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Spatio-temporal distribution of sewage sludge, its methane production potential, and a greenhouse gas emissions analysis

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ABSTRACT

With ongoing economic development and population growth in China, large quantities of wastewater are discharged and substantial amounts of sewage sludge are generated, which is a potential biomass resource for methane production. This study used data from statistics yearbooks and literatures to evaluate the spatio-temporal distribution of sludge generation, potential and distribution of methane production from sludge, and the potential of greenhouse gas (GHG) emissions reduction (PGER) from sludge treatment and disposal in provinces in mainland China. The results showed that a total of 6.03 Mt of dry solids in 2015. The eastern part of the country produced more sludge than that the western part. The standard coal equivalence of sludge was 3.5 Mt, ranged from 0.7 to 399.8 Kt, among the 31 provinces of mainland China. Total sludge could produce 1.27 billion m^3 of methane per year through anaerobic digestion (AD). The distribution of methane density exhibited that the east part was higher than the west part in China. The GHG emissions totaled 18.82 Mt CO_2-eq as a baseline for the current sludge disposal methods without AD technology. The PGER was 10.77 Mt CO_2-eq for the sludge disposal routes with AD technology. The sludge disposal for the project route of building material exhibited the highest PGER of 4.24 Mt CO_2-eq among the disposal methods. As the least GHG emissions method, sludge treated by AD and the residue disposed for land using as fertilizer should be recommended. Our findings provide a sludge disposal reference for the government and industries. For further study, it is suggested to take the co-digestion technology into consideration for sewage sludge to produce methane, which would perform a higher methane production and GHG emissions reduction potential.

1. Introduction

Sewage sludge is an inevitable product of the wastewater treatment process. Due to the ongoing economic development and population growth in China, increasing quantities of wastewater are being discharged (Yin and Sang, 2010). In 2015, a total of 47 billion m^3 wastewater was generated in China, more than 5.6% in 2014 (Ministry of Housing and Urban-Rural Development, 2016). China currently has been in a stage of rapid urbanization development and the amount of sewage sludge is still increasing at annual rate of 13% from 2007 to 2013 (Yang et al., 2015a). The sludge disposal and recycling has been raising great concerns due to its severe risk of ecological and environmental negative impacts (Chen and Kuo, 2016; Duan et al., 2017). The greenhouse gas (GHG) emissions from sludge has recognized one of the potential risks with sludge treatments and disposals.

On the other hand, sludge could be considered a biomass feedstock (Cao and Pawłowski, 2012; Romdhana et al., 2009) for biogas (containing mainly methane) production with anaerobic digestion (AD) technology since its introduction from the mid-1980s (Chernicharo et al., 2015; Cieślik et al., 2015). The AD technology has been one of the most predominant disposal approaches for reducing sludge mass and volume (Bashiri et al., 2016), increasing renewable energy of biogas (Zhang et al., 2014; Sebastian, 2015), and mitigating carbon footprint (Cao and Pawłowski, 2013; Zhang et al., 2014). The remaining sludge after AD process can be used for agriculture and soil reclamation (Cieślik et al., 2015). It has been applied in sewage sludgy disposal industry worldwide. In 24 countries of European Union, more than a half of sludge was disposed for agriculture after AD treatment (Kelessidis and Stasinakis, 2012). For example, more than 75% of sludge was

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anaerobically digested and about 85% was applied to agricultural soils in the Slovak Republic during 2010 (Bodík and Kubaská, 2013). In America, 80% of sludge is treated by anaerobic or aerobic digestion, in which about 60% treated sludge is recycled as fertilizer for land using (Ding, 2017).

However, sludge management has been very poor for many years and the disposal technology improvement is slow as well in China (Yang et al., 2015a). More than 80% of sludge was improperly dumped without stabilization some 10 years ago (Dai, 2011; Zhang, 2012), whereas this percentage was still more than 50% in 2016 (Yang, 2018). The proportion of sludge treated with AD could be currently less than 5% of the total sludge in the whole country. Taking samples of better cases, this proportion was 5.1% in the prefectural and capital city Nanjing of Jiangsu province and 9% in provincial city Shanghai (Zha, 2016). Accordingly, based on illustrating the spatio-temporal distribution and disposal status of sludge, the objectives of this study was to evaluate the potential methane production and the potential of GHG emissions reduction (PGER) with the AD from sewage sludge disposals. The findings of this research would be helpful for policy-makers and industry to improve regulation measures and promote sludge properly recycling for bioenergy production in China.

2. Literature review

2.1. Sludge disposal technical routes

Sewage sludge is a semi-solid waste produced from wastewater treatment processes. After its treatment with difference methods of thickening and conditioning dehydration for decreasing moisture and aerobic or anaerobic digestion for stabilization and incineration, it is finally landfilled or used for land application and building material (Pokorna et al., 2009; Yang et al., 2015a; Świerczek et al., 2018). The technical routes for landfilling, land application, incineration and building material are summarized and presented in Fig. 1.

A finial disposal of sludge for landfill is dehydrated with filter pressing technology and then directly transported to sanitary landfill after its water content is lower than 60% (Liu et al., 2013) (Fig. 1A). This route has been improved to introduce the AD technology before dewatering (Lam et al., 2016). The simple incineration route is that the sludge is dehydrated and then combusted directly, which is applied commonly in the industry (Lam et al., 2016); whereas its more advanced route is established with the AD technology after gravity thickening (Xu et al., 2014) (Fig. 1B). After incinerating the residue, which is much less ash, is landfilled as the final disposal. Land application of sludge after dewatering and aerobic composting is also a currently popular way to be used as fertilizer (Liu et al., 2013) (Fig. 1C). Niu et al. (2013) reported the technical route of sludge for land application with the addition of AD treatment after thickening and the fermentation residue was used in soils. Świerczek et al. (2018) reviewed the latest methods of using sludge (dried, dehydrated and raw) in building material. The typical technical route is that sludge is processed for building material after dewatering and incineration (Lam et al., 2016) (Fig. 1D). The AD technology as well has been introduced before the centrifugal dewatering treatment for building material. The AD of those mentioned sludge treatment routes were operated under mesophilic conditions based on the referenced literatures. The methane produced from AD burned as electricity generation for the AD self-sustainability (Lam et al., 2016; Niu et al., 2013; Xu et al., 2014).

2.2. Sludge treated by AD technology

Suh and Rousseaux (2002) and Corominas et al. (2013) reported that a combination of AD and land application is the most environmentally sustainable sludge treatment, because it has the lowest GHG emissions and energy consumption among all currently available methods. Yang et al. (2015a) summarized seven

