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DEWATERING OF URBAN LAKE SEDIMENTS USING CONSTRUCTED WETLANDS: A CASE STUDY IN HANOI, VIETNAM

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ABSTRACT: Over the past two decades, the large volume of dredged sediments with high water content from urban lakes pressurize the landfill site's area requirements and environmental sanitation in Hanoi, Vietnam. This paper evaluated the dewatering efficiency of sludge treatment wetlands (STW) with or without *Cyperus alternifolius* and aeration for dredged sediments from Bay Mau Lake (Hanoi). Three pilots simulated different conditions of STWs were conducted in the batch condition, pilot-scale within six months. The supernatant and leachate volumes were recorded daily, while sludge samples were collected from different sludge depths twice per month. Characteristics of sludge samples, including water contents (WC), total solids (TS), and the ratio of volatile solids to dry solids (% VS/DS), were analyzed to assess dewatering efficiency over time and end of experiments. Plant height and biomass were measured before vegetation and after harvesting to evaluate the growth of *C.alternifolius* in the sediment matrix. The optimum result was obtained in the aerated planted wetland with WC, sludge volume reduction, TS, and VS/DS of 36.2%, 33.6%, 63.8%, and 6.5%, respectively. After the adaptation period, *C.alternifolius* grew well and contributed to the dewatering process in STWs. Those results implied the possibility of using STWs for urban lake sediment treatment with *C.alternifolius*, aeration, and batch condition.

Keywords: Sludge treatment wetlands, Cyperus alternifolius, Lake sediments, Dewatering process

1. INTRODUCTION

The dredging activity, including removing sediments from lakes, and disposing of them in other sites, is a practical approach for permanently decreasing the internal loading of nutrients and controlling heavy metals [1-5]. That traditional approach is essential in lakes with vast sediment and unstable environments [4,6]. However, dredged deposition with high water contents requires large landfill sites and poses a high secondary pollution risk involving releasing contaminants into the surrounding environments [7, 8]. Such limitations have elevated the demand for innovative technologies that can reduce land requirements, improve sludge treatment, and be appropriate to local economic-technological conditions.

Among current treatment technologies, sludge treatment wetlands (STWs) are a nature-based system applied worldwide over a few decades and in various climates at different scales [9-11]. Sludge treatment wetlands were proven to dewater and work well with multiple sludges, from septic sludge, fecal sludge, industrial wastewater treatment plant, and wastewater treatment plants with different treatment process trains [9-14]. Although phytoremediation has been suggested for sediments from water bodies [15, 16], there needs to be more research on STWs for lake sediments.

Sludge treatment wetlands are constructed as vertical flow systems for sludge dewatering and stabilization, resulting in reduced sludge volume and efficient cost enhancement [17]. The operation regime in STWs is usually a semi-continuous condition in which the resting phase is arranged alternately between two consecutive feeding phases. Sludge is loaded to the basins in each loading phase until reaching the designated height and dewatered through passive drainage and evapotranspiration [18]. That procedure is suitable for the sludge that is consistently supplied over the operation cycles of STWs. However, the semi-continuous regime is not appropriate for lake sediments dredged depending on the project and dumped only once at the landfill site.

The plant species utilized in STWs are perennial, local, prolific, adaptable in watery, muddy, and anaerobic conditions, and possess high evapotranspiration rates [9]. Umbrella papyrus plants (*Cyperus alternifolius*) have been widely vegetated as the floating beds in Hanoi lakes to create an aesthetic landscape and clarify lake water. *C.alternifolius* can support oxygen and reduce organic matter and nutrients not only for lake water but also for domestic wastewater in Hanoi [19-21]. *C.alternifolius* adapted well and reduced organic content, nitrogen, and phosphorus concentrations in sludge from an industrial zone in the South of Vietnam [22]. Based on its ability to adapt to local natural conditions, grow well in the lake environment, and strongly absorb organic matter and nutrients, *C.alternifolius* is a potential plant candidate in STWs for Hanoi lake sediments.

2. RESEARCH SIGNIFICANCE

Even though STWs have been applied for various types of sludges, there needs to be more research on STW for lake sediments. In addition, the semi-continuous regime widely employed in STWs is not appropriate for the dredging schedule of lake sediments. This research specifically aimed to study the growth of *C.alternifolius*, investigate the ability of dewatering processes, and assess the effects of the batch condition, vegetation, and passive aeration in STWs for urban lakes in Hanoi (Vietnam). The pilots in this research are the first STWs planted with *C.alternifolius* for dredged lake sediment dewatering.

