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Pilot-scale water hyacinth bed for dewatering of sewage sludge

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ABSTRACT

Water hyacinth *(Eichhornia crassipes)*, an aquatic plant, was tested for its ability to improve the dewatering of sewage sludge to increase the capacity of existing or new conventional drying beds. Three experimental runs were conducted in an outdoor environment, two of them were in a batch lab-scale while the third was in a pilot scale. The effect of multiple addition of sludge and the plant density on the performance of the system were tested in the experiments. Controls were used in all experiments. The experiments were conducted using liquid sewage sludge collected from wastewater treatment plants in Egypt. The sludge used in the experiments represents a mixture of primary sludge and waste activated sludge collected before discharging into drying beds. The current study showed that the water hyacinth bed proved to be a very efficient system for sewage sludge dewatering and for increasing the capacity of conventional drying beds.

Keywords: Sewage sludge; Dewatering; Water hyacinth; Phyto-technology

1. Introduction

Currently, many technologies are available for sewage sludge dewatering. They include sophisticated technologies such as centrifugation and filter press. They also include simple technologies such as conventional drying beds and reed beds [1,2]. Each technology has its limitation in applications. In Egypt, conventional drying beds is the most commonly used technology in the dewatering of sewage sludge. This is mainly due to the simplicity of this technology as well as the warm climate of Egypt throughout most of the year. The main disadvantage of using drying beds includes the big land area required for the beds. The required land area may limit the use of this simple technology in areas of limited land availability. It may also prevent future expansion of drying beds of existing treatment plants in areas where the available land is limited. Therefore, there is a need for increasing the capacities of the existing drying beds without using extra land, to be able to receive excessive quantities of sludge in the future expansions of a wastewater treatment plant.

Constructed wetlands employing aquatic plants proved to be a promising alternative for wastewater treatment [3]. They have the ability to efficiently remove suspended materials, nutrients, and different pollutants from wastewater [4]. For several years, a number of constructed wetland systems have been employed for the treatment of various kinds of wastewaters including sewage sludge from conventional treatment plants [5]. This plant assisted treatment technology has been characterized by low investment, operation, and maintenance costs [6,7]. Plant-assisted drying beds [1] seems to be an ideal solution for increasing the capacity of the conventional drying beds. Very few studies showed the possibility of using plant-assisted drying beds employing reed plants [1,8] and *Panicum repens* L. [9] for sludge dewatering. However, there is a need to investigate the dewatering

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capabilities of other plants especially some aquatic plants which have high rates of evapotranspiration. There is also a need to study the application of this system on pilot/full scales. Water hyacinth (*Eichhornia crassipes*) is a perennial, floating aquatic plant of wide distribution in tropical, subtropical, and warm temperate regions throughout the world [10]. It is characterized by its very high evapotranspiration rates. It is also characterized by its prolific and rapid growth in freshwater canals and lakes [11,12]. The plant was ranked the eighth among the top ten fastest-growing weeds in the world [11]. The rapid growth of the water hyacinth plant and its evapotranspiration capabilities made it an ideal candidate for the dewatering of sewage sludge in a plant assisted drying bed.

Therefore, the main objective of the current research is to study the possibility of growing water hyacinth in sewage sludge matrix which is different than wastewater matrix. The study also aims at investigating the ability of this plant in dewatering sewage sludge as compared with the conventional drying beds. In addition, the operating parameters of the water hyacinth drying bed will be studied and tested at a pilot-scale level.

2. Materials and methods

2.1. General

All experiments were conducted using liquid sewage sludge collected from wastewater treatment plants in Egypt. The treatment plants receive wastewater from domestic use only. The treatment plants have a primary sedimentation followed by an activated sludge process. The primary sedimentation produces primary sludge that is collected and mixed with the waste activated sludge. The mixed sludge is being dewatered after thickening in conventional drying beds. The sludge used in the experiments was sampled from the mixed sludge after the thickening stage. Then, it was transported to the location of the experiments at the American University in Cairo (New Cairo, Egypt).

2.2. Experimental runs

Three main experimental runs were carried out in the current study. In the first run, the plant growth in sludge matrix as well as the effect of multiple addition of sludge on the system performance was investigated. In the second run, the effect of plant density on the system performance was studied. In the last run, pilot-scale drying beds were constructed to study the application of the concept of plant assisted dewatering vs. conventional beds. All experiments were conducted in open field environment. During the three experimental runs, the air temperature ranged from 10°C to 26°C. This range of air temperature is known to support the plant growth.

2.3. Reactors used in the first and second experimental runs

The first and second experimental runs were conducted in batch reactors. Each reactor is a plastic container that has a capacity of 17 L (24 cm × 24 cm, height 30 cm). At the start of the experiments, each reactor was loaded with about 10 kg of liquid sludge. The sludge used in the first and second experiments were collected from Katamyia Heights wastewater treatment plant in New Cairo, Egypt.

