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Performance of wastewater sludge ecological stabilization

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Abstract

In this article, wastewater sludge ecological stabilization (WWSES) was presented for sludge dewatering, mineralization, and stabilization, as well as for percolate treatment. Two years of pilot scale experimental results indicated that sludge volatile solid, triphenyltetrazolium chloride (TTC)-dehydrogenase activity (DHA), and moisture content as indicators showed the process and degree of sludge stabilization. The observation on dewatering process showed that dried sludge reached a content of 20%–50% total solid after two years of system operation. Sludge TTC-DHA in the first year was obviously lower than that of the second year, and TTC-DHA tended to decrease with an increase in the drying time of the sludge. Total nitrogen, total phosphorus, and organic contents of sludge decreased gradually from the top to the bottom of dried sludge layer. In comparison with natural stands on stands treated with sewage sludge, individual shoot was significantly higher, and coarse protein, coarse fat, and coarse fiber contents in reed roots, stems, and leaves in the system were higher than that of wild reed, especially coarse protein contents of reed roots in the system (7.38%) were obviously higher than that of wild reeds (3.29%).

Key words: constructed wetland; ecological stabilization; treatment and disposal; wastewater sludge

Introduction

Sludge generated during wastewater treatment has been traditionally regarded as a necessary nuisance by-product. Wastewater sludge is being viewed as a valuable resource during the treatment process, the final product is one of the best sources of an agricultural soil conditioner and a source of slow-release nutrients and microelements (Oleszkiewicz and Mavinic, 2002). Inappropriate sludge disposal might cause secondary pollution and waste of useful resources (Strauss *et al*., 1997). In China, wastewater sludge produced in wastewater treatment plant (WWTP) has been increasing greatly with the development of wastewater treatment industries; however, the present situation is that the public pay more attention to wastewater than to sludge. Most of the existing WWTP has no sludge treatment facilities, parts of dewatering sludge are used directly for farm land or land-filling, and all of these are mainly caused by the fact of the higher cost for sludge treatment (Yin and Tan, 2004). Sludge treatment technologies with low investment, operation, and maintenance costs like constructed wetlands (Kadlec and Knight, 1995; Cooper *et al*., 1996) are promising treatment alternatives.

Sludge stabilization is aimed at the organic matter existing in the sludge, which is the process of convertion of organic matter into inorganic matter through physical, chemical, or biological reactions under certain conditions (Wang and Jia, 2001). However, the definition of "stabilized" sludge is not uniformly accepted. The United States use the value of 38% reduction of volatile solids as the threshold for considering the sludge stabilization (Koottatep *et al*., 2001).

In this article, the concept of wastewater sludge ecological stabilization (WWSES) was put forward, i.e., the ecological technology was used for sludge stabilization. The function of WWSES contains three aspects: flow stabilization, i.e., dewatering; chemical stabilization, i.e., organic degradation; and microorganism stabilization, i.e., inactivity. The process of stabilization was indicated with moisture content, volatile solid (VS), and activity of triphenyltetrazolium chloride (TTC)-dehydrogenase (DHA).

The core of ecological stabilization is constructed wetland technology, which has proved to be an effective low cost treatment system that uses the interactions of emergent plants and microorganisms in the removal of wastewater pollutants (Yin and Shen, 1995). Constructed wetlands for treatment of biosolid are a combination of traditional sludge drying beds and natural wetlands, and these have been successfully used for solids and septage dewatering and stabilization in small cities across Europe and Asia (Cooper *et al*., 1996; Burgoon *et al*., 1997; Kengne Noumsi *et al*., 2006). Sludge contains plenty of organic matter and nutrients like N, P, and K and trace elements, such as Ca, Mg, Cu, and Fe, which are necessary for the growth of plant. Meanwhile, plant growth stimulates sludge stabilization and harmlessness. The treated sludge

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can be used as fertilizer for the aim of soil structure and fertilization amelioration and plant growth stimulation.

