga)</th>
<th>Padina pavonia Cadmium uptake (mg/gr dry alga)</th>
<th>Padina pavonia Nickel uptake (mg/gr dry alga)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aqueous solutions</td>
<td>100–130</td>
<td>50–60</td>
<td>80–120</td>
<td>40–60</td>
</tr>
<tr>
<td>Substitute wastewater</td>
<td>120–130</td>
<td>50–60</td>
<td>120–125</td>
<td>50–60</td>
</tr>
<tr>
<td>Municipal wastewater</td>
<td>110</td>
<td>55</td>
<td>80</td>
<td>45</td>
</tr>
</tbody>
</table>
and 80% for EDTA and hydrochloric acid, respectively. A desorption efficiency of 100% with HCl was achieved with hydrochloric acid and a 1:4 metal/desorbent molar ratio. Zhao et al. (1999) reported a zinc desorption efficiency of 97 and 86% from *Azolla filiculoides* by using a 1:3 metal/sulfuric acid molar ratio and a 1:3 metal/hydrochloric acid molar ratio (pH 1).

**Biosorption–Desorption Cycles.** Eight to nine consecutive cadmium and nickel adsorption–desorption cycles were conducted under conditions of maximal desorption. Figures 4 and 5 show the results obtained using hydrochloric acid (pH 1) and 10 mM EDTA as the desorbents. In the case of *Sargassum*, Figure 4 shows a more moderate decrease of 30 to 35% in cadmium uptake after the third cycle and a 15 to 20% decrease in nickel uptake after the third to fourth cycle. In the case of *Padina*, Figure 5 clearly shows a sharp decrease.
The decrease of 50 to 60% in cadmium and nickel uptake after the first cycle for hydrochloric acid and after the second or third cycle for EDTA. In all cases, after initially decreasing, the cation uptake capacities stayed constant until the last cycle. These capacities were approximately 90 mg Cd/gr and 45 mg Ni/gr for dry Sargassum and 45 mg Cd/gr and 15 mg Ni/gr for dry Padina.

The Sargassum cadmium and nickel uptake capacities after the reduction are still higher than those of other biomass capacities, as shown in Table 2, and close to the values that were estimated as a good base for effective biomass (Schiewer and Volesky, 2000). The gradual reduction of the metal cation uptake capacities (mostly for cadmium) after the first adsorption–desorption cycles probably indicates chemical or physical changes in the metal cation binding sites on the biomass cell surfaces. These sites on the biomass cell surfaces were either destroyed or morphologically altered by the desorbents. Concentrated hydrochloric acid can rupture the structure of alginate chains and destroy hydrogen bonds (Percival and McDowell, 1967). Alginate in the cell wall of brown algae like S. vulgaris and P. pavonia plays an important role in the uptake of metal cations. Strong chelating agents like EDTA can alter the configuration of the binding sites. Consequently, repeated exposure of Sargassum and Padina biomass to these agents could lead to a reduction in metal cation uptake capacities. The possibility of cell wall damage is supported by the observation of organic matter (measured by chemical oxygen demand assay) in the solution after the desorption stages (with hydrochloric acid). In all cases, after the initial decrease the cation uptake capacities stayed fairly constant until the last cycle. This indicates that, for each alga, there is a limit to the magnitude of the decrease in adsorption efficiency that can be elicited by the desorbents employed. This observation suggests that Sargassum, which showed a moderate decrease, can be used as an efficient biosorbent in many adsorption–desorption cycles. The results shown in Figures 4 and 5 suggest that both hydrochloric acid and EDTA were effective in stripping the adsorbed cadmium and nickel from the biomass. These metal cation uptakes by S. vulgaris and P. pavonia probably represent a readily reversible process with no significant accumulation of irreversibly bound cadmium or nickel in the biomass. However, repeated exposure of the biomass to both desorbents resulted in a cadmium and nickel uptake capacity decrease. The decrease in both metals uptake is higher for Padina, probably because of a different cell wall structure. For Sargassum, the decrease in the cadmium uptake capacity was higher than that of the nickel decrease. This possibly is due to different adsorption mechanisms (further investigated in the next steps of the research) and metal properties like ionic potential and ionic radius (Wang et al., 1999).

It is interesting to compare the results reported here with related studies. Kuyucak and Volesky (1990) conducted three batch adsorption–desorption cycles using sulfuric acid at pH 5.2 and hydrochloric acid at pH 2.7 for desorbing cobalt from the brown alga. Ascophyllum nodosum biomass. They reported a cobalt uptake capacity and a biomass weight decrease of 37 and 42%, respectively. Chu et al. (1997) conducted five batch adsorption–desorption cycles using hydrochloric acid at pH 2 and 3.24 mM EDTA for desorbing cadmium from the brown marine alga Sargassum bacculata. They reported a cadmium uptake capacity and a biomass weight decrease of 56 and 30%, respectively, for hydrochloric acid and 40 and 16%, respectively, for EDTA. These observations are in good agreement with the results reported here for P. pavonia. In the case of S. vulgaris, the cadmium and nickel uptake capacity decrease reported here was lower than the values mentioned earlier in related studies, despite the use of a higher desorbent concentration.

**Adsorption Isotherms.** The nickel and cadmium uptake
capacities of *P. pavonia* and *S. vulgaris* were evaluated by plotting the biosorption isotherms, and the data were analyzed by nonlinear regression according to eqs 3 and 4. The plotting and analysis were performed using scientific software (GraphPad Prism 3, GraphPad Software, Inc.).