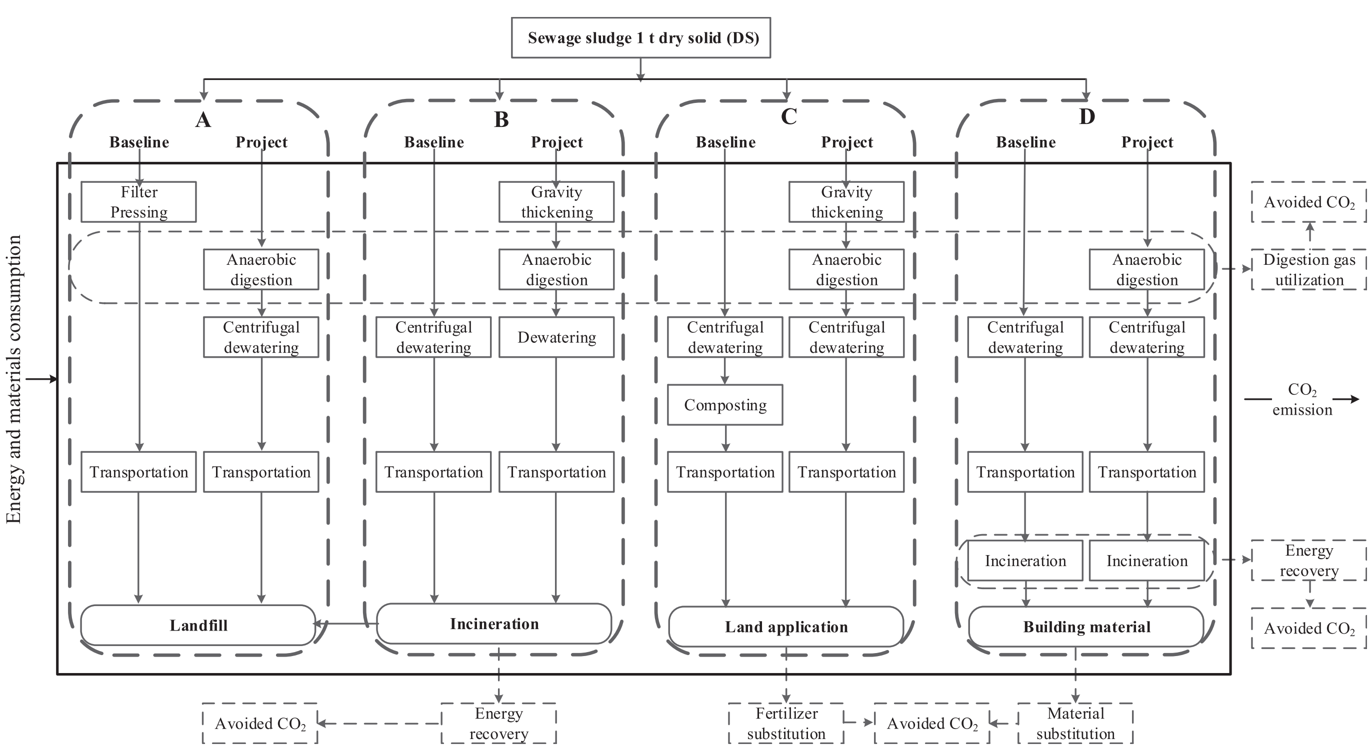

Fig. 1. Technical routes and system boundaries of sewage sludge treatment and disposal options for assessment of greenhouse gas (GHG) emissions reduction potential.

main technical routes of sludge disposals and concluded that the combine route of thickening, AD, dewatering and land application presented the most promising route in China.

2.3. Dynamics and distribution in sludge production in China

Wastewater treatment plants are the source of sewage sludge. The number of wastewater treatment plant and daily wastewater treatment capacity presented the continuous upward slope from 2006 to 2015 (Fig. 2a). The number of urban wastewater treatment plants increased from 9396 to 6910 at an annual rate of 63.6% in China (Ministry of Environmental Protection, 2007–2016). Jin et al. (2014) showed that the medium-scale wastewater treatment plants were the greatest, with a ratio of 75%, the small-scale and medium-scale wastewater treatment plants were generally distributed in medium and small size cities. The daily wastewater treatment capacity also increased at an annual rate of 13% during the same period. Zhang et al. (2016) reported that the highest daily wastewater treatment capacity was in Guangdong, followed by Jiangsu and Shandong.

The quantity of wastewater treated was increased from 16.31 billion t in 2006 to 53.23 billion t in 2015 (Ministry of Environmental Protection, 2007–2016), had an average annual growth of 25.1%, and the total sewage sludge in the county increased from 11.04 Mt to 30.16 Mt in the same period, at an annual growth rate of 19.2% (Fig. 2b). Accordingly, its annual production rate fluctuated from 5.63 to 7.97 t 10^{-4} t wastewater during the 10 years period.

3. Methodology

3.1. Data collection

The data of sewage sludge fresh weight and that used for landfilling, land application, incineration and building material in the 31 provinces were collected from the China Environment Yearbook (Ministry of Environmental Protection, 2007–2016). Administrative area was obtained from the China Statistical Yearbook (National Bureau of Statistics of China, 2016). The methane productivity of sewage sludge and the rate of GHG emissions from sludge were collected from the published literature.

3.2. Calculation of dry solids (DS) sludge and its standard coal equivalence (SCE)

The DS sludge quantity was calculated with the sewage sludge quantity in 2015 (Ministry of Environmental Protection, 2016) and the moisture content 80% for sewage sludge (Liu et al., 2015). The heating value based on the DS sludge is 17 MJ/kg (Cai et al., 2010; Liu et al., 2013), and the calorific value of standard coal is 29.27 MJ/kg. Thus, the SCE of sludge DS was calculated by the quantity of sludge DS multiplied by 17 MJ/kg, and divided by 29.27 MJ/kg.

3.3. Assessment of the methane production potential from sludge

The methane production potential from DS sludge was calculated using Eqs. (1) and (2).

$$MPP = VS \cdot MPR \tag{1}$$

$$VS = DSW \cdot VSR \tag{2}$$

where, MPP is methane production potential; VS is volatile solid of sludge; MPR is methane production rate from sludge; DSW is the DS sludge weight; VSR is the percentage of VS in the DS sludge. MPR was defined as the volume of methane produced from 1 t of VS, and the value of 350 m^3 CH_4 t^{-1} VS was collected from Han et al. (2017). The AD technology reported that was based on continuous thermophilic conditions in conjunction with the thermal pretreatment for enhanced methane production from sludge, which has been showed a stable performance for full-scale application in China (Han et al., 2017). The value 60% of VSR in DS sludge in China was collected from Niu et al. (2013).

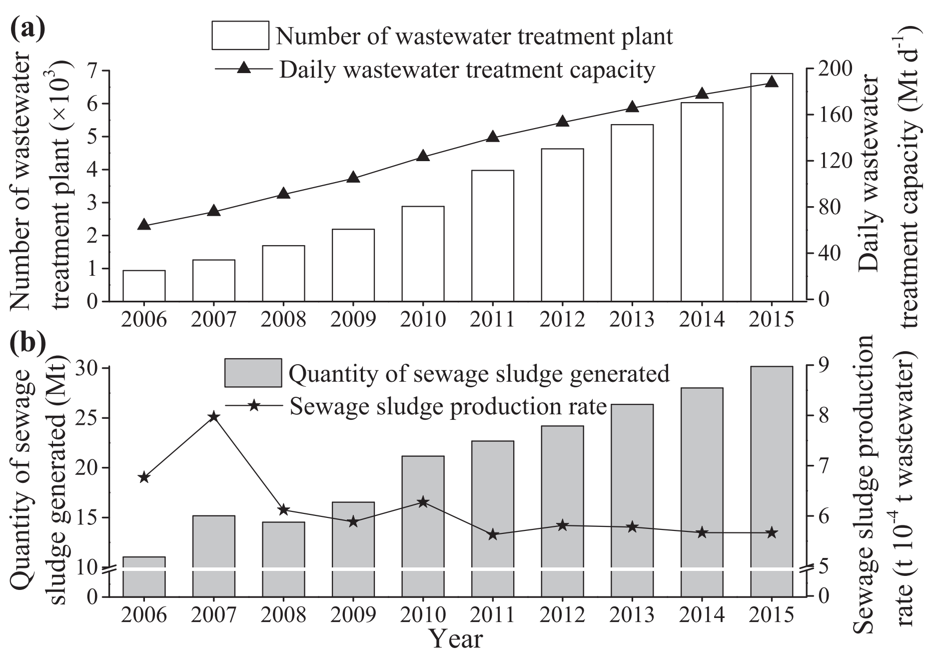

Fig. 2. Number of wastewater treatment plants and daily wastewater treatment capacity in China (a) and quantity of sewage sludge and its production rate (b) in mainland China from 2006 to 2015 (Ministry of Environmental Protection, 2007–2016).