In the process of sludge ecological stabilization, dewatering process can be ascribed to evapotranspiration, percolation, and mineralization (De Maeseneer, 1997). Planting of reeds in wastewater sludge showed several positive effects, such as higher dry weight contents of the residual sludge, enhanced decomposition of the organic matter, and better quality of the percolated water (Hofmann, 1990). These reeds have a positive impact on percolation that may be caused by the change in the colloidal structure of the sludge; in the immediate vicinity of the plant roots, humic acid sols are produced from which the water is more easily removed, and the movement of the stems in the fresh sludge improves the percolation of water (Hofmann, 1990).

The process of sludge stabilization is the process of mineralization; plants and microorganisms in sludge consist of a new ecological system. The root activities during the growth of plant can simulate the vicinity microorganism activity; the activities of the microorganism speed the process of conversion of the old roots and plant residue into humic matter, certain humic colloids take positive discharge, which can adsorb metal ion and form organic-inorganic complex (Li, 2006). Thus, this novel ecological system can complete sludge stabilization and harmlessness.

1 Materials and methods

1.1 Experimental setup

A pilot-scale vertical flow constructed wetland with a surface area of 80 m^2, having 60 cm sand-gravel matrix, supported by ventilated-drainage system and planted with common reed (*Phragmites australi*) in 2005 and planted with cattails (*Typha augustifolia*) in an area of apprximately 25% in 2006 was fed with thickened sludge from cyclic activated sludge technology (CAST) process, the 3rd WWTP located in Changchun City, China. The substrata in constructed wetland unit comprise a 20-cm layer of large gravel, a 20-cm layer of small gravel, a 10-cm layer of fine sand, and 10-cm layer of coarse sand from bottom to top, and a free board of 0.5 m was allowed for accumulation of dewatered sludge. The drainage system consists of perforated PVC pipes with a diameter of 20 cm at the bottom, and ventilation pipes with a diameter of 10 cm were mounted on the drainage pipes, extending 0.5 m above the matrix surface.

1.2 Operating conditions

The thickened sludge from CAST process combines primary settling and secondary settling sludge, which has relatively lower volatile solid (VS) of average 34.7%. Table 1 shows the characteristics of waste sludge and loading. During the two years, loaded sludge have a mean total solid (TS) of 22.34 g/L, VS of 7.76 g/L, and moisture content of 97%.

Table 1 Characteristics of wastewater sludge

	TS	VS	Moisture
Range	5.3–38.82 g/L	1.73–11.5 g/L	89%–99.5%
Average (n=25)	22.34 g/L	7.76 g/L	97%
SLR (avg.)	0.166–1.213 (0.691) kg TS/(m^2·d)	0.054–0.548 (0.24) kg VS/(m^2·d)	
SLR (avg.)	60.6–442.7 (252.2) kg TS/(m^2·a)	19.7–200 (87.6) kg VS/(m^2·a)	

TS: total solid; VS: volatile solid; SLR: sludge loading rate.

Cooper *et al*. (1996) suggested solid loading rates (SLR) to range from 30 to 80 kg TS/(m^2·a) for reed beds treating excess wastewater sludge, and loading frequency should be once in a week. On the basis of the research of Koottatep *et al*. (2001), SLR of 250 kg TS/(m^2·a) and application of the septage once in a week should be the suitable strategies (Hofmann, 1990). In this research, SLR averaged 0.691 kg TS/(m^2·d) or 252.2 kg TS/(m^2·a) for the aim of maximum land application efficiency.

Reeds collected from nearby natural wetland were planted in the unit and were watered with treated wastewater till the reed length was 1.5 m. To operate in a vertical flow mode, the sludge was then uniformly distributed on the surface of the constructed wetland.

The system was run in two stages in 2005: Run I and Run II, and both were batch flow mode. Run I was for 2 weeks, with high loading rate of 10 m^3/d, loading time was 8:00–10:00 each day. Run II was for 14 weeks, with low loading rate of 10 m^3 once in four days, loading frequency was once in every four days, loading time was 8:00–9:30 at the first day in each cycle.

