Research Article: Experimental results confirmed the possibility of continuous waste-water treatment for 22 h: any of the heavy metal ions or metalloid in the treated water exceeded 0.25 times of their original influent concentration. The presented treatment is cheap, environmental friendly, regenerable and shows high affinity towards variety of metal ions.

Development of Bench-Scale Bio-Packed Column for Wastewater Treatment from Optical Emission Spectrometry

K. Vijayaraghavan* and E. Segovia

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Development of Bench-Scale Bio-Packed Column for Wastewater Treatment from Optical Emission Spectrometry

An eco-friendly and inexpensive technique for wastewater treatment originated from inductively coupled plasma-optical emission spectrometry (ICP-OES) is presented within this paper. The proposed process comprised of loading waste crab shells in packed column for adsorption of heavy metal ions, followed by desorption using 0.01 M HCl. An exhaustive physical and chemical characterization of ICP-OES wastewater revealed the complex nature of effluent, including the presence of 15 different metals and metalloid under strong acidic condition (pH 1.3). Based on the preliminary batch experiments, it was identified that solution pH played a major role in metal sequestration by crab shell with pH 3.5 identified as optimum pH. Rapid metal biosorption kinetics along with complete desorption and subsequent reuse for three cycles was possible with crab shell-based treatment process. Continuous flow-through column experiments confirmed the high performance of crab shell towards multiple metal ions with the column able to operate for 22 h at a flow rate of 10 mL/min before outlet concentration of arsenic reached 0.25 times of its inlet concentration. Other metal ions such as Cu, Cd, Co, Cr, Pb, Ni, Zn, Mn, Al, and Fe were only in trace levels in the treated water until 22 h. The performance of the treatment process was compared with trade effluent discharge standards, and the process flow diagram along with cost analysis was suggested.

Keywords: Bioremediation; Biosorption; Heavy metals; Microprecipitation; Waste utilization

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emanating from inductively coupled plasma-optical emission spectrometry (ICP-OES). Previous publications identified that crab shell possess superior biosorption capacity towards variety of metal ions [11–14]; however, the efficiency of crab shell to decontaminate real wastewaters is relatively unknown. On the other hand, the wastes from ICP-OES have not given attention by research laboratories owing to their complex solution chemistry as well as irregular metal type/concentration. Treatment processes will also be affected owing to high acidic nature of ICP-OES effluent. As a result, it is very common for research laboratories to send the wastewater directly to waste collectors, who decide the treatment scheme. In an effort to minimize this point-source pollution, the research laboratories can design their own treatment scheme for the laboratory wastes. Since the metal concentration usually lies in the range of microgram to lower milligram levels and there is no requirement of metal specific removal, biosorption can be a good strategy [1] for remediation of ICP-OES effluent. Through this research, efforts will be made to develop an in-house treatment scheme based on crab shell biosorption for treatment of ICP-OES wastewater.

2 Experimental section

2.1 Materials and effluent collection

The effluent generated by ICP-OES (Perkin Elmer Optima 3000 DV), located in Temasek Laboratories (level 7) of National University of Singapore, Singapore was collected from January to March 2011. The waste collected every week was collected in plastic containers and stored in cold room (4°C). After the collection period, the composite samples were analyzed for pH, conductivity, total dissolved solids (TDS), light metal, heavy metal and metalloid concentrations. Conductivity, TDS and pH were measured using handheld multi-parameter instrument (YSI 556MPS). In the case of analysis of metals and metalloid, the samples were first filtered through a 0.45-μm PTFE membrane filter. The filtrate was analyzed using inductively coupled plasma-optical emission spectrometry (ICP-OES, Perkin Elmer Optima 3000 DV, Perkin Elmer, USA).

Shells of crab (Portunus sanguinolentus) were collected from markets in Chennai, India. Initially, the shells were washed extensively with tap water to remove the flesh and other impurities. The cleaned shells were dried in oven at 60°C overnight and crushed subsequently to yield particles in the average size of 750 μm. In order to remove excess calcium carbonate, the shell particles were then contacted with 0.1 M HCl at solid–liquid ratio of 10 g/L for 4 h followed by rinsing with deionized (DI) water for several times until the pH of wash water lies above pH 5. The wet shell particles were dried in oven at 60°C overnight and subsequently used for biosorption experiments.