In the first experimental run, five reactors were tested, two without plants (as a control) and three with plants. The initial plant masses in these reactors ranged from 4.93 to 6.78 kg with average initial mass of 5.69 kg. The first experimental run was conducted for 103 d, during which raw sludge batches were added whenever complete sludge drying took place.

In the second experimental run, different masses of the water hyacinth plant were grown in the liquid sludge. Four initial plant densities, in addition to control (without plants) were tested to study the plant growth and its sludge dewatering ability. Plant densities of 0.0, 12.2, 21.9, 31.5, and 49.5 kg wet mass of plants per m^2 of surface area (of liquid sludge in the container) were tested in different reactors. The plant densities were kept almost constant throughout the experiments of the second run. This was done by measuring the plant masses every 3 d and harvest it partially or add additional masses to keep the plants in the reactors within +/– 10% of its original masses at the start of the experiments. A total of 14 reactors were used in this experimental run. These reactors include three replicate reactors for each plant density (total 12 reactors) and 2 reactors as control (plant density = 0 kg/m^2). The reactors in the second experimental run were tested for up to 34 d during which no raw sludge was added.

2.4. Pilot-scale experiment

In the third experimental run, two identical pilot-scale drying-beds were constructed. The two beds simulate conventional drying beds used for sludge dewatering. They were constructed using two plastic basins, each with dimension of 2.5 m length, 1.5 m width, and 0.9 m height. An underdrainage system was created in each basin. The underdrainage system composed of two layers of pervious media. These layers include a 10 cm layer of crushed stones (size 10–20 mm) on top of a 10 cm layer of gravel (size 50 mm). The underdrainage system of each drying bed allows drainage of water in sludge through the media layers and retention of sludge solids on top of the crushed stones layer. Both basins were installed on a sloped layer of crushed stones to provide a slope of 1:10 in the bed bottom to ease the movement of water collected by the underdrainage system. To collect the percolated water through the pervious media, a perforated PVC pipe were installed within the gravel layer. The PVC pipe followed the same slope of the bed bottom toward an output orifice at the bottom of the basin, then to a floor drain. After installation of the pilot scale system, the third experimental run were conducted in two main steps, the filling step then the testing step. The filling step was carried out before starting the experiments of the pilot scale setup. During the filling step, the two basins were filled with raw liquid sludge which was added in successive batches to each basin for 6 d. During the initial 5 d, one batch of 500 L was added every day to each basin. Then, on the 6th day a batch of 1,000 L was added to each basin. The successive addition of raw sludge batches for 6 d during the filling step created in each basin a sludge layer of 45 cm above the crushed stones layer. After filling the two basins with sludge, the testing (experimental) step has started by adding 90 kg of water hyacinth plants to one of the basins to create the water hyacinth bed, while no plants were added to the other basin to work as a control (conventional drying bed). Fig. 1 shows the pilot-scale setup of both basins at different stages of their construction till the start of the experiments. The plants were kept without harvesting in the water hyacinth bed till the end of experiments. After starting of the testing step and as the sludge in both basins got semi-dried, raw sludge was added in batches of 1,000 L to each basin. For the water hyacinth bed, these batches were added every 2 d till the basin was full of semi-dried sludge after 22 d from the start of the experiments (28 d from the start of the filling step). For the control bed, the sludge batches were added at a longer frequency, every 8–12 d, till the basin was full of semi-dried sludge after 49 d from the start of the experiment (55 d from the start of filling step).

2.5. Plants used in the experiments

Water hyacinth plants (*E. crassipes*) were used in the current study. Water hyacinth is an aquatic plant that grows in water canals and drains in Egypt. All plants were collected from Al-Rahawi Drain, Egypt. Plants were then transported to the location of the experiments at the American University in Cairo. The plants were grown in tap water with nutrients for few months, in an open field environment. Before testing, plants were washed under running water. At the time of collection and experiments, all plants were healthy, and in a good condition.

2.6. Analysis of plant growth

Plant masses (on fresh mass basis) in all reactors were measured frequently. Relative plant growth, M_t/M_0, was calculated to evaluate the plant growth in the sludge matrix. Where, M_t is the plant fresh mass at time t, M_0 is the initial fresh mass (at t_0 = time 0). Plant masses were measured by removing the plants from sludge, wait for 5 min to allow draining of water in the roots then measure the plant masses using a digital balance.

2.7. Efficiency of sludge dewatering

To evaluate the dewatering process of the sewage sludge, each reactor was weighted throughout the experiments to estimate the water lost due to evaporation/evapotranspiration. The experiments included control reactors (without plant cover) to investigate the effect of plants on dewatering of sludge. The dewatering efficiency can be calculated using Eq. (1):

$$\text{Dewatering efficiency}\left(\%\right)=\frac{M_{W\text{ Evap}}}{M_{S\text{ added}}}\times 100 \quad (1)$$

where $M_{W\text{ Evap}}$ is the total cumulative mass of evaporated/evapotranspirated water after time t, from the start of the experiment. $M_{S\text{ added}}$ is the highest total mass of sludge that was added during the experiment to the reactors.

