Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2019.23681

149 (2019) 91–97
May

Stabilization and sanitization of concentrated domestic bio-wastes with improved septic tank technology

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Received 10 July 2018; Accepted 25 December 2018

ABSTRACT

High-rate resourcing disposal tank (HRDT) based on improved septic tank technology was first designed in this work to achieve the stabilization and sanitization of the concentrated domestic bio-wastes (CDBWs). Parasite eggs were not detected in the third-chamber effluents during different hydraulic retention time and temperature. With the packing unit, the second-chamber made some contributions to remove parasite eggs. The concentration level of faecal coliforms in the third-chamber effluents had met the limited level of WHO guidelines resulting from the lower pH and the higher concentrations of volatile fatty acids in the tank. An average of 27.4% of organic matter were converted into CH_4 under different operating conditions, which resulted in the annual emissions of about 0.1 tonne CO_2 equivalents per capital. The third-chamber effluents contained rich macro and trace elements and were suggested to replace some chemical fertilizers. With simple structure, easy operation and low cost, applying HRDT to sanitize and stabilize CDBWs requires a volume of 0.25 m^3/cap, the vacuum source-separating sanitation system proposed in this study will be an efficient sanitation system integrated with sustainable agriculture.

Keywords: Stabilization; Sanitization; Concentrated domestic bio-wastes; Improved septic tank technology

1. Introduction

Owing to the most of the pollutants and nutrients presented in domestic wastes originating from human excrements and kitchen wastes, separated collection and targeted treatment of domestic bio-wastes have been proposed in some sanitation concepts, represented by ecological sanitation [1,2], sustainable sanitation [3,4] or resource-oriented sanitation [5]. The goals of these sanitation concepts are to achieve the closed loop of material flows between sanitation and agriculture [6]. Vacuum source-separation sanitation (VSS-San) is the most promising candidate technology that can close the loop on the premise of conforming the modern sanitation standards [7,8] (Fig. 1) [14]. It uses vacuum technology to realize separated and water-saving collection and transportation of the domestic bio-wastes. The obtained concentrated domestic bio-wastes (CDBWs) is generally an intermixture of faeces, urine, kitchen wastes (grounded), and washing water, which contains about 90% of the chemical oxygen demand (COD), nitrogen, and phosphorus in domestic wastewater and solid wastes with the ratio of solid to liquid (w/w) about 1%–2%. Then, stabilization and sanitization of these concentrated bio-wastes are compulsive for safety reuse in agriculture. The main objects of stabilization and sanitization are to remove the pathogens, helminth eggs, to stabilize organic matter and to recover nutrients.

Generally, most researches have focused on the biogas technology to stabilize CDBWs with various anaerobic

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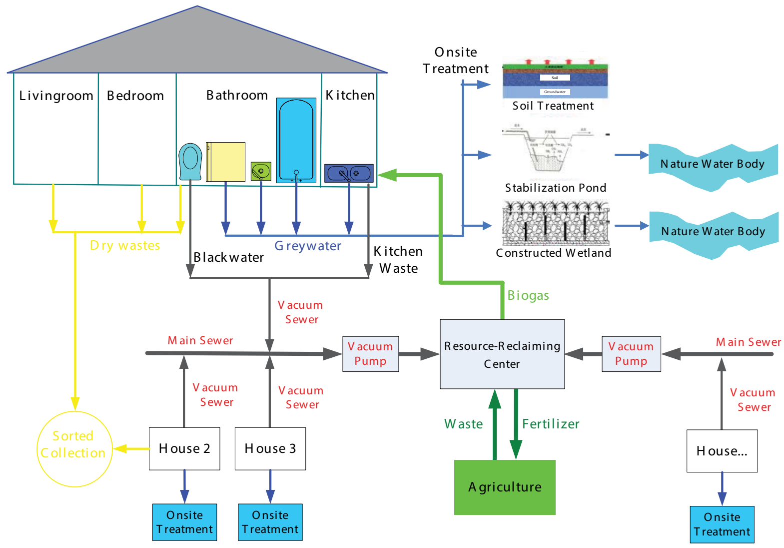

Fig. 1. Schematic diagram of vacuum source-separation sanitation system (VSS-San).

