Floating treatment wetlands and submerged vegetation for water quality improvement of an urban lake in megacity Jakarta, Indonesia

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Abstract. Most of urban lakes in Megacity Jakarta have become shallow, polluted and in eutrophic condition due to solids and nutrient pollution which requires urgent handling and management. Aquatic vegetation especially emergent and submerged plants in the lake littoral area have been known to play an important role to reduce the contaminants in the lake water. Floating Treatment Wetlands (FTWs) are cultivated plants growing on buoyant mats in open water. FTWs are an innovative tool that has been widely used for ponds and storm water quality improvement. This study aims to examine the effect of submerged plant and the ability of two different plants grown on Floating Treatment Wetlands (FTWs) system to improve an urban lake water quality. One urban lake has been selected for this study where the lake littoral at the inlet area has been overgrown by the submerged aquatic plant of Myriophyllum verticillatum. Two units of Floating Treatment Wetlands (FTWs) (size of 3 m² each) made of rubber mat and PVC pipes (3 inches) as buoyant material and planted with Heliconia densiflora and Vetiveria zizanioides. The performance of the FTWs applied and M. verticillatum was assessed by calculating the removal efficiency of nutrients and solids concentrations in the lake water of the coverage area. The observations of several water quality parameters including total nitrogen (TN), total phosphorus (TP) and total suspended solids (TSS) were made at the site before and after the submerged plant and FTWs. Both FTW_ H. densiflora and FTW_V. zizanioides removed more nutrients and also suspended solids per m² area than M. verticillatum. Although both submerged vegetation and FTWs can be used as tools to manage a long-term stability for good urban lake water quality, it will require intensive harvesting to control productivity of submerged vegetation.

1. Introduction
One of the serious problems facing urban water bodies is the pollution especially in the region where the urban development is not managed and sanitation facility is not available. Most of urban lakes in Megacity Jakarta receive garbage dump, untreated sewer and storm water runoff. Lake water pollution, siltation/sedimentation and eutrophication have been serious problem reported on urban lakes in Megacity Jakarta [1,2,3]. Water pollution problems faced by most of urban lakes include nutrient pollution, fecal and metal contamination and harmful algal bloom [2,3,4]. Non-point source pollution from urban runoff including excessive nutrients and solids become one of the largest uncontrolled sources of pollution to the lake. Lake siltation causes the lake become shallow and triggers invasive growth of emergent and submerged macrophytes [1,2]. The health condition of lake ecosystem such as impaired water quality has been a major concern due to most lakes have been used as water supply for drinking water plant, irrigation and fishery. The lakes are also used as recreational area and for fishing activity [1,2].
Restoration and management of urban lakes become crucial to reduce the pollutants especially nutrients and solids in the urban water bodies to decrease the risk of eutrophication and siltation. The use of plants to reduce nutrient concentration in the water bodies have been worldwide. Natural submerged plants have been reported to be able to restrain resuspension of bottom sediments to improve lake water quality of a eutrophic shallow lake [5] while Xu et al. [6] indicates that controlled biomass of submerged plant improve lake’s ecological health. Re-establishment of natural submerged plants is important to manage a long-term stability for clear water condition [7,8]. Common dominated shallow ponds submerged aquatic plant of *Myriophyllum verticillatum* has been studied in a constructed wetland system to treat nutrients contaminated waters [9]. Emerging green technology to improve lake water quality in situ has been introduced by Headley and Tanner [10,11,12] known as Floating treatment wetlands (FTWs). FTWs involve emergent plants growing on a buoyant mat floating on the surface water. The upper parts of plants grow above the water level while the roots extend down in the water column, creating root system which plays an important role on the nutrient uptake and pollutant transformation. The FTWs root network system provides surface area for biofilm which is responsible for biochemical transformation of contaminants [13,14,15]. Many studies have been done to examine the effectiveness of FTWs using single or a combination of two different types of emerging plants on nutrient removal or other type of contaminants from various wastewater sources. Most studies were done in mesocosm laboratory scale [10,12] and/or in field application in ponds [15,16,17].

