Reduction in greenhouse gas emissions from sewage sludge aerobic compost in China

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ABSTRACT

Sewage sludge is an important contributor to greenhouse gas (GHG) emissions and the carbon budget of organic solid waste treatment and disposal. In this case study, total GHG emissions from an auto-control sludge compost system, including direct and indirect emissions and replaceable reduction due to sludge compost being reused as fertilizer, were quantified. The results indicated that no methane generation needed to be considered in the carbon debit because of the advantages of auto-control for monitoring and maintenance of appropriate conditions during the composting process. Indirect emissions were mainly from electricity and fossil fuel consumption, including sludge transportation and mechanical equipment use. Overall, the total carbon replaceable emission reduction owing to sludge being treated by composting rather than landfill, and reuse of its compost as fertilizer instead of chemical fertilizer, were calculated to be 0.6204 $tCO_2e\ t^{-1}$ relative to baseline. Auto-control compost can facilitate obtaining certified emission reduction warrants, which are essential to accessing financial support with the authentication by the Clean Development Mechanism.

Key words | compost, emission, greenhouse gas, landfill, sewage sludge

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INTRODUCTION

In China, the volume of sludge produced as a result of sewage treatment has increased greatly in recent years with the expansion of urbanization (Lee *et al.* 2006; Chen *et al.* 2012). Accordingly, disposal technologies and intensive investment in facilities for treatment of sewage sludge have gained a great deal of attention in waste associated research fields. Moreover, there is a demand for low energy consumption and greenhouse gas (GHG) emissions nationwide. Solid waste is known to be an important contributor to total atmospheric GHG emissions (IPCC 2007), with sewage sludge accounting for nearly 3% of the GHG contributed by solid waste (Guo *et al.* 2012). Accordingly, controlling GHG emissions during sludge treatment and disposal is important to municipal facilities management and reduction of urban waste associated GHG emissions.

Aerobic composting utilizes nutrients contained in sludge regardless of factors that have negative effects when sludge is reused, such as heavy metals and salinity (Hubbe *et al.* 2010). It is generally known that fertility losses of soil where macronutrients were mainly provided by chemical fertilizer have become more severe worldwide, especially in China. So, amendment from organic biosolid such as sewage sludge compost is important and gradually accepted (Wang *et al.* 2008; de Andres *et al.* 2012). Sludge compost application to land can improve soil; for instance, sludge compost increases microbial activity in amended soil (Sciubba *et al.* 2013). Beside this, water-storage capacity and the resistance against drought were found to increase with the application of sludge compost (Mariscal-Sancho *et al.* 2011). However, more importantly, the amendment of soil with sludge and its compost is recommended because it enables nutrient recovery and reclamation. Moreover, phosphorus recovery by sludge amendment to soil is another concern (Kidd *et al.* 2007; Linderholm *et al.* 2012) because of increasing phosphorus in sludge through the sewage treatment system accompanied by rapid urbanization in China (Chen *et al.* 2012).

Sludge being treated with composting prior to land application or soil amendment is necessary to accelerate organic matter degradation and stabilization. From a resource recycling aspect, more nutrients beneficial to soil can be recovered with composting followed by its product soil amendment. Although phosphorus leaching risk and

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low amount for plant uptake are in debate (Shober & Sims 2003; Kidd *et al.* 2007), it is still regarded as an appropriate path for phosphorus cyclic utilization. On the other hand, heavy metals are an inevitable and bottleneck concern; heavy metal concentration in sludge decreases gradually along with separation of effluent and sanitary sewage in China (Yang *et al.* 2009). Meanwhile, strict heavy metal thresholds have been issued in China (CJ/T 309-2009, Ministry of Housing and Urban-Rural Development of China 2009) to control excess heavy metal input from sludge to amended soil. Lastly, from viewpoint of energy consumption and treatment cost, sludge composting is more economical compared to incineration. In China, most of the sludge is low calorific value and additional fuel remains essential (Cai *et al.* 2010). Also sludge is mainly co-incinerated with cement kiln in China with inadequate gas decontaminating facilities resulting in high cost to reduce emissions. In summary, sludge composting is the optimum technical pathway and at least matches Chinese national conditions (Liu & Zhang 2013).