reactors, such as continuous stirring tank reactor [9,10], accumulation reactor (AC) [11], upflow anaerobic sludge blanket (UASB) [12], UASB-septic tank (UASB-ST) [13] and upflow solid reactor (USR) [14]. A disinfection step to sanitize the effluents is mandatory when direct reuse of effluents is possible, such as thermophilic or chemical process [15]. However, a cost comparison of different sanitation systems was carried out, and the results showed the economy efficiency of VSS-San system improved with the increase of population size owing to the more biogas power generation and nutrient reuse [16]. With a population size of 697 people, the total cost of VSS-San system was slightly less than that of conventional sanitation (Con-San) system, while the total cost of VSS-San was 20% less than that Con-San with a population size of 5,000 people. Moreover, the impacts on environmental performance of applying biogas technology in VSS-San system are greater than those of none biogas utilization [7] by using the life cycle assessment. The reason is the accessional process in biogas system, such as reactor heating, biogas purification, biogas storage. Interestingly, the application of biogas technology for concentrated domestic bio-wastes in VSS-San system seems similar to a chicken rib.

Septic tank technology has a long-history and wide-spread applications in decentralized wastewater treatment because of its simple structure, easy operation and maintenance, and it has played an active role in the prevention of health and epidemic, and the degradation of pollutants [17]. Septic tank technology has been introduced in the toilet reinventing project of rural China, represented by the three-chamber septic tank toilet, the dual-urn funneling toilet. With the function to decrease, eliminate and inactivate the biological virulence factors of human excreta, agriculture applications are promoted through the harmless treatment of human excreta with septic tank technology. However, the sanitization results are related to the temperature and the hydraulic retention time (HRT), especially of the fluctuations of HRT [18,19]. The sanitization results will not achieve the limited level of WHO guidelines if the blackwater production increases, thus to limit the safe reuse in agriculture.

In this study, considering the characteristics of CDBWs, also the applicability of septic tank technology, a high-rate resourcing disposal tank was designed to stabilize and sanitize CDBWs in this study. The objective of this study is to demonstrate the technology practicability and feasibility of improved septic tank technology to stabilize and sanitize CDBWs under different realistic conditions, such as HRT and temperature.

2. Materials and methods

2.1. Feedstock and inoculum sludge

The CDBWs were the mixtures of concentrated black water (CBW) and kitchen waste (KW). CBW was collected from a vacuum toilet installed in an apple orchard in Wangjiayuan Settlement (Liucun Town, Beijing City, China). As estimated, vacuum toilet will produce 5–6 L blackwater per capital per day. KW was made from a mixture of 20% cooked kitchen waste (CKW) and 80% raw kitchen waste (RKW). The CKW was collected from a restaurant, and RKW was made up of 50% pre-prandial waste and 30% fruit waste. The mixed KW was shredded to a size less than 2 mm. The feedstock used in this study was on the average of 6 L of CBW and 500 g KW per capital per day. Characterization of the CBW, KW and feedstock mixture is given in Table 1. Because of the much greater amount of KW generated per capital per day (500 g/capital/d, China; 200 g/capital/d, Germany [9]; 150 g/capital/d, Singapore [10]), the feedstock in our study had a higher concentration of total chemical oxygen demand and total solid compared with other research.

2.2. Reactor and experimental design

Stabilization and sanitization of concentrated domestic bio-wastes were performed in a high-rate resourcing disposal tank (HRDT) (Fig. 2), which was divided into three chambers with baffles and had a working volume of 1.4 m^3. The volume ratio of the first, second and third chamber was 3:1:2. The first chamber (*F*-chamber), where decomposition,

Table 1
Characteristics of concentrated domestic bio-wastes (CDBWs)

Parameter	Feedstock
TS (%)	2.1
VS (%)	1.8
TCOD (g/L)	2.86
SCOD (g/L)	1.31
TN (g/L)	1.4
NH_3–N (g/L)	0.75
TP (mg/L)	202.3
SP (mg/L)	163.1
TVFA (g/L)	1.07

TS, total solid; VS, volatile solid; TCOD, total chemical oxygen demand; SCOD, soluble chemical oxygen demand; TN, total nitrogen; TP, total phosphorus; SP, soluble phosphorus; TVFA, total volatile fatty acid.

