Phyto-dewatering of sewage sludge using Panicum repens L.
A. S. El-Gendy, H. I. El-Kassas, T. M. A. Razek and H. Abdel-Latif

ABSTRACT

Experiments in the field environment have been conducted to study the growth of Panicum repens L., an aquatic plant, in the sewage sludge matrix. The experiments were also carried out to investigate the ability of this plant to dewater sewage sludge to increase the capacity of conventional drying beds. In addition, the ability of Panicum repens L. to reduce the sludge contents of certain elements (copper (Cu), Iron (Fe), Sodium (Na), lead (Pb), and Zinc (Zn)) was also investigated. All experiments were carried out in batch reactors. Different plant coverage densities were tested (0.00 to 27.3 kg/m²). The liquid sewage sludge was collected from a wastewater treatment plant in Helwan city, Cairo Governorate, Egypt. The collected sludge represents a mixture of the primary sludge and waste activated sludge before discharging into drying beds.

Key words | metal removal, Panicum repens L., phytoremediation, plant growth, sludge dewatering

INTRODUCTION

Many technologies for sewage sludge dewatering are available. They range from sophisticated technologies such as centrifugation and filtration using filter presses to simpler ones such as evaporation using drying beds (Metcalf & Eddy 2005) as well as reed bed sludge drying systems (Nielsen & Larsen 2016). Each technology has its advantages and disadvantages that may limit its use. The weather conditions and the simplicity of operation make drying bed technology the main technology used for sludge dewatering in Egypt. However, drying beds require a huge land area, which may pose an obstacle in expanding the existing treatment plants for future needs. This is considered a problem in areas where the available land is limited. Therefore, there is a need to find a solution to increase the ability of the existing drying beds, to accommodate the capacity needed for sludge dewatering in future expansions of wastewater treatment plants without using additional land area. The use of plant-assisted drying beds (Nielsen & Larsen 2016) seems to be an ideal solution for increasing the capacity of the existing drying beds.

Sewage sludge also carries different types of pollutants, since many wastewater treatment plants receive discharges from residential areas as well as industrial areas (Bright & Healey 2005; Dai et al. 2007). Some of these pollutants, such as heavy metals, are mobile, non-biodegradable, and become toxic at certain levels. The presence of heavy metals in sewage sludge may inhibit its application as a soil amendment, since metals tend to accumulate along the food chain (Dudka & Miller 1999; Amir et al. 2005). Based on investigations of pilot and field-scale systems, the technology of constructed wetlands employing aquatic plants has proven to be a promising alternative for wastewater treatment (US EPA 1988). This technology has been characterized by low investment, operation and maintenance costs (Cooper et al. 1996; Kadlec & Knight 1996). For several years, a number of constructed wetland systems have been employed to treat various kinds of wastewaters, including sewage sludge, from conventional treatment plants (Heinss & Kootatap 1998). They have the ability to efficiently remove suspended materials and nutrients from wastewater (El Zawahry & Kamel 2004). In addition, aquatic plants can reportedly be used as natural catalysts to absorb and accumulate heavy metals in their tissues from wastewater (Taggart et al. 2005; Skinner et al. 2007; Mishra & Tripathi 2008; Vymazal & Kröpfelová 2008).

It has been widely demonstrated that these aquatic plants are involved in almost every major function within the wetland treatment systems. In addition, plant-assisted
Drying beds have been successfully used in some areas employing reed plants (sludge treatment reed beds) (Pandey & Jenssen 2015; Nielsen & Larsen 2016). In addition, some of these plants such as Eichhornia crassipes and Panicum repens L. have a high evapotranspiration ability. Thus, there is a need to investigate the ability to use different aquatic plants that grow locally in a constructed wetland for sewage sludge dewatering and treatment.

The main objective of the current research is to study the possibility of growing Panicum repens L. in a sewage sludge matrix, which is different to a wastewater matrix. This plant is growing locally in Egypt and many areas worldwide on the banks of waterways, canals and drains. The study also aims at investigating the ability of this plant to dewater sewage sludge compared with conventional drying beds. In addition, the associated reduction of certain heavy metals that may present in sludge will be investigated.

**MATERIALS AND METHODS**

**General**

All experiments were conducted on liquid sewage sludge collected from the Arab Abo-Saed wastewater treatment plant (AAS-WWTP) in Helwan city; Cairo Governorate, Egypt. The treatment plant receives wastewater from municipal as well as industrial activities. The AAS-WWTP has a primary sedimentation stage 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 before entering the drying beds at AAS-WWTP. The collected sludge was then transferred to the location of the experiments.