Although FTWs have been studied worldwide, there is no field study on FTWs has been done in any type of lake in Indonesia. We have conducted a preliminary study to examine the efficiency of two FTW systems with different type of plants in reducing nutrient and suspended solid concentrations in a small urban lake in Megacity Jakarta area where part of its littoral area at the lake inlet has been overgrown by submerged vegetation of *Myriophyllum verticillatum*. We used *Vetiveria zizanioides* and *Heliconia densiflora* for the FTWs study. *V. zizanioides* has been widely studied [18,19], while no study has been reported on *H. densiflora*, however one study has been reported on *H. psittacorum* which has been evaluated in a constructed wetland system to treat domestic waste water [20]. We also examine the effectiveness of existing submerged vegetation in the lake in reducing nutrient and suspended solids concentrations in the lake as well.

2. Materials and methods

2.1. Study site

Field study of FTWs was conducted at Lake Cibuntu, an urban lake with small area of 2.11 ha and the depth range of 0.5 - 3 m. The lake is located in Bogor area (S 6°29’27.67” E 106°51’04.80””) with single inlet and outlet. Natural side of lake’s side is covered with grass type of riparian vegetation. Lake littoral on the inlet area is covered by submerged plant of *Myriophyllum verticillatum*. The total coverage area of the *M. verticillatum* studied was around 250 m² which is to the right part of the lake from the island. The lake water flows from the lake inlet passing through *M. verticillatum* area and continues to flow through the FTW system (Figure 1). The lake inlet channel is a connection of domestic waste drainage from neighbouring village in which constantly mixed with garbage dump. The garbage in the drainage system is trapped by a bamboo fence in the lake up stream so only the water enters the lake. The lake also receives storm water runoff from the office area. The lake water is slightly greenish and slightly turbid.

2.2. Design of Floating Treatment Wetland (FTW) systems

Two FTW systems were applied in Lake Cibuntu in 2015. The system each was consisted of 6 units of FTWs. The plants used in the FTWs are *Heliconia densiflora* (FTW_Hel) and *Vetiveria zizanioides* (FTW_Vet). Each unit of FTW (1 x 0.5 m, L x W) built with PVC pipes (3-inch Ø) (square floating frame) as buoyant material and holed rubber mat. Each unit FTW has 15 plants with single plant grown in the individual hydrophonic plastic cup (6 cm Ø (bottom) x 15 cm (height) x 10 cm Ø (top)) filled with growth media (Figure 2). The bottom layer plastic cup was removed before putting a single plant cup into each mat hole. The total number of plants for each FTW system were 90 with a total area of 3 m².
2.3. Sampling and lake water analysis

Water samples were collected every two weeks from August 14 to November 15, 2015 at the lake inlet (Lake_in), at the point after the water passing through M. verticillatum area (Myr), before passing the FTW (FTW_in) and after passing the FTW system of H. densiflora (FTW_Hel) and the FTW system of V. zizanioides (FTW_Vet) and at the lake middle which was 10 m distance from the FTWs (Figure 1).
1. Water temperature, pH, dissolved oxygen (DO), Total Dissolved Solids (TDS) and conductivity were measured directly every time sampling using a Water Quality Checker (Horiba U-10). Total Nitrogen (TN) and Total Phosphorus (TP) were analysed using spectrophotometric methods and Total Suspended Solids (TSS) determined using a gravimetric method. All lab analyses procedures were done according to APHA standard methods [21].

2.4. Plant growth and productivity
The growth of plants was observed by measuring randomly the plant root length after 1 months and 7 months, while biomass of FTW plants was measured after 35 days of observation. Total biomass (above and below part of the plants) from 4 plants were harvested and then air dried and oven dried (50°C) until the constant weight was obtained.

2.5. Data and statistical analysis
Removal efficiency and removal of nutrients and TSS per area were calculated using the following expression:

\[
\text{Removal Efficiency (RE)}(\%) = \left( \frac{\text{inlet conc.} - \text{outlet conc.}}{\text{inlet conc.}} \right) \times 100 \tag{1}
\]

\[
\text{Removal (mgL}^{-1}\text{m}^{-2} = \left( \frac{\text{inlet conc.} - \text{outlet conc.}}{\text{Area}} \right) \tag{2}
\]

Plant biomass density and productivity were calculated according to Olguín et al. [15]:

\[
\text{Biomass density (gm}^{-2}) = \text{Biomass dry weight (g) by surface of the units (m}^{2}) \tag{3}
\]

\[
\text{Productivity (g}^{-2}\text{d}^{-1}) = \left( \frac{\text{biomass density at t2} - \text{biomass density at t1}}{t1-t2} \right) \tag{4}
\]

The mean and standard deviation were calculated for plant shoot and root. All statistical analyses were conducted with Microsoft Office Excel (2013).

