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SEPARATION OF ALGAL PARTICLES FROM WASTE STABILIZATION PONDS BY FLOATING AQUATIC PLANT: DESIGN APPROACH

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Abstract : We demonstrated that water hyacinth ponds (WHPs) can polish the effluent from waste stabilization ponds(WSPs) by separating SS, insoluble COD and nutrients efficiently. High pH of the WSPs effluent was easily adjusted to 6~7 as it passed through the WHPs. However, the use of water hyacinth rapidly reduced dissolved oxygen at the first cell to less than 3 mg/L or very frequently to a level of anaerobic state. Associated with the passage of the WSPs effluent through the WHPs, possibility of the regrowth was investigated. It was found that water hyacinth ponds did not interfere with the inactivation level of WSPs when they were used for polishing purpose. Reduction of suspended solids at the WHPs mainly depends on the detention time and pH. An empirical separation model incorporating the detention time and pH dependence was developed. Design calculation shows that about 58.4 ha of the surface area per 10^6 m^3 of the effluent from WSPs during the summer is required to obtain 90% separation efficiency of SS. In addition, this model can be incorporated into the organic and nutrients reduction models of WHPs, thus can help design the required length of water hyacinth channels for upgrading the WSPs effluent to the goal of treatment.

Key Words : algal particles, water hyacinth ponds, waste stabilization ponds

INTRODUCTION

Waste stabilization ponds (WSPs) have been extensively used to treat wastewater in the U.S., South America, Europe, and South East Asia.1) Because of their low cost and simplicity of operation and maintenance, WSPs predominate among the small wastewater treatment systems owned by small communities.1) In the U.S., approximately 90% of WSPs are located in communities of 5,000 people or less.1)

Operational experience from the U.S. has revealed that the main problem to meet the effluent discharge limit is caused by algae, which not only show up as suspended solids, but also exert an oxygen demand and other problems on the receiving stream. New European standards of the pond effluent could request a reduction in the suspended solids by requiring a final effluent concentration lower than 30 or even 20 mg/L.2) It is known that 1 kg of algae (measured as SS) exert a 5-day biochemical oxygen demand (BOD_5) of 1 kg. Thus, separation of the algae is an essential step to produce lower concentrations of BOD_5, suspended solids, and nutrients as well.

Various technologies such as physical, chemical and biological processes have been developed and several prospective methods were introduced in the literature3) as a means for

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removing algal particles from pond effluent. Among these, biological control and separation processes such as aquatic plants, were recognized as a very effective means for removing algae, microorganisms, and other suspended particles.

Wolverton and MacDonald[4)] studied the effect of water hyacinths on the effluent water quality when they were placed at the downstream side of a facultative pond. A facultative pond with these vascular plants maintained an effluent BOD_5 below the EPA discharge limit of 30 mg/L throughout an entire year. A lagoon without hyacinths achieved an average reduction in BOD_5 of 76% while another lagoon with aquatic plants reduced BOD_5 by 94%. Dinges[5)] carried out an intensive study on the functions of water hyacinth and found that controlled culture of water hyacinths in shallow basins was effective in removing algae, other suspended particles, and dissolved impurities in the effluent from WSPs. He reported that water hyacinth grew to a height of approximately 0.9 m, and the canopy almost completely shaded the water surface and served to minimize mixing of basin waters by wind action.

From a pilot-plant study, Kim et al.[6)] examined the individual effect of the water hyacinth leaves and stems and root mat on the algal concentration. The results showed that filtration and settling almost equally contributed to the separation of algal particles. Canopy effect of the leaves and stems, which suppressed algal growth, was equivalent to the half of the amount of algae removed by gravity settling. Similar observations have also been reported when duck weed (*lemmna giba*) and other wetland plants were used.[7)] However, water hyacinth appeared to be effective for algal removal due to their long and dense root system as well as large leaves covering the sunlight. The treatment concept has been developed through extensive laboratory and pilot-scale research as well as from the evaluation of full-scale facilities.[8)]

According to previous studies on the use of water hyacinth for treating raw sewage, removal mechanisms of suspended solids are mainly settling and filtration.[9)] A portion of the suspended solids in the influent sewage is removed by settling in the pore of root zone, as it flows into the water hyacinth channel. Another portion of the suspended particles that will not settle by gravity is screened by filtration as wastewater flows through the root mat of the water hyacinth. Because filtration is of great importance in removal mechanism, transport of the wastewater to the root zone is a critical designing consideration in water hyacinth treatment systems.

