Control and separation of algae particles from WSP effluent by using floating aquatic plant root mats

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Abstract In this paper, the potential uses of water hyacinth and its root mats for separating algae particles in the effluent from waste stabilization ponds (WSPs) were discussed. Pilot-scale integrated processes consisting of WSPs and multiple WHPs (water hyacinth ponds) were operated in order to extract effects of the root mats on the reduction of algae concentrations. Root mats in the bottom of WHPs separated significant amount of the algae cells through attachment as the effluent from WSPs passed through them. Attachment of the algae particles to the surface of live roots was found to be similar to adsorption phenomena but it lasted even at saturation, probably due to the continuous reproduction of active attachment sites by detachment and growth of the roots. Additionally, this paper discusses attachment mechanisms and other issues concerning design and polishing of the WSPs effluent by WHPs.

Keywords Algae particles; attachment; roots; waste stabilization ponds (WSPs); water hyacinth ponds (WHPs)

Introduction Excessive loss of the algae from waste stabilization ponds (WSPs) would highly deteriorate effluent qualities. In particular, when proper hydraulic residence time is not provided for the WSPs, the content of suspended solids and organic matters in the effluent can be higher than those of the influent. This has been recognized as one of the most troublesome operational problems (WEF and ASCE, 1994). Thus, separation of the algae is essential to produce lower concentrations of BOD₅, suspended solids, and nutrients as well.

For removing algae particles from pond effluent, various methods have been proposed in the literature such as maturation or polishing ponds, fishing ponds, land or wetland treatment, sand or gravel filtration, microstrainer, dissolved or induced air floatation, chemical precipitation and engineered predation using zoo plankton or protozoa. In several countries, some of those methods combined with full-scale WSPs were successfully applied to the field.

Many studies have discussed the potential of floating aquatic plants for reducing nitrogen and phosphorus levels in wastewater and they are gaining attention in various parts of the world. Roots these plants are known to serve not only as the sites for attachment growth of bacteria responsible for significant roles in biodegradation of organic matter (Polprasert et al., 1997) but also as the media for filtering out algae and other micro-organisms from the flow of WSPs (Tchobanoglous and Schroeder, 1985). In addition, they reduce the amount of solar radiation penetration, which results in suppressing further algae growth (Kim and Kim, 1999), and prevent wind action to the water surface, thus providing excellent conditions for settling of particles.
Water hyacinth (*Eichhornia crassipes*) has been used for secondary and tertiary treatment of wastewater for upgrading the performance of WSPs. It grows with fairly dense leaves and hairy roots. Its root can grow more than 100 cm in length and have numerous hair roots especially when the nitrogen and phosphorus levels for growth are extremely low (Reed *et al*., 1988; Metcalf and Eddy, 1991). Specific surface areas of the roots are reported to range from 5.76 to 20.83 m²/kg on a dry weight basis (Polprasert *et al*., 1997; Kim and Kim, 1998). The aim of this study was to investigate potential use and roles of the plant root mats on the polishing of algae cells when water hyacinth ponds (WHPs) were coupled with WSPs. This paper mainly addresses how the live root mats separate particles of the algae and factors affecting their attachment procedure. Additionally, this paper discusses some issues concerning polishing of the WSPs’ effluent by WHPs and their design methods.

Methods and materials

A pilot-scale plant treating a domestic wastewater was built near the residential area of the University Campus. Figure 1(a) shows a schematic diagram of that integrated-ponding system consisting of primary water hyacinth ponds (WHPs), waste stabilization ponds (WSPs) and final WHPs. The objective of this project was to test overall performance of these particular coupled systems as they are built in rural residential areas of Korea. These systems aimed to maximize removals of organic matters’ and nutrients with a least land requirement. In Figure 1(a), final WHPs were intended to work as separation and control tools of the algae particles from the WSPs.