3. MATERIALS AND METHODS

3.1 Research Object

Bay Mau Lake (N21°01', E105°51') has a surface area of 0.15 km^2 and an average depth of 2m. The lake plays a vital role in stormwater regulation in the center of Hanoi. To reduce internal pollution loading and enhance the regulation depth of the lake, Hanoi Sewerage and Drainage Company (HSDC) has separated domestic wastewater from lake water and treated it in Bay Mau Wastewater Treatment Plant since 2008. Since then, sediment dredging activity has been conducted every five years. In 2021, the HSDC company dredged a one-meter-thick sludge layer from a surface area of 3000 m^2. The sediment was hauled by barges to the sampling site during the daytime and dredged ashore by excavators at night. After that, the dredged sludge was sucked by a suction machine and transported to the Yen So landfill site, which receives all Hanoi sludge. For this experiment, dredged sludge was collected directly from Bay Mau Lake with the support of HSDC in November 2021.

3.2 Experimental Diagram and Pilot Operation

3.2.1 Experimental diagram

Three pilots simulated different conditions of constructed wetlands, as shown in Fig. 1, including a pilot with aeration and plant (CW1), a pilot with plant and no aeration (CW2), and a pilot without plant and aeration (CW3). Each pilot was built from 5 mm-thick layers of poly methyl methacrylate, with a dimension of 0.5m×0.5m×1.2m (L×W×H). Two sludge holes were designed corresponding to the top and bottom layers to collect sludge samples over the resting phase. Another sampling spot was installed at the bottom of each pilot to collect leachate daily. The saplings of *C.alternifolius* were supplied by HSDC and vegetated in CW1 and CW2 immediately after sludge loading. The plant density was 16 saplings·m^{-2}, similar to the pilots in another research [19, 22].

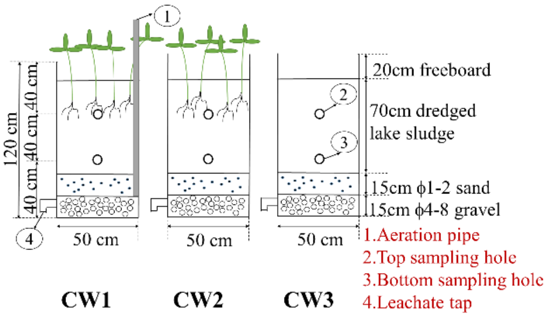

Fig.1 A schematic diagram of constructed wetlands

3.2.2 Pilot operation

Dredged sludge was loaded in three pilots immediately after being collected from Bay Mau Lake. The pilots were operated in batch condition, as shown in Table 1. The resting phase stopped when the sludge depth did not change anymore. The supernatant was withdrawn using a manual suction pump when its depth reached a constant value. The leachate tap was opened every day to drain all the leachate into the plastic containers. That tap was closed when there was no more leachate leaking out.

3.3 Sample Collection, Preservation, and Analysis

The sample collection and monitoring for the supernatant, leachate, and sludge were conducted as below:

The supernatant and leachate: the depth was measured daily to assess the rate, accumulated volume, and water balance.

Sludge: Top and bottom sludge layers were sampled, and sludge depth was measured approximately twice per month. Sludge samples were collected and preserved under TCVN 6663-13: 2000 (ISO 5667-13: 1993) and TCVN 6663-15: 2004 (ISO 5667-15: 1999). Physical characteristics of sludge samples, including water content (WC), total solids (TS), and the ratio of volatile solids to dry solids (VS/DS), were analyzed according to TCVN 4196:2012 "Soils - Laboratory methods for determination of moisture and hygroscopic water amount" and EPA Method 1684 "Total, Fixed, and Volatile Solids in Water, Solids, and Biosolids"

(Table 2).

Plant: *C.alternifolius* bushes were divided into two equal parts before being planted. The former was washed off dirt, air dried, measured in length, and weighed wet biomass. The trees were then cut into small pieces, dried at 103°C - 105°C for 2 hours, cooled down in a desiccator, and weighed again to identify dry biomass. The latter was planted in pilot CW1 and CW2, as described in 3.2.1. After an operating period, plants from CW1 and CW2 were harvested and measured with the same procedure as before vegetation.