2.8. Sludge analysis

The raw liquid sludge was sampled and analyzed for the batches at the start of all experiments. The analysis of raw liquid sludge was also carried out for the batches added during the pilot scale experiments. The raw liquid sludge samples were analyzed for pH, total suspended solids (TSS), volatile suspended solids (VSS), total solids (TS), ammonia (NH_3–N), nitrate (NO_3–N), total nitrogen, total potassium (TK), total phosphorus (TP), chemical oxygen demand (COD), biochemical oxygen demand (BOD), and biological agents such as total and fecal coliform bacteria, *Salmonella*, and *Shigella*.

The dried sludge was sampled and analyzed at the end of the second experimental run for the reactors of highest plant density (49.5 kg/m^2) and the control reactors. The dried sludge samples were analyzed for ammonia (NH_3–N), nitrate (NO_3–N), total nitrogen, total potassium (TK), total phosphorus (TP), organic matter, organic carbon, total and fecal coliform bacteria, *Salmonella*, *Shigella*, and parasitism. Samples of dried sludge were also collected from the reactors of other plant densities for the microbial analyses only.

3. Results and discussion

3.1. Characteristics of the sludge

Table 1 shows the characteristics of the sludge used in the different experimental runs. The sludge contains high concentrations of TS, TSS, VSS, TN, TK, TP, BOD, and COD. Although many studies showed the ability of different plants in treating wastewater [13], the characteristics of the sludge samples used in the current study as shown in Table 1 is different than that of the high strength raw wastewater reported in literature [2]. Therefore, and due to this difference in characteristics, it is expected that the behavior of plants in the sludge will be different than in wastewater. This behavior may include plant growth pattern, ability for water transpiration, and their treatment performance.

3.2. Plant growth

Fig. 2 shows the change in plant mass expressed as M_t/M_0 with time for the replicates of the plant reactors in the first experimental run. As shown in Fig. 2, plants had acclimatization periods to adopt to the stresses of growing in the sludge matrix. After the acclimatization periods the plants started to grow. The acclimatization period of the water hyacinth plants in the sludge matrix lasted for about 3–7 d. After acclimatization periods, the plants started to grow and reached 65% increases of their masses on average after about 103 d from the start of the experiments.

3.3. Phyto-dewatering of sewage sludge

Fig. 3 shows the change with time of cumulative volume of the evapotranspirated water from sludge under multiple addition of raw sludge batches to the reactors in the first experimental run. Fig. 3 also shows the change in air temperature (°C) throughout the experiments. As shown in Fig. 3, the cumulative volume evaporated due to the plant cover is much higher than that of the control without plants