3.4. Assessment of potential of GHG emissions reduction from sludge disposals

3.4.1. Baselines and system boundaries of sludge disposal technical routes

Four pairs of technical routes were developed based on different sludge treatments and its final usages of landfill (A), incineration (B), land application (C) and building material (D) according to literature review and the industrial reality in China (Fig. 1). For each pair, the technical route without AD was considered as the baseline and the one with AD as the project. The system boundaries for GHG emissions of sludge treatment and disposal is presented in Fig. 1. The functional unit was defined as 1 t DS of sludge for all technical routes.

3.4.2. GHG emissions and the GHG emissions reduction rate of sludge disposal routes

The GHG emissions rate and the GHG emissions reduction rate are shown in Table 1, which were collected from previous studies.

3.4.3. Calculation for potential of GHG emissions reduction and its distribution density of sludge disposals

The potential of greenhouse gas emissions reduction (PGER) was defined as the difference in GHG emissions from the sludge disposal without (baseline) and with AD technology (project). The GHG emissions from baseline, project and PGER were calculated with the following equations.

$$GB_i = GBR_i \cdot SDQ_i \quad (3)$$

$$GP_i = GPR_i \cdot SDQ_i \quad (4)$$

$$PGER_i = GRR_i \cdot SDQ_i \quad (5)$$

where, GB and GP are GHG emissions from baseline and project, respectively; GBR and GPR are GHG emissions rate from baseline and project, respectively; PGER is the potential of GHG emissions reduction, GRR is the PGER rate; SDQ is sludge disposal quantity of ith disposal method; i is integers from 1 to 4, $i = 1$ for sludge disposed by landfill, $i = 2$ for sludge disposed by incineration, $i = 3$ for sludge disposed by land application and $i = 4$ for sludge disposed by building material.

The PGER distribution density was the quotient of the PGER divided by the administrative area of each provincial region.

Table 1
Greenhouse gas (GHG) emissions rate and its reduction rate for different sludge disposals based on dry solids (DS).

Sludge disposal	Baseline	Project	Reduction rate [a]
	(kg CO_2-eq t^{-1} DS)		(kg CO_2-eq t^{-1} DS)
Landfill	1992 (Liu et al., 2013)	568 (Lam et al., 2016)	1424
Incineration	5850 (Lam et al., 2016)	4000 (Xu et al., 2014)	1850
Land application	509 (Liu et al., 2013)	351 (Niu et al., 2013)	158
Building material	5840 (Lam et al., 2016)	842 (Lam et al., 2016)	4998

[a] The GHG emissions reduction rate is the difference in GHG emissions between baseline and project.

4. Results

4.1. Production of DS sludge and its SCE on the basis of provinces

The total production of DS sludge was 6.03 Mt, varied from 1.3 to 688.4 Kt in Tibet and Zhenjiang, respectively (Table 2). Provinces of Zhejiang, Jiangsu, Guangdong, Shandong and Hebei exhibited the highest level of sludge production varied from 388.5 to 688.4 Kt, or the proportion from 6.44 to 11.41% of the total in the country. Whereas Tibet, Hainan, Qinghai and Ningxia produced the lowest sludge ranging from 1.3 to 28.3 Kt, or the proportion from 0.02 to 0.47%. The SCE was 3503.0 Kt in 2015, ranged from 0.7 to 399.8 Kt, among the 31 provinces of mainland China. The sludge production rate, ranging from 50.5 to 196.6 t Mt^{-1} wastewater, exhibited a different pattern among the provinces (Table 2). The highest level of sludge production rate ranging from 156.8 to 196.6 t Mt^{-1} wastewater for Gansu, Zhejiang, Qinghai, Shaanxi and Beijing.

4.2. Status of sludge disposal

4.2.1. Landfill

The largest proportion of sludge (44.9%) was disposed with sanitary landfill in 2015 (Table 3), may be due to its low cost and easy operation. The quantity of landfilled sludge exhibited a large variation from 0.7 to 292.6 Kt among the provinces. Provinces of Guangdong, Hebei, Henan and Shanghai were responsible for the largest level of landfilled sludge ranging from 199.9 to 292.6 Kt, sum of which accounted for 36.9% of the total landfilled sludge in the country. Whereas Hainan, Tibet, Ningxia, Guangxi and Qinghai, disposed the sludge with landfill presented the lowest level ranging from 0.7 Kt to 18.7 Kt, or from 0.02% to 0.69% of the total landfilled sludge (Table 3).

The percentage of sludge landfilled in provinces ranged from 4.65% in Hainan to 100% in Qinghai (Fig. 3). In Zhejiang and Hainan provinces, less than 10% of sludge was landfilled. In 18 provinces, 13 of them in the west and north part of China, sludge disposed by landfill accounted for more than 50% of the total sludge. Sludge landfilled in the other 11 provinces, mostly located in eastern and southern China, exhibited a proportion varied from 16.62 to 46.58%.

4.2.2. Incineration

The total sludge used for incineration was 1349.1 Kt with a proportion of 22.4% DS in 2015 (Table 3). Among provinces, it ranged from 0.0 Kt in Tibet, Qinghai and Xinjiang to 453.0 Kt DS sludge in Zhejiang. The sludge incineration in Zhejiang and Jiangsu were the highest accounting for 33.58% and 30.92%, respectively of the total incinerated sludge in the country. Incinerated sludge was 139.5 Kt in Shandong, which ranked the third, and accounted for 10.34% of total sludge incineration. Sludge incineration ratio in each of the other provinces accounted for less than 5%.

The sludge incineration proportion with a province varied from 0.13% to 65.80% (Fig. 3). Zhejiang and Jiangsu accounted for 65.80% and 65.10%, which were the only two provinces to incinerate sludge as the major disposal method. Exceptionally, sludge incineration proportion were all lower than 30% in the other provinces, even less than 10% of the total sludge production in 17 provinces.

4.2.3. Land application

Sludge was used for land application with a proportion of 18.6% in 2015, approximately 1125.0 Kt of DS sludge for the country (Table 3). The quantity of DS sludge for land application varied from 0.0 Kt in Qinghai to 166.4 Kt in Shandong. The three provinces with the largest sludge land application were Shandong, Beijing and Hebei, which accounted for 14.79%, 13.15% and 9.02% of the total weight of sludge applied to land in China, respectively. In Hunan,

Table 2
Spatial distribution of sewage sludge production on the basis of dry solids (DS) and its standard coal equivalence (SCE) in the provinces of mainland China in 2015.

