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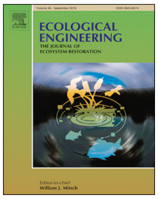

Earthworm effects on biosolids characteristics in sludge treatment wetlands

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ABSTRACT

As an ecological sludge treatment technology, sludge treatment wetlands (STWs) have the advantages of low investment and low energy consumption, have attracted more and more attention around the world. However, the role of earthworm on biosolids characteristics in STWs is not well known. In the present study, six STWs with two plant species (*Phragmites australis, Typha angustifolia*) and earthworm addition were investigated to evaluate their effects on sludge characteristics. Furthermore, feasibility for sludge land application after STWs was assessed. The results showed that the best sludge dewatering (total solids 38.3% during the feeding period) and stabilization condition (volatile solids to total solids 21.1%, dehydrogenase activity 0.65 g (TPF-tetrazole red formazan)/g (sludge) after two months of rest period) were determined in the earthworm assistant STWs planted with *P. australis*. The rapidly available phosphorus and available potassium contents in sludge were increased by the earthworm addition. The lowest *Escherichia coli* (600 MPN/g) and volatile fatty acid content (188.7 g/kg) were detected in the earthworm assistant STWs planted with *P. australis*. Scanning electron microscope analysis showed that sludge structure in the bottom was more loosen than in the surface, and the most loosen structure was observed in the earthworm assistant STWs planted with *P. australis*. The highest germination index (95%) and highest biomass (100 g/m^2) of the tested crop (*Brassica chinensis*) were observed in the system with sludge (from STWs planted with *P. australis*): soil = 1:3 and 1:1, respectively. Overall, the addition of earthworm in STWs exhibited a positive effect on sludge characteristics, which enhanced the quality of treated sludge for land application.

1. Introduction

Sludge produced by sewage treatment processes might be used as fertilizer for land application due to the large amount of valuable nutrients. However, the surplus sludge also contained large numbers of pollutants such as heavy metals, pathogens, and toxic organic compounds etc., which limiting their usage. Therefore, further treatments are needed. Generally, sludge treatment processes are divided into two purposes: (1) sludge dewatering to decrease sludge volume, thereby reduction transportation and treatment costs; (2) sludge stabilization to degrade the organic matter and remove other pollutants (e.g. heavy metals, pathogens), thus decreasing the sludge toxicity (Nielsen and Willoughby, 2007; Uggetti et al., 2010). However, the high cost of traditional sludge treatments and disposal approaches (e.g. sludge concentration, drying, composting, anaerobic digestion) are important issues for sewage treatment plants (Andrade et al., 2017). Therefore, it is of great significance for sewage treatment plants to develop low investment and low operating cost technology for sludge treatment. As an ecological sludge treatment technology, sludge treatment wetlands (STWs) have the advantages of low investment and low energy consumption, and thus have attracted more and more attention around the world.

The main processes of sludge dewatering in STWs include the drainage by the gravel and the sludge layer, evaporation and plant transpiration (Brix, 2017). Previous studies showed that the total solids (TS) content in sludge was decreased by 10%–60% after STWs treatment (Hu et al., 2017; Nielsen and Bruun, 2015; Uggetti et al., 2012a; Uggetti et al., 2010). Sludge stabilization is mainly achieved through the biochemical reactions around plant rhizosphere microorganisms (Begg et al., 2001; Brix, 2017). Moreover, the plant rhizosphere also can transport the oxygen to accelerate the biochemical reactions (Brix, 2017; Pedescoll and Sidrach, 2013). Uggetti et al. (2010) reported that the ratio of volatile solids (VS) to total solids (VS/TS) were reduced by 25%–30%, and eventually got the sludge with VS of 40%–50%. STWs technology is one of the most common sludge treatment technologies in Denmark, with 30% of the sludge is treated by STWs (Nielsen and Bruun, 2015; Nielsen and Larsen, 2016). So far, there are more than 200 full-scale STWs in operation in Denmark (Gagnon et al., 2013; Nielsen and Larsen, 2016). Meanwhile, full-scale STWs are also applied in Italy, France, Spain, United Kingdom, Poland, Germany, Brazil, United States

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and Palestine (Calderon-Vallejo et al., 2015; Nassar et al., 2006; Nielsen and Bruun, 2015; Nielsen et al., 2014; Nielsen and Willoughby, 2007; Obarska-Pempkowiak et al., 2003; Uggetti et al., 2009). Furthermore, our previous study showed that STWs can be successfully applied under the subtropical condition in China (Hu et al., 2017).

Sludge treated by STWs has a potential to be used as fertilizer for land application. However, some pollutants (e.g. heavy metals, pathogens, toxic organic compounds) in sludge are limiting its land reuse (Uggetti et al., 2010). Nielsen and Willoughby (2007) have shown that *Salmonella* and *Escherichia coli* were less than 2 MPN/100 g and 200 PFU/100 g after 3–4 months of stabilization, respectively. However, Magri et al. (2016) reported that the *E. coli* content in accumulated sludge did not achieve the standards to be applied in agriculture due to the short sludge stabilization time (13 days). Some literatures showed that heavy metals contents (Cu, Mn, Ni, Zn, Cr, Fe, Pb, Cd) in sludge were below the standards of EU and US (US EPA, 1994; EU, 1986, 2000) (Nielsen and Willoughby, 2007; Uggetti et al., 2010, 2012a,b). Nevertheless, Hu et al. (2017) reported that Cd content in the accumulated sludge was still higher than the Chinese standard for agriculture reuse due to the high Cd concentration in the raw sludge (Chinese EPA, 1984). Therefore, further treatments are needed before the sludge can be used for land application.