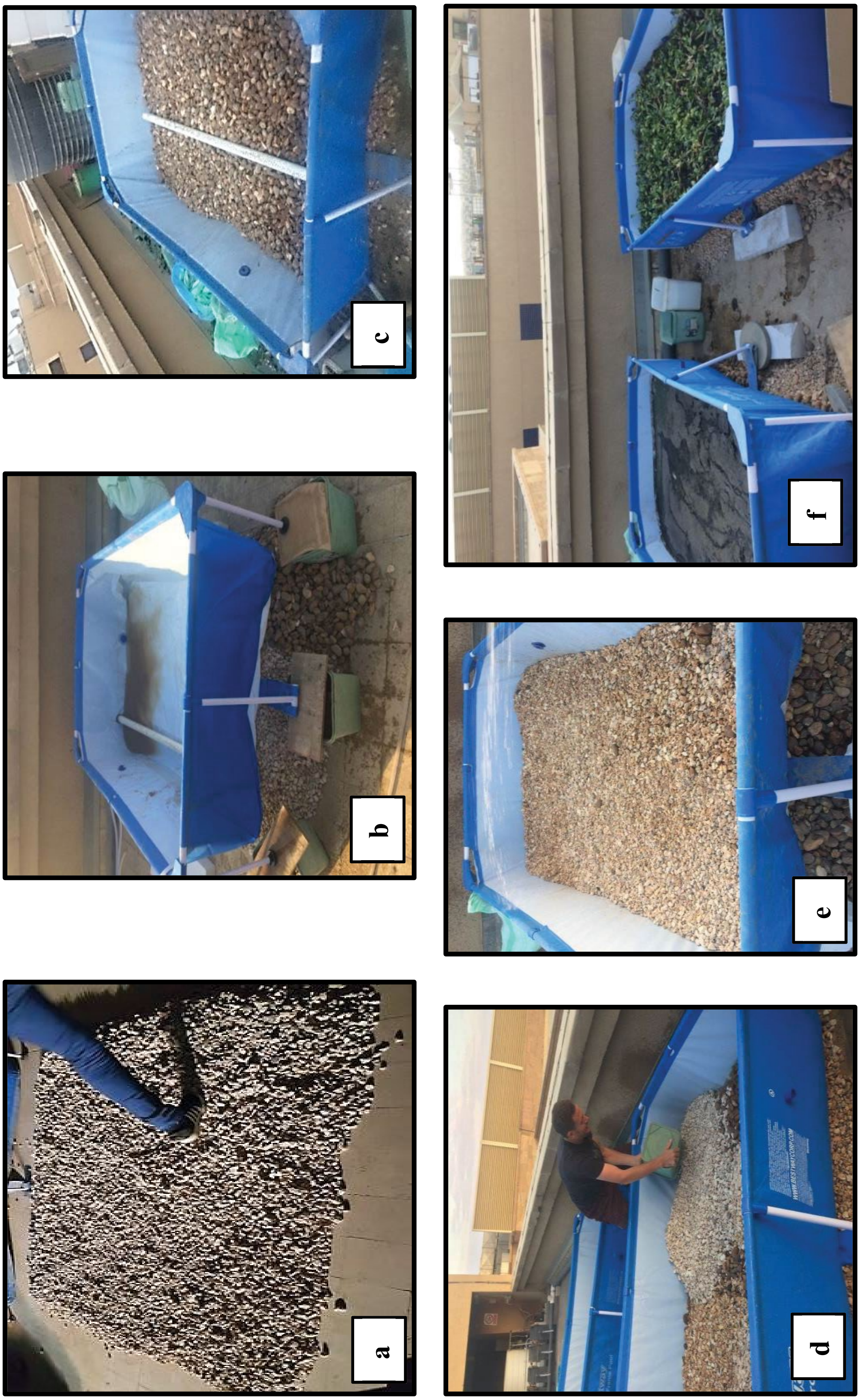

Fig. 1. Photos of the installation of the pilot-scale systems in the third experimental run. (a) Sloped layer of crushed stones beneath each basin, (b) the basin installed on top of the layer of crushed stones, (c) under drainage system: bottom gravel layer with perforated pipe installed inside each basin, (D) under drainage system: crushed stone layer on top of the gravel layer inside each basin, (e) one of the basins after installation of the under drainage system and before the addition of raw liquid sludge, (f) water hyacinth bed (right) and conventional drying bed (left) during operation at the start of the experiments.

Table 1
Characteristics of the raw sewage sludge (liquid) used in the experiments

Parameter	First experimental run	Second experimental run	Third experimental run*
pH	6.5	6.6	6.0
Total solids (TS), mg/L	20,000	35,600	56,400
Total suspended solids (TSS), mg/L	Not measured	32,600	39,400
Volatile suspended solids (VSS), mg/L	Not measured	25,000	31,670
Total nitrogen (TN), mg/L	780	1,870	1,870
Ammonia (NH_3–N), mg/L	370	94	Not measured
Nitrate (NO_3–N), mg/L	160	8	50
Total potassium (TK), mg/L	180	96	160
Total phosphorus (TP), mg/L	42	562	780
Chemical oxygen demand (COD), mg/L	9,500	7,250	7,600
Biochemical oxygen demand (BOD), mg/L	3,500	3,400	2,800
Total coliform bacteria, cell/mL**	Not measured	Not measured	14×10^3
Fecal coliform bacteria, cell/mL**	Not measured	Not measured	4×10^3
Salmonella and *Shigella*, cell/mL**	Not measured	Not measured	3×10^2

*Values represent the average value for all raw sludge batches added throughout the third experimental run.
**Values reported are for only one batch of raw sludge added during the third experimental run.

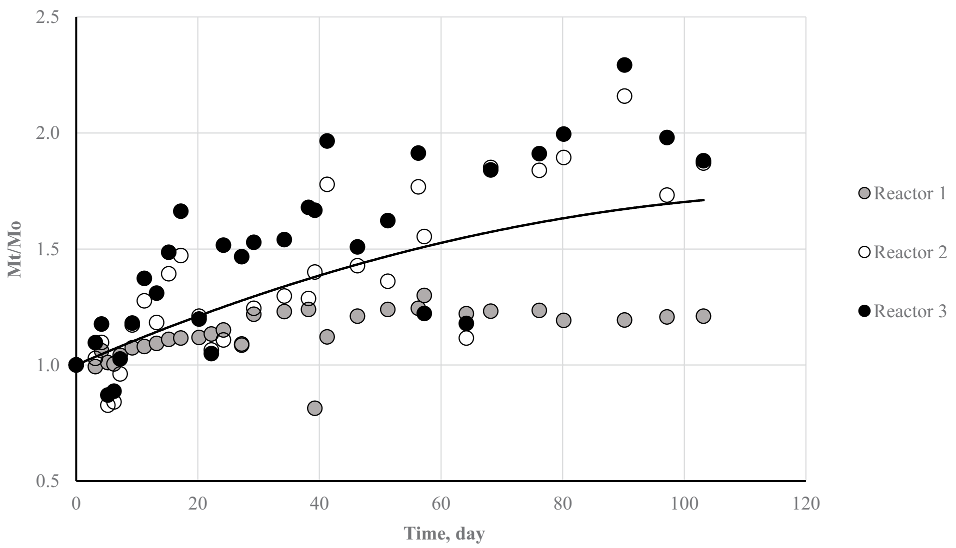

Fig. 2. Change in the plant growth (M_t/M_0) of water hyacinth with time throughout the experiments of the first run.