Indeed, this method is used worldwide in areas including the United States (Surampalli *et al.* 2008), European Union (Fytili & Zabaniotou 2008) and Asia (Lee *et al.* 2006; Singh & Agrawal 2008). This technique has also been vigorously developed in Japan, which is moving from sludge incineration to composting and land application of compost (Hong *et al.* 2009; Zhu *et al.* 2012). These regions and countries have shown a gradual increase in adoption of the use of aerobic compost among many current treatment technologies (Pritchard *et al.* 2010; Chen *et al.* 2012). In China, utilization of sludge compost as soil or agricultural substrate amendment has been recommended as an optimal treatment method and is listed in the *Guideline for Sewage Sludge Treatment and Disposal Technologies* issued by the Chinese government (Ministry of Housing and Urban-Rural Development of China 2011). However, detailed investigations of carbon emissions and their reduction during sludge composting and compost application have yet to be conducted.

Auto-control composting technology (control technology for biocomposting) is a method in which the sludge composting process is controlled by Compsoft® 3.0 (Chen *et al.* 2001a) based on a combination of temperature and oxygen concentration feedback from temperature (Chen *et al.* 2001b) and oxygen sensors (Chen *et al.* 2001c). In this method, the aeration parameters are adjusted at different stages based on the temperature and oxygen consumption rate (Chen *et al.* 2011). When compared with conventional composting technologies, such as forced ventilation static composting, auto-control composting can adjust the ventilation frequency to maintain aerobic conditions in time. The use of this technology can reduce GHG emissions via two mechanisms. Specifically, aerobic conditions result in less GHG (including methane and nitrous oxide) emissions, and these systems use less fossil fuel because the runtime of the air-blowers and turning devices are shorter and the application of compost instead of chemical fertilizer alleviates the need to consume fossil fuels for fertilizer production. In this study, the detailed carbon budget of an auto-control compost system, including its compost product utilization and baseline disposal method, were investigated with an emphasis on its GHG emission reduction merit.

METHODS

Definition of baseline scenario and quantification of its corresponding GHG emissions

In China, sewage sludge landfill accounts for 65–70% of sludge disposal (Guo *et al.* 2012), with 100% being disposed of by landfill in Qinhuangdao in eastern Hebei Province. Therefore, this study investigated a sludge disposal system in Qinhuangdao. There are no environmental laws or regulations mandating the treatment or disposal of sewage sludge. Furthermore, landfill gas recovery and utilization is not common in China, and no landfills in the investigated city employ this practice. Therefore, disposal of sewage sludge without the capture of landfill gas was taken as the baseline scenario in this study.

The total GHG emissions ($PE_{TD,y}$) from sewage sludge landfill were quantified as follows:

$$PE_{TD,y} = PE_{\mathrm{elec},y} + PE_{\mathrm{fuel,on\text{-}site},y} + PE_{\mathrm{tran},y} + PE_{d,y} \quad (1)$$

$PE_{\mathrm{elec},y}$: emission from electricity consumption on-site due to project activity (ton of carbon dioxide equivalent (tCO_2e)); $PE_{\mathrm{fuel,on\text{-}site},y}$: emission due to fuel consumption on-site (tCO_2e)); $PE_{\mathrm{tran},y}$: leakage emission from increased transport (tCO_2e); $PE_{d,y}$: direct emission from the landfill (tCO_2e).

$$PE_{\mathrm{elec},y} = EG_{PJ,FF} \times CEF_{\mathrm{elec}} \quad (2)$$

$EG_{PJ,FF,y}$: amount of electricity consumed from the grid as a result of the project activity; it is measured using an electricity meter (MWh); CEF_{elec}: carbon emission factor for electricity generation associated with the project activity ($tCO_2 \cdot MWh^{-1}$); it was determined based on the *Notification on Determining Baseline Emission Factors of China's Grid* (NDRC of China 2012).