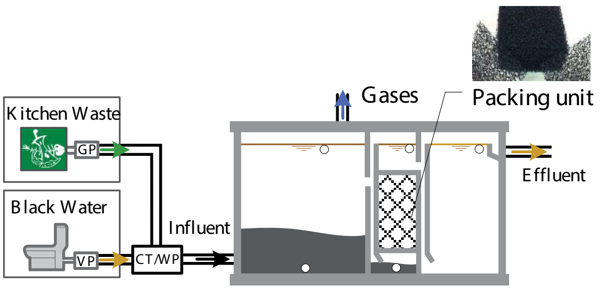

Fig. 2. Schematic diagram of high-rate resourcing disposal tank (VP, vacuum pump; GP, grinder processor; CT, collection tank; WP, wastewater pump).

settlement, stratification and digestion happening, was to ensure the effluent into the second chamber free from much solids and scums. The second chamber (*S*-chamber) was equipped with a packing unit to achieve further fermentation and filtration. The packing unit was made of polypropylene with the packing porosity of 96% and the specific surface areas of 65–85 m^2/m^3. The packing unit has the advantages of higher specific surface areas and little possibility of blockage, where sludge bed would be produced. The third chamber (*T*-chamber) was treated as a settlement and storage tank.

The reactor was fed with the mixture of CBW and KW once a week. The reactor was placed in a greenhouse with non-heating equipment and was similar to the temperature of buried reactor (6°C–30°C). The HRT of reactor was designed at an HRT of 60, 50 and 40 d (Fig. 3). The fluctuations of HRT and temperature were designed to simulate the realistic operation conditions. The inoculum sludge was taken from an anaerobic digester in a municipal wastewater treatment plant, Beijing. The average total solids (TS) and volatile solids (VS) concentrations were in the range of 30.72 and 15.08 g/L, respectively.

2.3. Analytical methods

TS and VS were analyzed according to the Standard Methods [20]. Total chemical oxygen demand (TCOD) and

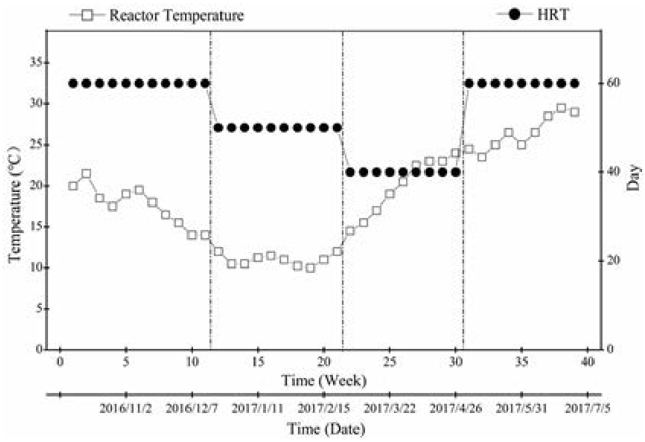

Fig. 3. Operation conditions of HRDT.

soluble chemical oxygen demand (SCOD) concentrations were measured using the fast airtight catalytic digestion method with titration of ferrous ammonium sulphate according to the Standard Methods [21]. SCOD concentrations were analyzed by measuring the samples filtered through a 0.45 µm membrane. Volatile fatty acids (VFAs), such as acetic, propionic, iso-butyric, butyric, iso-valeric and valeric acid, were determined using a gas chromatograph (Agilent Technologies 7890B, USA) equipped with a flame ionization detector and a DB-FFAP column (Agilent Technologies, USA). Total biogas production was monitored on a daily basis using a wet gas flow meter (Changchun Automobile Filter Co., Ltd., LMF-1, China). Biogas composition was analyzed by a gas chromatograph (Agilent Technologies 7890B, USA) equipped with a thermal conductivity detector and an HP-PLOT column (Agilent Technologies, USA). The counting of faecal coliforms, helminth eggs, and the concentration of total nitrogen (TN), NH_3–N, total phosphorus (TP), soluble phosphorus was measured according to the Standard Methods [21].

2.4. Calculations

The concentration of undissociated VFA in anaerobic reactor was calculated as following:

$$\left[\mathrm{UVFA}\right] = \frac{C_T\left[\mathrm{H}^+\right]}{K_a + \left[\mathrm{H}^+\right]} \tag{1}$$

where [UVAF] is the concentration of undissociated VFA in the reactor, C_T is the concentration of VFAs in the reactor, $[H^+]$ is the concentration of H^+ in the reactor, K_a is the dissociation constant of VFAs.