**Experimental conditions**

All experiments were conducted in an open field environment with the air temperature ranging from 22 to 43 °C, with an average value of 30 °C. This range of air temperature is known to support plant growth.

**Reactors used in the experiments**

All experiments were conducted in batch reactors. Each reactor has a capacity of 16 liters (base: 22.5 cm × 22.5 cm, top: 24.5 cm × 24.5 cm, height 29 cm). At the start of the experiments, each reactor was loaded with about 14 liters (on average) of sludge. As will be explained later, different masses of the Panicum repens L. plant were grown in the liquid sludge. To study the plant’s ability to grow in raw sludge, sludge dewatering and removal of heavy metals and elements from sludge, six initial plant densities were tested. Plant densities of 0.0, 5.4, 9.9, 16.3, 21.7 and 27.3 kg wet mass of plants per m² of surface area (of liquid sludge in the container) were tested in different reactors.

**Plants used in the experiments**

*Panicum repens* L. plants were tested in the current study. *Panicum repens* L. is an aquatic plant that usually grows near water canals and drains. All plants were collected from the edge of the Al-Hoor agriculture drain near El-Baslakon village in Kafer El-Dewar, Egypt. At the time of collection, all plants were healthy and in good condition. All plants used in the experiments were homogenous, with almost similar height and mass. Table 1 shows the average height of plant shoots for the plants used in the experiments. After collection from the drain edge, plants were washed with tap water then planted for 24 hours in nutrient solution before starting the experiments.

**Analysis of plant growth**

Plant masses (on a fresh mass basis) in all reactors were measured daily. To investigate the growth of the plant in the sludge matrix at a specific plant coverage density, $M_t/M_0$ was calculated and used for evaluation, where $M_t$ is the plant fresh mass at time $t$, and $M_0$ is the initial fresh mass (at $t_0$ = time 0). Plant masses were measured by removing the plants from the sludge, waiting for 5 minutes to allow draining of water in the roots, then measuring the plant masses using a digital balance.

The effect of different initial plant densities on the plant growth in the sludge matrix was evaluated by comparing the average values of the relative growth rate ($RGR$) for each plant coverage density. The $RGR$ can be calculated using

<table>
<thead>
<tr>
<th>Average height of plant shoots, cm</th>
<th>Plant cover density, kg/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>75.0 ± 1.4</td>
<td>27.3          21.7  16.3  9.9  5.4</td>
</tr>
<tr>
<td></td>
<td>1,511 g       1,200 g  900 g  550 g  300 g</td>
</tr>
</tbody>
</table>

Table 1 | The heights and masses of different plants for different coverage areas used at the start of the experiments
Equation (1) (Mitchell 1974):

\[
RGR = \frac{\ln M_t - \ln M_0}{\Delta t}
\]

(1)

where \(M_t\) is the plant fresh mass at time \(t\), \(M_0\) is the initial fresh mass (at \(t_0\)), and \(\Delta t\) is the duration of time and equal to \((t - t_0)\). Radford (1967) indicated that even if the instantaneous plant mass (or RGR) did not follow exponential growth, the mean RGR during the period in question, \(\Delta t\), could be represented by the above equation.

Efficiency of sludge dewatering

To evaluate the dewatering process of the sewage sludge, each reactor was weighted every day to estimate the water lost due to evaporation/evapotranspiration. The experiments included a reactor with no plant cover (plant density \(= 0.0\) kg/m\(^2\)) to investigate the effect of plants on dewatering of sludge compared to conventional drying beds (which have no plants). The dewatering efficiency can be calculated using Equation (2):

Dewatering efficiency, \(\% = \frac{M_{W\ Evap}}{M_{S\ Initial}} \times 100\)

(2)

where \(M_{W\ Evap}\) is the total mass of evaporated/evapotranspired water after time \(t\), from the start of the experiment. \(M_{S\ Initial}\) is the initial mass of sludge at the start of the experiment.

Sludge and plant analyses

The collected sludges were sampled and analyzed at the start and the end of the experiments. All analyses were carried out according to Standard Methods for the Examination of Water and Wastewater (APHA et al. 1998). The sludge samples were analyzed initially for pH (using the electrometric method: Method 4500-H+ B), total suspended solids (TSS), total dissolved solids (TDS) (by drying the raw sludge samples at 103 to 105 °C (method 2540 B)), ammonia (NH\(_3\)-N) (total ammonia was analyzed by using the primary distillation (method 4500-NH\(_3\) B) and the titration method (method 4500-NH\(_3\) C)), total phosphorus (TP) (using the vanado molybdo phosphoric acid colorimetric method (method 4500-P C)), chemical oxygen demand (COD) (using the closed reflux colorimetric method (method 5220 D)), biochemical oxygen demand (BOD), cadmium (Cd), copper (Cu), iron (Fe), sodium (Na), lead (Pb), and zinc (Zn) ((method 3120)). At the end of the experiments, sludge samples were analyzed for heavy metals only.