Table 1 Pilot operation

Parameters	Unit	Value
Loading phase	day	1
Lake sludge volume	L	175
Sludge loading rate	$kgTS \cdot m^{-2}$	180
Resting phase	day	166

Table 2 Characteristics of Bay Mau Lake sludge and analytical methods

Parameters	Mean (Min-Max)	Analytical method
WC (%)	81.0 (79.5-82.0)	TCVN 4196:2012
TS (%)	19.0 (18.2-19.6)	EPA Method 1684
VS/DS (%)	18.1 (17.2-19.3)	EPA Method 1684

3.4 Water balance estimation

The equation for water balance in this study was modified according to [23, 24] and illustrated in Eq. 1:

$$V_{W.LS} = V_{Sp} + V_L + V_{W.RS} + E_T \quad (1)$$

Where $V_{W.LS}$ is the water volume in influent sludge (L), and V_{Sp} represents the supernatant volume (L). V_L abbreviates for the leachate volume (L). $V_{W.RS}$ is the water volume maintained in residue sludge at the end of the resting phase (L). E_T represents the estimated evapotranspiration volume (L). In this research, precipitation was eliminated due to the condition of the experimental site.

3.5 Data and Statistical Analysis

A two-way analysis of variance between groups (two-way ANOVA) was conducted to investigate the effect of vegetation and aeration along time on the supernatant rate, leachate rate, water content, total solids, and VS/DS among three pilots. The Tukey test was utilized to evaluate the dewatering efficiency among the three systems, with the significant difference set at $p<0.05$. The statistical analyses were performed using StatPlus software v.7.6.5.0 (AnalystSoft, USA).

4. RESULTS AND DISCUSSION

4.1 Dewatering Efficiency

4.1.1 The supernatant and leachate

Water was separated from the upper sludge layers in all three pilots in the first seven days and then withdrawn. The depth of the supernatant layer reached 7.8cm, corresponding to 19.5L (Fig. 2a and 2b). The supernatant separation happened fastest on the first day and reduced until the seventh day. There is no significant difference among each pair of three pilots regarding the supernatant rate, as summarized in Table 3. That sludge-water separation phase has the exact mechanisms as those in a gravity sludge thickener.

Table 3 Results of statistical analyses among pilots on the supernatant rate, leachate rate, and characteristics of top and bottom sludge layers

Parameters	CW1 vs. CW2	CW2 vs. CW3	CW1 vs. CW3
Supernatant rate	N	N	N
Leachate rate	N	N	N
WC-top	Y	Y	Y
WC-bottom	Y	Y	Y
TS-top	Y	Y	Y
TS-bottom	Y	Y	Y
VS/DS-top	Y	Y	Y
VS/DS-bottom	Y	Y	Y

Y: significant difference; N: No difference; CW1: vegetated, aerated pilot; CW2: vegetated, unaerated pilot; CW3: unvegetated, unaerated pilot

The leachate was percolated from the model CW1, CW2, and CW3 until the 143rd, 146th, and 160th day, respectively (Fig. 2c and Fig. 2d). We observed that the solid and water separated the fastest in the first seven days in all three pilots. Our observation again confirmed that the dewatering happening in the first week was mainly due to the settling and percolation. After one week, the leachate rate reduced over time, meaning that the loss of free water did not play a significant role in dewatering as before. Table 3 illustrated no significant difference in leachate rate in the three pilots. Despite that, the percolation occurred the shortest in CW1, proving that vegetation and aeration enhanced the water losses more than in the other pilots.