3. Results and discussions

This paper mainly launches the performance evaluation for the improving septic tank technology to stabilize and sanitize the CDBWs from three aspects, including health and hygiene aspect, organic matter conversion aspect, and resource utilization aspect.

3.1. Health and hygiene aspect

The diseases via parasitism transmission and faecal–oral transmission are epidemic in developing countries owing to the poor sanitation conditions [22,23]. Helminth eggs and faecal coliforms have been identified as the health indicators for the reuse of domestic wastewater by the WHO [24]. Based on the sanitary standards of China, Ascaris, hookworm and schistosoma were selected among the parasites in this study. As a result of concentrated blackwater, the distributions of Ascaris, hookworm and faecal coliforms in the influents in this study were at a high concentration level, reaching 2,700 egg/L, 650 egg/L and $2E^{-8}$ L/count on average (Fig. 4). Eggs of schistosoma were not observed in the influents, hence indicate their absence in the effluents.

The removal of helminth eggs and faecal coliforms was achieved at different operating conditions (HRT, temperature; Figs. 5 and 6). Eggs of Ascaris and hookworm were not observed in the effluents at different operating conditions. The removal of parasite eggs in the reactor are in the action of sedimentation, stratification, anaerobic and ammonia inhibition [25]. The higher concentration of solids in the influents will help the sedimentation process at longer HRT. Compared with the concentrations of Ascaris eggs in the *T*-chamber effluents, the concentrations of Ascaris eggs in the *F*-chamber effluents increased with the decrease of HRT, which was due to the incomplete sedimentation in the *F*-chamber at the short HRT (50, 40 d). However, since Ascaris eggs were not detected in the *T*-chamber effluents has indicated the removal contributions of the *S*-chamber, where the sludge bed formed would prevent Ascaris eggs entering the *T*-chamber. It can be concluded that the removal contributions of the *S*-chamber increased with the decrease of HRT (Table 2). The temperature had no significant effects on the removal of helminth eggs, also the removal of helminth eggs was achieved at lower temperature (9°C).

Although helminth eggs were not observed in the *T*-chamber effluents, the concentrations of helminth eggs in the *F*-chamber sludge must be much higher at the end of experiment. Results have shown that the distribution of helminth eggs will achieve 5,400 egg/L on average. The sludge in *F*-chamber and *S*-chamber will be cleared once or twice a year. Hence, the sludge is suggested to be disposed harmlessly through thermophilic composting or chemical process to kill the helminth eggs [26].

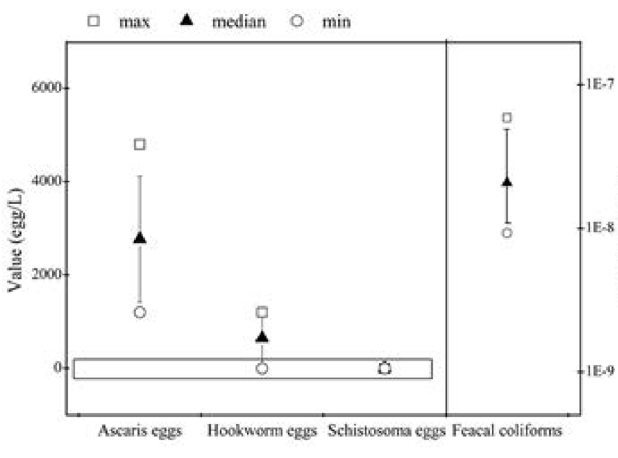

Fig. 4. Distributions of parasitic eggs and faecal coliforms in the influents.

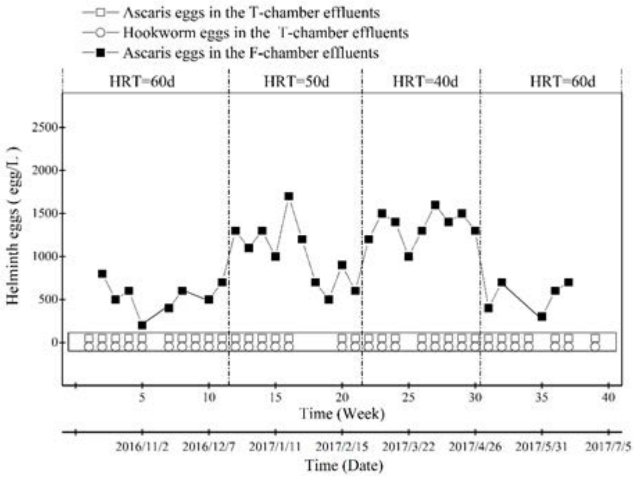

Fig. 5. Distributions of helminth eggs in the effluents.