Plant tissues were also analyzed at the start and at the end of the experiments. Plant tissues were prepared for analysis by washing fresh tissues under running water, oven drying at 70 °C for 72 hours, weighing to the nearest 0.01 g, and grinding in a stainless-steel grinder until the tissues turned into powder. Then the dried ground tissue was analyzed for its heavy metals content after nitric acid digestion (Logan & Feltz 1985; Jarvis et al. 1992).

Plant tissues were analyzed for Cd, Cu, Fe, Na, Pb and Zn. All analyses were carried out on the digested liquid sample according to Standard Methods for the Examination of Water and Wastewater (APHA et al. 1998). All heavy metals were analyzed in the plant shoots and roots separately.

RESULTS AND DISCUSSION

Composition of the sludge

Table 2 shows the composition of the sludge used in the experiments. The sludge contains high concentrations of TSS, NH\(_3\)-N, TP, BOD and COD (Table 2). The concentrations of heavy metals were in trace quantities for Cd, Cu, Pb and Zn; and in high quantities for Fe, and Na. Although many studies have been carried out for treating

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td></td>
<td>7.2</td>
</tr>
<tr>
<td>TSS</td>
<td>mg/L</td>
<td>25,550</td>
</tr>
<tr>
<td>TDS</td>
<td>mg/L</td>
<td>2,450</td>
</tr>
<tr>
<td>Ammonia (NH(_3)-N)</td>
<td>mg/L</td>
<td>110</td>
</tr>
<tr>
<td>TP</td>
<td>mg/L</td>
<td>300</td>
</tr>
<tr>
<td>COD</td>
<td>mg/L</td>
<td>8,450</td>
</tr>
<tr>
<td>BOD</td>
<td>mg/L</td>
<td>6,600</td>
</tr>
<tr>
<td>Cadmium (Cd)</td>
<td>mg/kg ds(^b)</td>
<td>0.007</td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>mg/kg ds(^b)</td>
<td>24.66</td>
</tr>
<tr>
<td>Iron (Fe)</td>
<td>mg/kg ds(^b)</td>
<td>3.862</td>
</tr>
<tr>
<td>Sodium (Na)</td>
<td>mg/kg ds(^b)</td>
<td>9.644</td>
</tr>
<tr>
<td>Lead (Pb)</td>
<td>mg/kg ds(^b)</td>
<td>12.40</td>
</tr>
<tr>
<td>Zinc (Zn)</td>
<td>mg/kg ds(^b)</td>
<td>6.910</td>
</tr>
</tbody>
</table>

\(^a\)mg of the element mass per liter of liquid sludge.

\(^b\)mg of the element mass per kg of sludge as dry solids.
domestic wastewater using different types of plants (Divya et al. 2012), the composition of the sludge used in the current experiments is different than that of the strong raw wastewater indicated in Metcalf & Eddy (2003). Hence, the sludge matrix is different than that of the sewage. Therefore, the pattern of growth for plants in such a matrix is expected to be different to that in sewage.

**Plant growth**

Figure 1 shows the change in plant mass expressed as $M_t/M_0$ with time for the different plant coverage densities of 5.40, 9.90, 16.3, 21.7 and 27.3 kg/m$^2$, respectively. As shown in Figure 1, plants had acclimatization periods to adapt to the stresses of growing in the sludge matrix. After acclimation periods, the plants started to grow. As shown in Figure 1, the acclimatization period of the *Panicum repens* L. in the sludge matrix lasted for about 5 to 8 days for the different plant coverage densities. During acclimatization, the plant growth decreased gradually and the plant masses reached 0.78, 0.71, 0.59, 0.72 and 0.71 of the initial masses ($M_0$) for plant coverage densities of 5.40, 9.90, 16.3, 21.7 and 27.3 kg/m$^2$, respectively. After the acclimatization periods, the plants started to grow and reached 43, 44, 26, 23 and 66% increases of their masses after 14 days from the start of the experiments for plant coverage densities of 5.40, 9.90, 16.3, 21.7 and 27.3 kg/m$^2$, respectively.

**Effect of coverage density on the plant growth**

Based on the results shown in Figure 1, it is concluded that *Panicum repens* L. can adapt to the sludge matrix and grow after an acclimation period. However, the effect of plant cover density on the plant growth needs further investigation. Therefore, the mean values of $RGR$ were used to investigate the effect of covering density on the plant growth.