under multiple addition of sludge. Batches of raw sludge were added to the reactors throughout the experiments of the first run. These batches were added after dewatering of each previously added batch to the reactor. The addition of raw sludge continues till the reactors were filled with dry sludge and therefore, the experiments of the first run were concluded. After 9 d from the start of the first run, each plant reactor received three batches of 10 kg raw sludge. These batches were followed by additional 10 batches of 5 kg raw sludge. These batches were added throughout the experiments of the first run. The total amount of raw sludge that was used in each plant reactor throughout the first experimental run (103 d) was 90 kg. This is compared to a batch of 5 kg of raw sludge which was added once to each of the control reactors after 56 d from the start of the experiments with a total amount of sludge added to each control equal to 15 kg. The cumulative volume of evapotranspirated water from the plant reactors exceeds the control reactors which shows that plant evapotranspiration is the main cause for this increase. Fig. 4 shows the change in the average plant density with time for the plant reactors. It also shows the change with time of the average ratio of cumulative volume evapotranspirated from the plant reactors to that evaporated from the control. As shown in Fig. 4, the ratio of evaporated cumulative volume increases with time. This can be related to the increase in plant density with time which results in the increase in the amount of water evapotranspirated through the plant leaves (Fig. 4). As shown in Fig. 4, the average plant density of the three reactors in the first experimental run, increased from 97 kg/m² at the start of the experiments to

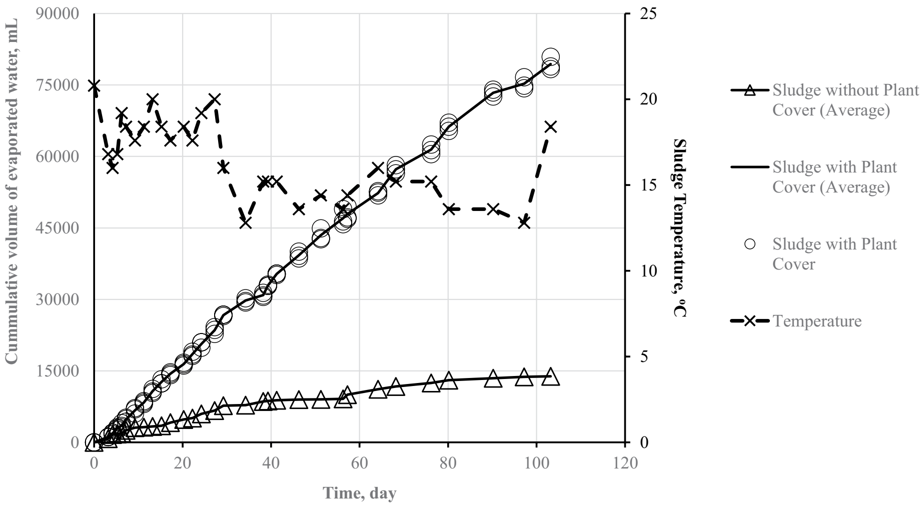

Fig. 3. Effect of the plant on cumulative evapotranspirated water volume from sludge with time under multiple addition of raw sludge batches.

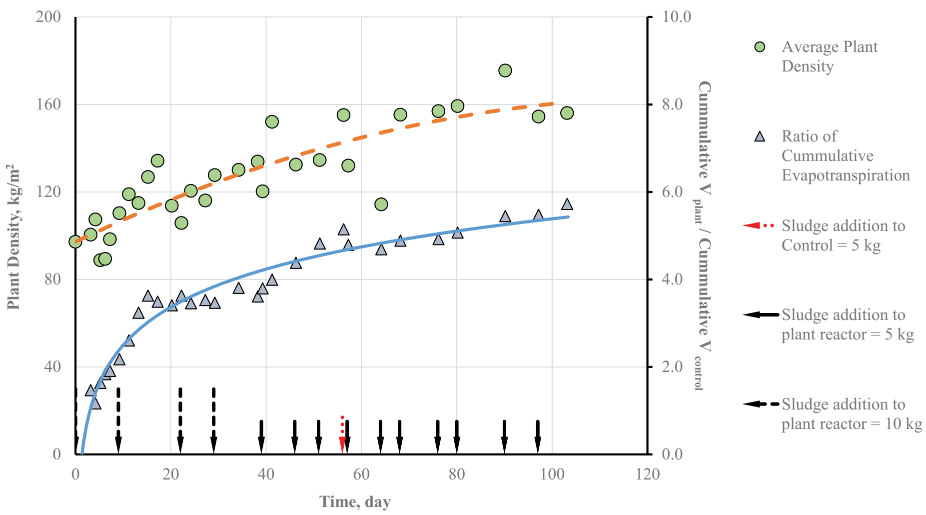

Fig. 4. Change in the average plant density and the average ratio of cumulative evapotranspirated water with time under multiple additions of raw sludge batches.