3. Results and discussion

3.1. Water quality
Figure 3 presents temporal variation of temperature, pH, total dissolved solids (TDS), conductivity in the water at all sampling points. Water temperatures at the lake inlet were 1 – 2 °C cooler than at the *M. verticillatum* area, FTWs and the lake middle. The pH values ranged from 6 to 7.5, although varied with time the pH values at all sampling points showed the increase trend. The pH values at all sampling points after *M. verticillatum*, before and after FTWs and at the lake middle were higher slightly than those in the lake inlet. The results of this study were in agreement with those of the previous studies which demonstrated the increase of pH in the lake water at the outlet of FTWs [15]. Both TDS and conductivity values decreased sharply after passing the area of *M. verticillatum* and showing slightly similar values at the area of both FTWs and at the lake. The results suggest that *M. verticillatum* with large enough of coverage area removes exceedingly suspended solids from the contaminated water inflow. Dissolved oxygen (DO) concentrations increased from around 4 mg/L at the lake inlet to as high as 12 mg/L (Table 1). The lake water is slightly greenish indicating moderate phytoplankton population. The lake is considered mesotrophic [22]. High DO concentration in the lake water could be attributed to the photosynthetic activity of the plants and phytoplankton as well [15,16,22]. This study showed that DO concentrations increased by 15 to 75%. Study by Olguin [15] indicates that FTWs using a combination of *Cyperus papyrus* and *Pontederia sagittata* increased DO pond water by average of 53%. The presence of FTWs is beneficial for ecosystem health by maintaining high DO level to support aquatic life and providing aerobic condition for microorganisms responsible in the lake self-purification process [15,17].
3.2. Performance of FTWs and submerged vegetation

Temporal variation of concentrations of total nitrogen (TN), total phosphorus (TP) and total suspended solids (TSS) in the water at all sampling points are shown in Figure 4 and 5. The concentrations of TN, TP and TSS in the lake water after passing the FTWs were < 1.5 mg/L, <0.1 mg/L and < 10 mg/L respectively. Similar results are shown by other study for TN and TP concentrations of pond water with FTW application [17]. The results show that concentrations of TN, TP and TSS decreased after passing *M. verticillatum* and the FTWs. *M. verticillatum* and both FTWs of *H. densiflora* and *V. zizanioides* gave a wide range of removal efficiency (RE) of nutrients and TSS (Table 2). *M. verticillatum* removed nutrients and TSS to as high as > 60% while both FTWs removed TN to the

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**Figure 3.** Temporal variation of temperature, pH, total dissolved solids (TDS), conductivity in the water at the lake inlet, after *M. verticillatum*, before and after the FTWs and at the lake.

**Table 1.** Ranged of Dissolved Oxygen (DO) in the water at the lake inlet, after *M. verticillatum*, before and after the FTWs and at the lake.

| Sampling Point | DO (mg/L)     |
|----------------|---------------|
| Lake_in        | 1.31 - 4.88   |
| Myr            | 9.73 - 12.33  |
| FTW_in         | 10.84 - 11.95 |
| FTW_Hel        | 9.7 - 12.07   |
| FTW_Vet        | 8.41 - 12.25  |
| Lake           | 9.88 - 11.95  |
highest of 60% and removed TP and TSS at around 40%. When we compare the RE of nutrients and solids in total area studied, *M. verticillatum* had slightly better performance than those of FTWs. However, both FTWs clearly had much higher RE of nutrients and solids per m² area while *M. verticillatum* only gave RE of pollutant at the highest of 0.25% per m² area (Table 3).

![Figure 4](image1.png)

**Figure 4.** Temporal variation of total nitrogen (TN) and total phosphorus (TP) concentrations in the water at the lake inlet, after *M. verticillatum* (above), before and after the FTWs and at the lake (below).

![Figure 5](image2.png)

**Figure 5.** Temporal variation of total suspended solid (TSS) concentrations in the water at the lake inlet, after *M. verticillatum* (right), before and after the FTWs and at the lake (left).

