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The biomethane producing potential in China: A theoretical and practical estimation☆

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ABSTRACT

Biomethane has been developed rapidly in many countries as a renewable energy which upgraded from biogas. China also began to pay attention to it even though we still at a initial stage, primarily, understanding the biomethane potential and development prospect, choosing appropriate biomass as the biomethane source is very important. In this work, the theoretical and practical biomethane producing potential from five main biomass resources in China were estimated with appropriate methods based on the data collected, and during calculation, two appropriate energy crops were assumed to be planted on marginal lands for biomethane production. Our estimation showed that the theoretical and practical biomethane potentials in China can reach to 888.78 and 316.30 billion m³ per year, agricultural waste should be the preferential development biomass, and planting energy crops on marginal lands is the most promising way to enhance biomethane production in China. Finally, biomethane is compared with natural gas, and the result showed that 48.15% of the practical biomethane potential can meet the total Chinese natural gas consumption in 2013.

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1. Introduction

Nowadays, the fossil fuels, especially coal, are still the main energy resources in China. In 2014, a total of 4.26 billion ton standard coal contributed 66% of the primary energy consumption. This heavy energy dependence on coal results in both serious environmental impacts [1]. Natural gas as a clean energy is an ideal substitute of coal, which can reduce dramatically environmental damage. In 2014, the amount of natural gas consumed in China was 190 billion m³, which is only 5% of the total energy consumption. Another limitation is that, about 30% of the consumed natural gas was imported from other countries [2]. According to the Chinese energy development strategy (2014–2020), the proportion of natural gas in primary energy sector needs to be increased 10% by 2020, which corresponds to a production of 400 billion m³ natural gas in 2020 [3]. It is of great importance to estimate the natural gas production potential in China and explore different resources to produce natural gas.

Among different natural gas resources, biomethane is considered as a very promising one and has been developed rapidly in many countries. Germany began to develop biomethane from 2006, and after years of study, there had been 107 biogas plants engaged in the

biomethane production by 2011 [4]. In Sweden, there had been more than 120 biomethane gas filling stations and 40000 biomethane cars were built up, and biomethane consumption had accounted for 10% of the national nature gas consumption by 2010 [5]. The number of biomethane gas filling stations was increased from 60 to 100 in Switzerland in 2005–2008, and Swiss Gas Industry Association had signed an agreement with Biogas Association, to make some cost discount for biomethane incorporating into natural gas pipe network [6]. And the development of biomethane production also has received an increasing attention in China for the past few years [7]. Biomethane is the fuel that obtained from biogas after removal of CO₂ and H₂S, also called biological natural gas. The methane concentration in biomethane can reach up to 95%–97% and meet the Chinese natural gas standard (GB 17820-1999), so that biomethane can be used as vehicle fuel gas or incorporated into natural gas pipe network as the substitute natural gas [8,9]. Biogas is obtained from the low-grade biomass anaerobic fermentation process, and the low-grade biomass is commonly used as substrates, including livestock manure [10], straw [11], municipal solid waste [12] and sewage sludge [13,14]. Some studies already investigated the biogas potential in China. Tian [15] estimated the biogas production potential based on the amount of livestock manure from large-scale farms in China in 2009, they concluded a biogas production potential of 47.21 billion m³ per year. Zhang *et al.* [16] estimated that the biogas production potential was 119.844 billion m³ in China in 2009 from all excrement, among which 24 billion m³ was from large- and medium-sized livestock and poultry breeding farms. Chang *et al.* [17] evaluated

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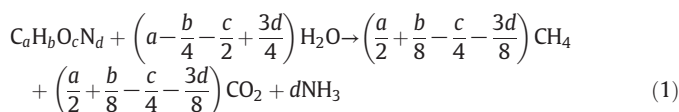
the biogas potential of crop straw and livestock manure through time-series and geographical approach, indicated the great regional differences in biogas potential between districts and provinces in China, and the most part of total biogas potential in China is allocated among Mid-South district, East district and South West district. And an international collaboration between China and Denmark was carried out to estimate the biogas production potential in 2011, the study considered resources such as livestock manure, municipal solid waste and sewage sludge. The biogas production potential was estimated to be 206.8 billion m³ (124.08 billion m³ biomethane) in 2009 [18]. However, in the above studies, the biogas potential was just estimated according to the current digestion technology in China, which was a more practical potential. When considering the development of technology, the efficiency of anaerobic digestion process can be increased, and the potential will be improved. On the other hand, many studies just considered the common low-grade biomass in China, the potential of energy crop has never been estimated. To increase the biomethane production, energy crops have been considered to be the better choice for its high biogas productivity and yield, and the broad marginal land resources are good place for energy crop planting, due to the large population and a very limited cultivated land in China [19–21].

In this work, based on the updated data collected from traditional biomethane production, the theoretical and practical biomethane potentials in China were estimated with appropriate methods (Buswell formula for the agriculture waste and energy crop, IPCC formula for the municipal solid waste and sewage sludge). And different with previous work, two appropriate energy crops were chosen from the screening process designed, and assumed to be planted on the marginal land to get the biomethane potential of energy crop in China. We hold that agricultural waste should be the preferential development biomass, planting energy crops on marginal lands is the most promising way to enhance biomethane production, developing biomethane is a promising way for energy supplement in China.