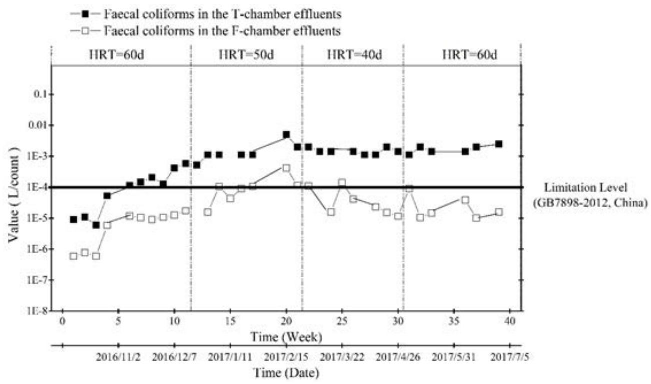

Fig. 6. Distributions of faecal coliforms in the effluents.

The effective removal of faecal coliforms was observed at different operating conditions, yet not all of faecal coliforms (Fig. 6). The concentration level of faecal coliforms in the *T*-chamber effluents had met the limited level of WHO guidelines [27] and China's standards (GB7898-2012) in the case of wastewater reuse for irrigating. The concentrations of faecal coliforms in the *F*-chamber effluents were out of the limited level, although the removal efficiency of faecal coliforms in the *F*-chamber had reached 99% (Table 2). It was attributable to the lower pH and the higher concentrations of VFA in the reactor, especially at the shorter HRT and lower temperature (Fig. 7). Studies have shown that efficient removal of pathogens would be achieved at lower pH with higher VFA concentration due to the increase of undissociated VFA concentration [28,29]. As calculated, the concentration of undissociated VFA in the *F*-chamber was about 1,800 mg/L, where an efficient removal of faecal coliforms was achieved in HRDT.

Overall, the sanitization results had achieved limited level of WHO guidelines at short HRT and lower temperature, which benefited from the packing unit of second chamber. The sanitization results were also not effected by the HRT

Table 2
Removal of Ae and FC in the *F*-chamber and *S*-chamber at different HRT

Parameters	HRT = 60 d		HRT = 50 d		HRT = 40 d	
	F-chamber(%)	*S*-chamber(%)	*F*-chamber(%)	*S*-chamber(%)	*F*-chamber(%)	*S*-chamber(%)
Removal of Ae	75.8	24.2	51.9	48.1	39.9	60.1
Removal of FC	>99	<1	>99	<1	>99	<1

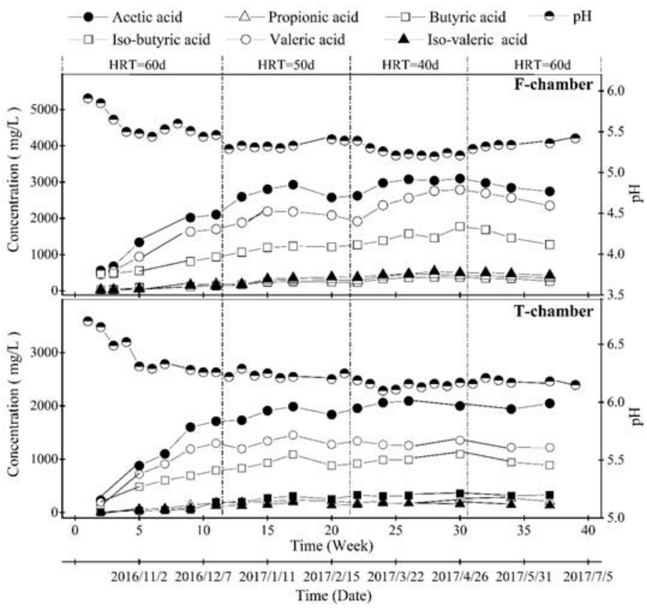

Fig. 7. Distributions of pH and VFAs in the reactor.