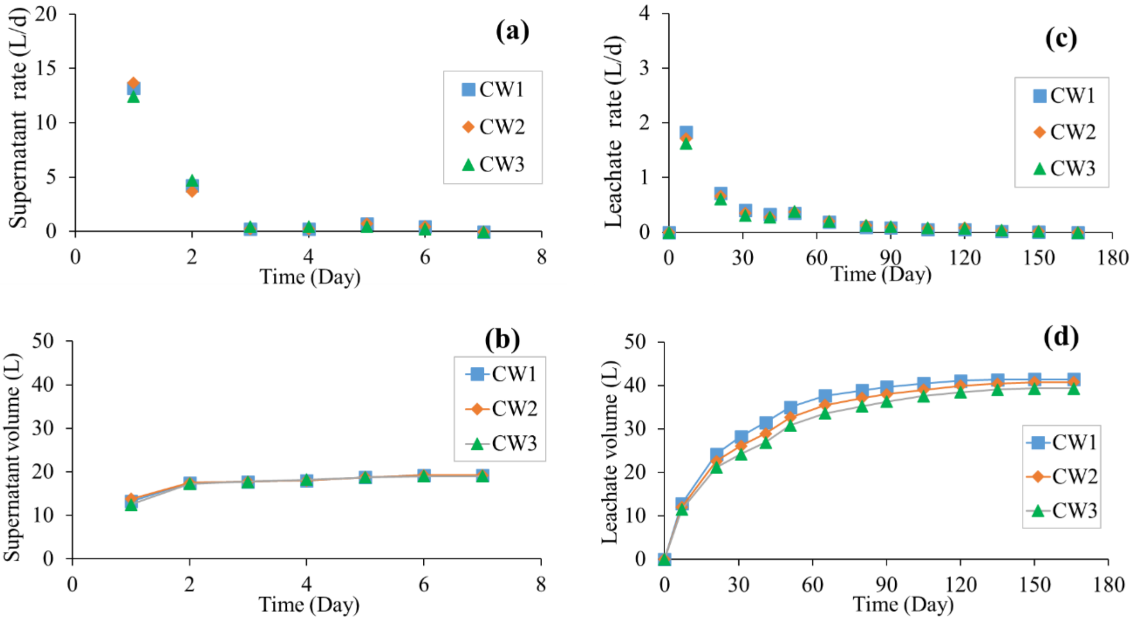

Fig 2 Longitudinal rate and accumulated volume of the supernatant and leachate (a. Supernatant rate; b. Accumulated supernatant volume; c. Leachate rate; d. Accumulated leachate volume)

Like the thickening sludge process, water was separated from the upper and bottom layers in pilot CWs. That sludge-water separation was different from the dewatering processes described in STWs for sewage sludge and fecal sludge, which did not report those separations [9, 13, 14, 24–28]. The reason may be due to the ratio of VS/DS in Bay Mau Lake sediments (Table 1) that is lower than in sewage sludges. The higher the organic matter in sludge is, the less free water and the more capillary water is, leading to low dewatering efficiency [18].

4.1.2 Water content and sludge volume

The top and bottom sludge layers' longitudinal water content (WC) can be observed in Fig. 3a and 3b, while Fig. 4a illustrates WC at the end of the resting phase. According to Fig. 4a, WC reduced over time and reached 36.2%, 37.5%, and 40.1% in CW1, CW2, and CW3, respectively. Water loss reduced in descending order from CW1, CW2, to CW3 with the value of 44.8%, 43.5%, and 40.9%, respectively. Meanwhile, sludge volume reduced from 175L to 116L, 120L, and 138L, meaning 33.6%, 31.7%, and 21.4% reduction in CW1, CW2, and CW3, respectively (Fig. 4b). Those results again demonstrated the advantages of sludge treatment wetlands in sludge dewatering and volume reduction. They agreed with the findings of previous studies using *C. papyrus*, *C.alternifolius*, and *C. alopecuroides* plants from the *Cyperus* Genus in the tropical region [12, 22, 25]. However, the water loss in our study was much higher than in STW for septic sludge and sludge from industrial WWTP (9%-15%) and slightly lower than in STW for sewage sludge (45%)[12, 25].

Table 4 presented no significant difference in WC among the three pilots at the end of the resting phase. However, statistical analyses showed differences in the WC of the top and bottom sludge layers among each pair of models (Table 3).

4.2 Total Solids and Volatile Solids

4.2.1 Total solids

Figures 3c and 3d showed TS in the top and bottom sludge layers over time, while Fig. 4c demonstrated TS in residue sludge after the experiments. It can be seen from those figures that TS increased over time and reached 63.8%, 62.5%, and 59.8% in CW1, CW2, and CW3, respectively. The increase of TS concentration in residue sludges from 3 pilots ranged from 40% to 44%, higher than the efficiency of 20.3% and 13.9% by STWs with common reeds (*Phragmites australis)* and broadleaf cattails *(Typha latifolia)* for activated sludge from an extended aeration tank in Greece, respectively [26].