In order to analyze the amount of algae removed by the plant root systems, four water hyacinth coupons were selected from each Channel of the final WHPs. They were washed with tap water and placed laterally, as shown in Figure 1(b), between other water hyacinths at about 0.4 metre intervals from the inlet to the outlet of the final WHPs (0.4, 0.8, 1.2 and 1.6 m). Then, those plant coupons were recovered from the ponds after variable root retention times (31, 48, 86, 120, 144 hours), and algae particles were carefully washed from the...
roots with a known volume of distilled water. Weights of them attached algae particles were calculated by measuring suspended solids concentrations. Meanwhile, whole plants and their respective roots were weighed just after the washing works. In order to find out the hydraulic effects on the particle attachments, flow rate was adjusted to 0.29, 0.44, 0.88 and 1.32 m³/d on the latest schedules. Other operational rational conditions of the pond systems are given in Table 1. This experiment was performed during the period of July 13 and November 11, 1998.

Results and discussion

Performance of the integrated ponding system. Effluent characteristics from the ponding systems are briefly presented in Table 1. Removal of COD, nitrogen and phosphorus by this particular system are discussed elsewhere (Kim and Kim, 1998). It should be noted that separation of the algae particles (measured as concentrations of the SS) from the WSPs effluent is remarkable as it flows through the final WHPs.

Attachment test. Figure 2(a) shows a plot of weight of SS attached to the surface of roots (which was recovered from the pilot scale final WHPs) versus wet root weight without considering flow rates (Q), distances from the inlet (x) and root residence times (tᵢ). Because attachment phenomena of the particles occur on the surface of roots, it is desirable to use their surface areas for relating to the attachment. However, in this study, surface areas were found to be closely related with the weights of roots that were grown at least under the same nutrient level (Kim and Kim, 1998). Thus, they were used here for convenience. As indicated in Figure 2(a), there is a tendency that increase of wet root weight also increases weight of SS particles attached. In the range of 70 to 250 grams of the coupon roots, 90 to 860 mg of SS adhered to the roots. Assuming that the WHP used for this study is a plug-flow reactor having its length and width of 2 and 1 metres, respectively, changes in the weights of SS attached were investigated with respect to the flowthrough time. Flow-through times (t) were plotted against the unit SS weights attached (i.e., the weights of SS attached per wet weight of roots). As shown in Figure 2(b), the unit SS weight attached was largest near the inlet part of the WHPs and then slowly decreased with the increase of flow-through time. In terms of the roots, rate of the particle attachment (slope of the curve) decreases with respect

<table>
<thead>
<tr>
<th>Operating conditions</th>
<th>Parameters</th>
<th>Influent</th>
<th>Effluent p-WHPs</th>
<th>WSPs</th>
<th>f-WHPs</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH 6.4±0.30</td>
<td></td>
<td>6.40±0.19</td>
<td>8.3±1.5</td>
<td>6.38±0.17</td>
<td></td>
</tr>
<tr>
<td>Q=1.12 m³/d</td>
<td>DO(mg/L)</td>
<td>1.76±0.45</td>
<td>1.05±1.5</td>
<td>11±3.2</td>
<td>2.1±1.3</td>
</tr>
<tr>
<td>T=28±1.2</td>
<td>COD(mg/L)</td>
<td>117±83</td>
<td>40±20</td>
<td>28±11</td>
<td>14±7</td>
</tr>
<tr>
<td>I=371±156</td>
<td>SS(mg/L)</td>
<td>174±62</td>
<td>16±11</td>
<td>13±7</td>
<td>3±2</td>
</tr>
<tr>
<td>T-N(mg/L) 8.64±2.46</td>
<td></td>
<td>3.69±1.38</td>
<td>1.86±1.25</td>
<td>1.13±0.43</td>
<td></td>
</tr>
<tr>
<td>T-P(mg/L) 1.24±0.43</td>
<td></td>
<td>0.39±0.19</td>
<td>0.15±0.10</td>
<td>0.10±0.05</td>
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<tr>
<td>pH 7.12±0.21</td>
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<td>6.60±0.17</td>
<td>8.5±1.5</td>
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<tr>
<td>Q=2.22 m³/d</td>
<td>DO(mg/L)</td>
<td>0.44±0.45</td>
<td>0.8±0.8</td>
<td>13±3</td>
<td>1.4±1.1</td>
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<tr>
<td>T=20.3±35</td>
<td>COD(mg/L)</td>
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<td>65±20</td>
<td>53±11</td>
<td>24±15</td>
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<td>I=258±87</td>
<td>SS(mg/L)</td>
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<td>11±3</td>
<td>24±8</td>
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<tr>
<td>T-N(mg/L) 23.6±10.74</td>
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<td>18.86±10.99</td>
<td>12.85±8.36</td>
<td>7.63±6.13</td>
<td></td>
</tr>
<tr>
<td>T-P(mg/L) 2.22±0.69</td>
<td></td>
<td>1.38±0.61</td>
<td>0.54±0.25</td>
<td>0.14±0.12</td>
<td></td>
</tr>
</tbody>
</table>