CEF_{elec} was 0.806 $tCO_2e\ MWh^{-1}$, which is the average of the grid in China.

$$PE_{fuel,on\text{-}site,y} = F_{cons,y} \times NCV_{fuel} \times EF_{fuel} \quad (3)$$

$F_{cons,y}$: fuel consumption on site (l or kg); NCV_{fuel}: net caloric value of the fuel ($MJ\ l^{-1}$ or $MJ\ kg^{-1}$), which was 4,2652 $KJ\ kg^{-1}$ in this study based on the *Notification on Determining Baseline Emission Factors of China's Grid* (NDRC of China 2012); EF_{fuel}: CO_2 emission factor of the fuel ($tCO_2\ MJ^{-1}$), which was 72,600 $kgCO_2\ TJ^{-1}$ based on the *Notification on Determining Baseline Emission Factors of China's Grid* (NDRC of China 2012).

$$PE_{tran,y} = \sum_{i}^{n} NO_{vehicles,i,y} \times DT_{i,y} \times VF_{cons,i} \times NCV_{fuel} \times D_{fuel} \times EF_{fuel} \quad (4)$$

$NO_{vehicles,i,y}$: number of vehicles for transport with similar loading capacity; $DT_{i,y}$: average additional distance travelled by vehicle (km); $VF_{cons,i}$: vehicle fuel consumption ($l\ km^{-1}$); NCV_{fuel}: calorific value of the fuel ($MJ\ kg^{-1}$); D_{fuel}: fuel density ($kg\ l^{-1}$); EF_{fuel}: emission factor of the fuel ($tCO_2e\ MJ^{-1}$), which was 72,600 $kg\ kJ^{-1}$ based on the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006).

$$PE_{d,y} = MB_y - MD_{reg,y} \quad (5)$$

MB_y: emission of methane (CH_4) from the landfill (tCO2e); $MD_{reg,y}$: amount of biogas collection or flaring (tCO_2e).

$$MB_y = MB_y = \varphi \times (1-f) \times GWP_{CH_4} \times (1-OX) \times \frac{16}{12} \times F \times DOC_f \times MCF \times \sum_{x=1}^{y} \sum_{i} W_{j,x} \times DOC_j \times e^{-k_j \cdot (y-x)} \times (1-e^{-k_j}) \quad (6)$$

φ: correction factor to account for model uncertainties, which was 0.9 here; f: fraction of methane captured at the solid waste disposal site (SWDS) and flared, combusted or used in another manner, which was 0 here; GWP_{CH4}: global warming potential (GWP) of methane (tCO_{2e}/tCH_4), which was 21 here; OX: oxidation factor, which was 0 in this study; F: fraction of methane in biogas, which was 0.5 in this study; DOC_f: fraction of degradable organic carbon in sludge, which was 0.5 here; MCF: methane correction factor, which was 1.0 in this study; W: amount of sludge prevented from disposal (t); DOC_j: fraction of degradable organic carbon, which was 0.5 here; k: sludge decay rate; x: year during the crediting period; y: year for methane emissions being calculated.

Quantification of GHG emissions from auto-control compost

The total GHG emission ($PE_{TC,y}$) of auto-control compost was quantified using the following formula:

$$PE_{TC,y} = PE_{elec,y} + PE_{fuel,on-site,y} + PE_{tran,y} + PE_{c,y} - BE_{compost,y} \quad (7)$$

$PE_{elec,y}$: emission from electricity consumption on-site due to project activity (tCO_2e); $PE_{fuel,on\text{-}site,y}$: emission on-site due to fuel consumption(tCO_2e); $PE_{tran,y}$: leakage emission from increased transport (tCO_2e); $PE_{c,y}$: direct emission from auto-control compost (tCO_2e); $BE_{compost,y}$: indirect emission from sludge compost substitution for chemical fertilizer (tCO_2e); $PE_{elec,y}$, $PE_{fuel,on\text{-}site,y}$ and $PE_{tran,y}$ were similarly calculated as described in the previous section.