Table 3 and Table 4 presented a significant difference in longitudinal TS among three pilots and CW1 and CW3, CW2, and CW3 at the end of our study. Despite no significant difference among each pair of pilots at day 166 (Table 4), TS decreased in descending order from CW1, and CW2 to CW3, implying the effectiveness of *C. alternifolius* and ventilation effectiveness in STWs.

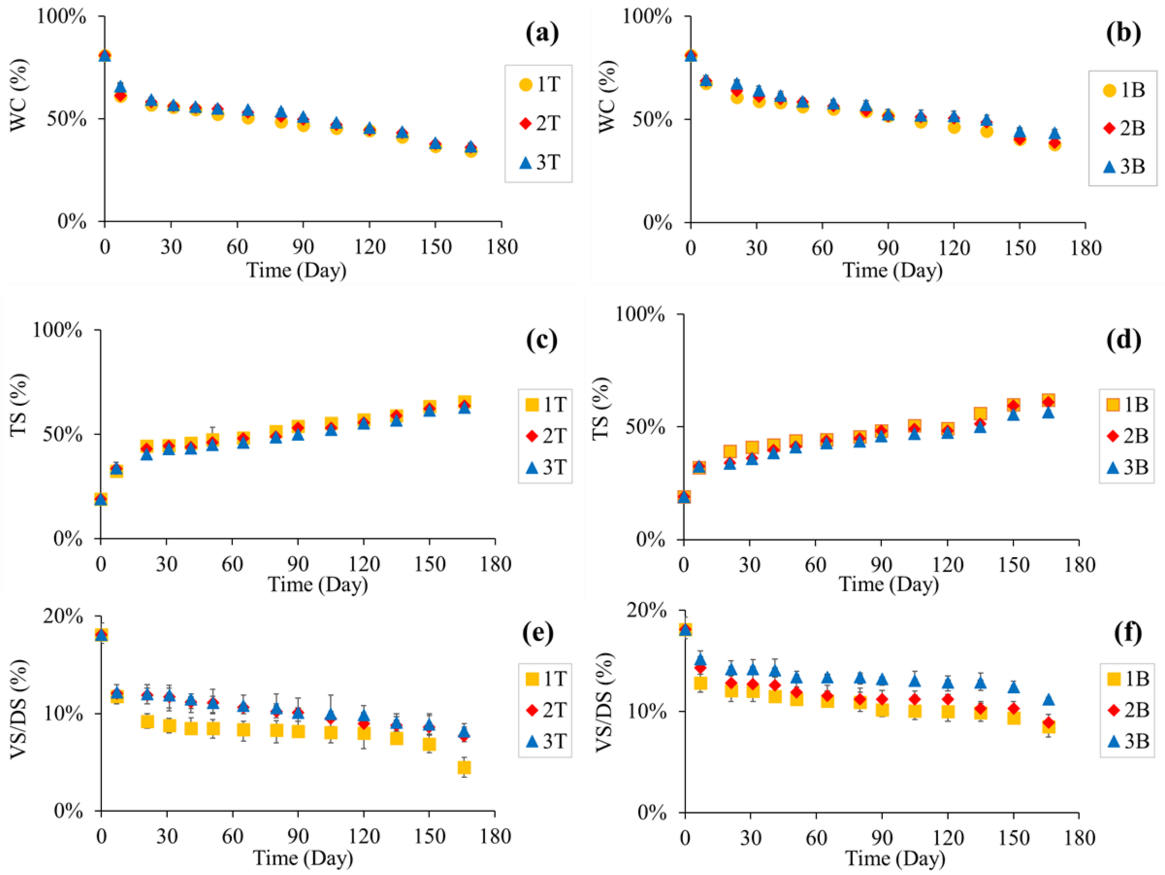

Fig.3 Longitudinal water content, total solids, ratio VS/DS of sludge layers in each pilot (T: top layer B: bottom layer, 1: planted, aerated pilot; 2: planted, unaerated pilot; 3: unplanted, unaerated pilot)