160 kg/m² at the end of the experiments. The corresponding values of the average ratio of evaporated cumulative volume increased from 1.5 at the start of the experiments to 5.7 at the end of the experiments, respectively. Since the plant density can affect the evapotranspirated volume from sludge, the second experimental run was conducted to study the effect of plant density on dewatering of sewage sludge.

Fig. 5 shows the dewatering efficiency of sludge with time at different plant densities in the second experimental run. As mentioned earlier, during this run, the plant masses were kept almost constant by harvesting or adding plants from or to the reactor. It was found that the plants showed continuous growth in all reactors throughout the experiments of the second run. Therefore, no plant biomass was added to any reactor, however, plants were harvested every 3 d. The average total harvested biomass throughout this experimental run were found to be 1.76, 1.94, 2.93, and 2.40 kg from reactors with plant densities of 12.2, 21.9, 31.5, and 49.5 kg/m², respectively. On average, the masses of the harvested plants are 2.55, 1.54, 1.63, and 0.84 times the initial plant masses for reactors with plant densities of 12.2, 21.9, 31.5, and 49.5 kg/m², respectively. This indicate that the plant growth rate is higher for the low plant density and it decreases with the increase in plant density. The average rate of biomass harvesting ranged from 0.06 kg/d for the highest density (49.5 kg/m²) to 0.10 kg/d for the lowest density (12.2 kg/m²), on fresh mass basis. As shown in Fig. 5, the dewatering efficiency of sludge increased with the increase in plant density. This is due to the increase in evapotranspiration rate as the biomass increased. Fig. 6 shows the change in plant dewatering ability of sludge with the plant density. The plant dewatering ability of sludge is expressed as the average ratio between the cumulative volume of water lost from the plant bed and that from the

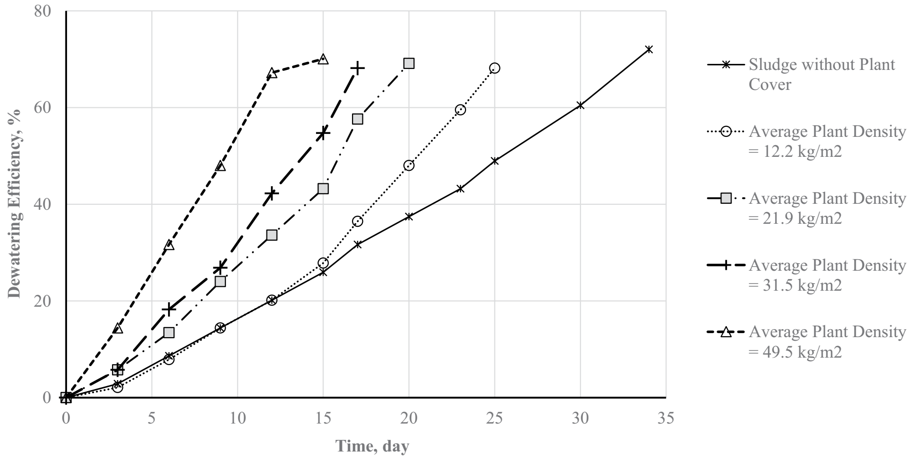

Fig. 5. Effect of plant density on the dewatering efficiency of sludge with time during the second experimental run.