T : Temperature (ºC), I: Light intensity (cal/cm² -day), pH and DO Daily average
to the flow-through time. This is due to the concentration effects. Root residence time ($t_r$) represents the span of time during which roots are in the pond and its effects on the algae attachment were analyzed. From this part of study, as roots stayed longer in the pond, the amount of attached SS weight for the plant coupons tested at the same distances and flow rates, increased to a certain degree.

**Breakthrough.** The normalized ratio between root retention time ($t_r$) and flow-through time ($t$) represents numbers of pond volume through the WHPs (widely known as numbers of bed volume in carbon adsorption studies). Figure 3 shows a correlation between the unit SS weight attached and numbers of the pond volume. Clearly, it is shown that attachment of the particles to the surface of living roots is very similar to adsorption. Maximum capacities appear to be more or less constant in all distances, whereas numbers of pond volume and slopes of the curves at saturation are different. These indicate that pond running time (or numbers of pond number) largely decreases as the saturation zone moves downward.

This does not agree with a general observation in adsorption that operational time usually increases as the numbers of carbon columns connected in a series increase. These differences might be caused by the fact that number of the adsorption site and its capacity of living plant roots is not constant as those of the activated carbon. In particular, it should be noted that, as generally known from other studies (Reed *et al.*, 1988; Metcalf and Eddy, 1991), roots of the water hyacinth raised under different nutrient levels show different

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**Figure 2** (a) Weights of SS attached versus the wet weights of root, (b) Amount of SS adhered per unit weight of wet roots versus the flow through time

**Figure 3** Amount of SS attached per unit weight of wet roots versus the numbers of the pond volume
growth characteristics. In this study, it was also found that water hyacinths of the primary WHPs treating sewage levels of the nitrogen and phosphorus (Figure 1 and Table 1) had very thick, short roots (10–20 cm) and fewer hair roots. Meanwhile, water hyacinth of the final WHPs receiving much lower levels of nutrients from the WSPs grew with much longer (30–60 cm), thinner roots having numerous hair roots. Even in the same final WHPs, along the distances from the inlet to the downstream, these trends were also consistent. In root zones near the inlet, some of the particles may be easily filtered out if they are favored for the attachment by the roots of those zones. However, particles passing through them would have more chance in attachment, as they are moving downward, since roots of the downstream are longer and more hairy. As attachment capacity of the roots in the inlet zone is being exhausted, more particles will be provided for the downstream root zones, thus resulting in a rapid particle attachment and exhaustion of roots’ capacities, i.e., decreases in the numbers of pond volume. Also, there is a possibility that decreases of the pH along the distance of WHPs enhanced attachment efficiency of the particles in the downstream direction, so that numbers of the pond volume at saturation were largely decreased. In fact, pH was greatly lowered due to the algal respiration as the effluent of the WSPs flew through the WHPs. During the daytime, pH of the WSPs was usually between 9 and 10, but it was sharply decreased to 6–7 at the outlet of the WHPs. According to the previous work (Kim and Kim, 1998), the surface of the water hyacinth root was found to have a negative charge. The decreasing pH along the flow direction would result in neutralization of negative charge at the surface of the root with increasing hydrogen-ion concentration, thereby reducing hindrance to diffusion and making available more of the active surface of the root for the algae particles.