2. Estimation Methods

2.1. Theoretical and practical biochemical methane potentials

In this work, the theoretical biochemical methane potential (TBMP) represented the maximum biomethane yield per volatile solid (VS). To get the TBMP, the organic carbon in biomass was assumed to be transferred into CH₄ and CO₂ completely during the anaerobic digestion process, which were the two main composition of biogas. In this respect, a formula was firstly proposed to simulate this extreme hypothesis by Buswell and Mueller based on the element compositions of different biomass [22], and this formula was also cited in some other studies. Møller *et al.* [23] used the Buswell formula to calculate the theoretical methane potential of different specific organic components in biomass, and Li *et al.* [24] studied the methane production of three organic wastes during a batch anaerobic digestion process, and the Buswell formula was used to calculate the theoretical methane yield of organic wastes. In the Buswell formula, the distribution ratio of organic carbon in CH₄ and CO₂ was determined via one mole of biomass with a known elementary composition, and the theoretical production of methane was calculated according to Eqs. (1) and (2):



The TBMP can be calculated by Eq. (2):

$$TBMP = \frac{V_m \cdot \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{8}\right)}{12.011a + 1.008b + 15.999c + 14.007d} \quad (2)$$

where V_m is the molar volume of methane at standard temperature and pressure.

When considering the actual digestion conditions, biomass can't be degraded completely by microorganism during the digestion process, so in order to get the practical biochemical methane potential (PBMP), an important factor needs to be taken into account, namely the biodegradability (BD) [25]. During the research process, Labatut *et al.* [26] thought that the extent of such an effect tends to be correlated with the composition in biomass. Triolo *et al.* [27] studied the relationship between biomethane potential and different compositions (lignin, neutral detergent fibers, acid detergent fiber, cellulose), they reported that the lignin content in volatile solid was the most important parameter for predicting biochemical methane potential of all kinds of biomass. And Li *et al.* [28] conducted a series of biomethane potential assay of many organic substrates (mesophilic digestion, VS concentration: 3 g·L⁻¹), to study the relationship between the lignin content and the biodegradability. After a series of data analysis, they observed a good linear correlation between lignin content and the biodegradability (BD) for the lignocellulose and manure wastes, this could be used as a fast method to predict the biodegradability of fiber rich substrates. In this work, we used this linear correlation (Eq. (3)) to estimate the BD of crop residue, livestock manure and energy crop:

$$BD = 80.4 - 2.7 \times C_{\text{Lignin}} \quad (3)$$

where C_{Lignin} is the lignin content (wt% VS) of different biomass.

Then the PBMP can be calculated from TBMP and BD by Eq. (4):

$$PBMP = TBMP \times BD. \quad (4)$$

2.2. Biomethane potential of crop residue

The biomethane potential of crop residue depends on their production and biochemical methane potential (BMP). The production of crop residue can be calculated based on the crop yield, straw grain ratio of different crop and the general crop residue collection rate.

In this work, the biomethane potential of crop residue was calculated by Eq. (5):

$$Y_{\text{bmc}} = \sum_i^n Y_{ci} \times SGR_i \times CR_i \times VS_i \times BMP_i \quad (5)$$

where Y_{bmc} is the biomethane potential of crop residue, representing the theoretical (Y_{tbmc}) or practical (Y_{pbmc}) biomethane potential, billion m³; Y_c is the yield of crop, 10⁴ ton; SGR is the straw grain ratio; CR is the residue collection rate; and BMP can be the theoretical (TBMP) or practical (PBMP) biochemical methane potential, L CH₄·(g VS)⁻¹.

2.3. Biomethane potential of livestock manure

The biomethane potential of livestock manure was calculated based on the manure production and BMP. Different with crop residue, the production of livestock manure depends on the yield of livestock, excretion coefficient, livestock raising cycle and the general manure collection rate.

In this work, the biomethane potential of crop residue was calculated by Eq. (6):

$$Y_{\text{bml}} = \sum_i^n Y_{li} \times P_i \times T_i \times CR_i \times VS_i \times BMP_i \quad (6)$$

where Y_{bml} is the biomethane potential of livestock manure and can be the theoretical (Y_{tbml}) or practical (Y_{pbml}) biomethane potential, billion m³; Y_l is the yield of livestock, 10⁴ capita; P is the livestock excretion coefficient, kg·capita⁻¹·d⁻¹; and T is the livestock raising cycle, d.

2.4. Biomethane potential of energy crop planted on marginal land

In order to calculate the biomethane potential of energy crop, we collected the data of different marginal land terrains and selected suitable energy crop species for planting. Depends on the general yield of different energy crop, their BMP and the marginal land area selected, the calculation of biomethane potential of energy crop is shown in Eq. (7):

$$Y_{bme} = \sum_i^n Y_{dei} \times VS_i \times BMP_i \times S_i \quad (7)$$

where Y_{bme} is the biomethane potential of energy crop planted on the marginal lands and it can be the theoretical (Y_{tbme}) or practical (Y_{pbme}) biomethane potential, billion m^3 ; Y_{dei} is the general yield of energy crop in dry-basis on the marginal land, $t \cdot hm^{-2} \cdot a^{-1}$; S is the area of each marginal land, million hm^2 .

2.5. Biomethane potential of municipal solid waste

Different from crop residue and manure, the composition of municipal solid waste is closely related to people's living condition and changed greatly with season and region, which means that the elemental composition in a certain region can't represent the nation-wide elemental composition. However, very few reports are involved with the precise data of different elemental compositions in national municipal solid waste, so in this work, we didn't use the BMP method to estimate the biomethane potential of municipal solid waste across the country. Instead, an approach to estimate the amount of nation-wide methane emissions from landfill to atmosphere was established by intergovernmental panel on climate change (IPCC), and the formula is shown in Eq. (8) [29]:

$$Q = (MSW_T \times MSW_F \times MCF \times DOC \times DOC_F \times F \times 16/12 - R) \times (1 - OX) \quad (8)$$

where Q is the amount of methane emissions from municipal solid waste, billion m^3 ; MSW_T is the municipal solid waste production, $10^4 t$; MSW_F is the municipal solid waste processing ratio; MCF is the methane correction factor; DOC is the biodegradable organic carbon content in municipal solid waste, wt%; DOC_F is the decomposition proportion of biodegradable organic carbon; F is general methane content in landfill gas; $16/12$ is the coefficient of carbon transfer into CH_4 , which is denoted by M in this work; R is the amount of methane already recovered, billion m^3 ; and OX is the methane oxidation factor.