In the second year (2006), the same running conditions were maintained with the Run II, for 21 weeks from May to October; comparisons of the variation of sludge compositions and microorganism activities and plant composition were conducted.

WWSES system built in Changchun City are in the northeastern China, which has about 120 freezing days from December to March in a year, freezing weather facilitates dewatering of the solids (Reed *et al*., 1994). However, the rest of the days were expected to be ideal for dewatering and stabilzing the biomass by WWSES technology.

1.3 Analyses

The percolate flow indices, including chemical oxygen demand (COD), ammonia nitrogen (NH_4^+-N), total phosphorus (TP), and the sludge biomass indices, including TS and VS, were measured according to Chinese Standard Methods for Examination of Water and Wastewater Analysis (2002).

Reed and sludge biomass were analyzed for TP and TN content after grinding with a mixer. A Kjeldahl digestion was conducted with 100 mg of each sample after which they were analyzed for TP and TN content with a FIA (Flow Injection Analyser) star 5000 Analyzer Foss Tecator. Biomass TTC-DHA was measured according to Yin *et al*. (2005).

2 Results and discussion

2.1 System start-up

2.1.1 Sludge dewatering

In Run I, the loaded sludge moisture ranged from 96% to 99.5%, dried sludge thickness was raised to 6 cm within two weeks. Considering the sludge dewatering and further increasing the solid content, the experiment was adjusted to low loading rate (Run II).

According to the statistics of dried sludge moisture content within each period, the fastest sludge moisture decrease rate generated at the first day decreased to 75% after dewatering 24 h and to 65% on day 4. Loaded sludge did not have significant effect on the bottom layer sludge moisture during the length of the whole start-up experimentation.

2.1.2 Dried sludge VS removal

Compared with conventional activated sludge process, VS from CAST process has lower contents of 28%–32%. During sludge drying, VS contents from different dried sludge layers were obviously different, which decreased gradually from surface layer of 28%–32% to subsurface layer (i.e., surface layer of last loading period) of 25%–27% and to bottom layer of 20%–23%.

2.1.3 Percolate analysis

Percolate COD and NH_4^+-N concentrations and removal efficiencies are listed in Table 2. Loaded sludge supernatant COD concentrations are very different, from 83 to 350 mg/L (Run I) and from 97 to 440 mg/L (Run II), nevertheless percolate COD concentrations tend to stabilize, with value of 32–130 mg/L (Run I) and 32–123 mg/L (Run II). In Run I, COD removals show an increasing trend with sludge drying time, with average 60%. In Run II, percolate COD removals increased to average 70%.

Influent and percolate NH_4^+-N concentration variation have the same trend with that of COD. Average NH_4^+-N removals are 47% (Run I) and 57% (Run II).

Percolate TP removals were not recorded in Run I. In Run II, influent TP ranged from 2.6 to 7.9 mg/L and percolate TP ranged from 0.6 to 2.1 mg/L, corresponding removal efficiency was 61%–77%. Percolate TP removals tend to stabilize in the system.

2.2 Results of the second year

2.2.1 Moisture and VS variation in dried sludge

Figure 1 shows the periodical variation of moisture of dried sludge and contents of VS. The abscissa of time seriation indicates 14 cycles for moisture and VS measurement during the whole experimentation for the aim of showing the trend of moisture and VS contents in different sludge layer with drying time. Within the same cycle, moisture and VS contents tend to decrease with the increase of sludge retention time, surface layer sludge moisture content decreased from 97% to 80%–90%, subsurface and bottom sludge moisture contents fluctuated from 60% to 80% and from 50% to 60%, respectively. Correspondingly, TS showed an increase from average 3% to 20%–50%, similar results were obtained in previous studies that ranged from 1%–2% to 30%–60% (Koottatep *et al.*, 2001). VS contents in sludge surface, subsurface, and bottom fluctuated approximately at 40%, 30%, and 20%, individually.