Both FTWs showed somewhat similar performance in removing nutrients and TSS. Our study gave similar RE of TN and TP with the FTWs of the previous study [10]. The FTW field study using a combination of *Cyperus papyrus* and *Pontederia sagittata* gave a wide range of phosphate and nitrate
removal percentage with the highest average of 76±0.49% and 67±3.53% respectively [15]. Plant harvesting strategy resulted in high nutrient removal by FTW and/or M. verticillatum [9, 15,16,17]. Submerged macrophyte removed 6 g N, 1 g P per m² at intermediate harvesting frequencies (3 x during growing season).

Table 2. Removal efficiency (%)

| Area (m²) | TN  | TP  | TSS |
|-----------|-----|-----|-----|
| FTW_H. discolor | 3   | 18 - 68 | 21 - 45 | 15 - 45 |
| FTW_V. zizanioides | 3   | 12 - 66 | 19 - 42 | 12 - 36 |
| M. verticillatum | 250 | 33 - 71 | 39 - 62 | 18 - 62 |

Table 3. Total nitrogen (TN) and total phosphorus (TP) removal per area

| TN removal (mg.L⁻¹.m⁻²) | TP removal (mg.L⁻¹.m⁻²) |
|-------------------------|-------------------------|
| Weeks                   | Weeks                   |
| 2   | 4   | 5   | 7   | 2   | 4   | 5   | 7   |
| FTW_Hel | 0.083 | 0.472 | 0.801 | 0.07 | 0.007 | 0.007 | 0.02 | 0.007 |
| FTW_Vet | 0.045 | 0.514 | 0.799 | 0.043 | 0.003 | 0.01 | 0.013 | 0.07 |
| Myr   | 0.004 | 0.008 | 0.012 | 0.016 | 0.0003 | 0.0005 | 0.0006 | 0.0002 |

In tropical land, such as Indonesia, to give high nutrient removal and to avoid nuisance problem in the lake ecosystem, the plant harvesting strategy should be at high frequency due to much higher plant growth rate. This study did not assess the nutrient uptake rate by each plant of FTWs and M. verticillatum. Assessment of nutrient uptake rate in the FTW field study was usually done by measuring nutrient content in the plant tissues using harvesting strategy of FTW plants in specified area [15,17]. Previous studies have reported different uptake rate of nutrients from the lab scale mesocosm and field studies. FTW_V. zizanioides could remove N and P from the waste water with the rate of 1.1-2.5 g.m⁻²·d⁻¹ and 0.1-0.88 g.m⁻²·d⁻¹ respectively [18]. Our other lab scale FTW study in batch trials with V. zizanioides had lower N and P removal rate of 0.13 and 0.03 g.m⁻²·d⁻¹ respectively, while H. densiflora only removed N with lower rate removal of 0.07 g.m⁻²·d⁻¹ [23]. V. zizanioides in constructed wetlands (CWs) showed RE as high as 59% for TN and only 25% for PO₄ [19]. H. densiflora gave high RE of TSS to about 80% but very low RE of TN and TP in CW system. The rate uptake of N was only 0.28 g.m⁻²·d⁻¹ [20]. Tanner and Headley [12] demonstrated that the FTWs in batch trials gave much higher areal removal rate of TN and TP than in flow-through field trials. In field studies with large volume and continuous water flow, the lake water constantly mix and pass by the FTWs much faster than in a controlled batch system giving insufficient time for the pollutant in the water into contact with the network root system of the FTWs.

The results of this study, supported by the results of previous other studies suggest that H. densiflora and V. zizanioides in the FTW system are capable of removing substantial amounts of nutrients and solids from eutrophic lake waters. With relatively small area, FTW removed more nutrients and solids than M. verticillatum in the sizeable area.