Kim and Kim[6)] reported that the separation phenomenon of algae particles by root surface is similar to adsorption processes. In other words, there is a maximum capacity in a given weight of roots, but effluent algal concentration did not increase at saturation due to the sloughing-off of attached particles as a clump from the roots and the continuous reproduction of new attachment sites caused by the growth of roots. In a similar study of SS removal from raw sewage by water hyacinth roots, Crities and Tchobanoglous[9)] also identified this mechanism but described it in a different way. They contended that a portion of the organic fraction of the SS attached to the roots undergoes biodegradation by biofilm activities. With the further passage of time, SS particles attached to roots continue to accumulate and ultimately, the roots senesce, and drop and accumulate to the bottom, which additionally contributes to filtration. In any cases, water hyacinth ponds remain unsaturated, providing thus an efficient method for particles removal.[10)]

How algal and other suspended particles are retained on the surface of roots is not clearly known yet. The attachment mechanism may include electrostatic interactions and chemical bridging, or specific adsorption, all of which would be affected by chemical characteristics. Microscopic examination of the roots revealed that a gelatinous matter, which covered the root surface, surrounds algal particles. These materials are only assumed to provide an attachment force between roots and particles.[6]

Water hyacinth systems have been often used for separating algae from WSPs and significant amount of data has been accumulated. However, most of the data have been rather observational than quantitative.[11] Further, organic loading as a design parameter has been traditionally used, and hence there is no rational approach for designing the water hyacinth systems based on the required level of suspended solids (algae) removal in the effluent from WSPs.

In this paper, an algae separation model which was developed from operational data of a pilot-scale WSPs coupled with water hyacinth system is proposed. Additionally, several issues regarding the functions and roles of water hyacinth are also discussed.

MATERIALS AND METHODS

Pilot-scale WSPs coupled with water hyacinth ponds (WSPs) were built near the residential area of the University Campus. Figure 1 shows a schematic diagram of final water hyacinth pond (F-WHPs) for treating the effluent from WSPs and primary water hyacinth ponds (P-WHPs). As shown in Figure 1, primary WHP was placed to reduce the settleable suspended solids, a portion of the biodegradable organic matters and nutrients in raw sewage.

This pretreatment was thought to reduce loads to the WSPs located downstream of primary WHP, so that the land requirement for WSPs could be decreased. WSPs remove the organic matter and nutrient load under high dissolved oxygen concentration and pH, which is caused by the photosynthetic activity, but they are not efficient in producing low effluent suspended solids concentration due to the algae production. Final WHPs was intended to mainly separate the algal particles and to reduce the nutrients and soluble organic matters left over from two previous units. It was operated in step-feed and plug-flow mode as indicated in Figure 1. More detailed information regarding the experimental set-up and operation is available in a previous work.[6]

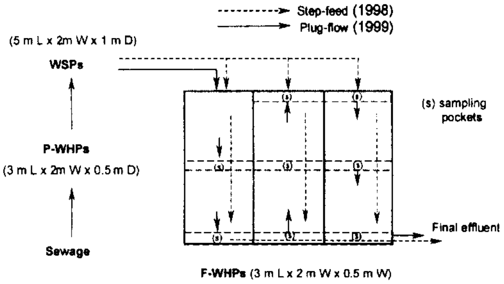
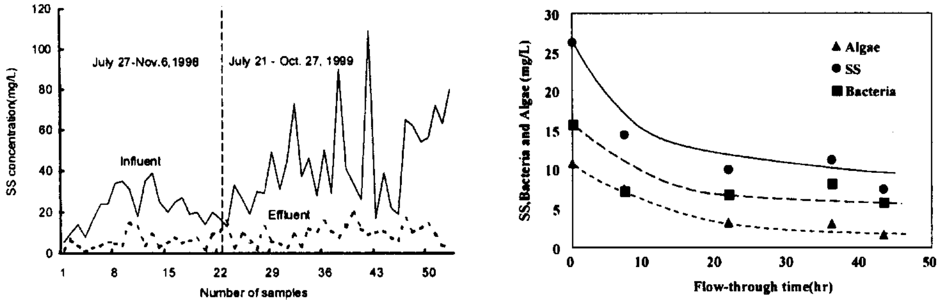


Figure 1. Schematic diagram of final water hyacinth ponds.