Province	Sludge production rate (t Mt^{-1})	Sludge production		Sludge SCE (Kt)
		Weight (Kt)	Percent [a](%)	
Beijing	156.8	227.5	3.77	132.2
Tianjin	97.4	83.5	1.38	48.5
Hebei	149.5	388.5	6.44	225.6
Shanxi	121.2	112.8	1.87	65.5
Inner Mongolia	118.4	92.6	1.54	53.8
Liaoning	96.5	209.8	3.48	121.9
Jilin	91.4	78.0	1.29	45.4
Heilongjiang	102.1	97.2	1.61	56.5
Shanghai	117.4	272.6	4.52	158.3
Jiangsu	137.9	640.9	10.62	372.2
Zhejiang	192.3	688.4	11.41	399.8
Anhui	93.4	181.3	3.01	105.3
Fujian	96.3	144.9	2.40	84.2
Jiangxi	66.4	78.5	1.30	45.6
Shandong	118.1	530.0	8.79	307.8
Henan	131.4	368.2	6.10	213.8
Hubei	70.1	151.9	2.52	88.2
Hunan	80.2	152.1	2.52	88.3
Guangdong	88.5	628.1	10.41	364.7
Guangxi	53.5	66.2	1.10	38.4
Hainan	50.5	15.9	0.26	9.2
Chongqing	97.4	105.0	1.74	61.0
Sichuan	82.8	175.2	2.90	101.8
Guizhou	87.6	62.1	1.03	36.0
Yunnan	90.9	93.3	1.55	54.2
Tibet	61.9	1.3	0.02	0.7
Shaanxi	158.5	181.8	3.01	105.5
Gansu	196.6	75.5	1.25	43.8
Qinghai	167.0	18.7	0.31	10.9
Ningxia	128.1	28.3	0.47	16.4
Xinjiang	130.9	82.2	1.36	47.7
China	**113.3**	**6032.3**	**100**	**3503.0**

[a] Percentage of DS sludge weight produced in each province to the total sludge production in China.

Guizhou and Tibet, the DS sludge used for land application were all less than 1 Kt, and only accounted for 0.05%, 0.05% and 0.03% of the total sludge for land application, respectively.

In terms of sludge disposal ratio in each province, Hainan had the highest value of sludge for land application (87.55%), followed by Beijing, Guangxi and Xinjiang accounted for 65.00%, 54.13% and 49.62% of total sludge disposed in each province, respectively (Fig. 3). These four provinces were disposed sludge mainly for land application. In Qinghai, there was no sludge applied to land, while in Hunan only 0.43% of sludge was applied to land. In the other provinces, the sludge proportion used for land application varied from 1.00% to 37.78%.

4.2.4. Building material

A total of 848.6 Kt of DS sludge was used for building material, which was a proportion of 14.1% in China in 2015 (Table 3). It indicates that the sewage sludge used as a building material was the lowest among the four sludge utilization methods. The quantity of DS sludge for building material production in China ranged from 0.0 Kt to 180.7 Kt. Guangdong was the largest to use sludge as building material with a proportion of 21.29% in the 31 provinces. Followed by Zhejiang province with 113.7 Kt, accounted for 13.4% of sludge as building material.

With a province, the sludge used as building material proportion varied from 0 to 44.01% in the 31 provinces. In Chongqing, the use of sludge to produce building material accounted for the highest of the total sludge disposal. There was no sludge used to produce building material in seven provinces, which were mostly located in western China (Fig. 3). In the other 11 provinces, the sewage sludge used as a building material was between 0.84% and 8.09% of the total sludge disposal.

4.3. Potential of methane production from sludge

The total methane production potential from sludge was estimated to be 1.27 billion m^3 in 2015. It ranged from 0.27 million m^3 in Tibet to 144.56 million m^3 in Zhejiang among the 31 provinces (Fig. 4). The methane production potential in Jiangsu, Zhejiang and Guangdong accounted for 32.45% of the national total, with the three provinces being the most economically developed regions. In Ningxia, Qinghai, Hainan and Tibet, which are less-developed economic areas, the methane production potential was total of 13.49 million m^3, only accounted for 1.06% of the total amount of methane production potential in China, with the corresponding figure in Tibet being only accounted for 0.02%.

The methane production potential distribution density varied from 0.22 to 9029.95 $m^3\,km^{-2}$ among the provinces in 2015 (Fig. 5). It indicates that the belt along the east coastal provinces from Liaoning to Guangdong was the densest sludge region (including Beijing, but excluding Hainan) varying from 297.66 to 9029.95 $m^3\,km^{-2}$. Adjacent to this belt region, the provinces Hebei, Shanxi, Shaanxi, Hubei, Anhui and Henan, mainly located in North region and Central-South region, produced the second densest sludge varying from 25.56 to 467.15 $m^3\,km^{-2}$. The sludge in Northwest region with Tibet, Xinjiang, Gansu, Qinghai and Inner Mongolia was the lowest density varying from 0.22 to 34.87 $m^3\,km^{-2}$. In total, methane density distribution exhibited that east part was higher than west part in China (Fig. 5).

4.4. The PGER from sludge disposal

GHG emissions from baseline without AD operation for sludge disposal was 18.82 Mt CO_2-eq, composed of 5.40 Mt CO_2-eq of

Table 3
Quantity of sludge with different disposals on the basis of dry solids (DS) in provinces of mainland China.

Province	Landfill		Incineration		Land application		Building material	
	Weight (Kt)	Percent [a] (%)	weight (Kt)	Percent [a] (%)	Weight (Kt)	Percent [a] (%)	weight (Kt)	Percent [a] (%)
Beijing	53.0	1.96	15.5	1.15	147.9	13.15	11.1	1.31
Tianjin	42.9	1.58	5.8	0.43	12.1	1.08	22.7	2.67
Hebei	267.7	9.88	12.3	0.91	101.5	9.02	7.0	0.82
Shanxi	59.4	2.19	8.2	0.61	42.6	3.79	2.6	0.31
Inner Mongolia	82.2	3.03	4.8	0.36	1.4	0.12	4.2	0.49
Liaoning	156.2	5.77	4.6	0.34	40.4	3.59	8.6	1.01
Jilin	57.7	2.13	13.2	0.98	7.1	0.63	0.0	0.00
Heilongjiang	85.3	3.15	3.4	0.25	7.4	0.66	1.1	0.13
Shanghai	199.9	7.38	45.8	3.39	7.1	0.63	19.8	2.33
Jiangsu	106.5	3.93	417.2	30.92	27.8	2.47	89.4	10.53
Zhejiang	52.3	1.93	453.0	33.58	69.4	6.17	113.7	13.40
Anhui	72.3	2.67	53.3	3.95	41.0	3.64	14.7	1.72
Fujian	46.9	1.73	32.2	2.39	20.7	1.84	45.1	5.31
Jiangxi	64.2	2.37	3.0	0.22	2.8	0.25	8.5	1.00
Shandong	146.8	5.42	139.5	10.34	166.4	14.79	77.3	9.11
Henan	239.7	8.84	10.9	0.81	94.2	8.37	23.4	2.76
Hubei	68.1	2.51	17.0	1.26	28.1	2.50	38.7	4.56
Hunan	124.5	4.59	8.1	0.60	0.6	0.05	18.9	2.23
Guangdong	292.6	10.80	54.9	4.07	99.9	8.88	180.7	21.29
Guangxi	18.4	0.68	1.4	0.10	35.8	3.18	10.6	1.25
Hainan	0.7	0.02	1.3	0.10	13.9	1.24	0.0	0.00
Chongqing	47.0	1.73	4.4	0.33	7.4	0.66	46.2	5.44
Sichuan	60.6	2.23	27.5	2.05	44.1	3.92	43.0	5.07
Guizhou	56.3	2.08	4.6	0.34	0.6	0.05	0.6	0.07
Yunnan	81.0	2.99	0.5	0.04	11.8	1.05	0.0	0.00
Tibet	1.0	0.04	0.0	0.00	0.3	0.03	0.0	0.00
Shaanxi	83.5	3.08	4.6	0.34	34.1	3.03	59.5	7.01
Gansu	66.9	2.47	0.1	0.01	7.4	0.66	1.2	0.14
Qinghai	18.7	0.69	0.0	0.00	0.0	0.00	0.0	0.00
Ningxia	15.9	0.59	2.0	0.16	10.4	0.91	0.0	0.00
Xinjiang	41.4	1.53	0.0	0.00	40.8	3.63	0.0	0.00
China	**2709.6**	**100**	**1349.1**	**100**	**1125.0**	**100**	**848.6**	**100**

[a] Percentage of DS sludge weight produced to the total sludge for each disposal method in provinces.