Earthworms are widely used to treat sewage sludge, due to their abilities to breakdown organic materials, enrich heavy metals and reduce pathogens in sludge (Kwon et al., 2009; Yang, 2011). Zhao et al. (2010) revealed that the organic matter of wastewater sludge was decreased by 46% with the presence of earthworms. Moreover, earthworms are also applied in constructed wetlands (CWs) to treat sewage (Xu et al., 2013a,b). Some research reported that pollutants removal in sewage were increased by 2–10% for nitrogen (N), 7–12% for phosphorus (P) in earthworm assistant CWs (Li et al., 2011; Xu et al., 2013a). Although a large number of studies have reported on the sludge treatment by earthworm and sewage treatment by earthworm assistant CWs, very few study focus on the effect of earthworms in STWs technology. Chen et al. (2016) provided a preliminary study on the effects of earthworms for sludge dewatering and stabilization in sludge treatment reed beds system. However, detail investigation on the effect of earthworm on sludge characteristics in STWs is still not well known.

Therefore, the aim of this study were to: (1) evaluate the effect of earthworm on sludge characteristics in STWs; (2) assess the feasibility of land application after sludge treatment by earthworm assistance STWs.

2. Material and methods

2.1. Experimental setup

This study was conducted using six vertical subsurface flow CWs in a greenhouse, the temperature and humidity were controlled at 25 °C and 65%, respectively. The STWs consisted by 50 × 20 × 50 cm (Length × Width × Height) plexiglass. Each STW was divided into a sludge treatment wetland and a leachate treatment wetland through a baffle, there were 12 small holes (diameter 10 mm) under the bottom of the baffle, which were used for leachate infiltration into the leachate treatment wetland (Fig. 1). The size for sludge treatment was 30 × 20 × 50 cm (Length × Width × Height). All the STWs were filled by three layers with substrate size increasing from top to bottom. The layers consisted of 10 cm of 4–8 mm gravel, 10 cm of 8–16 mm fine gravel and 10 cm of 25–40 mm coarse gravel. As a result, the average porosity of each STW was 0.44. *Phragmites australis* (average height of 70 cm) and *Typha angustifolia* (average height of 120 cm) were selected from the nature ponds in the campus, and 10 strains were planted in the STWs. *Eisenia foetida* was selected based on previous study and 400 g *E. foetida* (about 850) was added into some STWs. Therefore, the treatments of the six STWs were *T. angustifolia* + *E. foetida* (T + E), *T. angustifolia* (T), *P. australis* + *E. foetida* (P + E), *P. australis* (P), Unplanted + *E. foetida* (U + E) and Unplanted (U), respectively. Surplus sludge from Shahu domestic wastewater treatment plant (Wuhan, China) was fed into the STWs with the TS and VS/TS were 0.8% and 41.9%, respectively. The sludge volume and feeding frequency was 3L/2d, the average sludge loading rate was 45.6 kg TS/m^2/yr, and lasted for 5 months. The resting phase lasted 2 months. Afterwards, pot experiments were carried out to evaluate the feasibility of treated sludge for land application. Different proportions of sludge and soil (1:3, 1:1, 3:1, 1:0 and 0:1) were added into the pots, with three replicates. Seeds (10) of *Brassica chinensis* were added into each pot to observe germination index (GI). Each pot was watered daily with deionized water to maintain moisture content of 15% on a dry weight basis (55% water-holding capacity).The pot experiments was conducted in a greenhouse at a temperature of 25 °C (light) and 20 °C (dark), and 65% relative humidity. The biomass of *B. chinensis* were harvested after 35 days.

Fig. 1. Experimental setup of earthworm assistant STWs systems.

2.2. Sample analysis

The accumulated sludge samples of the six STWs were taken every six days during the feeding period, and were analyzed for TS, VS/TS, dehydrogenase activity (DHA), total nitrogen (TN), total phosphorus (TP), total potassium (TK), alkali-hydrolyzale nitrogen (Alkeline-N), rapidly available phosphorus (Olsen-P), available potassium (Available-K), *E. coli*, volatile fatty acid (VFA). These parameters were also analyzed every 15 days during the rest period. Sludge structure and relative element content in sludge were tested at the end of the experiment. Seeds GI and *B. chinensis* dry biomass were analyzed during the pot experiments to evaluate the sludge land application. TS was measured after drying under 105 °C for 24 h, VS was measured after drying in muffle furnace under 600 °C and ignited for 2 h, cool to balance temperature in an individual desiccator containing fresh desiccant, and weigh. DHA was measured by triphenyltetrazolium chloride (TTC) colorimetric method, tetrazole red formazan (TPF) dissolved in toluene was used to establish the standard curve, detailed steps based on Dai et al. (2013). TN, TP, TK, Alkeline-N, Olsen-P, Available-K and *E. coli* contents in the accumulated sludge were determined according to Chinese soil chemical analysis method (Bao, 2000). VFA was measured by distillation – titration method (Chinese EPA, 2005). Sludge structure was photographed by scanning electron microscopy (SEM). The sludge relative contents of all monitored elements were analyzed by the energy dispersive X-ray spectrometry (EDX). The seeds GI were calculated