



Journal of Environmental Science and Technology

ISSN 1994-7887

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Research Article

Organic Matter and Nutrient Removal in a Sequencing Baffled Steep-flow Constructed Wetland System

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Abstract

Objective: The performance of *Pistia stratiotes* (water lettuce) for the removal of organic compounds and nutrients in a sequencing baffled steep flow reactor was investigated in this study. **Methodology:** The reactor consist of five horizontal compartments (C1-C5) of various sizes with a steep-wise water depth for rapid wastewater flow. Acrylic made baffles were installed in reactor zones C1, C2 and C4 to prevent short circuiting. *Pistia stratiotes* were planted on the surface of each compartment of the reactor. Wastewater from a sewage effluent was used in this study and was applied to C1 at a high, fixed HLR of $10.2 \text{ m}^3/\text{m day}^{-1}$ (225 L day^{-1}) and fluctuating Organic Loading Rate (OLR) and Ammonium Loading Rate (ALR), respectively. Reactor performance was monitored for a period of 7 days. **Results:** Results show that the COD removal fluctuated between 7.1-54% from day 1-5. No COD removal was observed in day 6 and 7. The $\text{NH}_4^+\text{-N}$ removal also fluctuated between 13-94% from day 1-7. Phosphorus removal were found to fluctuate between 11.5-48% from day 1-7. **Conclusion:** The fluctuation noticed in the effluent concentration of each parameter could be attributed to the effect of the fluctuating influent feed. The reactor nutrient removal capacity clearly indicates that it could serve as a suitable phytoremediation configuration.

Key words: Phytoremediation, bioremediation, aquatic macrophytes, water lettuce, nutrient uptake

Received: January 05, 2016

Accepted: April 08, 2016

Published: June 15, 2016

Citation: Shamsul R.B.M. Kutty, Anthea Tessa Alvin Nagum and Ezerie Henry Ezechi, 2016. Organic matter and nutrient removal in a sequencing baffled steep-flow constructed wetland system. J. Environ. Sci. Technol., 9: 340-344.

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

The discharge of nutrients (nitrogenous compounds and phosphorus) and organic compounds into water bodies can cause several unwanted phenomena, such as eutrophication and methaemoglobinaemia¹. Eutrophication is the enrichment of water body with nutrients which could be unhealthy for aquatic organisms and cause algae bloom². Methaemoglobinaemia is a phenomenon caused by the anaerobic conversion of nitrate to nitrite in the human intestines of infants³. The presence of nitrite in the human intestines can also lead to the formation of nitrosamines (a known carcinogen in mammals) and result to cancers of the digestive tract. As a result, organic wastewater parameter, such as Chemical Oxygen Demand (COD) is widely used as an indicator of water quality⁴. Wastewater nutrient parameters such as ammonia, nitrate and phosphorus are also stringently regulated.

In order to mitigate water deterioration, suitable, cheap, efficient and accessible wastewater treatment techniques are required⁵. One of the methods that have gained significant attention is phytoremediation. Phytoremediation is a bioremediation process, which utilize green plants for the removal of hazardous pollutants in soil and water⁶. The principle of phytoremediation is based on the capacity of the plant root system to combine several processes, such as translocation, bioaccumulation, contaminant storage and degradation. It is a cheap alternative to other nutrient removal processes and it is widely accepted for the removal of heavy metals, nutrients, oil and other contaminants.

Macrophytes are commonly used in phytoremediation. Several macrophytes exist and are classified into different groups, such as free floating plants, floating leave plant, submerged plants and emergent plants⁷. It is the use of these macrophytes that have made phytoremediation, a feasible technique^{8,9}. The role of macrophytes during phytoremediation include to enable transportation between medium, provide ample area for growth of micro-bacteria through the root system, control the flow of water and its own growth as well as stabilize the sediment bed¹⁰. Free floating and submerged macrophytes are the two main plants commonly used in phytoremediation¹¹. However, several studies have focused on the free floating plants^{12,13}. In addition, several studies have investigated the performance of a single specie of the floating aquatic macrophyte known as water hyacinth using various constructed wetland designs¹⁴⁻¹⁷. It is obvious that water hyacinth have shown high capacity for organic and inorganic compound removal from wastewater.

The objective of this study is to investigate the performance of *Pistia stratiotes* (water lettuce) for the uptake of organic compound and nutrients (ammonium and phosphorus) in a sequencing steep-flow baffled constructed wetland reactor.