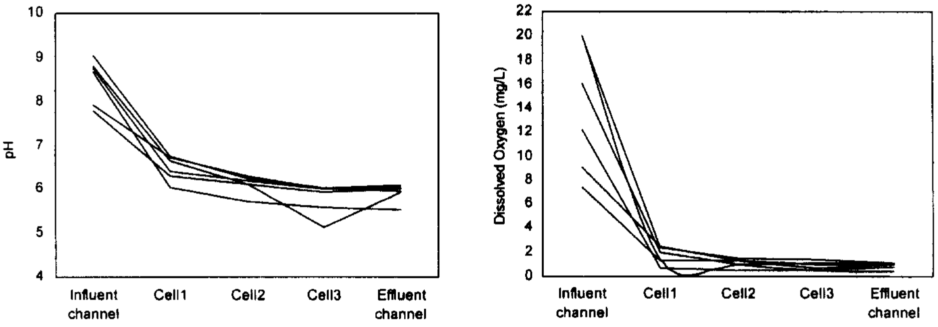
RESULTS AND DISCUSSION

SS Reduction. The suspended solids produced at the WSPs were removed as they passed through the water hyacinth roots. Figure 2(a) depicts the suspended solids profile of the influent and effluent, which were measured periodically during the operational periods of 1998 and 1999. The algal concentrations of the influent (measured as *Chlorophyll a*) were highly variable due to the changes in the light intensity and water temperature at the WSPs. The suspended solid concentrations of influent were in the range of 10 to 80 mg/L, but they usually reduced to much less than 10 mg/L during most of the operational periods after the passage through the final WHPs. *Chlorophyll a* and suspended solids of the water passing through the root mats were also frequently measured with respect to the flow-through time. A representative data set from these results is shown in Figure 2(b). Mixed liquor suspended solids (MLSS) were calculated by subtracting the algae from the SS concentrations. As indicated in Figure 2(b), SS, algae, and bacteria concentrations decrease as the water passed through the root mats, but decrease in amount of the algal particles is more distinctive than that of the bacteria. This can be attributed to the growth of bacteria using organic matters left over from the WSPs and to pH pattern along the WHPs (approximately neutral) which facilitates the growth of heterotrophic bacteria.



(a) (b)

Figure 2. (a) Influent and effluent SS concentrations of the final WHPs (98-99), (b) Reduction of SS, algae, and bacteria with respect to the flow-through time.



(a) (b)

Figure 3. (a) The change of pH along the flow-direction of the F-WHPs and (b) the dissolved oxygen profiles along the length of F-WHPs.

pH adjustment. High pH of the WSPs effluent (usually 9~10) was easily adjusted to 6~7 as it passed through the WHPs, because of the changes in the carbon-equilibrium, caused also by the algal respiration. The changes in pH along the WHP would effect the electrostatic interactions between algal particles and roots surfaces as well as sedimentation. It has been demonstrated that elevated pH favors sedimentation[2)] but lower (almost neutral) pH stand in favor of root adsorption processes.[6)] Several pH data sets[12)] measured along the flow-direction are provided in Figure 3(a). According to Figure 3, pH sharply decreases at the first cell (flow -through time 0.61 day per cell), then slowly reaching 5.5 to 6.5. These results imply that increased sedimentation may occur at the early stages (cell) of WHP while absorption processes predominate in the subsequent treatment cells. Experimental evidence and additional discussion on such effect of pH pattern along the hyacinth ponds on the efficiency of the particle separation processes will be afforded further below.