2.2 Batch experimental procedure

Several Erlenmeyer flasks (250 mL) were used to conduct batch experiments. The effluent volume and crab shell dosage were fixed at 100 mL and 2 g/L, respectively. The pH of the effluent was altered, if needed, using 0.1 M HCl or NaOH. During experiments, the flasks comprising effluent and crab shell was agitated in a rotary shaker at 160 rpm and 22 ± 1°C. After 30 min, the content of the flask was filtered through a 0.45-μm PTFE membrane filter. The filtrate was subsequently diluted and analyzed for metal concentration. The following protocols were employed for different experiments.

(1) pH edge experiments: five different equilibrium conditions (pH 1.3–3.5) were employed to study the influence of pH at fixed equilibrium time of 30 min.

(2) Kinetic experiments: At optimum pH of 3.5, experiments were conducted by withdrawing samples at regular time intervals to obtain time profile of residual metal concentration in ICP-OES effluent.

(3) Reuse of crab shell: Crab shell earlier exposed to ICP-OES effluent at pH 3.5 were filtered and washed with deionized water. The metal-loaded crab shell was exposed to 50 mL of 0.01 M HCl or NaOH in Erlenmeyer flasks and agitated for 30 min at 160 rpm and 22 ± 1°C. The remaining analysis procedure was same as stated earlier. After desorption, the metal-free crab shell was reused in next sorption process and the cycle of sorption followed by desorption continued for three times to evaluate the reuse capacity of crab shell.

2.3 Column experimental procedure

For continuous flow-through experiments, a glass column (internal diameter = 2.4 cm and height = 35 cm) was designed with height/internal diameter ratio >10. At the top of column an adjustable plunger was attached to adjust the bed height. Seventy-one grams of crab shell was packed within the column, yielding bed height of 25 cm and packing density of 628 g/L. There was a 5cm layer of glass beads at the bottom of column to distribute the effluent uniformly. The ICP-OES effluent at pH 3.5 was pumped upwards through the column using a peristaltic pump at a flow rate of 0.6 L/h. Column effluent samples were collected at regular time intervals and analyzed as stated in Section 2.2. Once the column was exhausted, desorption process was started using 0.01 M HCl as the influent at flow rate of 0.6 L/h.

The total quantity of metal mass adsorbed in the column (m_{ad}) is calculated from the area above the breakthrough curve (outlet metal concentration vs. time) multiplied by the flow rate. Dividing the metal mass (m_{ad}) by the biosorbent mass (M) leads to the uptake capacity (Q) of the biomass. The total amount of metal ions sent to the column can be calculated from the following equation:

\[ m_{\text{total}} = C_0 F t_e \]

where \( C_0 \) is the inlet metal ion concentration (mg/L); \( F \) is the volumetric flow rate (L/h); and \( t_e \) is the exhaustion time (h).

Total metal removal efficiency (%) with respect to flow volume can be calculated from the ratio of metal mass adsorbed \( (m_{ad}) \) to the total amount of metal ions sent to the column \( (m_{\text{total}}) \) as follows:

\[ \text{Removal efficiency (\%)} = \frac{m_{ad}}{m_{\text{total}}} \times 100 \]

All experiments were done in duplicates and the data presented are the average values of two independent experiments.

3 Results and discussion

3.1 Effluent characterization

The results of ICP-OES wastewater characterization revealed that the effluent had a very low pH value, high conductivity as well as high TDS (Tab. 1). A major requisite for sample preparation for ICP-OES is to acid-digest the samples; hence the wastewater emanating from

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Table 1. Characteristics of the ICP-OES effluent and trade effluent discharge standards