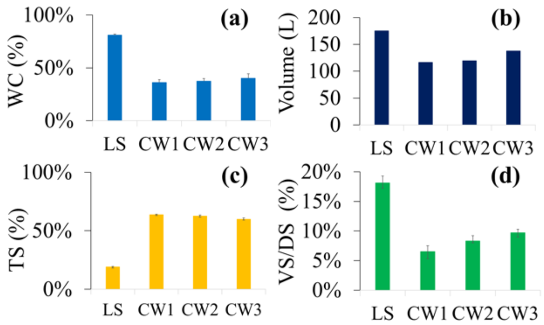

Fig.4 Water content (WC), sludge volume, total solids (TS), and ratio VS/DS of lake sediment and residue sludge

Table 4 Results of statistical analyses on WC, TS, VS/DS among residue sludges after experiments

Parameters	CW1 vs. CW2	CW2 vs. CW3	CW1 vs. CW3
WC	N	N	N
TS	N	Y	Y
%VS/DS	N	Y	Y

Y: significant difference; N: No difference; CW1: vegetated, aerated pilot; CW2: vegetated, unaerated pilot; CW3: unvegetated, unaerated pilot

4.2.2 Volatile solids

The ratio of volatile solids to dry solids are usually used to assess the level of organic matter in sludge [17, 27]. Although Bay Mau Lake only receives stormwater from the surrounding area, aquatic organisms still decompose and settle in the lake, resulting in organic matter in the sediment. The VS/DS decrease indicated the degradation of organic matter in all three pilots.

The decrease of longitudinal VS/DS in the top and bottom sludge layers is illustrated in Fig. 3e and 3f, while Fig. 4d depicts VS/DS ratio in residue sludge after the experiments. During the investigation, VS/DS decreased by 11.6%, 9.8%, and 8.4%, reaching the final values of 6.5%, 8.3%, and 9.7% in CW1, CW2, and CW3, respectively. These reductions were lower than those found in STWs with reed beds *(P.australis)* for activated sludge from UK and Poland (i.e., reduced by 15%-18%) but similar to the finding in Spain (i.e., reduced by 2%-15%) [9]. It is noteworthy that inlet sludge in reports from Spain recorded VS/DS ranging 42%-67% while VS/DS in Bay Mau Lake sediment was 18.1%.

Table 3 and Table 4 presented a significant difference in longitudinal VS/DS among three pilots and CW1 and CW3, CW2, and CW3 at the end of our study. Like the results concerning TS, statistical analyses showed no significant difference between CW1 and CW2 on the last day (Table 4).

4.4 Water Budget in Constructed Wetlands

The contribution of each process for dewatering efficiency was accounted as a percentage of the water volume in the inlet sludge (Fig. 5). The supernatant and leachate volumes were measured daily. Water volume in the influent and residue sludges was indirectly through TS, sludge volume, and sludge density.

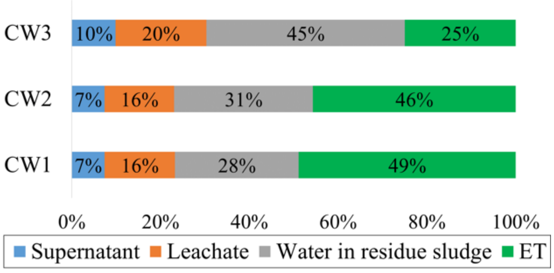

Fig. 5 Water budget in research pilots

Figure 5 revealed the role of settling and percolation in free water losses in STWs for lake sediments. Combining the contribution of the supernatant and leachate, free water losses in CW1, CW2, and CW3 ranged from 23%-30%. Thus, settling and percolation are essential in dewatering efficiency in STW with no plants and aeration tubes. Also, settling contributed to the separation of free water in lake sludge, rarely reported in the water budget resulting from STWs for other types of sludges [23]. It is probably due to the different content of organic matter in Bay Mau Lake sediments and those sludges.

Based on the water distribution in the three CWs, evapotranspiration (ET) ranged from 25%-49% in ascending order of CW3, CW2, and CW1. ET contributed less than the leaching and settling in pilot CW3. Also, ET in unvegetated pilot CW3 is less than in planted units CW1 and CW2. ET, thus, played the leading role in water loss in vegetated pilots, meaning the significant contribution of plants to the dewatering performance of STW. That result agreed with other studies and once again confirmed the roles of plants in STW [9, 11]. However, ET reported for vegetated units in this research were lower than those noted for other STWs with *Canna indica, Phragmites australis, and Typha angustifolia* of different sludges in the tropical region (57–77%) [13, 24, 28].