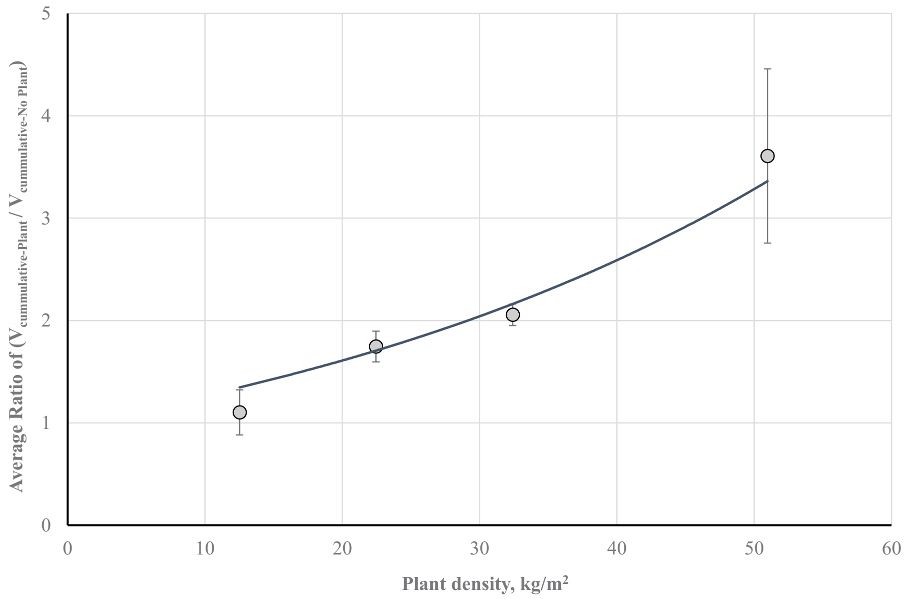

Fig. 6. Effect of plant density on the ratio of cumulative evapotranspirated volume to evaporated volume by control during the second experimental run.

control. As shown in Fig. 6, the ability to dewater sludge increases with the increase in plant density. On average, based on the bench scale experiments in the second run, for a minimum plant density of 29 kg/m^2, the amount of water removed from plant reactors can reach the double of that removed from the control. Fig. 7 shows the change in the flux of evapotranspiration with mean plant density during the duration of plant growth. The flux of evapotranspiration was calculated by dividing the cumulative evapotranspirated volume by duration of time needed for evapotranspiration of this volume by the surface area of sludge in the reactor. The mean plant density is the mean value calculated for plant density during the time duration of the cumulative evapotranspiration. As shown in Fig. 7, the flux of evapotranspiration ranged from 2.9 L/m^2/d for no plant cover (plant density = 0 kg/m^2) to 16.3 L/m^2/d for a mean plant density of 140 kg/m^2 on average basis.

Fig. 8 shows the sludge dewatering capacity of the pilot scale water hyacinth bed as compared to that of the pilot scale conventional drying bed after the filling step of the two basins. As shown in Fig. 8, the water hyacinth bed was able to receive more volumes of raw liquid sludge compared to the control bed. After 28 d from the start of the filling step (22 d from the start of testing), the water hyacinth bed was full with semi-dried sludge and already received a total of 15 m^3 of raw liquid sludge. This amount of sludge includes sludge received during the filling step and testing step. This is compared to 6 m^3 received by the control during the same duration of time (28 d). After 32 d from the start of the filling step (26 d from the start of the

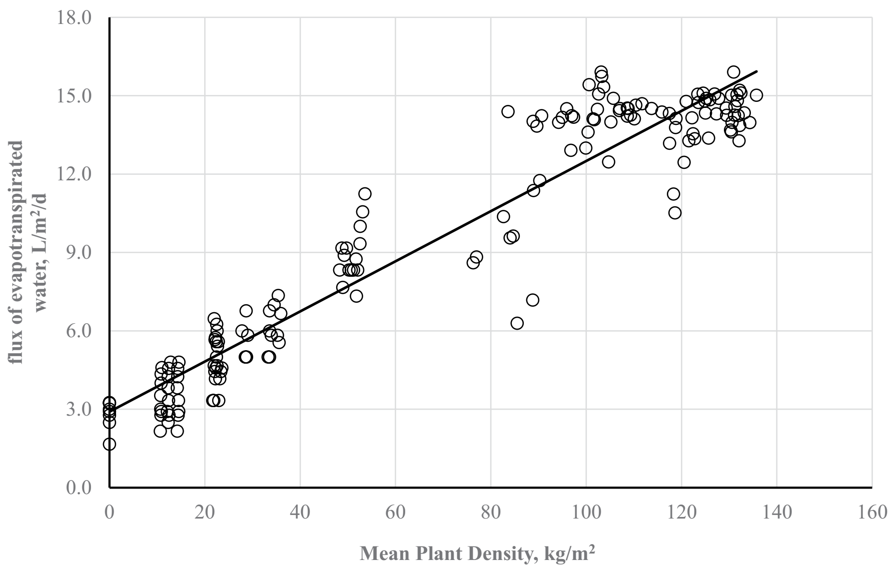

Fig. 7. Change in the flux of evapotranspiration with mean plant density during the duration of plant growth.