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ICP-OES wastewater</th>
<th>NEA discharge limit [15]</th>
<th>Treated ICP-OES wastewater by crab-loaded column[a]</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>1.30 ± 0.05</td>
<td>6–9</td>
<td>7.4–8.3</td>
</tr>
<tr>
<td>Conductivity (mS/cm)</td>
<td>5.81 ± 0.07</td>
<td></td>
<td>5.58–5.87 (5.75)</td>
</tr>
<tr>
<td>TDS (mg/L)</td>
<td>2650 ± 15</td>
<td></td>
<td>2549–2698 (2645)</td>
</tr>
<tr>
<td>Na (mg/L)</td>
<td>25.62 ± 0.41</td>
<td></td>
<td>&gt;1000 (&gt;1000)</td>
</tr>
<tr>
<td>K (mg/L)</td>
<td>6.31 ± 0.09</td>
<td>200</td>
<td>13.47–53.42 (25.58)</td>
</tr>
<tr>
<td>Ca (mg/L)</td>
<td>3.09 ± 0.17</td>
<td>200</td>
<td>87.5–137.8 (125.1)</td>
</tr>
<tr>
<td>Mg (mg/L)</td>
<td>2.41 ± 0.08</td>
<td>200</td>
<td>19.01–57.64 (28.30)</td>
</tr>
<tr>
<td>Al (mg/L)</td>
<td>4.92 ± 0.23</td>
<td></td>
<td>0.049–0.169 (0.087)</td>
</tr>
<tr>
<td>Fe (mg/L)</td>
<td>7.91 ± 0.12</td>
<td>10.0</td>
<td>0–0.162 (0.032)</td>
</tr>
<tr>
<td>As (mg/L)</td>
<td>2.28 ± 0.28</td>
<td>0.1</td>
<td>0–0.533 (0.183)</td>
</tr>
<tr>
<td>Co (mg/L)</td>
<td>1.02 ± 0.11</td>
<td></td>
<td>0–0.068 (0.009)</td>
</tr>
<tr>
<td>Cd (mg/L)</td>
<td>0.92 ± 0.05</td>
<td>0.1</td>
<td>0–0.031 (0.003)</td>
</tr>
<tr>
<td>Cr (mg/L)</td>
<td>1.29 ± 0.10</td>
<td>1.0</td>
<td>0–0.011 (0.001)</td>
</tr>
<tr>
<td>Cu (mg/L)</td>
<td>1.61 ± 0.09</td>
<td>0.1</td>
<td>0–0.154 (0.067)</td>
</tr>
<tr>
<td>Mn (mg/L)</td>
<td>1.42 ± 0.02</td>
<td>5.0</td>
<td>0–0.123 (0.028)</td>
</tr>
<tr>
<td>Ni (mg/L)</td>
<td>1.18 ± 0.08</td>
<td>1.0</td>
<td>0–0.092 (0.024)</td>
</tr>
<tr>
<td>Pb (mg/L)</td>
<td>1.41 ± 0.19</td>
<td>0.1</td>
<td>0–0.066 (0.006)</td>
</tr>
<tr>
<td>Zn (mg/L)</td>
<td>1.53 ± 0.12</td>
<td>1.0</td>
<td>0–0.111 (0.017)</td>
</tr>
<tr>
<td>Total metals (mg/L)</td>
<td>25.49 ± 0.14</td>
<td>10.0</td>
<td>0.049–1.513 (0.457)</td>
</tr>
</tbody>
</table>

Values in brackets represent average values of parameters during 22 h of column operation.

[a] Data obtained until 22 h of column operation.

ICP-OES is expected to have low pH value. The high conductivity and TDS confirm the elevated presence of dissolved fractions. The magnitudes of these physicochemical parameters observed for the ICP-OES wastewater were very high compared to trade effluent discharge standards (http://app2.nea.gov.sg/news_detail_2005.aspx?news_sid=20081119390733240 [15]). In the next phase of analysis, the presence of metal ions in ICP-OES wastewater was explored by testing the sample for different metal ions using multi-metal standards. The results confirmed the significant presence of different metals (Na, K, Ca, Mg, Al, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, and Zn) and metalloid (As). It is very clear from Tab. 1 that most of the heavy metal ions and metalloid were above effluent discharge standards [15] and need to undergo treatment before disposal.