$$PE_{c,y} = PE_{c,N2O,y} + PE_{c,CH4,y} = EF_{c,N2O} \times GWP_{N2O} \times M_{compost,y} + BE_{CH4,SWDS,y} \times S_{a,y} \quad (8)$$

$PE_{c,N2O,y}$: nitrous oxide (N_2O) emission during the composting process (tCO_2e); $PE_{c,CH4,y}$: emission during the composting process due to methane production through anaerobic conditions (tCO_2e); $EF_{c,N2O}$ is an emission factor for N_2O emission from the composting process (kg N_2O/t compost), which was 0.043 in this study (UNFCCC 1997); GWP_{N2O}: global warming potential of N_2O (tCO_{2e}/tN_2O), which was 298 in this study (IPCC 2007); $BE_{CH4,SWDS,y}$: CH_4 generation from the landfill in the absence of the project activity (tCH_4); $S_{a,y}$: share of the sludge that degrades under anaerobic conditions (%); $BE_{compost,y}$ can be expressed by the emission reduction as a result of substitution of sludge compost for chemical fertilizer (considered to be urea in this study).

RESULTS

Indirect GHG emission as a result of electricity and fossil fuel use associated with landfill

Because the moisture content of sewage sludge must be less than 60% for landfill disposal in China, indirect GHG emission caused by electricity consumption on-site (i.e. $PE_{elec,y}$)

in this study was mainly from sludge dewatering. Accordingly, $PE_{elec,y}$ was calculated as 0.0068 $tCO_2e\ t^{-1}$. The GHG emission due to fossil fuel consumption on-site was mainly from machines associated with landfill activities such as bulldozers, excavators, rotavators and compactors. Based on the formula given in Equation (3), $PE_{fuel,on\text{-}site,y}$ was quantified as 0.0238 $tCO_2e\ t^{-1}$. Another indirect emission source is leakage from sludge transportation. For the present study, the distance from the sewage plant to the sludge landfill site was assumed to be 20 kilometres, and the approved loading per sludge truck was limited to 5 t. Therefore, $PE_{tran,y}$ was calculated as 0.0028 $tCO_2e\ t^{-1}$. Overall, the indirect GHG emissions were 0.0334 $tCO_2e\ t^{-1}$.

Direct GHG emissions from landfill

Sludge anaerobic degradation produces significant amounts of CH_4 and CO_2. These CO_2 emissions are not included in national totals, because the carbon is of biogenic origin and net emissions are accounted for under the agriculture, forestry and other land use sector. Because the landfill site in this study was not equipped with a system for methane collection and utilization, the default value of $MD_{reg,y}$ was zero (0), and the corresponding value of '*f*' in the calculation formula of MB_y was also assigned as 0. In addition, '*k*' in the formula to determine MB_y was set at 0.06 based on the climate of Qinhuangdao, IPCC reported values of an annual average temperature of below 20 °C and an ratio of annual precipitation and potential evapotranspiration of <1. Overall, the quantity of direct methane emission from sludge landfill was calculated as 0.5692 $tCO_2e\ t^{-1}$.

Indirect GHG emissions from electricity and fossil fuel associated with auto-control compost

Similar to sludge landfill, indirect GHG emissions are made up of mechanical electricity and fuel consumption related to compost mechanical operations, sludge transport and loading. Despite compost being based on auto-control technology, many machines and electrical components are needed to accurately regulate the composting process (Table 1). Therefore, $PE_{elec,y}$ was quantified as 0.0367 $tCO_2e\ t^{-1}$. No dump trucks or forklifts are involved in the process, so the amount of diesel oil used is low; therefore, the value of $PE_{fuel,on\text{-}site,y}$ was determined to be 0.0006 $tCO_2e\ t^{-1}$. As shown in Figure 1, 0.37 tons of composted material per ton of sludge were produced and the residue was reused as a bulk agent. Moreover, the distance from the sewage plant to the sludge composting site and from the composting site to the land-use site were assumed to be 20 kilometres and 10 kilometres, respectively; therefore, the value of $PE_{tran,y}$ was calculated to be 0.0033 $tCO_2e\ t^{-1}$. Overall, this portion of the GHG emissions was calculated to be 0.0406 $tCO_2e\ t^{-1}$.