DO concentration. The use of water hyacinth to remove algal particles reduced dissolved oxygen levels of the treated water because of the shading effect by water hyacinths, which restricted respiration activity of the algae. Regardless of the ranges of dissolved oxygen from 10 to 19.99 (limit) in the influent, they were always less than 3 mg/L in the final effluent (very frequently anaerobic state). Figure 3(b) shows profiles of the dissolved oxygen concentrations along the F-WHPs. Dissolved oxygen was most seriously depleted during the passage of the first cell, indicating that the algal respiration actively occurs in this zone. The dissolved oxygen profiles explain the sharp decrease of pH at the first cell.

The excessive decrease of dissolved oxygen can be a disadvantage in two aspects when water hyacinth is used for polishing WSPs effluent. The very low dissolved oxygen can be a limiting factor for biofilm activity of the roots, thus affecting the removal of organic matters. In addition, it can lower the pH of the water due to carbon equilibrium reactions. Thus it reduces the performance of particle settling, which is abetted at high pH values. However, low dissolved oxygen levels prohibit the augmentation of heterotrophic bacteria, which can grow by utilizing the remaining soluble organic matter and nutrients left over from the previous treatment thus ensuring low effluent solids concentration.

Microbiological factors. One of the most important functions of WSPs is a natural disinfection, which is achieved by sunlight and high pH. Sunlight disinfection which has been considered as one of the most important factors, can not be expected from the water hyacinth ponds because of the canopy and lowered pH. Thus, as the effluent from WSPs passed through the F-WHPs, there is a possibility of regrowth of pathogenic bacteria using organic matters left over from the WSPs at the pH values usually observed (6~7), which generally favors the growth of heterotrophic bacteria.

This aspect of problem was investigated by monitoring a change of total coliform bacteria (*TC*) density (counts/100 mL). Figure 4 shows the profile of *TC* density with respect to the unit and cell and the operational days. During the experiment, the *TC* density in the influent was 3 x 10^6 - 8 x 10^6/100 mL, which is a typical range of sewage from the combined sewer. *TC* numbers rapidly decrease in WSPs and remain at the levels of effluent from WSPS. These data clearly demonstrate that there is no indication of increase in the *TC* density, which can be associated with the passage of the WSPs effluent through the F-WHPs. Therefore, it can be concluded that water hyacinth ponds do not interfere with the inactivation level of WSPs when they are used for polishing purpose.

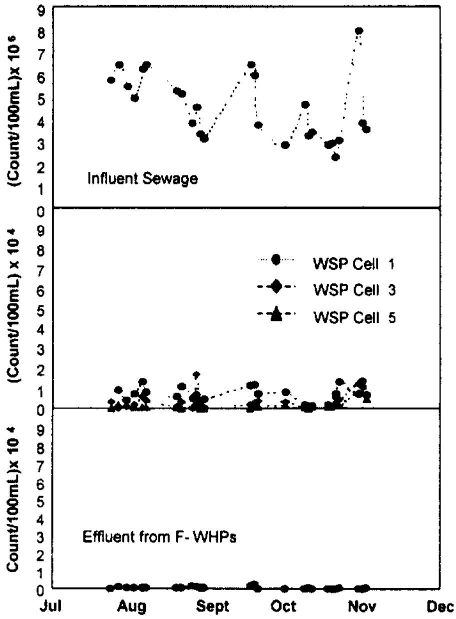
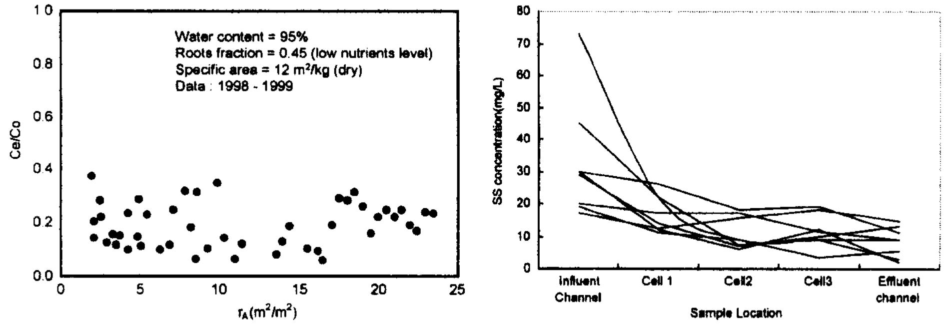


Figure 4. TC (total coliform bacteria) profiles with respect to the unit process and operational days.