3.2 Treatment of ICP-OES wastewater in batch mode

Crab shell has been characterized and identified as a potent biosorbent for a variety of heavy metal ions in single solute systems [2]. With this established biosorbent, attempts were now made to develop a treatment scheme for remediation of ICP-OES wastewater. Initially, the influence of pH on the biosorption potential of crab shell towards different ions in ICP-OES wastewater was studied (Fig. 1). Owing to strong acidic nature of effluent, the performance crab shell was mediocre at native pH of 1.3. Once the pH was adjusted to 2, a significant increase in metal removal efficiency was observed. For some metal ions such as Al, Fe, and Pb, crab shell exhibited complete removal at pH 2. Further increase to pH 2.5 resulted in disappearance of Cr and Zn from the effluent. For other metal ions, crab shell exhibited high removal efficiencies at pH 3.5. Experiments with pH > 3.5 were not attempted owing to the formation of ferric hydroxide precipitate [16]. Crab shell mainly comprise of calcium and magnesium carbonates, chitin along with some proteins [11]. The removal mechanism of crab shell is based on microprecipitation of metal ions, followed by adsorption on the surface of crab shell [17]. In solutions, the leached calcium carbonate dissociates into calcium and carbonate ions. The free carbonate ions combine with metal ions to form metal carbonates, which were then settled on the surface of crab shell through chitin [12]. The leaching of calcium ions from the crab shell was also shown in Fig. 1 at different pH conditions. This mechanism of metal removal by crab shell was proven by other researchers through instrumental analysis such as Scanning electron microscopy [18, 19], Energy dispersive X-ray spectroscopy [18, 20], X-ray diffraction [12], and Fourier transform IR spectroscopy [12]. Analyzing the pH edge results (Fig. 1), it can be inferred that optimum pH condition to completely utilize the biosorption potential of crab shell was found to be pH 3.5, and hence it was maintained in all the subsequent experiments.

Next, the metal removal kinetics of crab shell was explored with the understanding that this data will be helpful to determine the residence time of solute in column experiments and scale-up processes [21]. Biosorption kinetics (Fig. 2) was found to be rapid with equilibrium achieved within 2–10 min for all metal ions. Metal ions such as Pb, Al, Fe, and Cd were completely sorbed by crab shell within...
4 min, followed by other metal ions. The kinetics data for Ca and Mg also found interesting as both ions were leached from crab shell and followed a trend exactly opposite to other sorbed metal ions (Fig. 2).

In an attempt to regenerate and reuse crab shell in multiple cycles, metal-loaded crab shell was desorbed under mild acidic (0.01 M HCl) and alkaline conditions (0.01 M NaOH). The elutants were selected on the basis of results (Fig. 1) that maximum biosorption occurred at pH 3.5; hence desorption may be obtained under strong acidic or alkaline environments. However, exposure of metal-loaded crab shell to 0.01 M NaOH resulted in poor elution efficiency (less than 34%) and severe damage to crab shell (weight loss >25%). This result is expected as alkaline conditions remove the bulk of protein from crab shell [22]. In contrary, 0.01 M HCl was found to be biosorbent friendly with no significant weight loss (<5%) and elution efficiencies >99% for all metal ions. To further investigate the reuse efficiency, crab shell was tested for three subsequent sorption–desorption cycles with 0.01 M HCl as the elutant (Fig. 3). Crab shell performed very well in all three cycles with 0.01 M HCl exhibited elution efficiencies >99%. The decline in biosorption capacity of crab shell was insignificant over three cycles with extent of reduction not exceeded 5% at the end of third cycle. Thus, the batch preliminary study confirms the superior biosorption, fast kinetics and reusability potential of crab shell in remediation of ICP-OES wastewater.

### 3.3 Treatment of ICP-OES wastewater in column mode

Next, the potential of crab shell to continuously cleanup ICP-OES wastewater was investigated in a packed column assembly. In process applications, a packed bed column is an effective process for cyclic sorption–desorption. This operating mode efficiently utilizes the biosorber capacity and results in a better quality of the effluent [2, 21]. Important column parameters, including the column retention capacity and % removal during entire column operation are presented in Tab. 2. Since different metal ions of varied regulatory limit were present in the wastewater, stringent limits were imposed for column service time which implies that the column will be stopped for regeneration when any of the outlet metal concentrations exceeded 0.25 times of its initial concentration.

The breakthrough curves emanating from crab shell-loaded column for each metal ion are presented in Fig. 4. Interestingly, crab shell performed very well for all heavy metal ions. For a total column operation of 22 h, the crab shell-loaded column able to retain all

![Figure 2](image1.png)

**Figure 2.** Concentration–time profile during metal removal from ICP wastewater by crab shell (pH 3.5; T = 22 ± 1°C).

![Figure 3](image2.png)

**Figure 3.** Performance of crab shell in three sorption–desorption cycles for the removal of metal ions from ICP wastewater (sorption pH 3.5; T = 22 ± 1°C; elutant = 0.01 M HCl).