Values of $RGR$ were calculated for the plants using Equation (1) at different durations of growth for different initial plant coverage densities. Figure 2 shows the change in the mean $RGR$ with different plant coverage densities after the acclimatization period. As shown in Figure 2, the highest mean value of $RGR$ ($0.0715 \pm 0.0187$ d$^{-1}$) was obtained at the lowest initial plant coverage density of 5.40 kg/m$^2$. Figure 2 also shows that the $RGR$ decreases with the increase in initial plant density, and it reached $0.0354 \pm 0.0080$ d$^{-1}$ at the highest initial plant density (27.3 kg/m$^2$). This is expected, because at lower densities more space for horizontal propagation and growth is available (there is less resistance for expanding the plant shoots and roots) and less competition for nutrients occurs. This agrees with Driever et al. (2005), who reported that aquatic plants tend to grow faster at lower densities than at packed higher densities. Therefore frequent harvesting of plants at high coverage densities is essential in plant-based treatment systems (Reddy & Sutton 1984). This will allow faster growth of the plant, which might improve the dewatering and the removal of pollutants per unit mass of the plant from the growth medium.

**Phyto-dewatering of sewage sludge**

Figure 3 shows the change in the dewatering efficiency, calculated using Equation (2), with time, for different plant cover densities. As shown in Figure 3, the water removed from the reactors by evaporation and evapotranspiration is increased with time. In general, as shown in Figure 3, the initial dewatering efficiency for reactors with plant cover were below the dewatering efficiency of the reactor without
plant cover. Then after 5 to 8 days, apart from the reactor with the lowest initial plant density, the dewatering efficiency in reactors with plant cover exceeded that in the reactor without plant cover. This is attributed to the acclimatization period needed for the plants to adapt to the stresses of growing in the sludge matrix, as discussed earlier (Figure 1). As also shown in Figure 3, the amount of water removed due to plants significantly increased with the increase in initial plant density. The time needed to dewater the sludge is also significantly reduced with the use of high initial plant cover density. Also, the time needed to dewater the sludge with the use of plants at the highest initial density (27.3 kg/m^2) can be reduced by more than half that needed to dewater the sludge without the use of plants. The significance of the effect of using different plant densities on the removal of water from sludge was tested using a paired t-test. Table 3 shows the t-values and the p-values of two tailed hypothesis and the level of significance for the paired t-test analyses. The statistical analysis showed that plants, after the acclimatization period and at different densities (except at 9.9 kg/m^2), have a significant effect on water removal from sludge at a level of significance of P < 0.05. At a plant density of 9.9 kg/m^2, the effect of plant was significant at a lower level of P < 0.10.

Figure 4 shows the change in plant dewatering ability of sludge with the mean plant density. The plant dewatering ability of sludge is expressed as a ratio between the mass of water lost in the presence of plants and the mass of water lost in the absence of plants. As shown in Figure 4, the ability to dewater sludge increases with the increase in mean plant density. On average, the effect of plant density on dewatering of sludge is small at mean plant densities below 15 kg/m^2. However, in order to increase the dewatering of sludge by double or more, the plant density in the reactor should be kept at a minimum value of 15 to 20 kg/m^2. This means that in a real-world application, a minimum plant density of 15 to 20 kg/m^2 is needed to be maintained in the drying beds to at least double the capacity of the bed in drying the sludge compared to conventional drying beds.

**Phyto-removal of heavy metals from the sludge matrix**

The use of plants in sludge dewatering has an additional advantage. This includes the ability of plants to uptake heavy metals that might be present in the sludge. Table 2 shows the initial concentrations of different heavy metals in the sludge used in the experiments. Table 4 shows the concentrations of heavy metals in sludge at the end of the
experiments for different coverage densities (from 0.0 to 27.3 kg/m²). As shown from Tables 2 and 4, there is no change in the metal concentrations of sludge for reactors without plant cover (plant density of 0.0 kg/m²). However, the concentrations of heavy metals in the sludge in the reactors with plant cover had been reduced compared to the initial concentrations. The decreases in the concentrations of Fe and Na were very small and insignificant. However, higher and significant decreases were observed for Cu, Pb and Zn concentrations. It is also noticed that, in general, the concentration of metals in sludge decreased with the increase in plant coverage density. This is expected, due to the increase in biomass and as a result the increase in the sorption surface of the plant materials (plant roots) on which metals are sorbed.