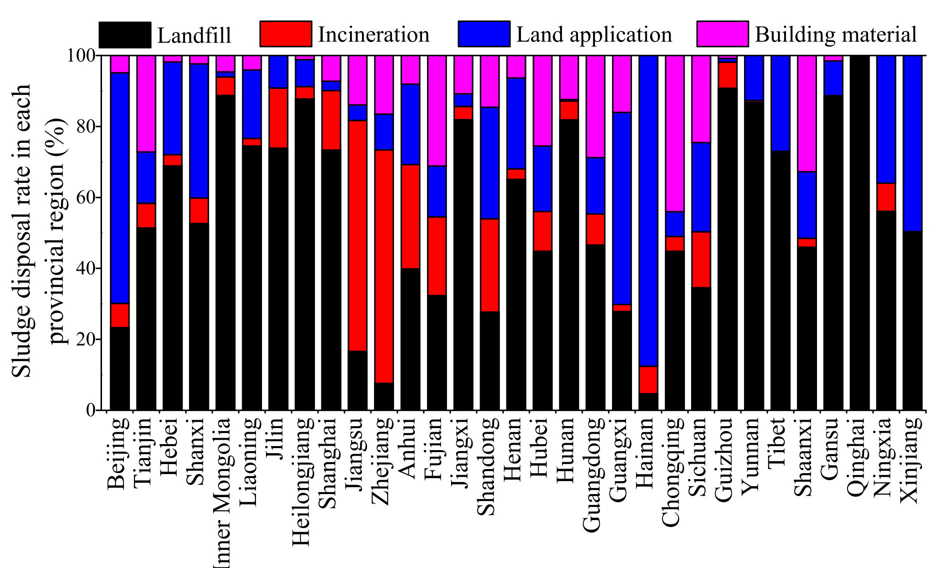

Fig. 3. Percentage of sewage sludge disposal in 2015 in provinces of mainland China.

landfill, 7.89 Mt CO_2-eq of incineration, 0.57 Mt CO_2-eq of land application and 4.96 Mt CO_2-eq of building material in China (Table S1). GHG emissions from project with AD operation was 8.05 Mt CO_2-eq, included 1.54 Mt CO_2-eq from landfill, 5.40 Mt CO_2-eq from incineration, 0.40 Mt CO_2-eq from land application and 0.71 Mt CO_2-eq from material production. A total PGER was 10.77 Mt CO_2-eq of sludge disposal, including 3.86 Mt CO_2-eq from sludge landfill, 2.50 Mt CO_2-eq from sludge incineration, 0.18 Mt CO_2-eq from sludge land application and 4.24 Mt CO_2-eq from sludge building material (Table 4). The PGER ranged from 0.001 to 1.49 Mt CO_2-eq among the provinces of China (Fig. 6). Zhejiang, Guangdong and Jiangsu exhibited the highest PGER, with reduction

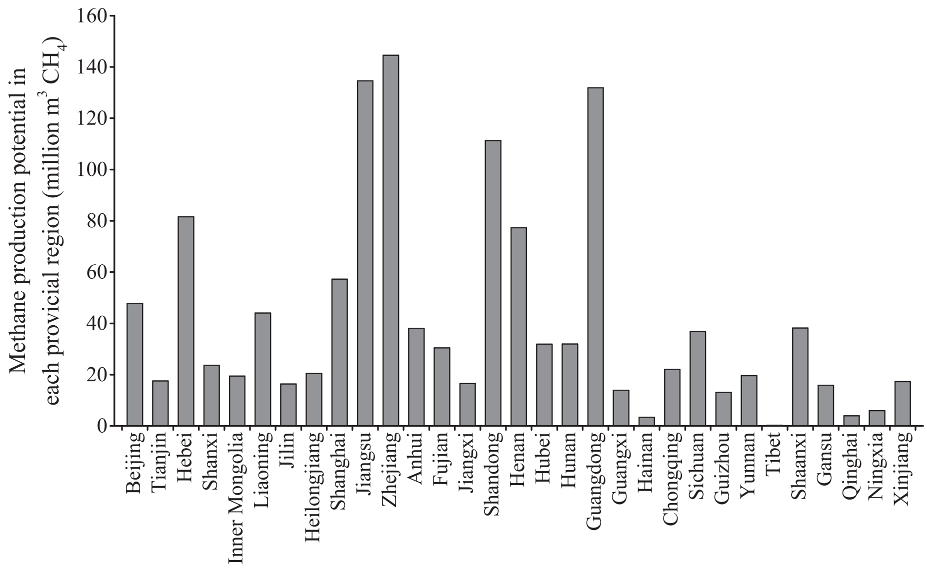

Fig. 4. Potential of methane production from sewage sludge in 2015 in provinces of mainland China.