### Table 2. Performance of crab shell-loaded packed column during the treatment of ICP wastewater

<table>
<thead>
<tr>
<th></th>
<th>Na</th>
<th>K</th>
<th>Ca</th>
<th>Mg</th>
<th>Al</th>
<th>As</th>
<th>Cd</th>
<th>Co</th>
<th>Cr</th>
<th>Cu</th>
<th>Fe</th>
<th>Mn</th>
<th>Ni</th>
<th>Pb</th>
<th>Zn</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Cf/C0) at 22 h</td>
<td>0.95</td>
<td>1.14</td>
<td>46.2</td>
<td>9.53</td>
<td>0.03</td>
<td>0.25</td>
<td>0.04</td>
<td>0.07</td>
<td>0.01</td>
<td>0.10</td>
<td>0.02</td>
<td>0.09</td>
<td>0.05</td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td>Uptake (mg/g)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Removal efficiency (%)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>97.8</td>
<td>86.0</td>
<td>99.3</td>
<td>99.9</td>
<td>99.9</td>
<td>99.9</td>
<td>99.7</td>
<td></td>
</tr>
<tr>
<td>Elution efficiency (%)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>99.0</td>
<td>99.7</td>
<td>99.9</td>
<td>99.9</td>
<td>99.9</td>
<td>99.9</td>
<td>99.7</td>
<td></td>
</tr>
</tbody>
</table>

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heavy metal ions with the outlet concentration reached only 0.1 times of the inlet concentration. This accounts to 117 bed volumes or 13.2 L of ICP-OES wastewater treated. For heavy metal ions such as Fe, Pb, Cr, and Cd, crab shell exhibited >99% total removal efficiency (Tab. 2). Even though removal efficiency strongly depends on initial solute concentration, it is encouraging to understand that crab shell possesses good biosorption efficiency towards variety of metal ions. Considering the uptake capacity, it can be inferred from Tab. 2 that crab shell exhibited a mediocre metal biosorption capacity per gram of biosorbent. It is important to note that these values represent only the column operation until 22 h (117 bed volumes) and further capacity of column was not utilized as one of the contaminants reached service time concentration of outlet concentration/inlet concentration \( C/Q_{\text{inlet}} \). In the case of arsenic, crab shell able to keep \( C/Q_{\text{inlet}} \) below 0.1 for 2 h. As the time progressed, the effluent arsenic concentration gradually increased and reached 0.25 times of inlet concentration at 22 h. It should be noted that previous reports highlighted the poor affinity of crab shell towards arsenic [19, 23]. Even though no attempt was made to determine the speciation of arsenic, it can be inferred that calcium arsenate in the case of As(V) or arsenic carbonate in the case of As(III) was relatively unfavorable compared to metal carbonates of other heavy metal ions.

Monitoring the concentration profiles of light metal ions offered many interesting results, including their amplified presence in effluent concentration as time progresses. Especially for the cases of Ca and Mg, excessive leaching was observed from the crab shell (Fig. 4). For instance, at 20 min, Ca and Mg concentrations in the outlet effluent were 137.8 and 53.4 mg/L, respectively, in contrast to inlet concentrations of 2.6 mg Ca/L and 2.1 mg Mg/L. The leaching of Ca and Mg ions increased the effluent pH and a strong correlation between the inorganic leaching from crab shell and effluent pH can be seen in Fig. 4. The increase in effluent pH is due to dissolution of carbonate species from calcium carbonate in crab shells [12]. No interesting results were obtained whilst monitoring TDS and conductivity during column operation, as both parameters remained constant during initial column operations. The reason for this may be due to the mechanism that removal of metal ions was associated with leaching of light metal ions from crab shell.

Column regeneration was performed using 0.01 M HCl and the desorbent effectively elutes sorbed metal ions from crab shell within 1.5 h of operation. Elution curves of “inverted V-shaped,” which implies a sharp increase in concentration followed by a gradual decrease, were obtained for all metal ions. Also, it is worth noting that desorption process was non-preferential with the use of 0.01 M HCl, which means the kinetics of desorption process was almost same for all heavy metal ions. The elution efficiency was >99.6% for all contaminants (Tab. 2). The elution process resulted in only 0.9 L of effluent, which was 14.7 times lower than that of volume treated by the crab shell-column.