The results in Tables 2 and 4 show that removal efficiencies of Cu ranging between 36.7 and 54.4% were obtained for plant densities between 5.4 and 27.3 kg/m². In addition, the removal efficiencies for Pb from sludge ranged from 8.4 to 26.8% for plant coverage densities between 5.4 and 27.3 kg/m². Also, the removal efficiency of Zn from sludge ranged from 5.8 to 11.9% for the same plant coverage densities.

Tables 5 and 6 show the initial and final concentrations of different heavy metals in plant shoots and roots, respectively. As shown in the tables, the concentration of heavy metals in the plant tissues (shoots and roots) increased at the end of the experiments for different plant densities as
compared to plants before the experiments. This indicates the ability of plants to uptake different elements from the sludge matrix during the dewatering of sludge. This conforms to the findings of many researches, which have showed the ability of different plants to remove metals from wastewater. However, limited studies have been carried out on the use of plants for the removal of metals from sludge. Table 5 also shows that all metals are translocated from the roots to the shoots, as the concentration of metals in the shoots at the end of the experiments is higher than that before the experiments. This agrees with Dushenkov et al. (1995), Maine et al. (2006) and Marchand et al. (2010), who indicated the ability of plants to translocate metals absorbed in the plant roots to the shoots.

### Table 5 | Concentrations of metals in plant shoots for different plant coverage densities

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Concentration before the experiments</th>
<th>Concentration at the end of experiments for different plant coverage densities</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>5.4 kg/m²</td>
</tr>
<tr>
<td>Cd mg/kg ds&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.04</td>
<td>1.02</td>
</tr>
<tr>
<td>Cu mg/kg ds&lt;sup&gt;a&lt;/sup&gt;</td>
<td>19</td>
<td>20.3</td>
</tr>
<tr>
<td>Fe mg/kg ds&lt;sup&gt;a&lt;/sup&gt;</td>
<td>4,491</td>
<td>4,584</td>
</tr>
<tr>
<td>Na mg/kg ds&lt;sup&gt;a&lt;/sup&gt;</td>
<td>9,755</td>
<td>9,861</td>
</tr>
<tr>
<td>Pb mg/kg ds&lt;sup&gt;a&lt;/sup&gt;</td>
<td>43.7</td>
<td>44.2</td>
</tr>
<tr>
<td>Zn mg/kg ds&lt;sup&gt;a&lt;/sup&gt;</td>
<td>28.4</td>
<td>29.1</td>
</tr>
</tbody>
</table>

<sup>a</sup>Metal concentrations in the dry solids of the plant tissues.

### Table 6 | Concentrations of metals in plant roots for different plant coverage densities

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Concentration before the experiments</th>
<th>Concentration at the end of experiments for different plant coverage densities</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>5.4 kg/m²</td>
</tr>
<tr>
<td>Cd mg/kg ds&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.01</td>
<td>0.91</td>
</tr>
<tr>
<td>Cu mg/kg ds&lt;sup&gt;a&lt;/sup&gt;</td>
<td>22.1</td>
<td>22.92</td>
</tr>
<tr>
<td>Fe mg/kg ds&lt;sup&gt;a&lt;/sup&gt;</td>
<td>6,014</td>
<td>6,093</td>
</tr>
<tr>
<td>Na mg/kg ds&lt;sup&gt;a&lt;/sup&gt;</td>
<td>4,477</td>
<td>4,499</td>
</tr>
<tr>
<td>Pb mg/kg ds&lt;sup&gt;a&lt;/sup&gt;</td>
<td>51.6</td>
<td>51.66</td>
</tr>
<tr>
<td>Zn mg/kg ds&lt;sup&gt;a&lt;/sup&gt;</td>
<td>33</td>
<td>33.28</td>
</tr>
</tbody>
</table>

<sup>a</sup>Metal concentrations in the dry solids of the plant tissues.

### CONCLUSION

*Panicum repens* L. proved to be efficient in dewatering of sludge generated from wastewater treatment using an activated sludge system. The plant has the ability to dewater the sludge completely (up to 99%) in less time compared to conditions without the use of plants. A minimum plant density of 15 to 20 kg/m² needs to be maintained in the drying beds to at least double the capacity of the bed for drying the sludge compared to conventional drying beds. The plants also showed the ability to grow in the sludge matrix. However, they need an acclimatization period of 5 to 8 days before they can perform well in drying the sludge. In addition to their ability to dewater the sludge, the plants have the ability to reduce copper, lead and zinc in the sludge matrix while growing. The experiments revealed that the *Panicum repens* L. is able to uptake these metals through the plant roots then translocate them to the plant shoots.

### ACKNOWLEDGEMENT

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