MATERIALS AND METHODS

Reactor set-up: A sequencing baffled steep flow constructed wetland reactor with 5 compartments (C1-C5) and a total liquid volume of about 337 L was built with concrete in this study. The dimension of compartment 1 (C1) is 25 cm depth, 48 cm length and 47 cm width. Two vertical baffles of thickness 5 mm, length 39 cm and depth 23 cm were installed at a space of 17 cm from each other. The baffles were installed to avoid short-circuiting. A 12 cm gap connects C1 samples to C2. The depth of C2 was increased to 30 cm. A baffle was also installed at the middle of C2 and a 12 cm gap connects C2 samples to C3. The depth of C3 was increased to 35 cm. No baffle was installed in C3. The C3 sample flows into C4 through a 12 cm gap. The depth of C4 was 40 cm. A vertical baffle was installed 23 cm from the width. The baffle length was 40 cm, while the depth was 39 cm. Three 2 cm circular holes were made in the wall of C4 which connects samples to C5. The C5 is the overflow compartment. It serves as the settling tank. The depth of C5 is 48 cm. A 2 cm circular hole was made between 39-41 cm height of the compartment as effluent outlet. *Pistia stratiotes* were planted on the surface of all the reactor compartments (C1-C5). The reactor schematic is shown in Fig. 1.

Reactor operation: The reactor was installed at the effluent line of the sewage treatment plant in Universiti Teknologi Petronas (UTP) under a transparent shield that allows the penetration of sunlight but not of rainfall. The influent sample was applied to C1 at a flowrate of 225 L day⁻¹ in a downflow pattern. Since the sample was applied to C1, the dimension of C1 was used to calculate the Hydraulic Loading Rate (HLR), the

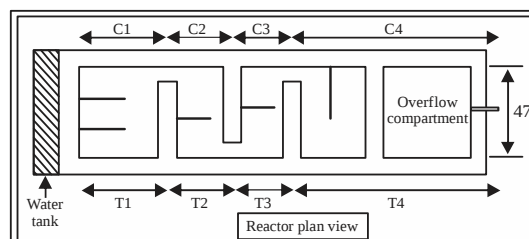


Fig. 1: Schematic of the steep flow wetland reactor

Organic Loading Rate (OLR) and the Ammonia Loading Rate (ALR). The HLR for the reactor operation was $10.2 \text{ m}^3/\text{m day}^{-1}$ at hydraulic retention time of 6 h for C1. The sample was fed to C1 using a Masterflex Peristaltic pump. The OLR fluctuated between $3\text{--}16 \text{ g COD}/\text{m}^3 \text{ day}^{-1}$, while the ALR also fluctuated between $0.01\text{--}0.5 \text{ g NH}_4^+\text{-N}/\text{m}^3 \text{ day}^{-1}$ due to the inconsistent influent feed concentration. After wastewater have filled each compartment, sample collection was initiated at 3 h intervals. The COD, ammonia nitrogen and phosphorus were measured using Hach method¹⁸. The pH and temperature were also monitored throughout the experiment using a pH meter (Sension™) and a thermometer. All sample measurements were triplicated.