In the approach proposed by IPCC, we can observe that it also means the organic carbon in municipal solid waste completely transfers into the landfill gas during digestion process, and the carbon distribution ratio is determined by the general content of methane in landfill gas. Moreover, the key parameter needed in this formula is the carbon content of nation-wide municipal solid waste, which have reported in some studies. In this work, this formula was made some modification, and used to calculate the biomethane potential of municipal solid waste in China. In the modified formula, Y_{MSW} was the amount of municipal solid waste clean-up, the parameter MCF which depends on the digestion condition was changed to correspond to the condition in anaerobic fermentation reactor, so it could be applied to biogas, and degradable organic carbon (DOC) was used to indicate biodegradability of biomass which correspond to the practical biomethane potential. Meanwhile, the total organic carbon content (TOC) in municipal solid waste could be used to calculate the theoretical biomethane potential in municipal solid waste. R and OX were external factor, we removed it. The modified IPCC approach used in this work is given by Eqs. (9) and (10):

$$Y_{tbmm} = Y_{MSW} \times MCF \times TOC \times F \times M \quad (9)$$

$$Y_{pbmm} = Y_{MSW} \times MCF \times DOC \times F \times M \quad (10)$$

where Y_{bmm} is biomethane potential of municipal solid waste and it can be the theoretical (Y_{tbmm}) or practical (Y_{pbmm}) biomethane potential, billion m^3 ; Y_{MSW} is the amount of municipal solid waste, $10^4 t$; MCF is related to the landfill management condition and equal to one when the waste is managed well in a complete anaerobic condition [29]; F is the methane content of biogas due to biomethane is upgraded from biogas; M is the coefficient of carbon transfer into CH_4 , equal to $16/12$.

2.6. Biomethane potential of sewage sludge

Similar to municipal solid waste, the composition of sewage sludge also changes greatly with the season and region and IPCC [29] has developed a method to estimate the amount of nation-wide methane emissions from sewage sludge, as given in Eq. (11):

$$Q = (TOW - S) \times B_o \times MCF - R \quad (11)$$

where Q is the amount of methane emissions from waste water, billion m^3 ; TOW is the total organic material in waste water, $(kg \text{ COD}) \cdot a^{-1}$; S is the organic component removed from sludge, $(kg \text{ COD}) \cdot a^{-1}$; B_o is the maximum methane production capacity of sewage recommended by IPCC experts, $kg \text{ CH}_4 \cdot (kg \text{ COD})^{-1}$; MCF is the methane correction factor; and R is the amount of methane already recovered, billion m^3 .

In the IPCC formula, chemical oxygen demand (COD) was used to represent the organic matter content in sewage sludge, and B_o ($kg \text{ CH}_4 \cdot (kg \text{ COD})^{-1}$) was used as the key parameter. In our work, B_o was used to represent the theoretical methane production capacity and expressed as B_{to} . Meanwhile, B_{po} was used to represent the practical methane production capacity of sewage sludge in China collected from literature. MCF was changed to correspond to the condition in anaerobic digestion reactor. R is external factor. The modified equation is shown as Eqs. (12) and (13):

$$Y_{tbms} = Y_{COD} \times B_{to} \times MCF \quad (12)$$

$$Y_{pbms} = Y_{COD} \times B_{po} \times MCF \quad (13)$$

where Y_{bms} is the biomethane potential of sewage sludge and it can be either the theoretical (Y_{tbms}) or the practical (Y_{pbms}) biomethane potential, billion m^3 ; Y_{COD} is the total COD emission from sewage sludge, ton COD ; MCF is related to the sewage sludge treatment situation and equal to 0.8 when sewage sludge was treated in an anaerobic reactor [29].

3. Results and Discussions

3.1. Theoretical and practical biochemical methane potentials

Based on Buswell formula, the TBMP and PBMP of different biomass was calculated, and the calculation results of the biomass other than municipal solid waste and sewage sludge are listed in Table 1 and illustrated Fig. 1. In calculation, the data was taken from Phyllis2 (biomass database designed by energy research center of the Netherlands) [30] and the literature [28,31,34]. Meanwhile, the data of livestock manure was taken from the literature [28,32,33].

Based on the calculation, it can be seen that the horse manure had the maximum TBMP. This is mainly due to its high carbon content and low oxygen content. However, the PBMP of horse manure was low because of the high lignin content. In contrast, the sugar beet top was the most promising biomass with a maximum PBMP value of $0.3338 (L \text{ CH}_4 \cdot (g \text{ VS})^{-1})$. This is because the main composition in sugar beet top is saccharide and the lignin content is very low.