**Calculated and measured Eff.SS.** Amounts of SS particles removed by roots can be expressed as concentrations in the flow passing through the WHPs. Average daily weight of the SS particles attached in individual root zones, \( M_{ai} \) (g/d) could be given by

\[
M_{ai} = \frac{(S_{ai})(W_{ri})}{t_r}
\]

where \( S_{ai} \) is the weight of SS attached per wet weight of roots in the \( i \)th coupon (g/kg), \( W_{ri} \) is total wet weight of roots in the zone including the \( i \)th coupon (kg) and \( t_r \) is the root retention time (hrs). Concentration of the SS removed in the \( i \)th root zone (SS \( a_i \)) can be obtained by dividing the \( M_{ai} \) by daily flow rate, \( Q \) (m\(^3\)/d).

In these ways, final effluent SS concentrations (Eff.SS) from the WHPs (considering only attachment) can be calculated as follows,

\[
\text{Eff.SS} = \text{Inf.SS} - (SS_{a1} + SS_{a2} + SS_{a3} + SS_{a4})
\]

where Inf.SS is SS concentration in the inflow to the WHPs from the WSPs and \( SS_{a1} \), \( SS_{a2} \), \( SS_{a3} \) and \( SS_{a4} \) represent the amounts of the attached SS expressed on a concentration basis (mg/L) in the flow of individual root zone, respectively. Eff.SS concentrations calculated from Eq. (2) should approach the values of Inf.SS, since all the root zones were eventually saturated, regardless of the location of coupons, although the numbers of pond volume at saturation were different.

Figure 4 shows a relationship between the calculated and the measured ratios of the Eff.SS to the Inf.SS, which suggests that the calculated ratio rapidly increases as expected, whereas measured values remain relatively constant. Apparently, part of them is related with the portions of SS removed by settling and decay of the algae particles, but they do not provide a whole explanation for all the differences between two ratios. Either detachment of the particles from the root surface or growth of the roots would produce new active sites for the attachment. As a thickness of the layer of the attached particles increases, it can be
sloughed off as a clump from the roots, because balance of the forces existing between the root surface and the layer of the particles is not kept. Sizes of these clumps (easily observed at the time of cleaning the roots for SS measurements) are large enough for gravity settling. If this is true, sites once used for attachment by previous particles will be available for collecting other incoming ones.

Also, production of the new attachment sites due to the growth of roots even during the time in which particle attachment is still in progress, settling and decay of the algae are thought to contribute to the constant levels of Eff.SS (Figure 4). The attachment mechanism may involve electrostatic interactions and chemical bridging, or specific adsorption, all of which are affected by chemical characteristics of the water and the root medium. Microscopic examinations for the roots were undertaken to find out how algae particles are positioned on the root surface (Kim and Kim, 1999). Photomicrographs show that algae particles are attached on the gelatinous matter covering the root surface. This matter is thought to provide attachment force between roots and particles. Use of the water hyacinth for separating algae particles significantly reduced dissolved oxygen levels of the treated water resulting from the respiration activities of algae, because of the shading effect by water hyacinth (Table 1). Regardless of the range of dissolved oxygen concentrations from

![Figure 4](https://iwaponline.com/wst/article-pdf/43/11/315/428999/315.pdf)

**Figure 4** Calculated and measured Eff.SS/Inf.SS versus the number of ponds volume

![Figure 5](https://iwaponline.com/wst/article-pdf/43/11/315/428999/315.pdf)

**Figure 5** SS, algae and bacteria concentrations versus the flow-through time
10 to 16 mg/L in the flow from the WSPs, they were always less than 3 mg/L in the final effluent of WHPs (very frequently complete anaerobic state). However, high pH (9–10) of the WSPs effluent was easily adjusted to 6–7 as it flew through the WHPs because of the changes in the carbon-equilibrium, caused also by algae respiration (Table 1).