### 3.4 Process evaluation and cost analysis

Analyzing the results, it was clear that crab shell performed well in remediation of ICP-OES wastewater. The crab shell-loaded column was able to minimize the liquid waste from 13.2 to 0.9 L with concentration factor of 14.7. During the treatment, the column retained all the heavy metal ions under the limit of \( C/Q_{\text{inlet}} < 0.1 \) and metalloid at \( C/Q_{\text{inlet}} < 0.25 \). Results obtained from the packed column loaded with crab shell were also compared to the standards proposed by National Environmental Agency (NEA), Singapore [15]. During the entire operation period of 22 h, the column was found to be capable of removing heavy metal ions well below the trade effluent discharge standards (Tab. 1). As can be seen from Fig. 4, the pH of treated effluent lies in the range of 7.4–8.3 and this range is within the allowable limits for trade effluent (Tab. 1). It is worth noting that the concentration of arsenic found in the treated effluent was higher than the discharge standards (Tab. 1). During the entire column operation, strong leaching of Ca and Mg from crab shell was observed. In most of the environmental regulatory limits, Ca and Mg are excluded owing to their relative less toxicity. High concentrations of Ca and Mg are always related to TDS, water hardness, scale formation and water bitterness [24, 25]. Hence, evaluating the treatment scheme on the basis of Ca and Mg leaching can be ignored for trade effluents.

Figure 5 presents an overall scheme of the biosorption process for the treatment of dilute multi-metal solutions. The initial procurement of crab shell can be managed with seafood industries with low price or free of cost. Crab shells are considered as wastes and often dumped directly in landfills [26]. Transportation costs can be minimized if the source for crab shell is near to treatment facility. Processing the crab shell may result in acid wastes, which can be utilized in other processes. The pH of influent, the dilute multi-metal wastewater from ICP-OES, should be enhanced to 3.5. Once metal-bearing wastewater makes contact with crab shell inside the column, the sorbent is expected to retain metal ions and metal free effluent can be collected at the exit of the column. The final effluent
can be analyzed based on the trade effluent discharge standards. Once any of the contaminant concentrations reach the permissible limit, the column operation has to be stopped, and flow should be diverted to column service (desorption). Mild acid (0.01 M HCl) should be allowed to flow through the column to free the bounded metal ions and the concentrated metal solution can be collected at the exit. Once no significant metal concentration is observed in the outlet, desorption process should be stopped and utility water can be used to wash the biosorbent bed. After the effluent pH of utility water reaches to that of the inlet, the rinsing process can be stopped, and biosorption column will be ready for next cycle. Once crab shell is completely utilized in multiple cycles, the exhausted biosorbent can be disposed/further utilized. Disposal of solid waste through incineration or land fill will substantially increase the process cost; therefore, efforts should be made to completely strip the metal ions and further utilize the crab shell in other processes such as compost for soil [27].

4 Conclusions

The following conclusions can be summarized for the present study,

(1) The wastewater generated by ICP-OES was found to comprise of several metal ions (Na, K, Ca, Mg, Fe, Al, Cu, Zn, Mn, Pb, Cr, Ni, Co, Cd) and metalloid (As) in highly acidic solution (pH 1.3).

(2) A small-scale treatment process based on crab shell was proposed for the treatment of ICP-OES effluent. The treatment scheme found to be an efficient and inexpensive alternative to remove toxic heavy metal ions continuously from the contaminated wastewater.

(3) Crab shell found to be an excellent biosorbent to remove multiple heavy metal ions in highly complicated solutions. Microprecipitation followed by adsorption on the surface was identified as the major removal mechanism for metal ions by crab shell.

(4) Batch experiments revealed the importance of pH, which influenced the metal speciation as well as sorption performance of crab shell. Altering the pH of wastewater to 3.5 improved the biosorption performance of crab shell. Furthermore, with the aid of 0.01 M HCl, the metal-loaded crab shell was regenerated and subsequently reused for three sorption-desorption cycles.

(5) Column experiments confirmed the possibility of continuous treatment of wastewater for 22 h without any of the heavy metal ions or metalloid in the treated water exceeded 0.25 times of their original influent concentration.

(6) With unique characteristics such as being cheap, environmentally friendly, regenerable and high affinity towards variety of metal ions, the present treatment scheme can be recommended for effluents comprise of dilute toxic metals.

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References


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