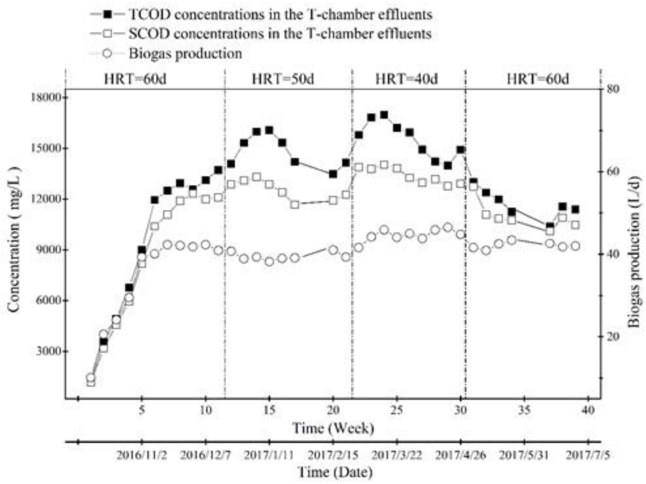

Fig. 8. Residual COD in the *T*-chamber effluents at different conditions.

Table 3
Gases production and composition at different conditions

Parameters	HRT = 60 d	HRT = 50 d	HRT = 40 d
Gases production (L/p/cap)	41.7	39.8	44.5
CH_4 percentage (%)	33.42	26.25	34.91
CO_2 percentage (%)	37.19	38.50	35.33

fluctuations. Basing on the production of concentrated domestic bio-wastes of 6 L/cap/d, the volume of HRDT was about 0.24 m^3/cap under the HRT of 40 d.

3.2. Organic matter conversion aspect

The conversion of organic matter was conducted under anaerobic conditions, and was expressed by the conversion of COD in the effluents. The COD concentrations of the *T*-chamber effluents were higher (Fig. 8), indicating land application of the *T*-chamber effluents would enhance the soil organism and benefit the crop growth. More than 90% of COD in *T*-chamber effluents were mainly in soluble form, which would be the source of dissolved organic matter in soil. It could be concluded that the organic matter in solids were converted to simpler organics through hydrolysis and fermentation process. The conversion of organic matter into CH_4 depended on the HRT and temperature (Fig. 8, Table 3). The methane production at an HRT of 50 d was less than that of at an HRT of 60 d resulting from the lower temperature conditions (9°C). The methane production at an HRT of 40 d increased with increasing temperature. The determined gases production was about 10–16 L CH_4 and 14–16 L CO_2 per cap/d at different operating conditions in this study, hence an average of 26.4% of organic matter was converted into CH_4.

The gases produced in HRDT was discharged as greenhouse gases (GHG), the annual emissions were estimated to be about 0.1 tonne of CO_2 equivalents per capital. The GHG emissions from HRDT in VSS-San system can be ignored as the amount represents a little fraction of the total carbon footprint for a capital in a world average, about 4.9 tonne CO_2 equivalents per capital per year [30]. Moreover, the GHG effect of applying septic tank technology in VSS-San system will be much less than that of applying biogas technology due to the accessional process in biogas system, such as reactor heating, biogas purification, biogas storage [7]. Hence, the GHG emissions from HRDT in VSS-San system might be ignored.

3.3. Resource utilization aspect

Direct reuse of the *T*-chamber effluents would be possible due to the minimum hygienic risk. The production of nutrients and resources in the *T*-chamber effluents contained macro elements and trace elements (Table 4), which are indispensable to plant growth. The forms of C, N and P were

Table 4
Element compositions of the *T*-chamber effluents

Parameters	Effluents
C, g/L	3.5
N, g/L	1.2
P, g/L	0.1
Mn, μg/L	529.7
Fe, μg/L	664.8
Cu, μg/L	23
Zn, μg/L	105.7
Cr, μg/L	30.01
As, μg/L	4.9
Cd, μg/L	0.2
Pb, μg/L	4.2

mainly in soluble forms, the soluble nitrogen was mainly in ammonium form. The concentrations of NO_2^- and NO_3^- in *T*-chamber effluents were less than 10 mg/L. The nutrient contents of N, P and K in the *T*-chamber effluents were more than 0.2%, hence the *T*-chamber effluents might be reused in agriculture as second fertilizers or supplemented with other nutrients, which resulted in a nutrient recovery of 2.6 kg N/cap/year and 0.22 kg P/cap/year.