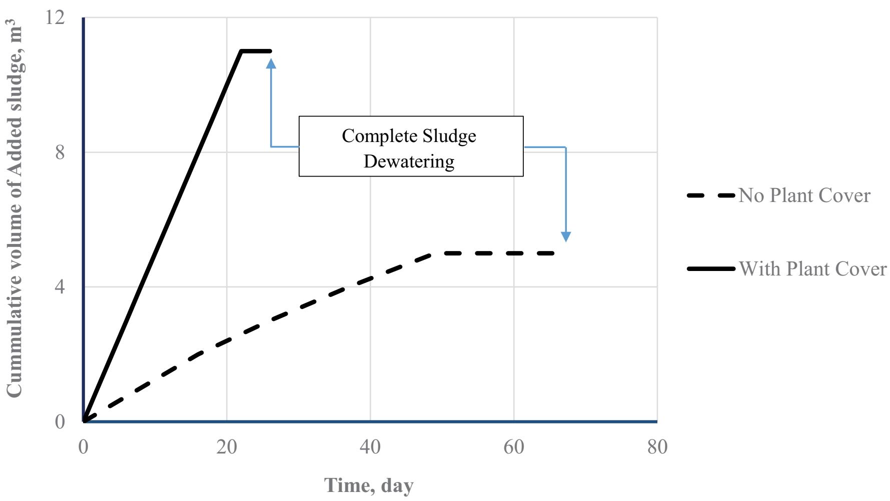

Fig. 8. Sludge dewatering capacity of the pilot-scale systems.

experiments), complete dewatering of sludge took place in the water hyacinth bed and the experiment were concluded in for the water hyacinth bed. In addition, Fig. 8 also shows that after 55 d from the start of the filling step (49 d from the start of testing), the control bed was full of partially dried sludge and already received a total of 9 m^3 of raw liquid sludge. This amount of sludge includes sludge received during the filling step and testing step. After 73 d from the start of the filling step (67 d from the start of the experiments), complete dewatering of sludge took place in the control bed and the experiment were concluded in for the control bed. The results of the pilot scale testing showed that the dewatering of sludge in the water hyacinth bed took place in a duration less that that required by the control be by 58%. In addition, the amount of sludge received by the water hyacinth bed during one cycle of dewatering was 67% higher than that received by the control. This means that the water hyacinth bed can receive 30 m^3 of raw sludge and dewater this amount in about 64 d (two cycles of dewatering) compared to 9 m^3 received by the control (conventional drying bed) to dewater in 76 d (once cycle of dewatering). This means that the capacity of conventional drying beds can be tripled with the use of water hyacinth for the dewatering of sewage sludge.

3.4. Phyto-treatment of sludge

The use of plants in sludge dewatering has an additional advantage. This include the ability of plants to stabilize and improve the quality of sludge. Table 2 shows the characteristics of dewatered sludge in reactors of different plant densities used in the second experimental run. As shown in the Table 2, the sludge characteristics after dewatering using plants has less contents of TN as compared

Table 2
Characteristics of dewatered sludge for different plant densities by the end of experiments of the second experimental run

Parameter	Plant density, kg/m^2		
	0 (no plants)	12.2, 21.9, and 31.5	49.5
TN, %	5.5	Not measured	4.9
NH_3–N, mg/kg	94	Not measured	750
NO_3–N, mg/kg	8	Not measured	Not detected
TP, %	1.58	Not measured	2.06
TK, %	0.26	Not measured	0.23
Organic matter, %	72	Not measured	72.1
Organic carbon, %	34	Not measured	41.8
Total coliform bacteria, cell/g	20×10^4	Not found	Not found
Fecal coliform bacteria, cell/g	15×10^3	Not found	Not found
Salmonella and *Shigella*, cell/g	10×10^2	Not found	Not found
Parasitism	*Entamoeba coli*, *Balantidium coli*, *Entamoeba histolytica*	Not found	Not found

with control. It also contains higher ammonia compared to the control. This indicates the transformation of organic nitrogen (which is the major part of the TN) to ammonia in sludge dewatered by plants. In addition, the nitrate cannot be detected in dewatered sludge with plant cover as compared to control. Table 2 shows also the pathogens and parasitism were eliminated from sludge dewatered with the use of water hyacinth. This is compared to the high concentration of pathogens and the existence of parasitism in the control at the end of the experiments. This agrees with the literature, which shows that fecal coliform was reduced in water hyacinth ponds used for wastewater treatment [14]. This is due to the ability of water hyacinth to concentrate microorganisms around its roots and shoots when grown in water bodies [15]. The concentration of pathogens in water hyacinth plants found in water bodies is undesirable because the plants remain as a part of the water bodies [14]. However, in the current study, this accumulation is desirable to improve the quality of dewatered sludge. Thus, the ability of water hyacinth to stabilize sewage sludge needs further investigations.

4. Conclusions

The current study demonstrated that plant assisted drying bed can be efficient in dewatering of sewage sludge collected from a biological treatment utilizing activated sludge process. The experiments showed that water hyacinth (*E. crassipes*) can grow in sewage sludge matrix after an acclimatization period of 3–7 d. In addition, the use of water hyacinth bed can significantly reduce the time needed for dewatering of sewage sludge as compared with the conventional drying beds. As a result, the capacity of the drying bed, to receive, and dewater more sludge, is increased. The pilot scale experiment in the current study showed that the ability of conventional drying beds in dewatering sewage sludge has tripled with the use of water hyacinth plants at an initial density of 24 kg/m^2. In addition, the water hyacinth plants improved the quality of the sludge after dewatering by eliminating pathogens and parasites from sludge as compared to conventional system.

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