3.3. Plant growth and productivity

Both H. densiflora and V. zizanioides grew well in the FTW system indicating by the root development beneath the floating mats. The root length for both plants increase to as high as 50% in 6 months observation (Table 4), although the root masses of H. densiflora were not as dense as the masses of V. zizanioides roots. Our lab scale FTWs study demonstrated better root development and much denser root masses for both plants [23]. The development of root system of the plants is the key for the FTWs performance of nutrients removal. The denser root masses are the more nutrient uptake
from the waters. The root masses provide extensive surface area for attachment of microbial biofilms, assimilate nutrients from water columns, transform other pollutants and changes environmental condition beneath the mat [12,14]. Tanner and Headley [12] demonstrated higher N:P ratio removal by the FTWs in the water column than in the shoot tissue N:P ratio for the flow through study indicating that more N removal was taking place in the presence of FTWs than could be counted for by plant uptake alone. The total biomass productivity estimated for shoot and root masses dry weight (DW) of V. zizanioides was almost doubled in comparison to H. densiflora biomass productivity (Table 5). Our observation from both lab scale and in field studies indicated that the growth of H. densiflora much slower at the initial phase, however when they have adapted with the environmental condition H. densiflora will continue to grow and develop more siblings and it does not require regular harvesting. The use of H. densiflora for FTWs will be beneficial for long term lake water quality management. On the other hand, M. verticillatum has very fast growth rate and cover large area but it has much lower DW biomass density of 28.93 g.m\(^{-2}\) than DW biomass density of V. zizanioides (2675.19 g.m\(^{-2}\)) and H. densiflora (6687.90 g.m\(^{-2}\)) in the FTW system. Higher plant biomass density results in more nutrients removal in the waters. The previous studies have demonstrated that the FTWs with high plant productivity gave high removal of nutrients [12, 15, 16, 17].

**Table 4. Root length of FTW plants**

| Plant          | Root length\(^{1}\) (cm) | Root length (cm)\(^{2}\) |
|----------------|----------------------------|--------------------------|
| H. densiflora  | 20±9.59                    | 50.16±17.79              |
| V. zizanioides | 23.9±5.29                  | 53.13±16.94              |

\(^{1}\)one month observation; \(^{2}\)7 months observation

**Table 5. Productivity of FTW plants**

| Plant          | Productivity (g.m\(^{-2}\). d\(^{-1}\))\(^{a}\) |
|----------------|-----------------------------------------------|
| H. densiflora  | 24.86                                         |
| V. zizanioides | 60.93                                         |
| M. verticillatum | 28.93\(^{b}\)                               |

\(^{a}\)Biomass (shoot and root masses dry weight (DW)) productivity in 35 days
\(^{b}\)Biomass density (dry weight) (g.m\(^{-2}\))

Based on the coverage area, the FTWs have better performance in removing nutrients and solids in the lake water than submerged vegetation such as M. verticillatum. It requires a vast area for M. verticillatum to have significant nutrients removal efficiency. M. verticillatum will be ideal for nutrients removal in a constructed wetland system [9], but overabundance of these species can become a nuisance to the ecosystem. This fast growing submerged macrophyte species has long been known to severely impair fishing, recreation and hydrological functioning of the lake ecosystem. Therefore, they require to be managed to reduce these problems. In tropical urban lakes, such as Lake Cibuntu and other urban lake in Megacity Jakarta, M. verticillatum grows much faster and has long known to cause lake siltation and nuisance problem to the lake [22]. It requires more frequent harvesting in order to control their massive growth which will add the lake management cost [9]. Regardless of requiring extensive and frequent harvesting, the presence of M. verticillatum is important for the ecosystem to control phosphate release and to prevent solids resuspension from sediments and furthermore maintaining lake ecosystem health [5,6,22]

4. Conclusion

Our preliminary filed study demonstrated the potential of Vetiveria zizanioides and Heliconia densiflora in FTW system in removing nutrients and suspended solids in a small urban lake. The presence of submerged vegetation of Myriophyllum verticillatum in a controlled area was very beneficial to trap solids from the contaminated inflow and control phosphate release from sediments.
Both the FTWs along with controlled submerged vegetation can be used as tools to manage a long-term stability for good lake water quality. The important service to the lake ecosystem by FTWs and the presence of *M. verticillatum* is the increasing of DO in the lake water. High DO is one of indicators that ecosystem is healthy in supporting aquatic life and providing aerobic condition for microorganisms responsible in the lake self-purification process. FTWs clearly have advantages over submerged vegetation to remove nutrients and solids in the water column, but the presence of submerged vegetation has the advantages over FTWs to remove nutrient and to sustain solids in the lake sediments although it requires a large area for submerged vegetation to have significant pollutant removal efficiency. Disadvantage of the presence of submerged vegetation is the need for more frequent harvesting to control the productivity and to avoid nuisance effect and lake siltation which indeed will add to the management cost.

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