The initial metal concentrations in the contact solutions ranged from 100 to 1000 mg/L. The initial and final pH were between 5 and 7; the solution pH was not controlled during the experiment. The correlation coefficients ($R^2$) of the isotherms were higher than 0.91 except for cadmium adsorption to *Padina*, which was 0.74 to 0.76 (Table 3).

The adsorption isotherms followed the typical Langmuir and Freundlich adsorption pattern, as shown by the nonlinear regressions (Figures 6 and 7). The isotherm parameters are shown in Table 3. The parameters $q_{\text{max}}$ and $K_t$ can serve as indicators for the maximal metal cation uptake capacity of the algal biomass. The parameters $b$ and $n_f$ can reflect the affinity of the sorbent for the solute (Holan and Volesky, 1993). Based on these parameter definitions, *Sargassum* possesses higher potential as a biosorbent for nickel and cadmium. *Sargassum* also showed higher $q_{\text{max}}$ values than the reported biomasses for different sorbents and similar values observed with other brown algae (Table 2). Although *Padina* showed lower sorption capacities than *Sargassum*, the sorption capacities for *Padina* were higher than most of the reported sorbents in Table 2.

### Conclusions

Nickel and cadmium uptake by *S. vulgaris* and *P. pavonia* biomass is relatively fast in that total metal uptake was achieved within 30 minutes of contact. Hydrochloric acid and EDTA were found to be effective in stripping adsorbed nickel and cadmium from *S. vulgaris* and *P. pavonia* biomass. The desorption stage was fast and most of the metal was released from the biomass after 10 minutes. A molar metal/desorbent ratio of 1:1 was found to be sufficient for successful desorption. Both desorbents damaged the binding site, and the metal cation uptake capacities were reduced

### Table 3—Langmuir and Freundlich isotherm parameters (the values given represent the means ± standard deviation values for each).

<table>
<thead>
<tr>
<th>Alga</th>
<th>Metal</th>
<th>$q_{\text{max}}$ (mg/gr)</th>
<th>$b$ (mg/L)</th>
<th>$R^2$</th>
<th>$K_f$</th>
<th>$n_f$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sargassum</td>
<td>Cd</td>
<td>134.9 ± 10.1</td>
<td>0.018 ± 0.005</td>
<td>0.97</td>
<td>14.5 ± 5.18</td>
<td>2.96 ± 0.533</td>
<td>0.923</td>
</tr>
<tr>
<td></td>
<td>Ni</td>
<td>62.6 ± 3.87</td>
<td>0.023 ± 0.005</td>
<td>0.96</td>
<td>9.89 ± 1.5</td>
<td>3.516 ± 0.33</td>
<td>0.972</td>
</tr>
<tr>
<td>Padina</td>
<td>Cd</td>
<td>87.6 ± 16.1</td>
<td>0.033 ± 0.02</td>
<td>0.74</td>
<td>18.35 ± 6.9</td>
<td>4.156 ± 1.22</td>
<td>0.76</td>
</tr>
<tr>
<td></td>
<td>Ni</td>
<td>34.4 ± 1.65</td>
<td>0.0625 ± 0.013</td>
<td>0.967</td>
<td>8.68 ± 1.9</td>
<td>4.5 ± 0.8</td>
<td>0.912</td>
</tr>
</tbody>
</table>

![Figure 6—Langmuir isotherms for *Sargassum* (top) and *Padina* (bottom) at 23 °C, pH 5 to 6.5.](image)

![Figure 7—Freundlich isotherms for *Sargassum* (top) and *Padina* (bottom) at 23 °C, pH 5 to 6.5.](image)
50 to 60% and 15 to 35% for \textit{P. pavonia} and \textit{S. vulgaris} biomass, respectively. The adsorption isotherms followed the typical Langmuir and Freundlich sorption models.

\textbf{Nomenclature}

- \( q \) = metal cation uptake capacity (mg metal/gr dry alga)
- \( C_{fa} \) = metal cation concentration in completely digested metal-laden algal sample (mg/L)
- \( C_{fa} \) = metal cation concentration in completely digested raw algal sample (mg/L)
- \( S \) = dry weight of algal sample (gr)
- \( V_{d} \) = digested algal sample volume (mL)
- \( C_f \) = final metal cation concentration in the solution, after the adsorption test (mg/L)
- \( C_i \) = initial metal cation concentration in the solution, before the adsorption test (mg/L)
- \( V \) = solution volume (mL)
- \( q_{\text{max}} \) = Langmuir maximum metal uptake capacity (mg/gr)
- \( b \) = Langmuir adsorption affinity constant (mg/L)
- \( K_f \) = Freundlich maximum metal uptake capacity
- \( n_f \) = Freundlich adsorption affinity constant

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Authors. Ofer Raize is a Ph.D. candidate and Yerachmiel Argaman is a professor and the Millstone/St. Louis Chair in Environmental Engineering with the Faculty of Civil Engineering, Technion-Israel Institute of Technology, Haifa, Israel. Yannai Shmuel is a professor with the Faculty of Food Engineering and Biotechnology, Technion-Israel Institute of Technology. Correspondence should be addressed to Ofer Raize, Environmental and Water Resources Engineering, Department of Civil Engineering, Technion-Israel Institute of Technology, Technion City, Haifa 32000, Israel; e-mail: raiz@tx.technion.ac.il.

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