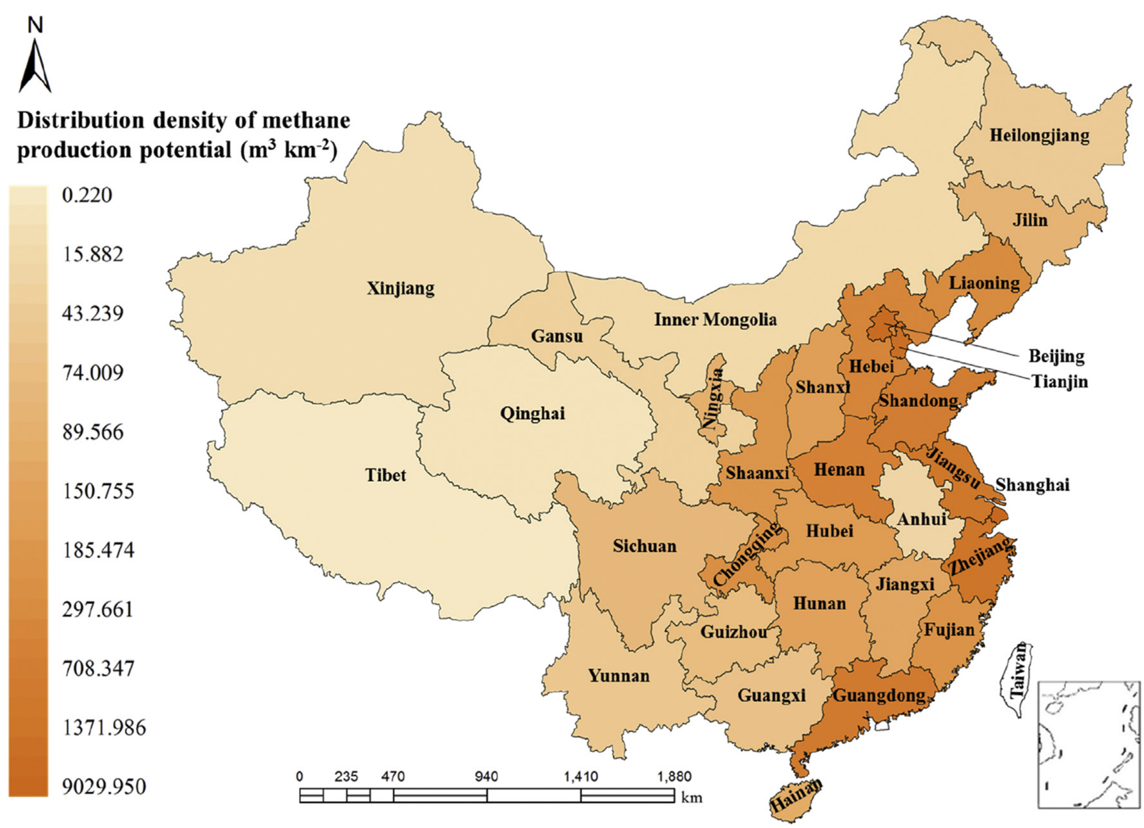

Fig. 5. Distribution density of methane production potential from sewage sludge in 2015 in provinces of mainland China.

values of 1.49, 1.44 and 1.37 Mt CO_2-eq, respectively. The PGER in Tibet and Hainan were extremely low, only 0.001 and 0.006 Mt CO_2-eq, the other 5 provinces of Qinghai, Ningxia, Xinjiang, Guangxi and Guizhou had lower than 0.1 Mt CO_2-eq PGER. The rest of 21 provinces had the PGER ranged from 0.10 to 0.88 Mt CO_2-eq.

A total PGER of sludge landfill was 3858.61 Kt CO_2-eq, varied between 1.00 Kt CO_2-eq in Hainan and 416.66 Kt CO_2-eq in Guangdong, accounting from 0.03% to 10.80% among the 31 provinces (Table 4). Besides Guangdong province, the PGER in Hebei, Henan, Shanghai, Liaoning and Shandong all larger than 200 Kt CO_2-eq, and the total quantity of these 6 provinces accounted for 48.09% of the PGER in China.

Sludge incineration exhibited an amounted of 2498.39 Kt CO_2-eq of the PGER. Among provinces for sludge incineration, the PGER in Xinjiang, Qinghai and Tibet were 0.00 Kt CO_2-eq, whereas it was varied from 0.19 to 838.05 Kt CO_2-eq in the other provinces

Table 4
Potential of greenhouse gas emissions reduction (PGER) for different sludge treatment and disposal routes in 2015 in provinces of mainland China.

Province	Landfill		Incineration		Land application		Building material	
	Quantity [a] ($Kt\ CO_2$-eq)	Percent [b] (%)	Quantity [a] ($Kt\ CO_2$-eq)	Percent [b] (%)	Quantity [a] ($Kt\ CO_2$-eq)	Percent [b] (%)	Quantity [a] ($Kt\ CO_2$-eq)	Percent [b] (%)
Beijing	75.47	1.96	28.68	1.15	23.37	13.15	55.48	1.31
Tianjin	61.09	1.58	10.73	0.43	1.91	1.07	113.45	2.68
Hebei	381.06	9.88	22.76	0.91	16.04	9.03	34.99	0.83
Shanxi	84.59	2.19	15.17	0.61	6.73	3.79	12.99	0.31
Inner Mongolia	117.05	3.03	8.88	0.36	0.22	0.12	20.99	0.49
Liaoning	222.57	5.77	8.51	0.34	6.38	3.59	42.98	1.01
Jilin	82.16	2.13	24.42	0.98	1.12	0.63	0.00	0.00
Heilongjiang	121.47	3.15	6.29	0.25	1.17	0.66	5.50	0.13
Shanghai	284.80	7.38	84.73	3.39	1.12	0.63	98.96	2.33
Jiangsu	151.66	3.93	771.82	30.92	4.39	2.47	446.82	10.54
Zhejiang	74.48	1.93	838.05	33.57	10.97	6.17	568.27	13.40
Anhui	102.96	2.67	98.61	3.95	6.48	3.65	72.97	1.72
Fujian	66.79	1.73	59.57	2.39	3.27	1.84	225.41	5.32
Jiangxi	91.42	2.37	5.55	0.22	0.44	0.25	42.48	1.00
Shandong	209.04	5.42	258.08	10.34	26.29	14.79	386.35	9.11
Henan	341.33	8.85	20.17	0.81	14.88	8.37	116.95	2.76
Hubei	96.97	2.51	31.45	1.26	4.44	2.50	193.42	4.56
Hunan	177.29	4.59	14.99	0.60	0.09	0.05	94.46	2.23
Guangdong	416.66	10.80	101.57	4.07	15.78	8.88	903.14	21.30
Guangxi	26.20	0.68	2.59	0.10	5.66	3.18	52.98	1.25
Hainan	1.00	0.03	2.41	0.10	2.20	1.24	0.00	0.00
Chongqing	66.93	1.73	8.14	0.33	1.17	0.66	230.91	5.44
Sichuan	86.29	2.24	51.06	2.05	6.97	3.92	214.91	5.07
Guizhou	80.17	2.08	8.51	0.34	0.09	0.05	3.00	0.07
Yunnan	115.34	2.99	0.93	0.04	1.86	1.05	0.00	0.00
Tibet	1.42	0.04	0.00	0.00	0.05	0.03	0.00	0.00
Shaanxi	118.90	3.08	8.51	0.34	5.39	3.03	297.38	7.01
Gansu	95.27	2.47	0.19	0.01	1.17	0.66	6.00	0.14
Qinghai	26.63	0.69	0.00	0.00	0.00	0.00	0.00	0.00
Ningxia	22.64	0.59	4.07	0.16	1.61	0.91	0.00	0.00
Xinjiang	58.95	1.53	0.00	0.00	6.45	3.63	0.00	0.00
China	**3858.61**	**100**	**2496.39**	**100**	**177.71**	**100**	**4240.80**	**100**

[a] Quantity of PGER was calculated with the data in Tables 1 and 3 using Eq. (5).
[b] Percentage of PGER to the total GHG emissions reduction quantity for each disposal method in provinces.

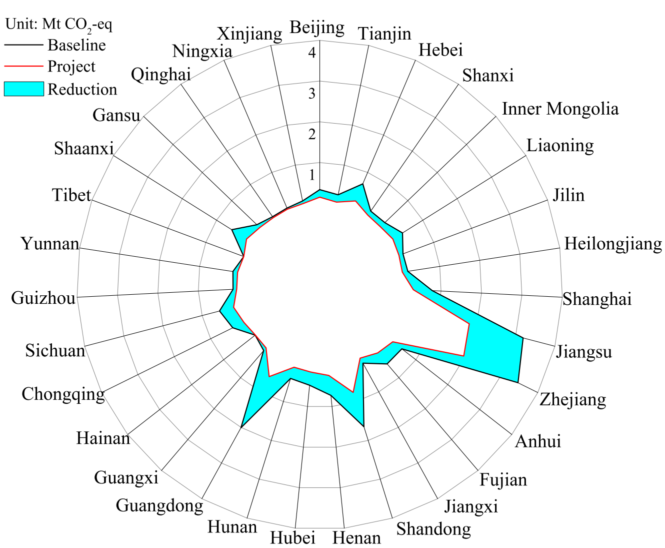

Fig. 6. Potential of greenhouse gas (GHG) emissions reduction between baseline and project of sewage sludge disposals in provinces of mainland China.