Model Development. Reduction of suspended solids at the F-WHPs depends on various and complicated factors such as (1) the attachment rate of algae and bacteria by the root mats, (2) their settling efficiency, (3) a decay rate of algae due to the dark condition, (4) algae loss rate due to predation, (5) a growth rate of bacteria, and (6) a decay rate of bacteria. These factors depend on various parameters such as degree of sunlight penetration,6) grazing of algae by protozoa3) as well as several physico-chemical parameters such as pH, DO, Temperature etc., as previously discussed.

Hydraulic parameters such as the hydraulic detention time may also play a significant role in algal particle separation. The surface area of the roots per unit area (r_A) might be an important factor that provides algal particles with the sites for attachment. According to previous studies, specific surface area of the roots is reported to range from 5.76~20.83



(a) (b)

Figure 5. (a) The relationship between the unit surface area of roots and influent -effluent SS ratios and (b) suspended solids profile with respect to the sample location.

m^2/kg on a dry weight basis.[8,12,13)] Using the method previously described[8)] the growth of water hyacinth was monitored, so as to estimate the change of r_A during the operation.

The correlation between r_A values and the ratios of the influent and final effluent SS (C_e/Co) was pursued and the results are presented in Figure 5(a) (parameters used for calculating r_A are also given). The data in Figure 5(a) do not show any indication of enhancement effect on the SS separation by increase in r_A. This trend does not change even when effects of hydraulic residence time is considered. In contrast, the SS separation ratios seem to be more or less constant between r_A values, 2.0 m^2/m^2 (wet plant density = 7.8 kg/m^2) and 23.4 m^2/m^2 (wet plant density = 86 kg/m^2). In Figure 5(b), the suspended solids concentration versus the number of cell are plotted. The individual curve represents a day of measurement, which was randomly selected during the operational period. From the figure, it seems that an assumption of plug-flow operation is valid, especially when considering the long detention time and the multiple cell ponds. Consequently, solids removal processes in WHPs can be encountered by a first-order, plug flow model according to the generalized expression:

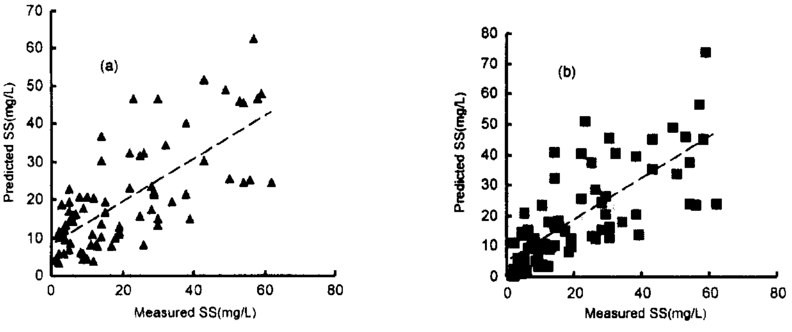
$$C_e/C_o = e^{-kf(t,\, r_A,\, pH,\, I,\, DO,\, S,\, P,\, T,\, etc.)} \quad (1)$$

where C_o and C_e are influent and effluent SS concentrations (mg/L) respectively, and k is an overall first-order SS reduction rate constant. Other parameters include a function of detention time (t), root surface area per unit area (r_A), pH, light intensity (I) through the F-WHPs pond, dissolved oxygen (DO), soluble organic contents (S), protozoa density (P) and water temperature (T). Eq. (1) includes almost all factors, which can influence the performance of the WHPs. The individual or synergistic effect of each factor can be evaluated by means of properly designed experiments. However, in this study, suspended solids were the overall parameter of concern rather than any particular form of particles. In this respect, only detention time, pH, and water temperature were considered for developing a particle separation model. Based on this rationale, Eq. (1) can be reduced to a simplified form, according to the following formula:

$$C_e/C_o = e^{-kf(t,\, pH,\, T)} \quad (2)$$

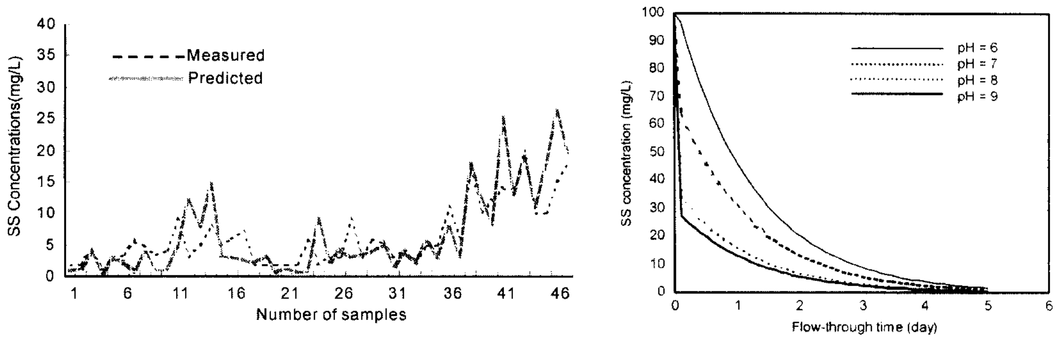
Eq. (2) was tested using 75 data collected at each cells in series of the final WHPs during July-November 1998 and June- October 1999. Temperature dependence was directly incorporated into Eq. (2) by the following basic relationship:

$$k_{tT} = k_{t(20)}(\theta)^{(T-20)} \quad (3)$$



(a) (b)

Figure 6. (a) Effects of hydraulic detention time, (b) Incorporating the change of pH.



(a) (b)

Figure 7. (a) Comparison between measured and calculated SS in the final effluent and (b) diagram that is built to illustrate the effect of pH.

where k_{tT} = temperature and time-dependent rate constant and $\theta = 1.039$. Model parameters were evaluated with Excel Non-Linear Solver program. At 20°C, the detention-time dependent removal component is;

$$C_e/C_o = e^{-0.82t} \tag{4}$$

The regression analysis of these data produces correlation coefficient 0.74 and the result is shown in Figure 6(b). The pH dependence was determined independently by using the influent pH data set under the same detention time and temperature conditions. Temperature dependence for the pH was considered by the same basic relationship as Eq. (5):

$$k_{pHT} = k_{pH20}(\theta)^{(T-20)} \tag{5}$$

where k_{pHT} = pH rate constant at temperature T, $\theta = 1.039$. The non-linear optimization result at 20°C (correlation coefficient 0.71) is shown in Figure 6(a) ;

$$C_e/C_o = e^{-0.34(pH-6.12)} \tag{6}$$

Eq. (7) will predict SS removal down to pH 6.12. Because temperature dependence was equally considered, it is possible to combine the Eq. (5) and (6) to evaluate the general case in Eq. (2):

$$\begin{aligned} C_e/C_o &= e^{-[0.82t+0.34(pH-6.12)]} \\ &= e^{-[0.82[t+0.42(pH-6.12)]} \\ (\text{or } C_e/C_o &= e^{-k_T\,[t+0.42(pH-6.12)]}) \end{aligned} \tag{7}$$

where:

$k_T = k_{20}(\theta)^{T-20}$
$k_{20} = 0.82$
$\theta = 1.039$

Eq. (7) is then used to predict the final SS concentrations (data in Figure 2) collected during the experimental periods, which are compared to the actual values in Figure 7(a). The correlation of $R^2 = 0.67$ obtained cannot be characterized as very satisfactory. However, considering the long-term data and large number of individual data points used for the evaluation, it can be concluded that the trend of predicted SS reasonably simulate the measured line. This means that Eq. (7) gives a valid estimate of suspended solids separation in the effluent from the WHPs. However, this model still lacks in rational explanation about interactions between pH, algal particles and plant roots. In addition to attachment by roots, algae loss due to settling and predation may be important function and must be considered to get better performance of the model.

The practical usefulness of Eq. (7) in interpreting real-time data is shown in Figure 7 (b). In this diagram, the effect of the pH on the separation is illustrated, assuming influent SS concentration of 100 mg/L, which is rather common for WSPs effluent during the summer. It indicates that algae are removed rapidly near the first inlet part of water hyacinth system as the pH increases while the rest of the ponds provide minimal treatment only.