Table 1
TBMP and PBMP of different biomass

Biomass	C (by mass, dry)/%	H (by mass, dry)/%	N (by mass, dry)/%	O (by mass, dry)/%	TBMP/L CH ₄ · (g VS) ⁻¹	C _{Lignin} (by mass, VS)/%	BD/%	PBMP/L CH ₄ · (g VS) ⁻¹
Rice straw [28]	39.7	5.4	0.9	38.2	0.4526	12.8	61.9 ^①	0.2802
Rice husk [28]	41.4	4.9	0.4	35.3	0.4832	24.8	10.0 ^①	0.0483
Wheat straw [28]	39.9	5.7	0.4	39.6	0.4549	8.8	53.7 ^①	0.2443
Corn stalk [28]	43.2	5.9	0.8	40.2	0.4675	11.4	51.4 ^①	0.2403
Corn cob [30]	46.5	5.7	0.5	44.1	0.4489	16.9	34.8 ^②	0.1561
Bean stalk [30]	43.0	5.6	0.8	44.9	0.4184	17.0	34.5 ^②	0.1444
Cotton stalk [30]	47.6	6.0	0.3	42.9	0.4737	15.5	38.6 ^②	0.1826
Peanut shell [30]	47.6	5.4	1.7	37.1	0.4943	24.0	15.6 ^②	0.0771
Peanut straw [31]	43.9	5.7	1.6	48.2	0.3917	12.5	46.7 ^②	0.1827
Rape stalk [31]	45.4	6.0	0.7	47.0	0.4251	21.4	22.6 ^②	0.0962
Sesame straw [31]	44.9	5.9	0.7	47.9	0.4132	19.2	28.6 ^②	0.1180
Sugarcane top [30]	39.8	5.5	0.2	46.8	0.3888	18.4	30.7 ^②	0.1195
Sugarcane bagasse [30]	45.5	5.3	0.2	36.7	0.5038	21.1	23.4 ^②	0.1180
Sugar beet top [30]	44.5	5.9	1.8	42.8	0.4403	1.7	75.8 ^②	0.3338
Sugar beet pulp [30]	35.5	4.74	1.28	34.09	0.4424	4.7	67.7 ^②	0.2995
Pig manure [28]	34.8	4.7	2.2	30.3	0.4664	5.9	68.7 ^②	0.3204
Cow manure [28]	37.6	5.1	2.8	28.9	0.5031	23.3	10.1 ^①	0.0508
Chicken manure [28]	35.9	5.1	3.4	30.5	0.4663	2.1	63.0 ^①	0.2938
Sheep manure [32]	30.7	4.6	1.8	44.0	0.3073	25.4	11.8 ^②	0.0363
Horse manure [33]	46.9	4.2	2.3	26.3	0.5623	22.1 [30]	20.7 ^②	0.1166
Switch grass [28]	43.6	6.4	0.4	44.8	0.4466	11.8	54.9 ^①	0.2452
Miscanthus [30]	47.0	5.7	0.5	42.1	0.4682	22.7	19.1 ^②	0.0895
Sweet sorghum [30]	47.3	5.8	0.4	41.7	0.4767	6.3	63.4 ^②	0.3022
Alfalfa [30]	46.7	5.9	3.1	35.6	0.4996	23.1	18.0 ^②	0.0901
Napier grass [30]	45.2	6.0	–	45.7	0.4419	19.3 [34]	28.3 ^②	0.1250
Giant reed [30]	44.1	5.2	0.3	47.4	0.4000	18.6	30.2 ^②	0.1207

^① The value of BD was taken from reference [28].

^② The value of BD was calculated by Eq. (3) [28].

3.2. Biomethane potential of agricultural waste

Both crop residue and livestock manure can be classified as the agricultural waste. The biomethane potentials of main crop residue and livestock manure in China were listed in Tables 2 and 3. For the crop residue, the total collection quantity in 2010 was 6.484×10^8 ton, and the estimated theoretical biomethane potential of crop residue was 237.67 billion m³. Among the studied crop residue, the corn stalk represented the biggest contribution with a proportion of 28.02%, and it was followed by the rice straw (21.67%) and wheat straw (16.74%). The total

practical biomethane potential was 110.82 billion m³, where the corn stalk shared the biggest contribution with a proportion of 30.88% and it was followed by the rice straw (28.77%) and wheat straw (19.28%). Furthermore, the proportions of corn stalk, rice straw and wheat straw in practical biomethane potential were higher than those in theoretical biomethane potential because of their low lignin contents. The average biodegradability of crop residue in China was estimated to be 46.63%

For livestock manure, the total collection quantity in 2010 was 1.195×10^9 ton. The average biodegradability of livestock manure in China was estimated to be 31.53%. The estimated theoretical biomethane

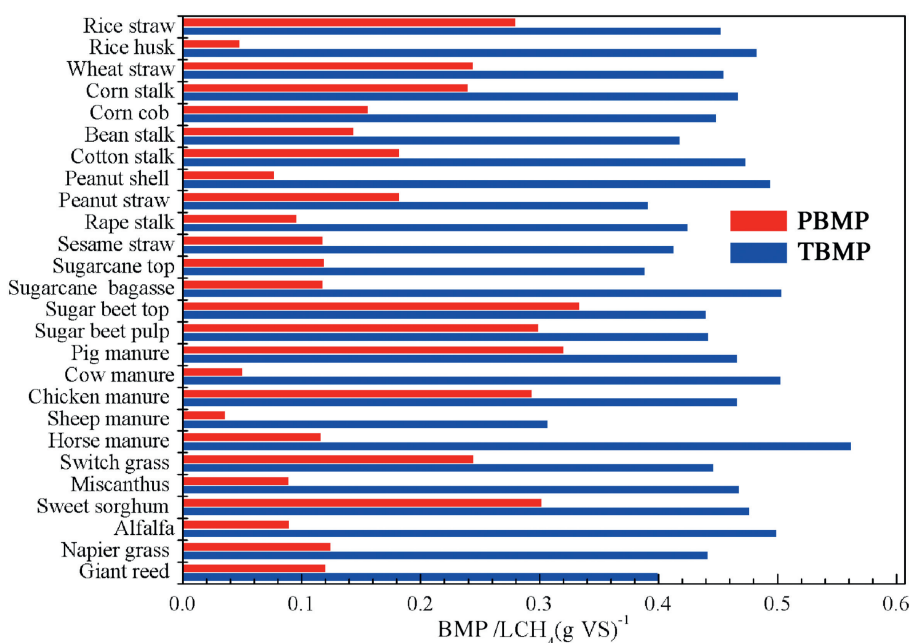


Fig. 1. Histogram of TBMP and PBMP for different biomass.