(Table 4). The highest value was in Zhejiang, followed by Jiangsu with 771.82 Kt CO_2-eq, Shandong with 258.08 Kt CO_2-eq in the third place, the sum proportion of the three provinces accounted for 74.83% of the total PGER in the country.

The PGER of sludge used for land application was 177.71 Kt CO_2-eq in China, ranged from 0.00 Kt in Qinghai to 26.29 Kt CO_2-eq in Shandong (Table 4). The sum of PGER in Shandong, Beijing, Hebei, Guangdong and Henan was accounted for 54.22% compared with its total in China. The PGER in each province of Jiangxi, Inner Mongolia, Guizhou, Tibet and Qinghai accounted for a level lower than 0.3%.

There was total of 4240.80 Kt CO_2-eq PGER of sludge for building material production, which was also the highest one of these four sludge disposal methods (Table 4). In 31 provinces, the reduction value varied from 3.00 Kt CO_2-eq in Guizhou to 903.14 Kt CO_2-eq in Guangdong, which excluding the seven provinces without sludge used as building material. Proportion of PGER of Guangdong, Zhejiang, Jiangsu, Shandong and Shaanxi was 61.36% of China.

Distribution of the PGER density varied from 0.001 t CO_2-eq km^{-2} in Tibet to 74.07 t CO_2-eq km^{-2} in Shanghai among the 31provinces. The density in Tianjin with 15.70 t CO_2-eq km^{-2} was the second, which was lower 3.7-fold than that in Shanghai. The distribution of the PGER density showed east part higher than the west part in China (Fig. 7).

5. Discussion

According to this study, sewage sludge was disposed in China with four methods including landfill for 2.71 Mt DS, incineration for 1.35 Mt DS, land application for 1.13 Mt DS, and building material for 0.85 Mt DS in 2015. However, landfill not only consumes a large area of land, but also increases the potential of landfill leachate to groundwater and poses risks to human health (Xu et al., 2014).

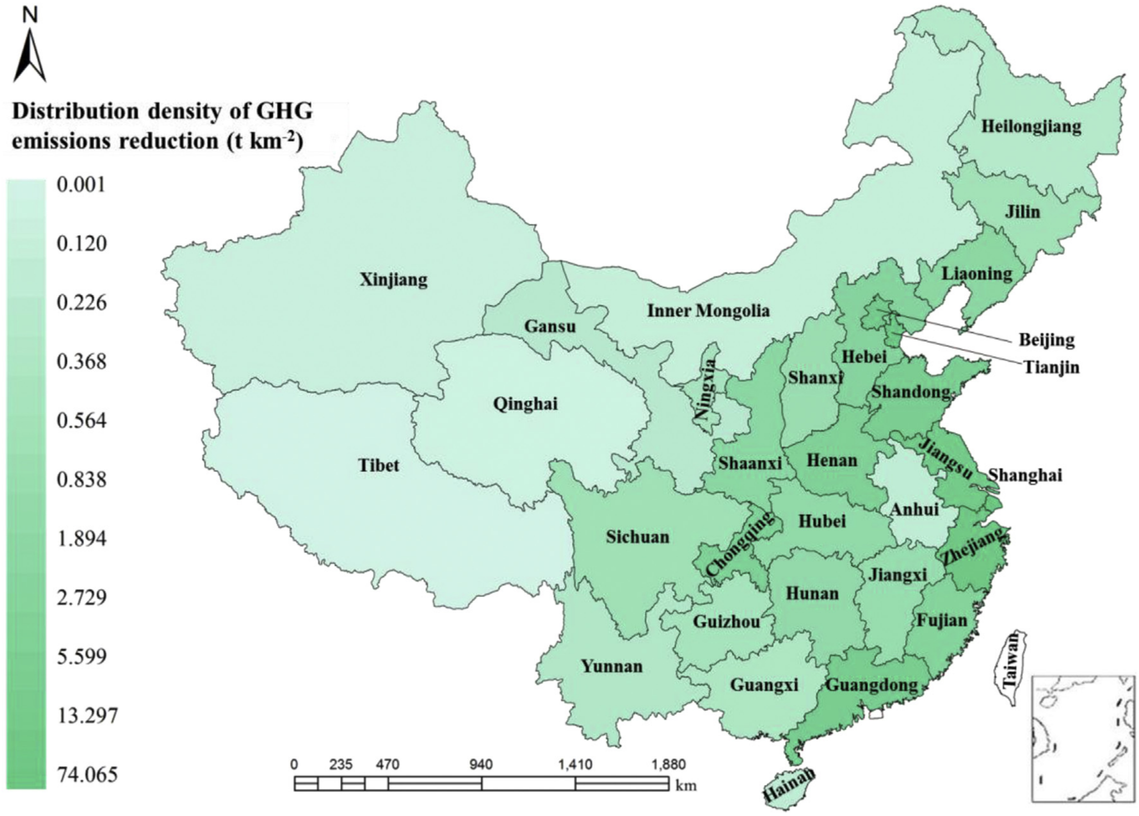

Fig. 7. Distribution density of greenhouse gas (GHG) emissions reduction potential from sewage sludge disposals in 2015 in provinces of mainland China.

Sludge incineration has been shown to contribute to ozone depletion, photochemical oxidant formation and terrestrial ecotoxicity (Xu et al., 2014). The cost of incineration is high, and the process wastes with many chemical elements (e.g., nitrogen, phosphorous and potassium). Sludge used for building material need the incineration step, also exists the disadvantages of wasting the chemical elements of the sludge. The Ministry of Housing and Urban-Rural Development in China encourages sludge for land development applications (Yang et al., 2015a). For the PGER, economic and other reasons, the disposal of sewage sludge to land for use as a fertilizer is considered the most advantageous disposal method (Liu et al., 2013).

According to the result of this study, the methane production potential was 1.27 billion m^3 in China. This is a conservation value for accessing methane production potential, Song et al. (2011) and Li et al. (2007) reported that the methane production rate of sludge AD was 492 and 470 m^3 CH_4 t^{-1} VS, respectively in Beijing and Henan.

However, many researchers reported that if sludge is co-digested with other matter, the methane production rate could be substantially improved. Dai et al. (2013) co-digested sludge with food waste at a ratio of 2:3 and obtained a methane yield of 400 m^3 CH_4 t^{-1} VS. Mixing sewage sludge with grease trap sludge at a ratio of 4:1 achieved a methane yield of 462 m^3 CH_4 t^{-1} VS (Noutsopoulos et al., 2013). Grosser et al. (2017) mixed sewage sludge, grease trap sludge and the organic fraction of municipal solid waste at a ratio of 4:3:3, and obtained a high methane yield of 547 m^3 CH_4 t^{-1} VS. Anaerobic co-digestion of sludge with lignite (Yang et al., 2015b) and microalgae (Olsson et al., 2014) resulted in significantly increased methane production compared to the digestion of sewage sludge alone. It showed that a higher methane production capacity of sludge mixed with other organic waste, which could be the popular method for methane production from sludge. However, due to it is a big challenge for gathering sludge with other waste because of both waste location and collection cost, study methane production potential from sludge alone is more appropriate.