The effluents were rich in the elements of Mn, Fe, Cu, and Zn, and the concentrations of Cr, As, Cd, and Pb were considerably lower than the limited concentrations of heavy metals in biogas slurry (NY1110-2006, China). Assuming that the *T*-chamber effluents were reused as fertilizer, the contents of the potential toxic metals (Cd, Cr, Cu, Pb, and Zn) with per kg phosphorus input were much lower compared with blackwater sludge [31], cow manure [32], and P-fertilizer [33], the element of As excepted (Table 5). The promotion of agriculture application of blackwater effluents will reduce the accumulation of toxic elements in soil/food cycle.

3.4. Practical application

Applying improved septic tank technology to sanitize and stabilize CDBWs of VSS-San system in this study was proved and applied in an apple orchard in Wangjiayuan Settlement (Liucun Town, Beijing City, China), where a vacuum toilet is installed to serve tourists and farmers. The VSS-San system installed in the apple orchard has three main advantages. First, the water conserving effect of vacuum toilet is remarkable compared with the conventional water-flush toilet. About 40 tonnes of water annually will be saved for the apple orchard, while the electricity consumption is merely about 200 KWh. Second, with simple structure, easy operation and low cost of HRDT, the sanitization and stabilization of CDBWs have been achieved under different realistic conditions. Neither heating equipment nor mixing equipment is required. The packing unit of polypropylene is cheap and easy to install, also no blockage was founded in the packing unit in experiment period. As estimated, the construction cost is about 300–400 Renminbi (China Yuan) per capital, provided the tank is made of fiber reinforced plastic. The cost will decrease with the increase of population size. The steady performance was also guaranteed at lower temperature (6°C) and shorter HRT (40 d). Third, the material loop in the system is closed. In the experiment periods, the safe effluents from the HRDT have been reused as liquid fertilizer in agriculture with drip-irrigation system, where a simple filter of nylon sieve was designed to prevent clogging. With the nutrient contents in the effluents of this study, land application of the safe effluents could replace some chemical fertilizers, benefit the crop yields and improve the soil quality. The VSS-San system proposed in this study will be an efficient sanitation system integrated with sustainable agriculture.

Table 5
Contents of heavy metals with per kg phosphorus input of different fertilizers (mg/kg phosphorus)

Element	Blackwater sludge	Cow manure	P-fertilizer	Blackwater effluent
As	12	Nd	33	49
Cd	13	33	91	1.9
Cr	731	1,145	1,245	300
Cu	3,720	14,397	207	230
Pb	69	695	154	42
Zn	13,919	25,947	1,923	1,057

The choice between septic tank technology and biogas technology in VSS-San system mainly depends on the population size and decentralization degree in rural areas. China has a relatively dense rural population especially in flat areas, where a rural settlement is mostly with 50–500 households (200–2,000 capita) and a residential density of 50–100 capita/hm^2. To build the VSS-San system in rural China, it is suggested that septic tank technology can be adopted in a small population size of less than 1,000 people, and biogas technology can be promoted in the regions with larger population size or sufficient fermentation materials.

Moreover, it is suggested to focus on the applying technology of the safe blackwater effluents, concerning on how to control the fertilization rate and frequency to enhance the crop field and quality, and how to apply the effluents to decrease the environmental impacts, such as ammonia emission, odorous emission and organic contamination.

4. Conclusions

The stabilization and sanitization of concentrated domestic bio-wastes were achieved with a high-rate resourcing disposal tank designed in this study. In respect of health and hygiene, the concentration levels of parasite eggs and faecal coliforms in *T*-chamber effluents under different conditions had satisfied the limited level of WHO guidelines. An average of about 27.4% of organic matter was converted into CH_4, which resulted in the annual emissions of 90 kg CO_2 equivalents per capital. The nutrients in T-chamber effluents were rich in macro and trace elements. The promotion of agriculture application of blackwater effluents will reduce the accumulation of toxic heavy metals in soil/food cycle. With simple structure, easy operation and low cost, applying HRDT to sanitize and stabilize CDBWs requires a volume of 0.25 m^3/cap.

Acknowledgements

This work was supported by the National Key Research and Development Plan (grant number 2016YFC0400806) and the Science and Technology Service Network Initiative (grant number Y301).

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