Table 2
Biomethane potential of crop residues in China

Crop	Y_c [35] $\times 10^{-4}$ /t	SGR [36]	CR [37]	VS (by mass, ar)/%	TBMP/L $CH_4 \cdot (g VS)^{-1}$	Y_{tbmc} /billion m^3	PBMP/L $CH_4 \cdot (g VS)^{-1}$	Y_{pbmc} /billion m^3
Rice	19,576.1	0.95 (straw)	0.75	81.60 [28]	0.4526	51.51	0.2802	31.89
		0.21 (husk)	0.75	74.30 [28]	0.4832	11.07	0.0483	1.11
Wheat	11,518.1	1.30 (straw)	0.75	77.90 [28]	0.4549	39.79	0.2443	22.37
Corn	17,724.5	1.10 (straw)	0.95	76.90 [28]	0.4675	66.59	0.2403	34.23
		0.21 (cob)	0.95	90.06 [30]	0.4489	14.29	0.1561	4.97
Bean	1896.5	1.60 (straw)	0.88	85.93 [30]	0.4184	9.60	0.1444	3.31
Cotton	596.1	5.00 (straw)	0.90	82.32 [30]	0.4737	10.46	0.1826	4.03
Peanut	1564.4	0.28 (husk)	0.88	84.51 [30]	0.4943	1.61	0.0771	0.25
		1.50 (straw)	0.88	84.01 [31]	0.3917	6.79	0.1827	3.17
Rapeseed	1308.2	2.70 (straw)	0.89	83.86 [31]	0.4251	11.20	0.0962	2.54
Sesame	58.7	2.80 (straw)	0.88	83.44 [31]	0.4132	0.50	0.1180	0.14
Sugarcane	11,078.9	0.10 (straw)	0.88	92.28 [30] (dry)	0.3888	3.50	0.1195	1.07
		0.24 (bagasse)	0.88	87.26 [30] (dry)	0.5038	10.27	0.1180	2.41
Sugar beet	929.6	0.10 (straw)	0.88	95.20 [30] (dry)	0.4403	0.34	0.3338	0.26
		0.04 (pulp)	0.88	75.61 [30] (dry)	0.4424	0.11	0.2995	0.07
Total	66,251.1					237.67		110.82

potential was 147.36 billion m^3 where the cattle manure shared the biggest contribution with a proportion of 57.70% and was followed by the pig manure (29.52%). The estimated practical biomethane potential for live-stock manure was 46.46 billion m^3 where the pig manure was the biggest contribution with a proportion of 64.33% while the cattle manure was the second biggest contribution (18.49%). This is mainly because of the high lignin content in the cattle manure.

3.3. Biomethane potential of energy crops planted on marginal lands

Considering the actual situation in China, we assumed that the energy crops would be planted on the marginal lands to increase the biomethane production. During the calculation, the areas of marginal lands and the selection of energy crops are two important factors.

Marginal lands refer to the unexploited lands which are unsuitable for food but can be used for energy plants [43]. Kou *et al.* [44] considered five kinds of marginal lands that are suitable for energy crops in China and calculated the total area of the marginal lands with a value of 26.80 million hm^2 . Furthermore, Shi [45] thought that the barren hill and sandy land can also be used to plant energy crops, and their total area is 57.04 million hm^2 . However, they only used the land slope as the key factor to select the availabilities of marginal land, and the classification was unclear. Recently, Jiang *et al.* [46] studied the change of the marginal lands that are suitable for energy crops during 1990–2010 in China based on the GIS technology, and in their research, limiting factor (land slope, temperature, moisture, soil character, energy plant characteristics, policy limiting factor and land use data in China) were used to screen the appropriate marginal lands for energy crops planting. They reported the spatial–temporal distribution and area of different marginal land terrains suitable for energy crops in China. In this work, the data

reported by Jiang was used to estimate the biomethane potential of energy crops in the marginal lands. The spatial distribution of the marginal lands was depicted in Fig. 2. It should be mentioned that data of the shrub land as well as dense and moderate-dense grasslands was not used because the exploitation of these marginal lands can't cause eco-environmental problem [47]. The areas of different marginal land terrains suitable for planting energy crops in China are listed in Table 4.

Because the marginal land suitable for energy crops in Jiang's work indicated that this land could meet the minimum limits of necessary constraints for energy plant growth, so for marginal land, the appropriate growing land type of different energy crops became the main marginal land limiting factor. In terms of energy crop, the kind of energy crops planted on marginal land is another key factor that should to be considered for the biomethane potential calculation. In this work, six kinds of promising energy crops (switch grass, miscanthus, sweet sorghum, alfalfa, napier grass, giant reed) and three limiting factors (Y_{de} , TBMP, types of marginal lands) were considered in selecting suitable energy crops to achieve the largest biomethane potential. The theoretical and practical biomethane potentials of different energy crops were calculated based on Eq. (7), and the calculated results are listed in Table 5.