Table 1 | Electricity consumption by machines and electronic equipment associated with auto-control composting process

Functional unit	Equipment	Electricity consumption (KWh t^{-1})
Blowing unit	Air blower	5.91
Turning unit	Turner	0.11
Pretreatment unit	Grinder Mixer	0.19
Transferring unit	Belt conveyor Bunker	0.52
Control system unit	Temperature/oxygen/odor related monitoring probe; electric valve; industry control computer	0.01
Deodorization unit	Induced draft fan Filter pump	3.3
Other units	Multi-function machine Line shift machine Screening machine	0.02
Total	–	10.06

Direct GHG emissions from auto-control compost and emission reduction from replacement of chemical fertilizer with composted sludge

The GHG from sludge composting primarily consists of CH_4 and N_2O. However, according to methodology AM0025 approved by the Clean Development Mechanism (CDM) Executive Board (CDM Executive Board 2012) no CH_4 generation is considered once the oxygen content in the sludge pile is higher than 10%. Accordingly, the oxygen content in the sludge pile remains above 10% throughout the composting process when auto-control technology is employed (Zheng *et al.* 2004; Chen *et al.* 2011). Therefore, CH_4 was not considered in this study and the value of $PE_{c,CH4,y}$ was assigned as 0. As a result, N_2O emissions represent the direct total GHG emissions from the composting process. The direct GHG emission from the sludge auto-control composting was calculated to be 0.0084 $tCO_2e\ t^{-1}$. In China, sludge and its compost product is usually used as the main component of base fertilizer, and about 75% of the nutrients taken up by plants are from base fertilizer (Liu *et al.* 2010). The inorganic nutrient (total NPK) contents of composted

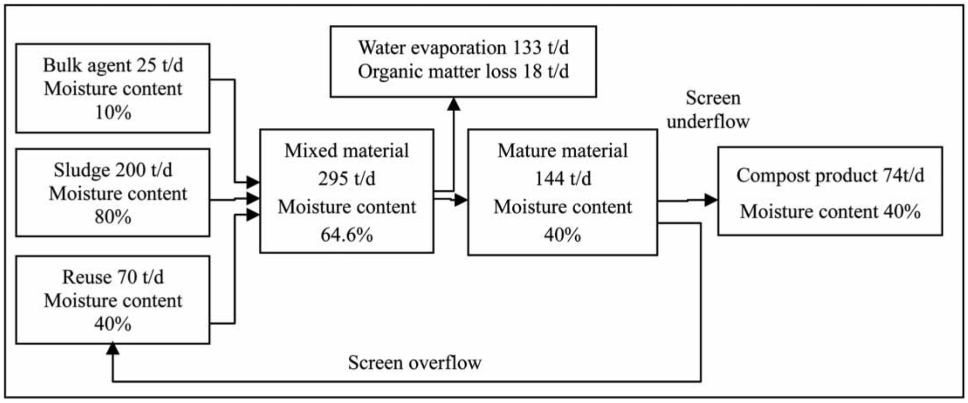

Figure 1 | Flow chart of material balance during auto-control sludge aerobic composting (sludge treatment rate = 200 tons per day).

sludge and urea are 5 and 35%, respectively; therefore, 21.4 kg urea can be saved by replacement of sludge compost. Moreover, the GHG emission coefficient of urea synthesis is 3.1217 t CO_2e t^{-1}. Accordingly, the emission reduction factor for sludge compost utilization in the form of replacement chemical fertilizer is 0.0668 tCO_2e t^{-1}.