4.5 Plant Growth and Dewatering Efficiency

4.5.1 Plant growth

Table 5 summarizes the plant height and biomass change before plants were vegetated and after they were harvested from pilots. We observed that the plants started to grow after one week when the accumulated supernatant was manually withdrawn from the pilots. Plant height increase doubled while biomass yielded 178%-187% and 140%-165% regarding raw and dry biomass, respectively.

Comparing the growth of *C. alternifolius* in the lake sediments with that in sludges from industrial WWTP, it was found that the height of the plants in the two experiments increased equally. The plant height increased by 31-37cm for six months with Bay Mau Lake sludge and by 16cm for three months with industrial wastewater sludge [22]. Our research yielded biomass of *C.alternifolius* higher than that of *P. australis*, *C.alopecuroides*, and *T. latifolia* in Greece and Egypt [25, 27, 29]. Biomass of common reeds (*P.australis)* increased by 243.9-1133.3g·m^{-2} in the second and third years of the operation period and reduced by 794.0 g·m^{-2} at the end of the experiment in Greece. Broadleaf cattails (*Typha latifolia)* increased weight by 121.1g·m^{-2} in the first year. The biomass of *P.australis* and *C.alopecuroides* increased by 90% and 50% in pilot-scale STWs in Egypt. The sludge loading rate, organic matter, and nutrient content in the above sludges are higher than in the Bay Mau Lake sediment. *Cyperus alternifolius* grew well in the sediment matrix of Hanoi lakes since it had probably been adapted in advance to the environment of lake water.

Table 5 Plant height and biomass before vegetation and after harvest

Plant	Height (cm)	Raw biomass (g·m^{-2})	Dry biomass (g·m^{-2})
Before vegetated	30 (28-31)	384.64	58.44
CW1	67 (62-72)	1102.00	154.80
CW2	61 (55-68)	1068.80	140.00

CW1: vegetated, aerated pilot; CW2: vegetated, unaerated pilot

4.5.2 Cyperus alternifolius plants' role in the dewatering process

As mentioned above, the TS increase in lake sludge by *C.alternifolius* was better than in sewage sludge by *P.australis* and *T.latifolia* [27, 29]. The mineralization capacity of *C.alternifolius*, as assessed by VS/DS, was equivalent to *P.australis* for sludge from Spain [9]. Compared with other *Cyparus* Genus plants in STWs in the tropical region, the moisture-reducing capacity of *C.alternifolius* is similar and should be considered for different sludges [12, 22, 25].

Our results regarding physical characteristics and reduced volume of residue sludges reinforced the point that plants play an essential role in STWs. The dewatering processes in vegetated systems (CW1 and CW2) include leaching, settling, evapotranspiration (ET), and microbial activities. Plants can use capillary water and bounding water to yield biomass. In addition, the fibrous root systems create cracks in the sludge surface, making it easier for water to evaporate. In addition, oxygen is transported into the rhizosphere around plant roots, leading to more sufficient microbial activities [9, 30].

Table 5 shows that plants in CW1 grew slightly better than in CW2. The results of sludges from CW1 and CW2 also confirmed the effectiveness of ventilated CW compared with non-ventilated CW and agreed with previous studies [31]. The aeration tubes facilitate oxygen supply to the bottom sludge layer, promoting aerobic conditions for heterotrophic microorganisms. As a result, the amount of water in the sludge is further consumed in the microbial population's metabolic and energy exchange activities. Passive aeration promotes the organic matter change into humus and improves plant growth.

5. CONCLUSIONS

According to our study, sludge treatment wetlands with umbrella papyrus and passive aeration are appropriate solutions to minimize large landfill site areas for Hanoi urban lake sediments. *C.alternifolius*, planted widely in Hanoi lakes, was an ideal candidate for wetland plants since CWs with plants provided lower water content, VS/DS ratio, and higher total solids in residue sludges. *C. alternifolius* could grow in a sediment matrix, accelerate dewatering, and support mineralization after a short adaptation period. The simultaneous presence of ventilation pipes and plants improved the dewatering efficiencies regarding physical sludge characteristics and sludge volume reduction. Instead of operating in a semi-continuous regime like STW for other sludges, STWs applied to lake sediments in Hanoi (Vietnam) should be conducted in batch mode without intermittent sludge loading for better dewatering efficiency.

6. ACKNOWLEDGMENTS

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