It can be seen that sweet sorghum and napier grass were screened to be the two most promising energy crops planted on the marginal lands, due to the maximum theoretical biomethane potential on their appropriate growing land type. Then the practical biomethane potential was calculated based on the two energy crop selected. Sweet sorghum was suitable to plant on the alkaline and bare lands, and in China the corresponding available area could be 4.213 million hm^2 . Meanwhile, the shoal/bottom land as well as the sparse-forest and sparse-grass lands were suitable for planting napier grass, and the total available area

Table 3
Biomethane potential of livestock manure in China

Livestock	$Y_l \times 10^{-4}$ [38]/capita	P [39,40]/ $kg \cdot capita^{-1} \cdot d^{-1}$	T [40,41]/d	CR [42]	VS (by mass, AR)	TBMP/L $CH_4 \cdot (g VS)^{-1}$	Y_{tbml} /billion m^3	PBMP/L $CH_4 \cdot (g VS)^{-1}$	Y_{pbml} /billion m^3
Pig	66,686.43	3.55	199	0.9	22.0 [28]	0.4664	43.51	0.3204	29.89
Draft cattle	2467.46	22.39	365	0.6	28.8 [28]	0.5031	17.53	0.0508	1.77
Beef cattle	6738.90	22.06	365	0.6	28.8 [28]	0.5031	47.18	0.0508	4.76
Dairy cattle	1420.07	45.10	365	0.6	28.8 [28]	0.5031	20.32	0.0508	2.05
Broiler chicken	958,347.00	0.14	55	0.6	19.5 [28]	0.4663	4.03	0.2938	2.54
Egg chicken	271,914.80	0.13	365	0.6	19.5 [28]	0.4663	7.04	0.2938	4.43
Sheep	28,087.89	0.87	365	0.6	40.8 [32]	0.3073	6.71	0.0363	0.79
Horse	677.06	5.90	365	0.6	21.3 [33]	0.5623	1.05	0.1166	0.22
Total	1,336,339.61						147.36		46.46

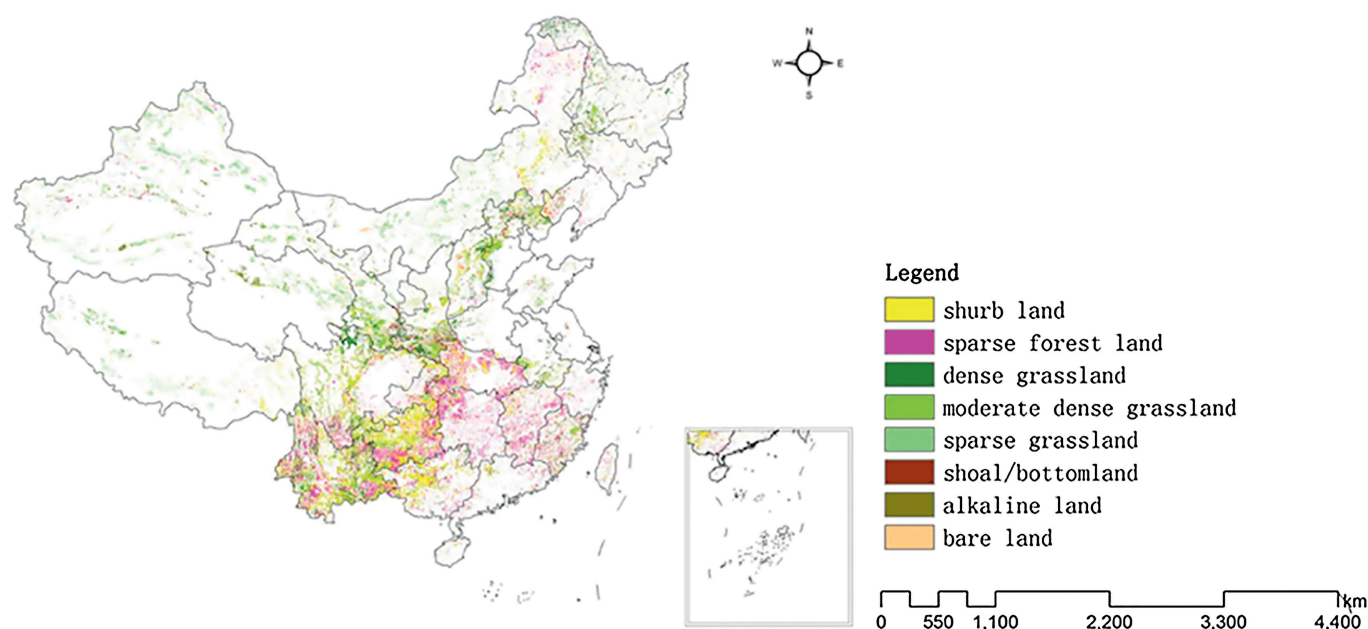


Fig. 2. Spatial distribution of the marginal lands suitable for energy crops in China in 2010 [46].

Table 4

Areas of different marginal land terrains suitable for energy crops in China in 2010 [46,47]

Marginal land	Sparse forest land	Sparse grassland	Shoal/bottom land	Alkaline land	Bare land	Total
Area/million hm ²	23.821	16.270	1.341	3.613	0.600	45.645

was 41.432 million hm². Based on this, the theoretical and practical biomethane potentials of energy crops on the marginal lands in China were 473.65 and 145.72 billion m³, respectively.