These results are in concurrence with previous findings that showed attachment of SS on the roots decreases with the flow-through time.[6] At pH 8, 65% of SS is reduced within 2～3 hr of flow-through time. Again, this result supports the needs of step-feed along the length of the ponds.[11] Eq. (7) can be incorporated into organic and nutrient reduction models of water hyacinth ponds. Then, we can develop an integrated model for designing the required length of water hyacinth channels for upgrading the WSPs effluent to the degree of treatment. Unfortunately, at present, there is no universal design equation for this purpose, even though there are several models such as CSTR organic reduction models in 8 reactors series[9] or steady-state biofilm models.[13]

Upgrading Effluent Quality. The introduction of an intermittent sunlight-exposed chamber into the water hyacinth ponds was also examined as means for enhancing SS reduction. In the water hyacinth ponds, one of the three chambers (defined as a photo-aeration chamber) was exposed to the sunlight (without plants) so that the algal growth resumes, thus increasing the pH and dissolved oxygen concentrations. This concept was qualitatively tested.[12] As expected, dissolved oxygen and pH rapidly decrease at the first cell (detention time 0.61 day per cell) filled with plants, but they recover as the flow passes through the next photo-aeration chamber. Although further research is still needed to assess the effectiveness of this method over a wide range of experimental conditions (temperature, flow, load etc.), several advantages seem to emerge from its application.

SUMMARY AND CONCLUSION

In this paper, some observations commonly experienced when the water hyacinth was used for polishing the effluent from waste stabilization ponds are presented. Suspended solids (mostly algal particles) were efficiently separated, which also resulted in the reduction of insoluble forms of COD and nutrients. Associated with the passage of the WSPs effluent through the WHPs, water hyacinth ponds did not interfere with the inactivation level of WSPs. Reduction of suspended solids at the WHPs mainly depends on the detention time and pH. Based on the experimental data sets, empirical model was developed. Sample calculation indicates that about 58.3 ha of the surface area per 10^6 m^3 of the effluent from WSPs during the summer is required to obtain 90% separation efficiency of SS. The proposed empirical model can be integrated into organic and nutrients reduction models of WHPs, thus providing efficient tools for the scale-up of water hyacinth channels for upgrading the WSPs effluent to meet the design objectives.

ACKNOWLEDGEMENT

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APPENDIX

Design Example. When WSPs are coupled with WHPs for removing algal particles, Eq. (7) might be useful for estimating a required length of water hyacinth channels, although its validity has to be verified through a field study. Example design calculation for this is as follows.

Daily flow rate = 1,890 m^3*/day*

Average influent SS concentration from the WSPs to WHPs during summer (four months) = 100 mg/L

Design effluent SS concentration from WHPs = 10 mg/L

Average pH during summer = 8.5, Average water temperature = 25°C

An overall separation rate constant = 0.82 @ 20°C

Required flow-through time from Eq. (7),

$t = -\ln[C/Co]/k_{25} - 0.42(pH - 6.12) = - \ln(10/100)/0.905 - 0.42(8.5 - 6.12) = 1.545$ days

Designing the water depth of WHPs as 0.5 m like pilot-plant operational conditions and its maximum width suitable for maintenance and operation (a single pond) is 10 m, Capacity, surface area, and the length of water hyacinth channel required are

Capacity of WHPs = Q x t = 1,890 m^3/day x 1.545 days = 2,920 m^3

Surface area of WHPs = 2,920 m^3/0.5 m = 5,840 m^2 (0.5840 ha) or 58.4 ha/10^6 m^3

Total length of channel = 2,920 m^3/(0.5 m x 10 m) = 584 m

If five equal sized channels were provided, length of a single channel would be 117 m. This size of WHPs would accomplish 90% of suspended solid in the effluent from WSPs. At the same time, the separated algae (90 mg/L) is equivalent to giving reduction effects of approximately 90 mg/L, 9 mg/L, and 1 mg/L in BOD_5, TN and TP, respectively.[14] Additionally, soluble organic matters and nutrients removal can be expected by root biofilm activity and plant uptake.

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