From Fig.1 it can be observed that the moisture and VS contents of the bottom layer sludge have a decreasing trend during the length of the whole experimentation. With the increase of dried sludge thickness, moisture in the fresh sludge was withheld by sublayer sludge during percolation; at the same time, reeds growth and evapotranspiration consumed moisture. This can be explained by the phenomenon of moisture decrease. It is suggested that VS decrease was caused by sludge biomass self-digestion. Although fresh sludge contains several nutrients, percolate could not be distributed evenly in sludge layer but infiltrated into the matrix along roots and sludge crack. Most of the microorganism in the sludge consumed selfnutrients, which caused decrease of VS. This showed the process of sludge stabilization from the point of organic stabilization.

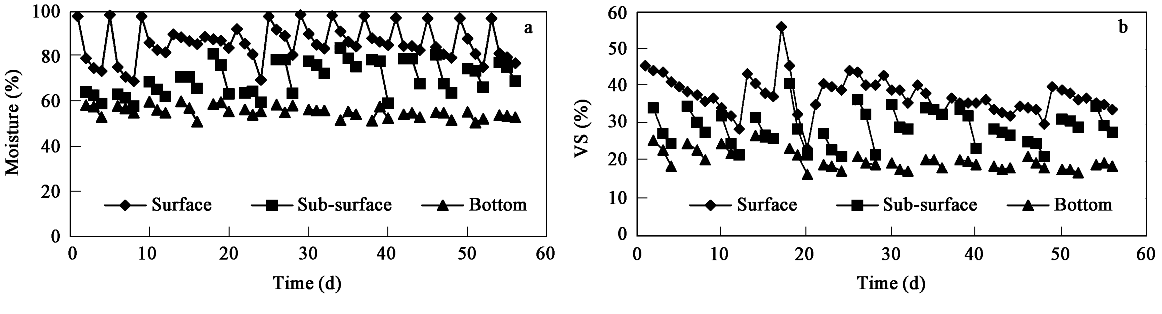

Fig. 1 Moisture (a) and volatile solid (b) in dried sludge for 4 d per period.

Table 2 COD and NH_4^+-N concentrations in WWSES percolate and removal efficiencies

	COD			NH_4^+-N		
	Influent (mg/L)	Effluent (mg/L)	Removal (avg.) (%) (*n*)	Influent (mg/L)	Effluent (mg/L)	Removal (avg.) (%) (*n*)
Run I	83–350	32–130	31–77 (60) (8)	16–52	9–26	21–63 (47) (8)
Run II	97–440	32–123	62–81 (70) (12)	18–79	10–33	41–69 (57) (12)

2.2.2 Activities of microorganism in accumulated sludge

Triphenyltetrazolium chloride (TTC) is used as indicators of bacterial respiration, because respiration is closely associated with cellular metabolism, detection of dehydrogenase activity (DHA) by reduction of tetrazolium salts, such as TTC to triphenyl formazan (TF), has been used to detect respiring cell and to measure their activity (Yin *et al*., 2005). Also, DHA has been described as respiratory potential or electron transport system (ETS) activity (Ragusa *et al*., 2004). In this research, TTC-DHA was selected to indicate the degree of sludge stabilization. Obviously, lower TTC-DHA corresponds to higher sludge stabilization degree.

The sludge samples were taken from surface layer, 10, 5, and 0 cm (bottom) layers from the top to the bottom of dried sludge. The thickness of dried sludge during the first year was approximately 10 cm, so the sludge from 0 to 5 cm is the dried sludge of the first year, whereas sludge from 10 cm and above layers was produced in the second year, surface layer sludge represents fresh sludge. Table 3 shows that TTC-DHA of old sludge accumulated in the first year is obviously lower than that of second year sludge, and TTC-DHA decreases with an increase in the sludge drying time, which indicates that sludge stabilization degree is improved with sludge retention time. On the basis of the mechanism of TTC-DHA analysis, VS represents the amount of microorganism, if VS contains a number of very old and dead microorganism cells, TTC-DHA should be lower, corresponding to higher degree of sludge stabilization.