3.4. Biomethane potential of municipal solid wastes

The theoretical and practical biomethane potentials of municipal solid waste in China were calculated by Eqs. (9) and (10). The calculation results were listed in Table 6. The total organic carbon (TOC) and the biodegradable organic carbon (DOC) were used for the calculation of the theoretical and practical biomethane potentials, respectively. Because very few reports including the TOC content of nation-wide

municipal solid wastes, we used the average organic material (OM) content and the empirical constant (TOC/OM) to calculate the TOC content. MCF was set to be 1 for municipal solid waste due to the complete anaerobic condition of biomethane production. The general methane content (F) in biogas was set to be 0.5. Therefore, the theoretical and practical biomethane potentials of municipal solid wastes in China were estimated to be 20.22 and 9.58 billion m³, respectively, and their average biodegradability was 47.38%.

3.5. Biomethane potential of sewage sludge

The biomethane potential of sewage sludge (industrial and domestic sewage sludge) was calculated based on Eqs. (12) and (13). The calculation results are listed in Table 7. MCF from IPCC was set to be 0.8 for sewage sludge because of the complete anaerobic condition of biomethane production. B_{to} and B_{po} were used for calculating the theoretical and practical biomethane potential, respectively. The theoretical and practical biomethane potentials of sewage in China were estimated to be 9.88 and 3.72 billion m³, respectively, and their average biodegradability was 37.65%. Compared with the domestic sewage sludge, industrial sewage sludge have higher practical biomethane potential,

Table 5

Biomethane potential of promoting energy crops planted on marginal lands in China

Energy crop	$Y_{de}^{\text{①}}/t \cdot hm^{-2} \cdot a^{-1}$	TBMP/ $L CH_4 \cdot (g VS)^{-1}$	Appropriate marginal land type	$S [46,47]/million hm^2$	$Y_{tbme}/billion m^3$	PBMP/ $L CH_4 \cdot (g VS)^{-1}$	$Y_{pbme}/billion m^3$
Switch grass	14.20 [48]	0.4466	Sparse forest land, sparse grassland, bare land [49,50]	–	–	0.2452	–
Miscanthus	11.70 [48]	0.4682	Sparse forest land, sparse grassland, shoal/bottom land [49,50]	–	–	0.0895	–
Sweet sorghum	17.45 [49]	0.4767	Sparse forest land, sparse grassland, alkaline land, bare land [49,51]	4.213	33.40	0.3022	21.17
Alfalfa	10.00 [48]	0.4996	Sparse forest land, sparse grassland, bare land [51]	–	–	0.0901	–
Napier grass	25.50 [51]	0.4419	Sparse forest land, sparse grassland, shoal/bottom land [49,51,52]	41.432	440.25	0.1250	124.55
Giant reed	16.55 [53]	0.4000	Sparse forest land, sparse grassland, shoal/bottom land, alkaline land, bare land [49,50]	–	–	0.1207	–
Total					473.65		145.72

① The average Y_{de} of energy crops on marginal lands were set to be the half of the Y_{de} on normal arable land or the Y_{de} on medium arable land in China, because of bad ecological environment of marginal land.

Table 6
Biomethane potential of municipal solid wastes in China

$Y_{MSW} \times 10^{-4}$ [54]/t	MCF [29]	F	OM [55] ^① (by mass, dry)	TOC/OM [56] empirical constant	TOC (by mass, ar)	Y_{tbmm} /billion m ³	DOC [55] (by mass, ar)	Y_{pbmm} /billion m ³
15,804.8	1	0.5	50.75	0.47	13.72	20.22	6.50	9.58

^① The average organic material content of municipal solid waste in China.

Table 7
Biomethane potential of sewage sludge in China

	Y_{COD} [54,57]/ton	MCF [29]	B_{to} [29]/kg CH ₄ ·(kg COD) ⁻¹	Y_{tbms} /billion m ³	B_{po} [58]/kg CH ₄ ·(kg COD) ⁻¹	Y_{pbms} /billion m ³
Industrial sewage sludge	18,501,519.3	0.8	0.25	5.17	0.140	2.89
Domestic sewage sludge	16,858,900.0	0.8	0.25	4.71	0.044	0.83
Total	35,360,419.3			9.88		3.72

which is due to the high organic matter content in industrial sewage sludge.

3.6. Biomethane distribution and development prospect in China

Based on the above calculation, the biomethane potential distribution of different kinds of biomass in China was indicated in Table 8. It can be seen that the energy crop shared the largest biomethane potential with a theoretical proportion of 53.29% and practical proportion (46.07%) respectively, this is probably due to its high biomass production and large potential planting area. And it showed that planting energy crop can be the most promising way to enhance biomethane production. For the agricultural wastes including crop residue and livestock manure, their total biomethane potential was slightly lower than that of energy crops. However, the huge quantity of agricultural wastes cause serious environmental pollution each year, converting the agricultural wastes into biomethane, in addition to get large number of bioenergy, but also reduce pollution. Agricultural waste should be the preferential development biomass for biomethane production in China. Municipal solid waste and sewage sludge only had a small contribution to the total biomethane potential, which is probably due to the high inorganic matter content in it. Finally, the total theoretical and practical biomethane potentials in China were estimated to be 888.78 and 316.30 billion m³ respectively, and the general efficiency of the current anaerobic digestion process was calculated to be 35.59%.

The biomethane potential was compared with the latest Chinese natural gas consumption in Table 9, which shows that natural gas consumption only accounts for 48.15% of the practical biomethane

potential and 17.14% of the theoretical biomethane potential in China. Considering the huge amount of CO₂ emissions from natural gas and other fossil fuels in China, as well as the clean and renewable benefit from biomethane, it will be very wise to develop biomethane production rapidly in China. And according to the Chinese energy development strategy, in 2020, 400 billion m³ natural gas will be needed in China [3]. Moreover, the total practical biomethane potential in China is slightly lower than the demand of natural gas set for 2020, but the maximum biomethane potential is more than twice of the natural gas demand. Therefore, with the development of anaerobic digestion process, the demand of natural gas set for in 2020 can be met. Developing biomethane is a promising way for energy supplement.