RESULTS

The experiment was initiated at fixed HLR of $10.2 \text{ m}^3/\text{m day}^{-1}$. The OLR and ALR for COD and $\text{NH}_4^+\text{-N}$ fluctuated between $3\text{--}16 \text{ g COD}/\text{m}^3 \text{ day}^{-1}$ and $0.01\text{--}0.5 \text{ g NH}_4^+\text{-N}/\text{m}^3 \text{ day}^{-1}$, respectively. The time course profiles for COD and $\text{NH}_4^+\text{-N}$ removal from the effluent zone are presented in Fig. 2 and 3, respectively. On day 1 of the experiment, the OLR for COD was maximum at $9.8 \text{ g COD}/\text{m}^3 \text{ day}^{-1}$ in the initial stage. A corresponding effluent COD concentration of $7.7 \text{ g COD}/\text{m}^3 \text{ day}^{-1}$ were noticed. However, towards the end of the day, COD removal was negative, indicating an extended acclimation period. The $\text{NH}_4^+\text{-N}$ ALR was $0.06 \text{ g NH}_4^+\text{-N}/\text{m}^3 \text{ day}^{-1}$ but decreased to $0.05 \text{ g NH}_4^+\text{-N}/\text{m}^3 \text{ day}^{-1}$ at the end of day 1. On day 2, at OLR of $7 \text{ g COD}/\text{m}^3 \text{ day}^{-1}$, a residual effluent concentration of $5.3 \text{ g COD}/\text{m}^3 \text{ day}^{-1}$ was noticed. On the other hand, residual effluent $\text{NH}_4^+\text{-N}$ concentration of $0.04 \text{ g NH}_4^+\text{-N}/\text{m}^3 \text{ day}^{-1}$ was obtained from ALR of $0.2 \text{ g NH}_4^+\text{-N}/\text{m}^3 \text{ day}^{-1}$. The $\text{NH}_4^+\text{-N}$ removal stabilized on day 2. However, the COD removal was yet to stabilize. On day 3, the OLR and ALR fluctuated throughout the day for both COD and $\text{NH}_4^+\text{-N}$. At OLR of $13.5 \text{ g COD}/\text{m}^3 \text{ day}^{-1}$, an effluent COD concentration of $7 \text{ g COD}/\text{m}^3 \text{ day}^{-1}$ were obtained. A high $\text{NH}_4^+\text{-N}$ removal was also achieved on day 3 from ALR of $0.41 \text{ g NH}_4^+\text{-N}/\text{m}^3 \text{ day}^{-1}$ to an effluent concentration of $0.07 \text{ g NH}_4^+\text{-N}/\text{m}^3 \text{ day}^{-1}$. The reactor performance on day 3 shows a completion of the acclimation period. On day 4, similar fluctuations in the OLR were noticed. At OLR of $16 \text{ g COD}/\text{m}^3 \text{ day}^{-1}$, an effluent concentration of about $7.34 \text{ g COD}/\text{m}^3 \text{ day}^{-1}$ were obtained. For $\text{NH}_4^+\text{-N}$ removal, a residual effluent concentration of $0.05 \text{ g NH}_4^+\text{-N}/\text{m}^3 \text{ day}^{-1}$ was obtained from an ALR of $0.13 \text{ g NH}_4^+\text{-N}/\text{m}^3 \text{ day}^{-1}$. On day 5, OLR fluctuations were also noticed. However, a decrease of the reactor performance for organic matter removal was noticed.

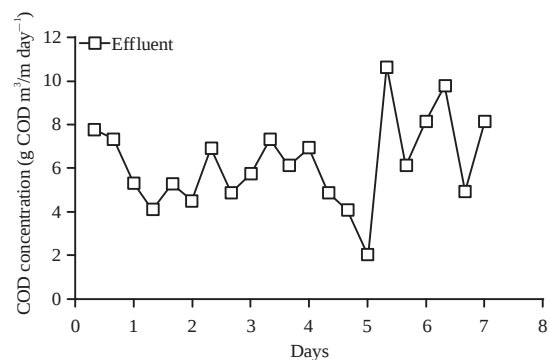


Fig. 2: Effluent COD concentration

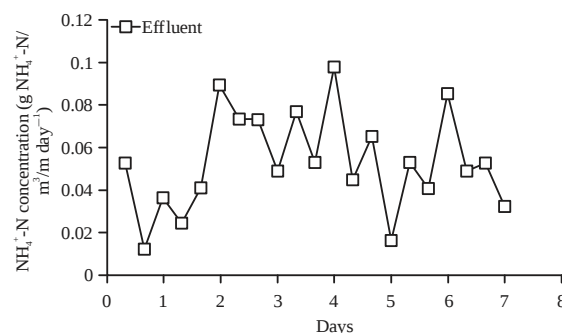


Fig. 3: Effluent $\text{NH}_4^+\text{-N}$ concentration

At OLR of $8.15 \text{ g COD}/\text{m}^3 \text{ day}^{-1}$, a residual effluent COD concentration of $4.9 \text{ g COD}/\text{m}^3 \text{ day}^{-1}$ was obtained. On the contrary, $\text{NH}_4^+\text{-N}$ removal increased on day 5. At ALR of $0.3 \text{ g NH}_4^+\text{-N}/\text{m}^3 \text{ day}^{-1}$, a residual concentration of about $0.016 \text{ g NH}_4^+\text{-N}/\text{m}^3 \text{ day}^{-1}$ were obtained. On day 6, a negative COD removal was achieved even at low OLR. No COD was removed on day 6. Similarly, $\text{NH}_4^+\text{-N}$ removal also dropped. A residual effluent $\text{NH}_4^+\text{-N}$ concentration of $0.053 \text{ g NH}_4^+\text{-N}/\text{m}^3 \text{ day}^{-1}$ was obtained from an ALR of $0.15 \text{ g NH}_4^+\text{-N}/\text{m}^3 \text{ day}^{-1}$. On day 7, no COD removal was noticed. The $\text{NH}_4^+\text{-N}$ removal slightly increased with a residual effluent concentration of $0.053 \text{ g NH}_4^+\text{-N}/\text{m}^3 \text{ day}^{-1}$ from ALR of $0.18 \text{ g NH}_4^+\text{-N}/\text{m}^3 \text{ day}^{-1}$. The experiments were then terminated with no further improvement in COD removal.