Table 3 Sludge biomass activities at different dried sludge thickness

Sampling port (cm)	TTC-DHA (μg TF/(g VS·h))	Average (μg TF/(g VS·h)) (*n*=50)
0 (bottom)	102–1373	457
5	91–3258	896
10	525–13715	6216
Top layer	4243–20324	10603

2.2.3 Nutrients in dried sludge and reeds

Sludge nutrients at different dried sludge thickness are given in Table 4. Obvious variation trend can be observed from Table 4, TN, TP, and organic contents decrease gradually from the top to the bottom of dried sludge layer, and the nutrient contents of dried sludge in the first year were obviously lower than that of the second year. It is also found that the reed roots planted in the matrix in the first year had grown into the sludge layer, it is possible that the decrease of sludge nutrients with the drying time has relationship with growth of reeds. So the main compositions of reed roots, stems, and leaves in wild and in the system are required to compare and analyze.

Table 4 Sludge nutrients at different dried sludge thickness

Sampling port (cm)	TN (%)	TP (%)	Organic matter (%)
Top layer	2.52	1.42	22.1
10	2.40	1.37	21.9
5	1.98	1.25	19.6
0 (bottom)	1.13	0.96	14.4

For the aim of accurate comparison, wild reed samples were taken from the place where the reeds in the system were obtained (Table 5). It is observed that coarse protein, fat, and fiber contents in reed roots, stems, and leaves in the system are higher than that of wild reed, especially coarse protein contents of reed roots in the system (7.38%) are obviously higher than that of wild reeds (3.29%). It is suggested that one of the main reasons for the decrease of the sludge nutrients with sludge drying time is plant adsorption during the growing season.

Table 5 Comparison of reed composition (%)

Sampling	Moisture	Coarse protein	Coarse fat	Coarse fiber
Root in wild	70.56	3.29	1.04	26.00
Root in system	70.12	7.38	1.15	33.64
Stem and leaf in wild	58.29	6.96	1.37	33.63
Stem and leaf in system	58.21	7.77	2.21	35.77

Theoretically, sludge contains several nutrients for the growth of plant, while short of concrete indices to illustrate it. Reeds length in the wild and the system were measured during growing season from May to July, 2006 (Fig.2). Fig.2 shows a significant trend, i.e., the reeds growth superiority in the system is more obvious with plant growing time. Compared to the system, the nutrients for wild reeds are obtained from the soil, whereas soil nutrients are limited because of shortage of external nutrients supply. But this is different in the system, the sludge contains several nutrients, fresh sludge and percolate also become nutrient resources. When soil nutrients become the factor of limitation for the growth of reeds, abundant nutrients in the system ensure and simulate the growth of reeds. From Tables 4 and 5, we can conclude that most of the decreased nutrients in dried sludge were converted to reed composition. Thus, from the point of nutrients recovery, the system completes sludge ecological stabilization, and at the same time, the nutrients in the sludge are transformed.

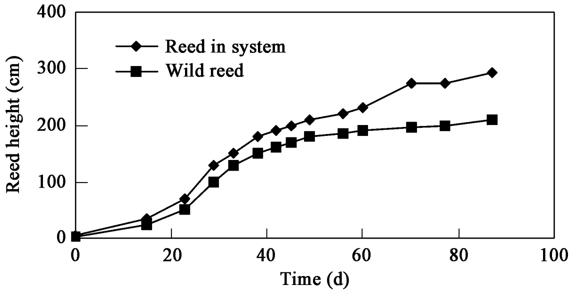

Fig. 2 Comparison of reed length.

3 Conclusions

The SLR of 0.691 kg TS/(m^2·d), once in every four days, and excess wastewater sludge application are suitable parameters for local climate. In dried sludge, TTC-DHA and moisture, VS, organic matter, and nitrogen and phosphorus contents decrease with the increase of sludge drying time, which can indicate the process of sludge stabilization. COD, NH_4^+-N, and TP in percolate were efficiently removed, the removal efficiencies are 60%–80%, 50%–70%, and 60%–80%, respectively. Although more indices, such as pathogen, are required to indicate the degree of sludge stabilization, the results show that the WWSES is a promising technology for developing countries.

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