Total GHG emission reduction of auto-control compost in comparison to landfill

The carbon debit includes indirect and direct emissions, while the carbon credit only includes emission reduction by use of sludge compost instead of chemical fertilizer. As shown in Table 2, total emissions from landfill were quantified as 0.6026 tCO_2e t^{-1}, while those from auto-control compost were −0.0178 tCO_2e t^{-1}. These findings are attributed to indirect emission reduction triggered by fertilizer replacement. Accordingly, a decrease of 0.6204 tCO_2e per ton of sludge can be achieved by simply not disposing of the sludge in landfills.

Table 2 | Comparison of sludge treatment or disposal carbon budget for auto-control compost and baseline scenario

Sludge treatment or disposal technology	Carbon debit (tCO_2e t^{-1})		Carbon credit (tCO_2e t^{-1})	Total emission (tCO_2e t^{-1})
	Indirect emission	Direct emission	Replaceable emission reduction	
Baseline scenario (landfill)	0.0334	0.5692	–	0.6026
Auto-control compost	0.0406	0.0084	0.0668	−0.0178
Total emission reduction				0.6204

DISCUSSION

Among current sewage sludge treatment or disposal technologies, composting and its product offer the possibility of nutrient resource recovery, especially that of organic substances, as well as reduced GHG emissions (Yoshida *et al.* 2012), which is similar to anaerobic digestion (Zitomer *et al.* 2008). Previous studies reported that CH_4 and N_2O are formed during composting as by-products of microbial respiration in severely anaerobic environments (Brown *et al.* 2008). When compared with conventional composting technologies such as forced ventilation and mechanical turning, auto-control has the advantage of detecting the absence of oxygen and temperature changes inside the sludge pile to accurately regulate aeration frequency and decrease the occurrence of anaerobic conditions. Subsequently, less electricity is consumed for aeration and less methane is emitted. Carbon dioxide is also generated from decomposing organic matter in compost piles, but this portion of the emissions enters the short-term carbon cycle, meaning that carbon dioxide has been absorbed from the atmosphere and then released back into the atmosphere. Therefore, composting itself does not lead to elevation of atmospheric carbon dioxide, and it is not considered a GHG emission in carbon budgets (Janse & Wiers 2007; Brown *et al.* 2008; Barber 2009).

Compost also reduces emissions via replacement of chemical fertilizer. Indeed, in this study the degree of the decrease (i.e. carbon credit) was in excess of the total carbon debit from the composting process. However, this effect is highly dependent on the quality of sludge compost and application techniques of the user (Singh & Agrawal 2008). For instance, immature sludge compost may result in more CH_4 release. Moreover, Chinese farmers favor chemical fertilizers over organic ones because they allow delayed nutrient release, larger volume and more labor. Currently, the amount of chemical fertilizer applied in China is enormous; thus, application of sludge compost product has the potential to greatly reduce alternative carbon emissions.

The carbon budget of compost should also be extended to GHG emissions from soil amended with sludge compost. Many reports indicated that the amounts of GHG released, including CH_4 and N_2O, were all positively related to the sludge compost application dose (Paramasivam *et al.* 2008; Chiaradia *et al.* 2009; Fernandez-Luqueno *et al.* 2009; Lopez-Valdez *et al.* 2011; Rodriguez *et al.* 2011). However, interaction between soil and amended compost is so complicated that the amount of GHG emitted from soil and sludge compost cannot be quantified. As a result, the direct GHG emission after sludge compost application to soil is not usually taken into consideration. But, it is not to be doubted that amended soil by sludge compost is able to store a huge amount of carbon; in other words, amended soil, to some extent, plays a sink role in capturing carbon dioxide to mitigate climate change, consequentially.

The reduction of 0.6201 tCO_2e per ton of sludge treated by auto-control compost is important to obtaining certified emission reduction (CER), which can enable access to financial support from developed countries to developing countries in the CDM frame (Rogger *et al.* 2011). So far, approximately 300 tons of sludge is produced daily in Qinhuangdao; therefore, if assuming such large amounts of sludge waste can be treated by auto-control compost technology rather than landfill disposal, there is the potential to obtain CERs of about 67,900 tCO_2e annually through widespread implementation of the system investigated herein.

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