DISCUSSION

It is well known that nitrogenous compounds are essential for the growth of microorganisms, plants and animals¹⁹. The removal of organic matter and $\text{NH}_4^+\text{-N}$ from the reactor could be attributed to several mechanisms such as adsorption, nitrification/denitrification and carbonaceous substrate consumption.

The COD and $\text{NH}_4^+\text{-N}$ removal fluctuated from day 1-7 of this study. The fluctuations in the residual effluent

concentrations could be attributed to the fluctuations in the influent feed. From day 1-5, COD removal fluctuated between 7.1-54%. However, a higher $\text{NH}_4^+\text{-N}$ removal was achieved in the range 13-94% from day 1-7. Phosphorus removal was also monitored and the reactor was found to achieve a removal in the range 13-48% from day 1-7. The COD removal could be attributed to the formation of biofilm by microorganisms at the root of the water hyacinth plant, which forms a complexation that promotes microbial degradation of organic matter²⁰. This is in agreement with previous findings in planted and unplanted wetlands^{21,22}. The presence of the water hyacinth also promoted nitrification, resulting in higher $\text{NH}_4^+\text{-N}$ removal. Higher ammonia removal in this study could be explained thus: At the root/soil interface, atmospheric oxygen is transferred to the root zone through the wetland plants thus creating an aerobic layer similar to the one that exist at the media/water or media/air interface. Nitrification process occurs in the aerobic rhizosphere where ammonia is oxidized to nitrate which is either taken up by the plants or diffuses into the reduced zone to be converted to N_2 or N_2O by denitrification²³. The removal of phosphorus by the plant could be attributed to the plant roots. It is well known that the roots of plants, especially aquatic macrophytes, both emergent and submerged, work as a giant biological filter that removes organic matter of all kinds. At the same time, microorganisms residing in the submerged roots in the wastewater can degrade other pollutants that are later absorbed by the plants²⁴. It has been reported that highly productive water hyacinth plants have higher nutrient uptake capacity²⁵.

An assessment of the contribution of duckweed *Lemna gibba*, a macrophyte and its associated microorganisms (algae and bacteria, forming an attached biofilm) for nutrient removal showed that the biological floating mat complex (plants and microbes) is responsible for up to 75% nutrient elimination in the wastewater. The macrophyte contributed up to 52% of phosphorus removal through its growth, the associated organisms and microorganisms removed the rest²⁶. Sun *et al.*²⁷ achieved a BOD_5 removal of 57.4 and 75.2% for a 4 stage tidal flow constructed wetland system without and with recirculation, respectively using a *Phragmites australis* plant. The ammonium removal was also 26.9 and 47.9% without and with recirculation, respectively. The experiment was conducted at HLR of $0.43 \text{ m}^3/\text{m}^2 \text{ day}^{-1}$. In a 4 cell surface flow constructed wetland study using young sprouts of *T. angustata*, Ghosh and Gopal²⁸ reported a COD mass reduction of 97.05% at HRT of 4 days. The nitrogen mass reduction was above 80% between HRT of 2-4 days. The mass

reduction rate for phosphorus simultaneously increased from 26.05-55% and then to 92% as the HRT was increased from 1, 2 and 4, respectively.

Towards the end of this study, a significant number of new young shoots of water lettuce were noticed in all the zones from day 4-6, indicating stability and growth. The variation in the performance of the wetland reactors could depend on the plant species, reactor configurations and flow pattern. The influent pH fluctuated between 4-6, whereas the effluent pH fluctuated between 6-9. The reactor effluent temperature also fluctuated between 27-36 °C.

CONCLUSION

The performance of an aquatic plant (water lettuce) for nutrient removal from sewage effluent was monitored in a sequencing steep flow baffled wetland reactor at fixed HLR and fluctuating OLR and ALR. It was found that the reactor has the capacity to remove COD, $\text{NH}_4^+\text{-N}$ and phosphorus at fluctuating OLR and ALR. The COD removal reached 54%, while $\text{NH}_4^+\text{-N}$ removal reached 94%. Phosphorus removal also reached 48%. The steep flow reactor demonstrated rapid acclimation and effective removal of organic and nitrogenous compounds within a short time. New young shoots of the plant were noticed from day 4-6, which indicate plant stability and growth. Further study at varying HLR and OLR are recommended to investigate the maximum loading capacity of the reactor.

ACKNOWLEDGMENT

The authors are grateful to Universiti Teknologi PETRONAS (UTP) for supporting this study.

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