In our assessment, the methane production rate from the digestion of sludge alone was slightly higher than the findings in previous studies (Dai et al., 2013; Maragkaki et al., 2018). However, the references to experimental data in our study was significance as reference values, because the methane production rate of this research used was obtained from a stable experiment, that can be put into the large-scale methane production industries to use (Han et al., 2017). The Chinese government can make sludge treatment decisions according to our estimations, and industrial enterprises can also use the results as a reference when constructing future bioenergy production plans.

Total GHG emissions of baseline and project was 18.82 and 8.05 Mt CO_2-eq, respectively, indicating reduction of an amount 10.77 Mt CO_2-eq. The sludge treatment and disposal methods were analyzed and found that GHG emissions from sludge treated with AD were lower than from sludge treated without AD, which agreed with the results of Hong et al. (2009), thus, sludge treated by AD should be encouraged in China. Especially, for sludge disposed as building material, the PGER of the project route with AD exhibited the highest value with 4.24 Mt CO_2-eq of four pairs sludge disposal routes. Therefore, sludge treated by AD and disposed as building material presented the greatest PGER. Due to the lowest GHG emissions, we recognized that the lowest GHG emissions of these study routes occurred when sludge was treated by AD and disposed of by application to land. The specific operation of this route was sludge thickened by gravity firstly, the most widely used thickening technology is gravity thickening (Niu et al., 2013; Yang et al., 2015a).

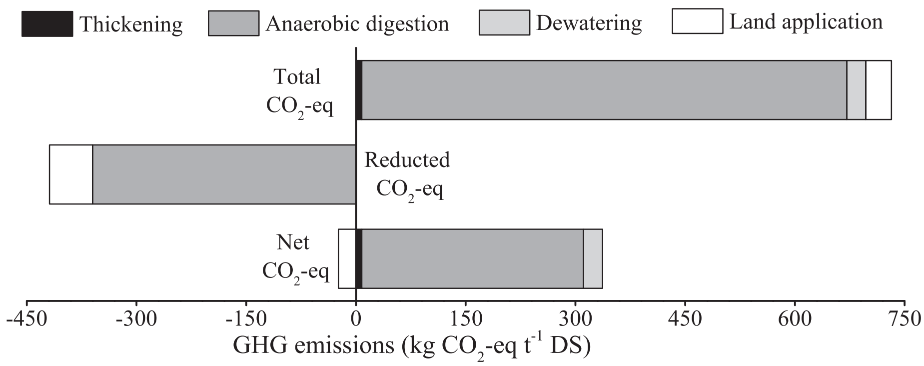

Fig. 8. Greenhouse gas (GHG) emissions rate from the optimal technical route after increasing the methane production rate of sludge treatment and disposal (Niu et al., 2013).

Following treated by AD, then for the dewatering, the main dewatering technologies include centrifugal dewatering and belt dewatering (Liu et al., 2013; Yang et al., 2015a). The finial disposal was land application, due to high mental contains, sludge used for land has many constraints, such as national standards (Ministry of Environmental Protection, 1984; Ministry of Housing and Urban-Rural Development, 2009b) and ministry standards (Ministry of Housing and Urban-Rural Development, 2009a, 2011), make sure the availability of sludge used for land. Therefore, sewage sludge thickening, AD, dewatering and land application was considered as the optimal technical route, and should be recommended for sludge treatment and disposal in China.

The result of this study showed that the GHG emissions was 0.4 Mt CO_2-eq from 1.1 Mt DS sludge of the optimal technical route, the PGER was 0.18 Mt compared to the baseline, and the methane production rate was 389 m^3 CH_4 t^{-1} VS (Niu et al., 2013). Sludge AD has great potential to increase PGER (Zhao and Zhang, 2019). Thus, if all the sewage sludge produced in China was treated and disposed of by the optimal technical route, will emit of 2.12 Mt CO_2-eq GHG. There would be a 16.7 Mt CO_2-eq reduction compared to the baseline emissions for the sewage sludge treatment and disposal options, also generated of 1.41 billion m^3 CH_4. When the methane production rate increased to 492 m^3 t^{-1} VS (Niu et al., 2013), the net GHG emissions rate of sludge treated by this route was 313 kg CO_2-eq t^{-1} DS. It comprised of 8 kg CO_2-eq t^{-1} DS for thickening, 303 kg CO_2-eq t^{-1} DS for AD, 26 kg CO_2-eq t^{-1} DS for dewatering and −24 kg CO_2-eq t^{-1} DS for land application (Fig. 8) (Niu et al., 2013). Thus, the total GHG emissions was 1.9 Mt CO_2-eq. With methane production rate increasing, the PGER rate from AD was increased from 322 to 360 kg CO_2-eq t^{-1} DS (Niu et al., 2013), the PGER of land application was still 59 kg CO_2-eq t^{-1} DS sludge, and GHG emissions from thickening, AD, dewatering and land application with 8, 666, 26 and 35 kg CO_2-eq t^{-1} DS, respectively. It indicates that with the increase of methane production rate, the PGER of AD increases (Huang and Guan, 2013). Fine and Hadas (2012) reported that for the optimal technical route, the PGER was approximately 23–55% compared to the other options. However, in our study, sludge managed according to the optimal route resulted in an 88% reduction in GHG emissions compared to the baseline value, this maybe means that sludge operation by AD is appropriately in China.

In addition, more than 1.41 billion m^3 methane will be produced by all sludge managed according to the optimal route, equals to 2.61 billion kW·h electricity, which is a valuable bioenergy resource for China. In our study, the highest PGER was sludge disposed as building material, thus, sludge as building material should treated by AD, which reduce the large amount of GHG. Based on the sludge generation pattern in the last 10 years, we estimate that by the year 2020, China will produce around 8 Mt of DS sludge; thus, 3.11 billion m^3 methane will be generated, and get PGER of 1.26 Mt CO_2-eq t^{-1}, enabling society to obtain economic and environmental returns from sludge treatment. Moreover, the PGER from sludge treatment and disposal is a contribution to the goal that in 2020 carbon dioxide emissions per unit of GDP are 40–45% lower than in 2005 (The State Council Information Office of the People's Republic of China, 2014).

6. Conclusions

A total of 6.03 Mt DS of sewage sludge were generated in wastewater treatment plants in China in 2015, and sludge disposed with landfill, incineration, land application, and the production of building material accounted for 44.9, 22.4, 18.6 and 14.1%, of all sewage sludge disposal, respectively. A total of 1.27 billion m^3 of methane can potentially be produced in one year for bioenergy, and distribution of methane density in east part was higher than in west part in China. According to the sludge disposal status, GHG emissions of sludge treated with AD were all lower than without. The baseline GHG emissions were 18.82 Mt, when using the four disposal methods to treat and dispose of the sludge, the project values indicated the PGER of 10.77 Mt CO_2-eq. The highest PGER was 4.24 Mt CO_2-eq from sludge treated by AD and disposed as building material, this route with the largest potential of PGER. Thus, if sludge disposed as building material should treated by AD. As the least GHG emissions method, the residue disposed for land using as fertilizer should be recommended, increasing methane production rate is an important way to reduce GHG emissions of AD technology. Our findings provide a sludge disposal reference for the governments and industries.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.117895.

Abbreviation list

AD	anaerobic digestion
d	day
DS	dry solids
GHG	greenhouse gas

Kt	kilo (thousand) metric tons
Mt	million metric tons
PGER	potential of GHG emissions reduction
SCE	standard coal equivalence
t	metric tons
VS	volatile solids

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