**Design approach.** In this part of study, Chlorophyll a and SS concentrations of the water passing through the root mats were directly measured with respect to the flow-through time. Those results are presented in Figure 5. Bacteria concentrations (MLSS) were calculated by subtracting the algae from the SS concentrations. As indicated in Figure 6, SS, algae, and bacteria concentrations decrease as the water passed through the root mats, but decrease of the algae particles is more impressive than that of the bacteria. Probably, this may be due to the growth of bacteria using organic matter left over from the WSPs.

It seems that reduction of the SS and algae at the f-WHPs could be modeled as the following first-order equation

\[
d(\text{SS}/dt) = -k(\text{SS}) \quad \text{or} \quad dC/dt = -k_cA
\]

where \( A \) is algae concentration (mg/L) and \( k (k_c) \) is an overall first-order SS (or algae) reduction rate constant (1/hr). The principal components of the overall rate constant for SS can be written as

\[
k = k_a + k_s + k_{ar} + k_p + k_d + k_{mg}
\]

where \( k_a \) is an attachment rate constant of algae and bacteria by the root mats, \( k_s \) is a rate constant by settling, \( k_{ar} \) is a decay rate of algae due to the dark condition, \( k_p \) is algae loss rate due to the predation, \( k_{mg} \) is a growth rate of bacteria, and \( k_d \) is a decay rate of bacteria. These components can be evaluated from the properly designed experiment.

The overall rate constant was obtained by linear regression of \( \ln[\text{SS}/SS_0] \) versus flow-through time which resulted in the value \( k=0.03/\text{day} \) (\( k_c=0.042/\text{day} \) in \( \mu \text{g/L} \) of Chlorophyll a). The correlation coefficient is 0.66, which indicates that it does not have much utility, but it can be refined from more studies.

When WSPs are coupled with WHPs for removing algae particles, this approach might be very useful for designing a required length of water hyacinth channels. Sample calculation for this is as follows.

![Figure 6](https://iwaponline.com/wst/article-pdf/43/11/315/428999/315.pdf)

**Figure 6** Evaluation of the first-order SS reduction rate constant
Daily flow rate=500 m$^3$/day (21 m$^3$/h), Influent SS concentration to WHPs from the WSPs=30 mg/L Design effluent SS concentration from WHPs=5 mg/L, then required flow-through time,

\[ \ln\left(\frac{SS}{SS_0}\right) = -kt, \quad t = \left(-\frac{1}{k}\right) \ln\left(\frac{SS}{SS_0}\right) = \left(-\frac{1}{0.03}\right) \ln\left(\frac{5}{30}\right) = 2.5 \text{ days (60 hrs)} \]

Assuming average water depth of WHPs is 0.5 m and its maximum width (a single pond) is 10 m, total length of water hyacinth channel required is

Capacity of WHPs=Q\times t=21 \text{ m$^3$/h}\times 60 \text{ h}=1,260 \text{ m$^3$} 

Surface area of WHPs=1,260 \text{ m$^3$/0.5 m}=2,520 \text{ m$^2$} 

Total length of channel=1,260 \text{ m$^3$}/(0.5 \text{ m} \times 10 \text{ m})=252 \text{ m} 

If five equal sized channels are provided, the length of a single channel would be 50 m.

**Summary and conclusion**

In this paper, roles of water hyacinths and their roots for reducing algae concentrations in the effluent of WSPs were presented. Mats of the roots in the bottom of WHPs filtered out algae particles when they passed through them. In some aspects, this phenomenon was similar to an adsorption process, but attachment of the particles lasted even at saturation probably due to the sloughing-off of pre-attached particles and growth of roots. Some issues concerning polishing of WSPs were also discussed.

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**References**