4. Conclusions

During the calculation of energy crop biomethane potential, sweet sorghum and napier grass were selected to be the two most promising energy crops planted on marginal land for biomethane production in China from the screening process designed. And five kinds of marginal land terrains were chosen for the energy crop planting. The theoretical and practical biomethane potential of energy crops on the marginal lands in China were 473.65 and 145.72 billion m³, respectively. And planting energy crops on marginal lands can be the most promising way to enhance biomethane production in China.

The total theoretical and practical biomethane potential of China were further estimated to be 888.78 and 316.30 billion m³, and the general efficiency of the current anaerobic fermentation process was calculated to be 35.59%. Energy crop shared both the largest theoretical and practical biomethane potentials, and sweet sorghum and napier

Table 8
The distribution of theoretical and practical biomethane potentials in China

Raw material	Theoretical biomethane potential/billion m ³	Contribution ratio for theoretical biomethane potential/%	Practical biomethane potential/billion m ³	Contribution ratio for practical biomethane potential/%
Crop residue	237.67	26.74	110.82	35.04
Livestock manure	147.36	16.58	46.46	14.69
Municipal solid waste	20.22	2.28	9.58	3.03
Energy crop	473.65	53.29	145.72	46.07
Sewage sludge	9.88	1.11	3.72	1.17
Total	888.78	100	316.30	100

Table 9
Biomethane potential compared with natural gas consumption in China

Energy	Quantity/billion m ³	Conversion coefficient [59]/kg·m ⁻³	Standard coal quantity/billion kg	Natural gas/biomethane/%
Natural gas	–	–	217.50 [60] ^①	–
Biomethane	888.78 (theoretical)	0.7140 (biogas)	1269.18	17.14
Biomethane	316.30 (practical)	0.7140 (biogas)	451.68	48.15

^① The quantity of natural gas was the consumption in China in 2013.

grass were screened to be the two most promising energy crop with a marginal land planting area 4.213 and 41.432 million hm^2 respectively. Compared with energy crop, agricultural wastes have a slightly lower biomethane potential with theoretical proportion (43.32%) and practical proportion (49.73%) respectively. Municipal solid waste and sewage sludge only had a minor contribution to the total biomethane potential.

When compared with other fossil energy, Chinese natural gas consumption in 2013 only accounts for 48.15% of the practical biomethane potential and 17.14% of the theoretical biomethane potential. And the demand for natural gas in 2020 could be met with the development of anaerobic digestion technology, developing biomethane is a promising way for energy supplement in China.

Nomenclature

BD	biodegradability, %
BMP	biochemical methane potential, $\text{L CH}_4 \cdot (\text{g VS})^{-1}$
B_{po}	practical methane production capacity of sewage sludge, $\text{kg CH}_4 \cdot (\text{kg COD})^{-1}$
B_{to}	theoretical methane production capacity of sewage sludge, $\text{kg CH}_4 \cdot (\text{kg COD})^{-1}$
CR	collection rate
C_{lignin}	lignin content, wt% VS
DOC	biodegradable organic carbon content in municipal solid waste, wt%, AR
F	general methane content in biogas
M	coefficient of carbon transfer into CH_4
MCF	methane correction factor
OM	average organic material content of municipal solid waste, wt%, dry
OX	methane oxidation factor
P	livestock excretion coefficient, $\text{kg} \cdot \text{capita}^{-1} \cdot \text{d}^{-1}$
PBMP	practical biochemical methane potential, $\text{L CH}_4 \cdot (\text{g VS})^{-1}$
R	the amount of methane recovered, billion m^3
S	area of each marginal land, million hm^2
SGR	straw grain ratio
T	livestock raising cycle, d
TBMP	theoretical biochemical methane potential, $\text{L CH}_4 \cdot (\text{g VS})^{-1}$
TOC	total organic carbon content in municipal solid waste, wt%, AR
VS	volatile solid, wt%, AR, dry
V_{m}	the molar volume of methane at standard temperature and pressure, $\text{m}^3 \cdot \text{mol}^{-1}$
Y_{bmc}	biomethane potential of crop residue, billion m^3
Y_{bme}	biomethane potential of energy crop, billion m^3
Y_{bml}	biomethane potential of livestock, billion m^3
Y_{bmm}	biomethane potential of municipal solid wastes, billion m^3
Y_{bms}	biomethane potential of sewage sludge, billion m^3
Y_{c}	the yield of crop, 10^4 t
Y_{COD}	the total chemical oxygen demand emission from sewage sludge, t
Y_{de}	general yield of energy crop in dry-basis on the marginal land, $\text{t} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$
Y_{l}	the yield of livestock, 10^4 capita
Y_{MSW}	the amount of municipal solid waste, 10^4 t
Y_{pbmc}	practical biomethane potential of crop residue, billion m^3
Y_{pbme}	practical biomethane potential of energy crop, billion m^3
Y_{pbml}	practical biomethane potential of livestock, billion m^3
Y_{pbmm}	practical biomethane potential of municipal solid wastes, billion m^3
Y_{pbms}	practical biomethane potential of sewage sludge, billion m^3
Y_{tbmc}	theoretical biomethane potential of crop residue, billion m^3
Y_{tbme}	theoretical biomethane potential of energy crop, billion m^3
Y_{tbml}	theoretical biomethane potential of livestock, billion m^3
Y_{tbmm}	theoretical biomethane potential of municipal solid wastes, billion m^3
Y_{tbms}	theoretical biomethane potential of sewage sludge, billion m^3

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